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The shape of the trunk of Scots pine in the stands of the Ukrainian Polissia

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Abstract. Due to the transition of Ukraine in 2019 to new regulatory documents on standardisation regarding the classification of round timber by quality classes, it became necessary to develop standards for evaluating volumes in accordance with the new requirements. The purpose of the study was to develop a mathematical model of the forming stem of Scots pine for trees of two groups of diameters. The study is based on the use of empirical material collected in different years by researchers of the Department of forest taxation and forest management of the National University of Life and Environmental Sciences of Ukraine, which is 583 model pine trees. The Kozak model was used as the basic model for modelling the forming Scots pine. A mixed effect model was calibrated to characterise the variability in the tree stem shape of Scots pine. Parameters for the role of random effects were selected based on their coefficients of variation using the bootstrap process. Data were grouped into two groups of diameters by analysing modelling residues and evaluating the quality of models based on the use of the Akaike information criterion (*AIC*). By dividing the data array into two groups of thickness degrees and developing models of the creator for each of the groups separately, a decrease in the indicator of the Akaike information criterion (*AIC*) was achieved to the level of $AIC = 7433.02$ for a group (8–28 cm) and $AIC = 13154.67$ for the group (32–76 cm), which increased the accuracy of the developed models. Enabling random effect parameters in model by A. Kozak for the developed mathematical equations allowed more accurately describing

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the variability of the tree stem of Scots pine. The obtained models give a clear and fairly accurate prediction of the determination of tree stem diameters along the entire length. The use of the developed models can serve as a basis for improving forest traction standards for estimating the volume of tree stem in the process of forestry production and predicting the yield of roundwood volumes by quality classes

Keywords: modelling; Akaike information criterion; species number; diameter groups; formation equation; shape variability

Introduction

Improvement of forest taxation regulation and reference support increases the accuracy of taxation of forest resources and ecosystem services of forest ecosystems. Modern methods of data collection and analysis and modelling can substantially improve tax standards in the context of systematic accumulation and addition of the research database (Robinson & Hamann, 2011). Modelling of the tree stem taper of the main forest-forming species of Ukraine provides initial conditions for taxing the volume of tree stem and round timber obtained from them (Bilous *et al.*, 2021b). Accurate accounting of the volume of business wood contributes to the development of a transparent wood market and fair relations between sellers and consumers of wood. Ukraine has recently adopted regulatory documents on standardization (DSTU EN 1927-2:2018..., 2018; TUU-00994207-001:2018..., 2018; TUU-00994207-003:2018..., 2018) focusing on the leading practice of the European Union countries for the classification of round timber, which led to the need to model the taper equation and update all standards for determining the stem volume in accordance with the new standards of standardization. The identification of new patterns in the taper equation and the development of forest taxation information support will contribute to rational forest management on the way to sustainable development. Improved logging standards should ensure a more

accurate accounting of wood during material and monetary assessment, logging and sales of products. The development of taper equations is a rather complex process that requires investigating a large number of felled model trees in modal stands.

Investigating the profile of a tree stem allows for describing the tree stem, having a detailed description of the stem diameters along its entire length, and determining the volumes for specified segments. The study of tree stem by S. Salekin *et al.* (2021) showed that they differ in their shape from the clod part to the tip, with a neiloid shape at the bottom, cylindrical in the middle and cone-shaped at the top, and possible intermediate shape types at certain areas of the tree stem height. Simple parametric models do not take these features into account, thus T. Pukkala *et al.* (2019) to solve this problem, it is recommended to use splines to approximate taper equation, having some values of diameters along the length of the tree stem.

P. He *et al.* (2020) proposed using an additive model based on the diameter at chest level, tree stem height, height at relative marks, and diameter at these marks to examine the taper equation of Scots pine. The generalised model consists of different additive elements, each of which is estimated using a spline function, and each dependent variable can be explained for each additive element separately.

For the segmented model, R. Özçelik & O. Alkan (2020) applied a nonlinear mixed effects modelling approach. The inclusion of random effects provided a better fit for the model compared to the fixed-effects model. In this paper, the effects of residual heterogeneity of variance and residual autocorrelation were included to model the variance-covariance matrix, but the inclusion of random parameters did not completely eliminate autocorrelation of heteroscedasticity in residues, so the inclusion of the variance function and the CAR(1) model was added to the model. But still, the model of A. Kozak (2004) is more widely used in a number of modern studies (Bilous *et al.*, 2021b; Myroniuk *et al.*, 2023). The study by Z. Adamec *et al.* (2019) also used model by A. Kozak (2004), with such a selection of parameters for the model, which includes the best combination of random parameters, also allows checking and compensating for the presence of heteroscedasticity and autocorrelation of prediction errors. The development of sufficiently accurate models of the generatrix provides opportunities for further modelling of tree stem volumes depending on the ratio between the diameter and height of trees.

Thus, A. Bilous *et al.* (2022) developed mathematical models of tree stem volumes at the height-diameter ratio for the main forest-forming species of Ukraine, which can be used to estimate the volume of harvested wood, predict the structure of forests and estimate the stock of tree stem wood. In addition, in this paper, the volume equations were combined into tables that give an estimate of the

volume distributions depending on the thickness class. Based on the models of generators for pine trees in the study of V.B. Bychenko *et al.* (2021), the methodological prerequisites for using a random process for modelling the distribution of the length of the business part of tree stem were described since the use of generating models in estimating volumes is a more advanced method since these models allow to predict the diameters from the butt to the top and calculate the median diameter of a certain segment and its volume. The purpose of the study was to examine the variability of tree stem shape and develop a tree stem taper equation for Scots pine.

Materials and Methods

Research material

For the study, the authors conducted fieldwork on the collection of experimental material in the test area, which was laid in 2020 in a ripe stand of Scots pine in the Horodnianske Forestry of the state enterprise “Horodnianske Forestry” in the Chernihiv region. 197 model Scots pine trees were measured on the test area. The study also uses research material collected in the area of Ukrainian Polissia in different years by researchers of the Department of forest taxation and forest management of the National University of Life and Environmental Sciences of Ukraine (hereinafter NULES of Ukraine), which was used to develop standards in previous years (Kashpor & Strochynskii, 2013; Bilous *et al.*, 2021a). The total research database is 51 trial areas (Table 1), which includes 583 model Scots pine trees (*Pinus sylvestris L.*) (Table 2).

Table 1. General characteristics of test areas

PP code	Number of models	H, m	D, cm	Administrative region
12001	197	27.3	36.8	Chernihiv region
15516	6	31.2	38.8	Kyiv region
15520	2	25.8	29.0	Lviv
15521	3	25.6	24.0	Lviv

Table 1, Continued

PP code	Number of models	H, m	D, cm	Administrative region
15522	5	20.1	27.6	Lviv
15523	6	16.1	15.4	Lviv
15529	15	16.6	18.4	Khmelnyskyi
15534	4	33.0	38.0	Rivne
15543	9	23.8	29.9	Kyiv region
15544	6	29.1	39.3	Kyiv region
15545	12	30.5	43.4	Kyiv region
15546	10	28.7	32.6	Kyiv region
15547	1	19.0	14.7	Kyiv region
15548	8	16.9	14.8	Kyiv region
15551	8	23.5	28.7	Kyiv region
15564	7	27.2	31.6	Lviv
15565	3	37.0	63.4	Lviv
15566	4	31.1	44.0	Lviv
15570	7	18.2	19.7	Khmelnyskyi
15572	8	16.8	15.8	Khmelnyskyi
15585	4	17.6	24.4	Rivne
16888	11	20.7	26.2	Rivne
16889	11	11.7	14.9	Rivne
16892	4	30.9	47.6	Rivne
16893	9	14.2	18.7	Rivne
16896	4	16.1	17.5	Rivne
16897	11	15.9	14.0	Rivne
16898	14	16.2	18.0	Rivne
103002	14	25.2	28.2	Zhytomyr Region
103003	12	25.4	28.5	Zhytomyr Region
111006	5	20.6	22.5	Zhytomyr Region
155132	10	22.5	26.4	Zhytomyr Region
155183	6	29.5	33.3	Khmelnyskyi
155201	6	16.2	16.6	Lviv
155203	7	25.8	33.1	Rivne
155206	5	17.3	23.2	Kyiv region
155213	9	28.7	33.3	Rivne
167108	16	16.5	14.2	Zhytomyr Region
167113	11	24.5	27.4	Zhytomyr Region
167133	8	23.4	30.4	Zhytomyr Region
182012	12	15.7	14.7	Volyn
182061	11	14.2	12.1	Volyn
182087	7	14.4	14.3	Volyn
183050	10	24.7	26.5	Zhytomyr Region
184004	5	18.7	15.1	Kyiv region
185011	5	23.3	26.1	Khmelnyskyi
186018	8	16.9	14.2	Zhytomyr Region
186019	1	30.2	28.7	Kyiv region
188014	7	14.4	14.5	Volyn

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Table 1, Continued

PP code	Number of models	H, m	D, cm	Administrative region
188015	10	13.1	12.3	Volyn
188017	9	12.3	12.1	Volyn

Note: PP – test area; H – average height, m; D – average diameter, cm

Source: compiled by the authors according to S. Kashpor & A. Strohynskii (2013), A. Bilous *et al.* (2021a)

Table 2. Distribution of model trees by thickness and height

Degrees of thickness	Height															
	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
8	1	-	3	4	4	5	3	2	-	-	-	-	-	-	-	-
12	-	-	2	4	5	16	5	11	13	2	1	-	-	-	-	-
16	-	-	-	3	3	5	10	10	15	6	5	7	4	1	1	-
20	-	-	-	-	2	1	1	3	7	5	4	5	4	2	3	2
24	-	-	-	-	-	-	2	2	1	7	4	1	4	6	4	8
28	-	-	-	-	-	-	-	-	-	1	1	2	-	3	3	10
32	-	-	-	-	-	-	-	-	-	-	1	1	1	1	3	5
36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	3
40	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1
44	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
48	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
52	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
56	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
64	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
72	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	1	0	5	11	14	27	21	28	36	21	16	16	13	14	15	29
Degrees of thickness	Height															
	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	2	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
24	7	3	2	1	-	-	-	-	-	-	-	-	-	-	-	-
28	7	13	11	12	5	-	1	-	-	-	-	-	-	-	-	-
32	8	9	12	20	4	9	4	-	-	-	-	-	-	-	-	-
36	5	7	11	13	12	6	3	4	-	-	-	-	-	-	-	-
40	2	8	6	9	13	8	4	6	1	-	-	-	-	-	-	-
44	-	1	2	6	7	7	9	3	2	-	-	1	-	-	-	-
48	-	-	-	-	1	7	2	1	5	1	-	-	-	-	-	-
52	-	-	1	-	2	-	2	-	-	2	1	-	-	-	-	-
56	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
64	-	-	-	-	-	-	-	-	-	1	-	-	-	-	1	-

Table 2, Continued

Degrees of thickness	Height															
	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
72	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-
Total	31	41	46	61	44	37	25	14	9	4	1	1	0	0	2	0

Source: compiled by the authors according to S. Kashpor & A. Stochynskii (2013), A. Bilous et al. (2021a)

A number of measurements were made to determine the taper equation on each model tree, including the establishment of the following parameters: stem diameter at a height of 1.3 m ($d_{1.3}$, cm), diameter at the middle of Sections 2 m long (i.e. 1, 3, 5 M, etc.), bark thickness, total stem height (h , m). The data were determined using forest taxation instruments in compliance with the established measure-

ment accuracy for each indicator. The characteristics of the general research material are shown in Table 3, where *Mean* – average value; *Min* – minimum value; *Max* – maximum value; σ – standard deviation; $v, \%$ – coefficient of variation; d – diameter at a height of 1.3 m; h – stem height; V_{ob} – tree stem volume in the bark; f_{ob} – species number in the bark; $q1, q2, q3$ – form coefficients.

Table 3. Descriptive statistics of Scots pine research data

Indicator	d	h	V_{ob}, m^3	f_{ob}	$q1$	$q2$	$q3$
<i>Mean</i>	30.6	24.3	1.05	0.473	0.851	0.699	0.460
<i>Min</i>	6.60	7.9	0.01	0.284	0.628	0.474	0.235
<i>Max</i>	74.3	38.4	7.03	0.656	1.00	0.944	0.910
σ	11.4	5.8	0.850	0.047	0.055	0.058	0.065
$v, \%$	37.3	23.8	80.8	9.9	6.5	8.3	14.2

Source: compiled by the authors according to S. Kashpor & A. Stochynskii (2013), A. Bilous et al. (2021a)

Calculation of the tree stem volume in the bark (V_{ob}), the species number in the cortex (f_{ob}), and coefficients of the form ($q1, q2, q3$) were conducted using the PERT programme, which was developed by researchers of the Department of forest taxation and forest management of NULES of Ukraine. The programme analyses the data of list taxation of model trees with measurement by sections of constant length and gives an exhaustive tax description of trees.

Developing a taper equation model

Model of A. Kozak (2004) was used as the basis for the study, because it provides a reliable and more accurate estimate of the determination of diameters along the entire length of the

tree stem, as indicated in previous studies (Li & Weiskittel, 2010):

$$d_i = a_0 * d^{a_1} * h^{a_2} * X_i^{(b_1 * z_i^4 + b_2 [1/\exp(D/H)] + b_3 * X_i^{0.1} + b_4 * \frac{1}{D} + b_5 * H^{Q_i} + b_6 * X_i)}, \quad (1)$$

where d_i – diameter outside bark at height h_i (cm), D – diameter at breast height 1.30 m (cm), h – height from ground level (m), H – total tree height above ground level (m), a_0 - a_1 and b_1 - b_6 – parameters of the equation. In the formula

$$X_i = \frac{h-h_i}{h-1.3/H^{(1/3)}}, Q_i = 1 - z_i^{1/3}, z_i = \frac{h_i}{h}.$$

The package was used to set the mathematical parameters of the model equation *nlme*

in the R (R Core Team, 2018) programming language because it allows a more reliable examination of the shape of a tree stem. A two-level model with mixed effects was also evaluated, which considers the presence of stem differences, which can be both on certain parts of the tree stem and on different tree stem in similar parts (Myroniuk *et al.*, 2023).

The bootstrap method was used to set the equation parameters. This method is a non-parametric re-sampling method, in which a large number of parameters of the same size are repeatedly selected with the replacement of one original sample. Initially, 1000 bootstrap parameters and their coefficients of var-

iation were obtained by fitting a fixed-effect model using a nonlinear least squares function (*nlme*). For this purpose, a sample of data was used, followed by calculating estimates of their average value, standard deviation, and coefficients of variation for each parameter.

The obtained average values of parameters for all samples were used as initial values for the function *nlme* (Table 4). Candidates for the role of random effect parameters were selected for the values of the equation parameters that were most substantial (based on statistics of calculated values) at the p-value level of 0.05 in more than 95% of the initial value samples.

Table 4. Values of the initial parameters of the equation of model of A. Kozak based on 100 bootstrap ratings

Indicators	Coefficients of the equation								
	a_0	a_1	a_2	b_1	b_2	b_3	b_4	b_4	b_6
Mean	0.91235	0.95776	0.07403	0.42935	-0.07030	0.37595	-0.04130	-0.00192	0.05410
v, %	1.45	0.95	18.2	2.29	61.88	3.13	409.13	75.9	36.0
SD	0.00329	0.00952	0.01346	0.00984	0.04350	0.01180	0.16899	0.00146	0.01946

Source: compiled by the authors

From the above data, it is decided that the values selected for the parameters used for the random effect role are a_2 and b_6 , since the values b_2 , b_4 and b_5 have a significance of less than 95% at the level of 0.05.

Using the initial parameters, the equation parameters were set for the entire data array. Using the Akaike information criterion (*AIC*), the error of extra-selective prediction and, consequently, the relative quality of the developed model was estimated, since it evaluates both the over-learning of the model and its under-learning with risk. For the entire data array, it was established that the criterion value is quite high and has the value $AIC = 21092.16$, therefore, the remainder of the simulation distributions was then estimated. The obtained analysis of residuals allows

choosing the best model, but it should solve a number of issues (Nikitin & Shvidenko, 1978), in particular: confirmation of the normality of the distribution of residuals; the constancy of variance and its independence from values; adequacy of the model on all segments of the intervals of change of the dependent variable or the possibility of its improvement by adding nonlinear parameters.

Results and Discussion

Analysing the distribution of simulation residuals for the entire data array (Fig. 1) it was established that there is some overestimation of the residuals, as a result of which a decision was made to divide the experimental database into groups of diameters and develop a model for each of these groups.

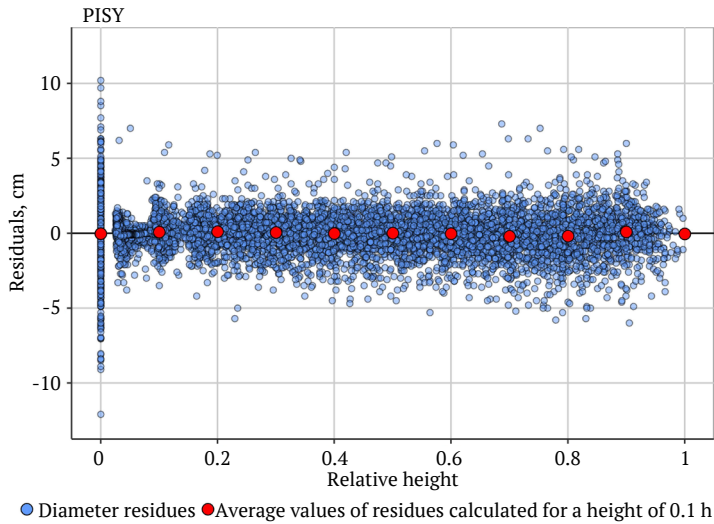


Figure 1. Distribution of residuals for the experimental data set of relative heights of model trees
Source: compiled by the author

Initially, the data array was grouped within the following thickness degrees: 8-20 cm, 24-28 cm, 32-40 cm, 44-56 cm, and 60-76 cm. For each array, the model parameters were set according to the method described above and the simulation residuals were calculated. Having obtained the values of the residuals for the established groups, it was decided to finally divide

the data array into 2 groups according to the thickness degrees – 8-28 cm and 32-76 cm. The choice of such grouping consists in the fact that in fact there is no substantial difference within the data array (8-20 cm) – (24-28 cm) and in the array (34-40 cm) – (44-56 cm) – (60-76 cm), as evidenced by the graphical interpretation of the residuals in Figures 2(A) and 2(B).

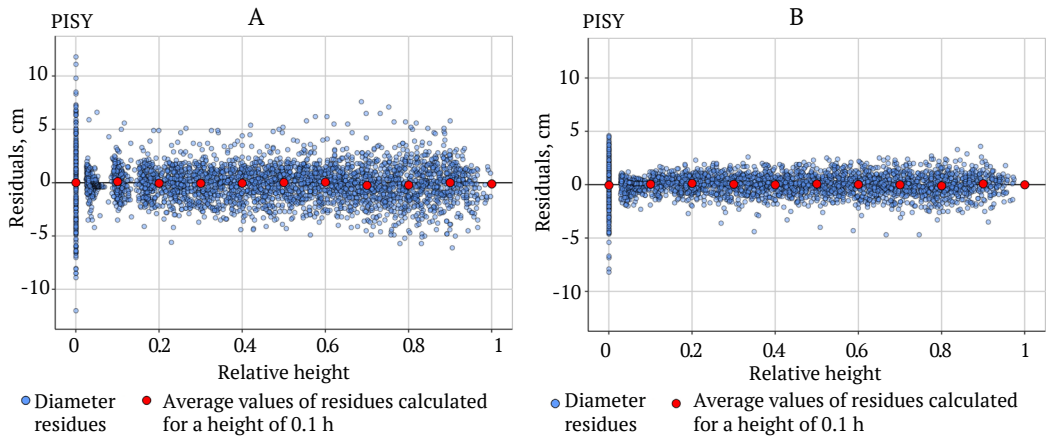


Figure 2. Distribution of residues by diameter groups

Notes: A – (8-28 cm); B – (32-76 cm)

Source: compiled by the author

In both cases, there is a certain tendency to slightly increase the residues from the butt to the top, and in the first group, this is less substantial. Notably, when using random parameters a_2 and b_6 , a slightly different method of grouping variables was adopted. In the paper of V. Myroniuk *et al.* (2023) when using parameters with a random effect, grouping took place on the principle of “trial area/model tree”, in turn, in this study, it was decided to group only by model trees. The error correlation structure in the model was also used using a first-order

autoregressive correlation structure for a group of model trees.

Due to the division of the entire research database into two groups, a decrease in the distribution of the Akaike information criterion was achieved (AIC) to the level $AIC = 7433.02$ for a group (8-28 cm) and $AIC = 13154.67$ for the group (32-76 cm) and the standard error for the residuals $SE = 0.154$ and $SE = 0.082$, respectively. For both groups, the equation parameters were obtained and the standard errors of each of the parameters were calculated (Table 5).

Table 5. Calculated parameters and their standard errors of the mixed effect generating equation

Coefficient	Values of coefficients for the diameter group			
	20-28 cm		32-40 cm	
	Value	SE	Value	SE
a_0	1.00048	0.02353	0.8679	0.06418
a_1	0.99920	0.01099	1.03442	0.01722
a_2	0.00232	0.01418	0.00315	0.02680
b_1	0.39502	0.00806	0.47792	0.00881
b_2	-0.36305	0.04281	-0.26415	0.07992
b_3	0.50456	0.01448	0.44119	0.01880
b_4	0.11721	0.14173	-1.13157	0.91466
b_5	0.00109	0.00092	-0.00214	0.00080
b_6	-0.00387	0.01329	0.10289	0.01856

Source: compiled by the authors

Using the obtained parameter values, the tree stem profiles for both data sets were adapted (Fig. 3). When constructing the taper equation, the value of the diameter at chest level and the height of the tree stem is taken as the average value for the sample. For the first data array, this indicator is $d = 20$ cm and $h = 19$ m, for the second data array $d = 39$ cm and $h = 28$ m. Based on the obtained parameter values for the model (Table 5), it was established that pine has a slight deviation in the forecast of tree stem diameters in the bark relative to the average trend of stem narrowing. Comparing the tree stem profiles, a higher variability of stem for larger trees is evident. In addition, a characteristic feature is a smooth reduction

in the diameter of the tree stem to the top of the tree. Using either of the two models in the entire database sample is inappropriate, as the simulation results are distorted. Therefore, for example, using a model developed for a group (32-76 cm) on thinner trees, the evaluation results in the lower part of the tree stem are underestimated and, accordingly, overestimated in the apical part.

This study uses the model of generating of A. Kozak (2004) as a basis for modelling the forming Scots pine. This is the second study of the formation equation with a variable indicator for characterising the taper equation of tree species in Ukraine. A similar study was done in Ukraine (Myroniuk *et al.*, 2023), but

it provides a general model of the generatrix for each tree species without dividing it into groups of diameters. The analysis showed that the developed models provide a clearer and

more accurate prediction regarding the determination of tree stem diameters along the entire length of the stem for different groups of diameters.

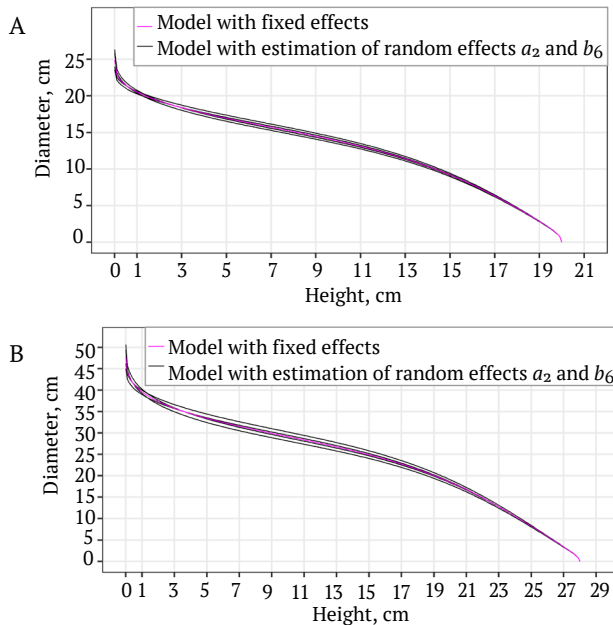


Figure 3. Variation in the tree stem shape based on the interquartile range of a random effect estimated from the selected parameters

Notes: A – (8-28 cm); B – (32-76 cm)

Source: compiled by the author

For the study, methodological approaches to modelling were applied almost identical to those of V. Myroniuk *et al.* (2023). In particular, a mixed-effect modelling approach was used, which gives better results compared to conventional least squares regression in terms of accessing a hierarchical data structure that includes repeated measurements. Since the research data has a hierarchical structure, ignoring autocorrelation in the simulation could lead to a violation of statistical data, such as hypothesis testing and confidence intervals. A method similar to the one in the study by R. Li & A.R. Weiskittel (2010) was used to solve this problem, which includes the specification of the autoregressive error structure and random

effects. Since the measurement data is collected at unequal heights along the tree stem, the inclusion of the correlation structure (corCAR1) solved the problem of data heterogeneity and independence (Zuur, 2009). Two random effect parameters (Arias-Rodil *et al.*, 2015) were also included in the mixed effects model. Random effect parameters were evaluated based on selection based on the principle of greater variability in different tree stem profiles. An approach based on the principle of repeated sampling in the initial loading of 1000 initial parameters from the initial data set and model restructuring for each sample is used to solve this problem (Myroniuk *et al.*, 2023). Thus, the two most variable parameters in the model were selected

and used as a random effect. Low values of the Akaike information criterion confirmed the feasibility of using random effect parameters (*AIC*) for developed models.

Mathematical models of the Scots pine stem developed, based on the equation of A. Kozak (2004) also showed good results for a number of species in different bioclimatic zones. Thus, A. Rojo *et al.* (2005) used 31 equations of the generating tree stem, of which the model of A. Kozak (2004) showed the lowest root-mean-square error, which was 4.5% less relative to other equations. R. Li & A.R. Weiskittel (2010) used 13 models of different types to estimate the taper equation of balsamic spruce, red spruce, and white pine. During the study, model of A. Kozak (2004) showed the best results for red spruce and white pine with an average absolute offset of 0.538 and 1.156, and an average percentage offset of 5.039% and 5.713%, respectively.

The accumulated research data and the obtained patterns of stem shape can be used in the future to prepare models of the dependence of the diameters of round forest materials in the upper section and in the middle of logs.

Conclusions

This study presents the results of modelling the taper equation of Scots pine in stands of Ukrainian Polissia for two groups of thickness degrees – 8-28 cm and 32-76 cm. Using model of A. Kozak as the base for modelling with the inclusion of random effect parameters. Random parameters of the mathematical model were

set and their errors were calculated using the bootstrap method. When developing models for different groups of diameters, the Akaike information criterion (*AIC*) was evaluated to assess the quality and accuracy of the model. Due to the division of the data array into groups by diameter, a decrease in its indicator was achieved, which in turn increased the accuracy of the obtained models. The use of random effect parameters allowed more accurate characterisation of the shape features of pine tree stem. Based on the established parameters of the model, the variation in the tree stem shape for two groups of diameters was estimated based on the interquartile range of the random effect. The resulting models provide a clear and fairly accurate prediction of tree stem diameters over its entire length.

The created models can serve as an applied basis for improving forest removal standards for assessing the volume of forest products, in particular, in accordance with the rules and best practices of forest management in European countries. The prospect of further research is modelling the coincidence of round timber of Scots pine based on the developed mathematical models for two groups of diameters and the development of standards for assessing the yield of round timber by quality classes.

Conflict of Interest

None.

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Форма стовбура сосни звичайної в деревостанах Українського Полісся

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Анотація. У зв'язку з переходом України в 2019 році на нові нормативні документи зі стандартизації щодо класифікації круглих лісоматеріалів за класами якості постала необхідність в розробці нормативів оцінювання об'ємів відповідно до нових вимог. Метою статті було розроблення математичної моделі твірної стовбура сосни звичайної для дерев двох груп діаметрів. Робота базується на використанні емпіричного матеріалу, зібраного в різні роки науковцями кафедри таксації лісу та лісового менеджменту Національного університету біоресурсів і природокористування України, який становить 583 модельних дерева сосни звичайної. Як базову для моделювання твірної сосни звичайної було використано модель Козака. Для характеристики мінливості форми стовбурів сосни звичайної проведено калібрування моделі змішаного ефекту. Параметри на роль випадкового ефекту відбиралися на основі їх коефіцієнтів варіації за допомогою процесу початкового завантаження (метод bootstrap). Групування даних на дві групи діаметрів проводилося за рахунок аналізу залишків моделювання та оцінювання якості моделей здійснювалось на основі використання інформаційного критерію Акаїке (AIC). За рахунок поділу масиву даних на дві групи ступенів товщини і розроблення моделей твірної для кожної з груп окремо досягнуто зниження показника інформаційного критерію Акаїке (AIC) до рівня $AIC = 7433,02$ для групи (8-28 см) та $AIC = 13154,67$ для групи (32-76 см), що підвищило точність розроблених моделей. Включення параметрів випадкового ефекту в модель А. Козак для розроблених математичних рівнянь дозволило більш точно описати мінливість деревного стовбура сосни звичайної. Отримані моделі дають чітке і достатньо точне передбачення визначення діаметрів стовбура по всій довжині. Використання розроблених моделей може бути базисом для удосконалення лісотаксаційних нормативів для оцінювання об'ємів стовбурів дерев у процесі лісгосподарського виробництва та прогнозування виходу об'ємів круглих лісоматеріалів за класами якості

Ключові слова: моделювання; інформаційний критерій Акаїке; видове число; групи діаметрів; рівняння твірної; мінливість форми