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ESTIMATION OF THE EFFECT OF STAND DENSITY ON SCOTS PINE STEM FORM

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Abstract. It was attempted to study the effect of stand density on the stem form of Scots pine trees. To estimate stand density the index SDI of Reineke (1933) was used. The analyses carried out showed that the stand density index has no significant effect on values of breast height and specific form factors. The detailed analysis of the stem form curve permitted to conclude that stand density affects the form of the top part of the stem profile. Trees in stands of low density in comparison with trees in stands of high density are characterized by lower values of relative diameters in the top part of the stem, especially in the range from 0.7 to 0.9 of the tree height. However, differences in stem profiles of trees from stands of different density are significant only in the range from 0.82 to 0.89 of the relative height. Using the stand density index in the empirical equation for determination of volume does not increase its accuracy.

Key words: stand density index (SDI), form factor, stem profile, stem volume

INTRODUCTION

The determination of volume of trees and their parts on the basis of two basic characteristics, DBH and height, advisable from the practical point of view, is burdened with errors resulting from stem form variation. This variation mainly results from differences in diameter growth rate at different stem heights as well as from differences in tree height increments [Mitscherlich 1970]. These differences may be caused by many factors, e.g. species variation, climatic factors, site quality, age, defoliation, and genetic factors [Muhairwe 1994, Karlsson 2000, Socha and Kulej 2005]. Tapering of the tree stems is also affected by length of the crown [Larson 1963, Socha 2002] and stand density [Ahnlund Ulvcrona et al. 2007]. Within the crown, tree diameters at individual heights are generally smaller in comparison with trees of the same size but of shorter crowns. Sometimes genetic factors decide on the stem form. In studies concerning provenance variation of grand fir [Socha and Kulej 2005] it was found that stem form variation is affected by the provenance. Provenances of which mother stands grew at

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higher altitudes were characterized by greater stem volume in comparison with provenances of lower altitudes, at equal DBH and height. In the case of European beech Dudzińska [2002] found differences between mountain and lowland trees in respect of the stem form. Similar conclusions were drawn for the Norway spruce stem form [Ciosmak 2002, Socha 2002].

The regularity about the distribution of diameter increment, changing along the stem depending on stand density, is commonly known [Assmann 1968]. The diameter increment in the bottom part of the stem increases, and in the top part decreases, with decrease of stand density. In consequence, the lowering of stand density causes decreasing of slenderness of trees thus making them more stable. It also increases their tapering. Although the influence of stand density on stem slenderness and tapering is obvious, there is no definite information whether it significantly affects the form factor and fullness of the stem. According to Grochowski [1958] the change of tapering does not mean the change of fullness. Trees significantly differing in tapering or slenderness may be characterized by the same fullness. Therefore the question arises whether stand density, apart from the effect on slenderness and tapering of trees, also significantly affects fullness of stems.

The objectives of this study were to analyse the effect of stand density on fullness of Scots pine stems, and to try to estimate the possibility of using stand density as the independent variable in empirical equations for determination of volume.

MATERIAL

The study was carried out on the empirical material collected in Scots pine stands of the Niepolomice Forest. A regular grid (750 × 750 m) of 5-are circular plots was established in this forest complex under the project Forest Environmental Monitoring and Management System (FOREMMS; 5FP IST; Fig. 1). In each plot DBH of all trees was measured. In a small circle, 2.5 are in area, height of all trees was measured. On the basis of these measurements average values of DBH and height were computed and used in selection of sample trees. In the circular plot, trees of DBH and height, nearest to average values, were found. These trees were felled, and discs from their stems were taken for the stem analysis. In the analysis, the first stem section was 1 m long, while the remaining sections were 2 m long for trees of smaller height and 3 m long for taller trees. The discs were cut at the middle of each stem section, as well as at the tree base and breast height. From among 186 circular plots, in 116 plots Scots pine was the main tree species, while in other plots oak or alder predominated. After discarding plots with very young plantations, finally, 109 average Scots pine trees were selected.

METHODS

In places of disc cutting diameters outside and inside bark were measured. Next, for each tree, diameters at 100 relative heights (0.00; 0.01; 0.02 ... 0.99) were computed by interpolation using the Hermite's method of the third degree spline functions (Fig. 2) [Kosma 1999].

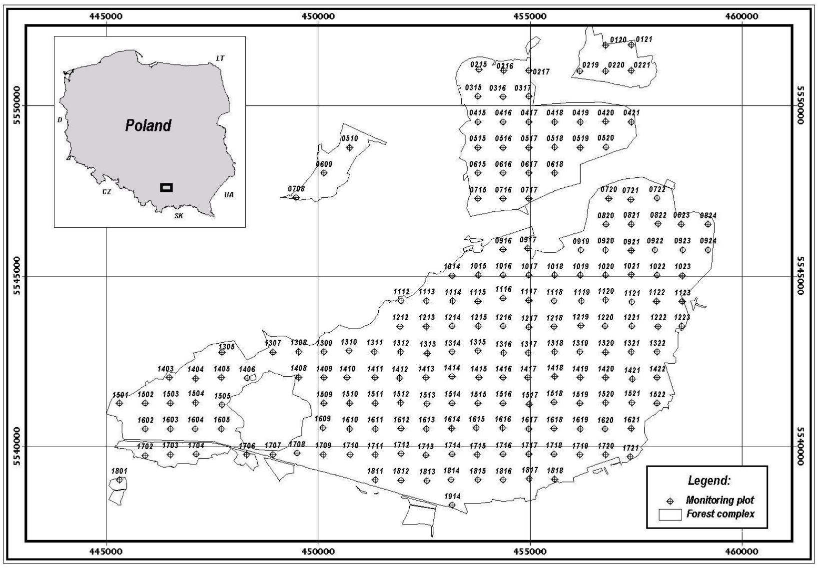

Fig. 1. The regular grid of FOREMMS monitoring plots in the Niepolomice Forest [Socha and Wężyk 2007]

Rys. 1. Regularna siatka powierzchni monitoringowych FOREMMS w Puszczy Niepołomickiej [Socha i Wężyk 2007]

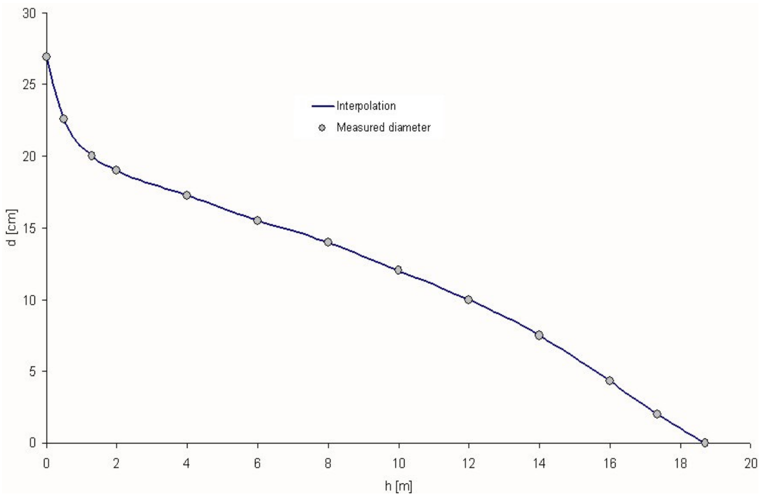

Fig. 2. The example of interpolation of diameters measured on the stem according to the Hermite's method of spline functions (h = 18.7 m, DBH = 20.05 cm)

Rys. 2. Przykład interpolacji grubości pomierzonych na strzale metodą funkcji sklejanych Hermite'a (h = 18,7 m, bhd = 20,05 cm)

Volume of the stem with and without bark was computed by the section method using sections equal to 0.01 of the tree length. Section volumes were computed using Smalian's equation. For each tree values of form factors were computed, i.e. the breast-high and specific form factors for which a comparative profile was computed on the basis of diameters at relative heights from 0.1 to 0.7.

In order to determine the relationship between the stem form and the stand density the stand density index (SDI) of Reineke [1933] was computed. This index is commonly used to determine stand density [Wodall et al. 2003, Zeide 2005] and it is a relative measure of density elaborated for even-aged stands. It is determined on the basis of the number of trees per hectare (TPH) and average DBH (DBH_q; equation 1).

$$SDI = TPH\left(\frac{DBH_q}{25}\right)^{1.6} \tag{1}$$

Study plots were divided into three groups depending on the stand density index:
1 – stands of the smallest density index ($SDI < 600$),
2 – stands of the average density index ($600 \leq SDI \leq 700$),
3 – stands of the highest density index ($SDI > 700$).

There were 32 trees in the first, 38 trees in the second, and 39 trees in the third stand density groups.

For each tree relative diameters d_w at 100 relative heights were computed (equation 2).

$$d_{wj} = \frac{d_j}{d_{0.1h}} \tag{2}$$

where:
d_{wj} – relative diameter at height j,
d_j – diameter at height j ($j = 0.00$ h, 0.01 h, 0.02 h, ... 0.99 h).

These diameters were used to compute mean relative diameters at individual stem heights for trees of three stand density groups. This way the average stem form curves were obtained for respective density groups.

Because differences in the stem profile may result from differences in diameter and height of trees the analysis of variance was used to find out whether mean heights and diameters of trees in individual density groups are significantly different.

The analysis of variance, preceded by the variance homogeneity test, was also used to compare the stem form curves of trees originating from stands of different density. For this purpose, for each of the 100 relative heights, the zero hypothesis stating that mean relative diameters at individual heights do not differ significantly depending on stand density, was tested.

The real aim of studies on the stem form variation is to improve methods of volume determination. For this reason it was attempted to find out whether using the stand density index may increase the exactness of empirical equations for determination of volume. Thus, a model of the linearized non-linear regression was used. In this model the tree volume was a dependent variable, and the stand density index (SDI), height (H), and DBH were independent variables. In the case of tree volume equations the distribution of residual components is of a heteroscedastic nature, which means that the residual variance increases as the explained values increase. This causes an erroneous estimation of significance of model parameters. For this reason, in order to correctly calculate the significance and values of the model parameters, its logarithmic transformation was used. Because the linear transformation lowers the value of independent variables the correcting factor (CF) was used [Zianis and Menuccini 2003].

The final form of the regression model was as follows:

$$\hat{V} = e^{\ln b_0 + b_1 \ln SDI + b_2 \ln DBH + b_3 \ln H + CF} + \varepsilon \tag{3}$$

where:

V – volume of a tree outside or inside bark,
b_0, b_1, b_2, b_3 – equation parameters,
H – tree height,
CF – correction factor equal $SEE^2/2$, and SEE is the standard error of the estimation:

$$SEE \sqrt{\frac{\left(\ln Y_i - \ln \hat{Y}_i\right)^2}{n - p}} \tag{4}$$

where:

Y_i – observed value of the dependent variable,
$\hat{Y}_i$ – determined value of the dependent variable.

To obtain homoscedasticity of residual components the parameters of equation 3 were computed after its logarithmic transformation. The significance of individual variables of the regression model, including the SDI, was tested using t statistics.

RESULTS

The sample trees analysed during this study were from 18 to 148 years old, and their DBH ranged from 12.3 to 55.3 cm (Table 1). In circular plots from which sample trees originated the stand density index varied from 294 to 994, while stand volume per hectare ranged from 76 to 561 $m^3 ha^{-1}$.

It was found that the stand density index is considerably correlated with stand basal area (Fig. 3). The coefficient of linear correlation for this relationship was 0.92. However, contrary to stand basal area, it does not depend on DBH and height of trees, and therefore it may be accepted as a better measure of stand density.

On the basis of a multiple regression no significant relationship between the breast-high form factor and the stand density index was found for Scots pine trees, while the SDI was correlated with value of true form factors $f_{0.3}$ and $f_{0.4}$. After elimination of the effect of DBH and height by taking into account these characteristics in the regression model the dependence of the SDI on $f_{0.3}$ and $f_{0.4}$ turned out, however, to be insignificant.

The detailed information on the stem form was obtained by comparison of the stem form curve of trees grouped according to the stand density index in three groups. The analysis of variance showed that the mean DBH and height in stand density groups under comparison did not differ significantly. Thus the results of analyses were not burdened with the effect of differences in values of these characteristics between groups.

Table 1. Characteristics of sample trees and plots
Tabela 1. Charakterystyka drzew próbnych i powierzchni badawczych

Object Obiekt	Characteristics Cecha	Mean Średnia	Minimum	Maximum	Standard deviation Odchylenie standardowe
Tree Drzewo	age, years – wiek, lata	72.7	18.0	148.0	31.7
	height – wysokość: H, m	24.0	11.6	32.4	4.1
	DBH, cm	29.8	12.3	55.3	8.1
Sample plots Powierzchnia próbna	breast height basal area, $m^2 \cdot ha^{-1}$ pole pierśnicowego przekroju	31.6	12.0	51.5	7.4
	stand volume – zasobność V_g, $m^3 \cdot ha^{-1}$	317	76	561	97
	number of trees – liczba drzew TPH	634	180	2380	341
	Stand Density Index – SDI	629	294	994	130

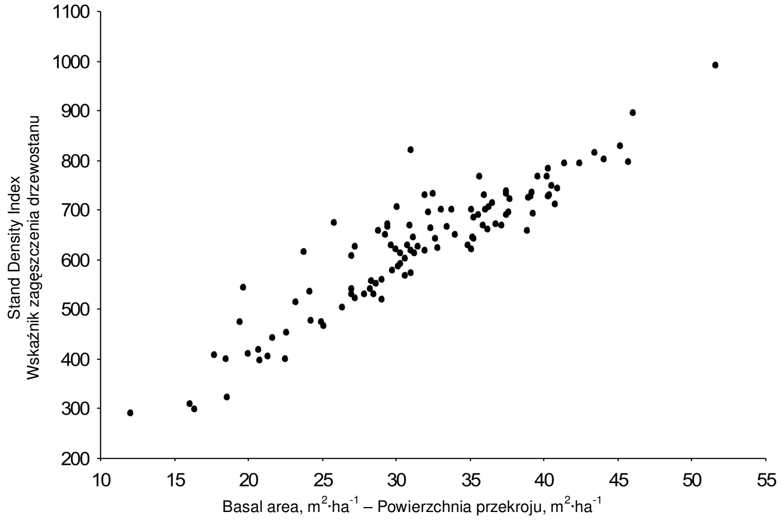

Fig. 3. Relationship between the stand density index and the stand basal area
Rys. 3. Zależność wskaźnika zagęszczenia drzewostanu (SDI) od pola pierśnicowego przekroju drzewostanu (BA)

When comparing average stem form curves of trees from three stand density groups it was found that the greatest differences in the progress of the stem form curve occurred in the top part of a tree. Trees originating from stands of the highest density index were characterized by greater relative diameters of the top part of the stem (Fig. 4). In the middle part of the stem, between about 0.2 and 0.5 h, trees from stands of the highest density were characterized by the smallest relative diameters.

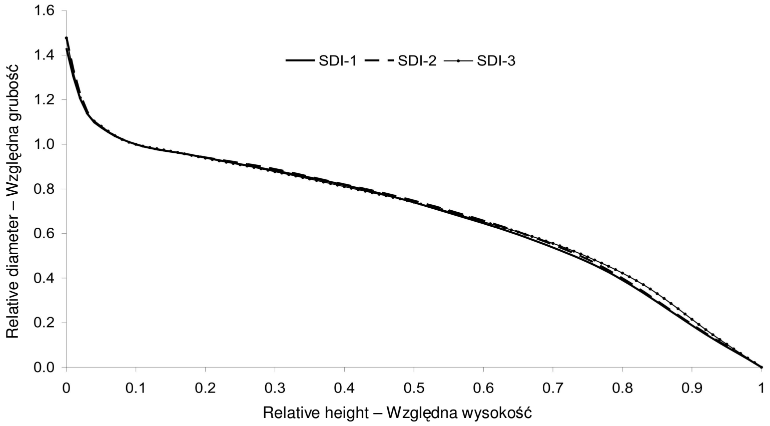

Fig. 4. Average stem form curves for trees of different stand density groups
Rys. 4. Przeciętne krzywe morfologiczne dla drzew pochodzących z różnych grup zagęszczenia drzewostanu

The more detailed information was obtained when differences between the mean relative diameters of respective stand density groups and the mean relative diameters computed for the entire study material were analysed (Fig. 5). On this basis it was found that trees from stands of the lowest density had the smallest relative diameters in the butt and top parts of the stem, while trees from stands of the highest SDI values were characterized by relative diameters greater than the average in the top part of the stem (above 0.6 of tree height). In the case of trees from the second stand density group the highest values of relative diameters were found for the butt and middle parts of the stem.

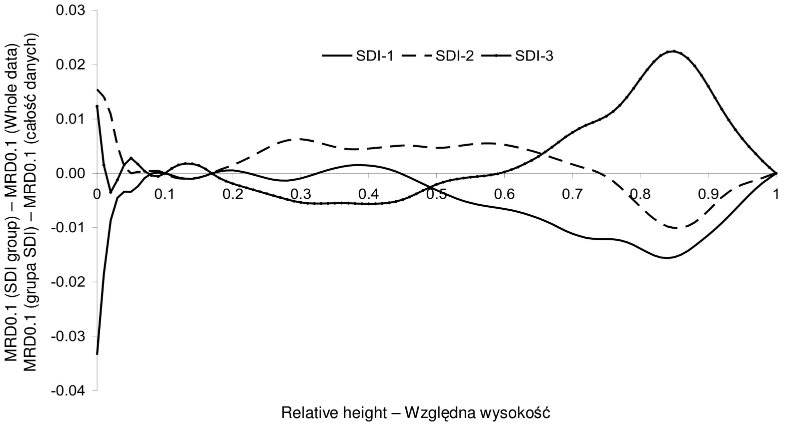

Fig. 5. Differences between the mean relative diameters of trees from different stand density (SDI) groups and the mean relative diameter (MRD) computed for the entire study material
Rys. 5. Różnice pomiędzy średnimi grubościami względnymi (MRD) drzew pochodzących z różnych grup zagęszczenia drzewostanów (SDI) i średnimi grubościami wyliczonymi dla całości materiału badawczego

Using the analysis of variance it was attempted to answer the question whether mean relative diameters of trees from three stand density groups significantly differ at individual relative stem heights. It was found that at the assumed level of significance $\alpha = 0.05$ the differences in mean relative diameter of trees from respective stand density groups were significant in the top part of the stem between 0.82 and 0.95 of the relative stem height.

In the regression equation for the determination of volume of stems outside bark as well as volume of stems inside bark the stand density index turned out to be a variable which is insignificant in the model. Thus, this variable does not increase the proportion of the explained variance (Table 2). In Scots pine stands analyzed in this study the use of the stand density index SDI did not increase the accuracy of the empirical equation for volume determination.

Table 2. Parameters of empirical equations for determination of stem volume outside bark (V_{ob}) and inside bark (V_{ib}) and estimation of their significance
Tabela 2. Parametry wzorów empirycznych do określania miąższości strzał w korze i bez kory oraz ocena ich istotności

Dependent variable Zmienna zależna	Parameter Parametr	Value of parameter Wartość parametru	Standard error Błąd standardowy	t – Statistics value Wartość statystyki t	Probability level Poziom prawdopodobieństwa
V_{ob}	b_0	0.0000380	0.095664	–106.403	< 0.00001
	b_1	–0.0131120	0.018888	–0.694	0.48903
	b_2	1.9229900	0.064828	29.663	< 0.00001
	b_3	1.1021786	0.084187	13.092	< 0.00001
V_{ib}	b_0	0.0000256	0.103228	–102.429	< 0.00001
	b_1	–0.0038817	0.020382	–0.190	0.84931
	b_2	1.8663428	0.069954	26.680	< 0.00001
	b_3	1.2374861	0.090843	13.622	< 0.00001

DISCUSSION

The comparison of the stem form of trees encounters various difficulties out of which a lack of an explicit measure permitting the estimation of the form is the most serious one. Sometimes the stem form is estimated using stem form factors. The stem factor may be accepted as a measure of fullness of the stem, but it does not reflect the nature of differences in stem form because it is computed in relation to the diameter at a certain stem height. Its application may bring good effects only in the case when differences in shape of stem form curves for compared groups of trees are of the same sign on the entire stem length. However, there are many examples showing that this condition is rarely fulfilled. Most of the factors have different effect on the stem form curve in the bottom and top parts of the stem, and this eliminates the possibility of determination of differences in the stem form on the basis of stem form factors. Also the methods of determination of the stem form on the basis of the form exponent, developed so far, do not give satisfactory results. It seems that the best method of comparing stem form is the comparison of stem form curves based on relative diameters computed for relative stem heights. Although in this method there is a certain amount of doubt as to the assumption of the diameter in relation to which relative diameters are computed. This does not remain without the effect on the result of stem form comparison. It seems that the best solution in this case is the application of diameters from relative heights as the reference. From the point of view of determination of volume of standing trees it seems justified to analyse the differences in stem form curves expressed in units relative to DBH.

The results of this study may seem to be somewhat surprising because one may expect the occurrence of considerable differences in the stem form due to different stand density. This study showed, however, that these differences are relatively small. The diameter increment in the bottom stem part increases and the increment in the top part decreases as the stand density decreases. Therefore, diameters in the bottom stem part increase faster than those in the top part. However, the diameter increase expressed in relative values does not necessarily accompany a faster increase of actual diameters. Also, the diameter, in reference to which individual relative diameters are computed, is changing, and this causes that value of the relative diameter remains the same in spite of a considerable increase of stem tapering and slenderness.

The fact that stand density in the study plots was determined in the moment of sample tree felling, while it may be supposed that the stem form also depends on an unknown density of individual stands during earlier years of tree life, is a certain shortcoming in this study. However, the aim of the study was to estimate the usefulness of stand density as a characteristic permitting to increase the accuracy of volume determination. In such a case it is only possible to take into account the stand density in the moment of volume determination.

Because this study was carried out on 109 average trees, and it concerned Scots pine stands only, the generalization of the hypothesis made requires its verification on the basis of a greater study material concerning a larger number of tree species. The determination of stand density creates a certain problem. However, according to the author, limiting the analyses to average trees may be considered as the advantage of this study. This way the effect of the biosocial position of trees, which could deform the analysis of the effect of stand density, was eliminated. However, the fact that results cannot be referred to trees considerably different from the average ones in a given stand is the disadvantage of such a comparison.

This study showed that stand density determines the stem form of trees to a certain degree. However, the differences in the stem form were relatively small and concerned the top part of the stem. Because the form of the top part relatively little affects the total stem volume the application of the stand density index in equations determining volume does not cause any significant increase of the proportion of the explained variance, and this seem to eliminate the usefulness of this characteristic as the independent variable in empirical equations for volume determination.

SUMMARY OF RESULTS

In this study it was attempted to estimate the effect of stand density on the stem form of Scots pine. The stand density index (SDI) proposed by Reineke (1933) was used to estimate density of stands. Contrary to stand basal area, which may also be considered to be a stand density measure, the SDI is not correlated with DBH and height of trees. The value of this index has no significant effect on variation of the breast height and true form factors. A detailed analysis of the stem form curves permitted to conclude that the stand density index mainly decides on the shape of the top part of the stem profile. Trees in stands of lower density in comparison with trees in stands of higher density are characterized by smaller values of the relative diameters in the top part of the stem, especially between 0.7 and 0.9 of tree height. Differences between stem form profiles of trees from stands of different density are, however, significant only in the range from 0.82 to 0.89 of the relative tree height. Using of stand density in empirical equations for determination of volume does not increase their accuracy. In connection with this the stand density index seems to be useless as the independent variable in empirical equations for volume determination.

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OCENA WPŁYWU ZAGĘSZCZENIA DRZEWOSTANU NA KSZTAŁT PRZEKROJU PODŁUŻNEGO STRZAŁ SOSNY POSPOLITEJ

Streszczenie. W pracy podjęto próbę zbadania wpływu zagęszczenia drzewostanu na kształt strzał sosny pospolitej. Do oceny zagęszczenia drzewostanu zastosowano wskaźnik SDI opracowany przez Reinkego (1933). Przeprowadzone analizy wykazały, że wskaźnik zagęszczenia drzewostanu nie wpływa istotnie na wartości pierśnicowej i właściwych liczb kształtu. Szczegółowa analiza przebiegu krzywej morfologicznej strzały pozwoliła na ustalenie, że zagęszczenie drzewostanu decyduje o kształcie wierzchołkowej części przekroju podłużnego strzały. Drzewa w drzewostanach o mniejszym zagęszczeniu, w porównaniu z silnie zagęszczonymi, charakteryzują się mniejszymi wartościami grubości względnych w wierzchołkowej części strzały, a szczególnie w zakresie od 0,7 do 0,9 wysokości drzewa. Różnice w przebiegu krzywych morfologicznych drzew pochodzących z drzewostanów o różnym zagęszczeniu są jednak istotne jedynie w zakresie od 0,82 do 0,89 wysokości względnej strzały. Zastosowanie wskaźnika zagęszczenia we wzorze empirycznym do kreślania miąższości nie wpływa na zwiększenie jego dokładności.

Słowa kluczowe: wskaźnik zagęszczenia drzewostanu (SDI), liczba kształtu, krzywa morfologiczna, miąższość strzały

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