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Development of Douglas fir merchantable stem volume model in the conditions of the Czech Republic

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Abstract: A precise merchantable stem volume model of Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] is missing in the Czech Republic. The aim of this study was to fit a new model through the reparametrization of volume equations (used in the Czech Republic or in other countries). We tested four volume equations (two from the Czech Republic, one from France and one from British Columbia) in the form of a nonlinear least squares model (NLS), weighted least squares model (WLS), and nonlinear mixed effects model (NLME). In all the tested models, the diameter at breast height of a tree and the total height of a tree were used as independent variables. Models were fitted on a dataset of 185 felled sample trees from eleven research areas with ages between 19–113 years. We have found that the model according to Omule et al. (1987) fits the merchantable stem volume as the best in the version of WLS model. Median value of the relative error of the final model was only –0.53%, which is less than the errors of models which are still used in the Czech Republic today.

Keywords: *Pseudotsuga menziesii*; relative volume error; Smalian equation; stem profiles; stem shape; volume equation

Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] is considered a promising introduced tree species in the Czech Republic. Douglas fir has higher resistance against drought, so it could be evaluated as a convenient adaptable tree species to climate change (Remeš et al. 2020). Due to its resistance to drought, it could be considered an alternative to the more drought-sensitive Norway spruce (Nicolescu et al. 2023). The production potential of Douglas fir in lower and mid altitudes is higher than that of other domestic tree species (Kubeček et al. 2014; Mondek, Baláš 2019). According to Mauer and Palátová (2012), Douglas fir in the Czech Republic is promising mainly in nutrient-medium sites from hornbeam-oak forests to fir-beech forests. Due to the current low percentage of Douglas fir in the forests of the Czech Republic, which makes up only 0.22% (5 800 ha; Zeidler et al. 2018), separate volume equations have not been developed in the Czech Republic

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yet, and instead, equations for fir (*Abies* spp.) are used. However, a large number of volume equations have been developed for Douglas fir mainly in North America, e.g. MacLean and Berger (1976), Kovats (1977), Wensel (1983), Omule et al. (1987), or in Germany (Bergel 1971).

Determining the growing stock in the stand is one of the most important conditions for proper and sustainable forest management, as it allows, among other things, to estimate the financial income from forest stands (Niño Lopez et al. 2018; González et al. 2018). According to Snorrasson (2006), measuring steam volume or weight (e.g. to determine carbon allocation) is laborious and expensive, as it involves harvesting the tree and maintaining precise measurements. Methods to estimate these variables have been developed by using functions that describe mathematical relationships between the volume or weight of the stem and other more easily measurable independent variables. Volume equations are, therefore, a mathematical function of the model of dependence between the volume of the stem or the whole tree (either total or merchantable) and other tree variables. Those variables could include the diameter at breast height of a tree (*DBH*), the total height of a tree, and possibly another variable (e.g. the height of the tree crown or the ratio of the length of the tree crown to the total height of the tree; Poudel et al. 2018). Van Laar and Akça (2007) state that many of the volume equations use independent variables either in basic or transformed form. These equations are often parametrized using linear regression or, in case there are more independent variables, multiple linear regression (Crow, Schlaegel 1988; Parresol 1999). Another option is nonlinear regression, which has been used more frequently in the recent studies (Stolariková et al. 2014, Hogg et al. 2021).

In the Czech Republic, equations with two independent variables are used most often, which indicate that the merchantable stem volume over bark for individual tree species is estimated according to the total tree height and *DBH* of the tree. These volume equations were compiled by Petráš and Pajtík (1991) for 11 tree species. Outside the Czech Republic, equations with the same two independent variables were compiled, for example, by Amateis and Burkhart (1987) or Tasissa et al. (1997).

In addition to equations with two independent variables, equations with one or three independent variables are also used (Gonzalez-Benecke et al. 2014). Equations with one independent variable are developed as a function of *DBH* or another diameter (e.g. diameter at the height of 0.5 m; Bjarnadottir et al. 2007). Equations with one independent variable are only applicable when the trees grow in a local population with similar site conditions or the ratio between tree height and *DBH* varies only slightly (Parresol 1999; Bjarnadottir et al. 2007). Equations with three independent variables, in addition to *DBH* and total tree height, also use a third variable that specifies either the shape of the stem (e.g. diameter at 7 m height or at 30% of tree height, height of the tree crown etc.), or age, stand density or productivity of the stand (Pienaar et al. 1987; Ďurský, Šmelko 2002; Gonzalez-Benecke et al. 2021).

When a new volume equation is developed, the accuracy of determining the volume by the equation alone is often compared to the volume determined by integration of the stem taper curve (STC). For Douglas fir, this comparison was dealt with, for example, by Poudel et al. (2018). Often, instead of developing a new volume equation, an older, regionally valid equation is used, with its reparametrization being carried out for the given site and the investigated locality, possibly also for a different tree species. This method was chosen for Douglas fir, for example, by Poudel and Temesgen (2016).

The volume equation by Petráš and Pajtík (1991) that is currently used for Douglas fir in the Czech Republic is essentially an equation for the merchantable stem volume over bark for fir. The merchantable stem volume over bark model for fir (ÚLT 1951) is still used also to determine Douglas fir volume. Same as the volume equation, the yield tables are not available directly for Douglas fir in the Czech Republic. As an alternative, yield tables calculated by Bergel (1985) for the area of Northwest Germany could be used. In 2015, there was an effort to make the determination of stem volume more precise for Douglas fir and other tree species. According to Valenta and Štipl (2015), the volume according to the older model (ÚLT 1951; for this model, sample trees were measured mostly outside the territory of the Czech Republic) is about 6% higher than the real volume over bark, and 15% for the volume inside bark, while for the volume equations according to Petráš and Pajtík (1991), the overestimation of the volume over bark is 4% and 14% for volume inside bark, respectively. The so-called debarking coefficient (0.8467) was added to the used

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volume equation for fir according to Petráš and Pajtík (1991), which was supposed to reduce the overestimation of the inside bark volume to 4%.

The aim of this study is to develop a new model of merchantable stem volume over bark for Douglas fir in the conditions of the Czech Republic. This will be implemented through the reparametrization of the four volume equation models that have been used so far for Douglas fir both in the Czech Republic and abroad. One of these models will be selected to replace the model currently used in the Czech Republic that was not designed specifically for Douglas fir and therefore lacking in precision.

MATERIAL AND METHODS

Study sites. The data used in this study were collected from 185 felled Douglas fir trees. In total, the measurement of the sample trees was carried out at 11 locations, which were located on the property of the Training Forest Enterprise Masaryk Forest Křtiny (organisation part of Mendel University in Brno), Písek Municipal Forests (Lesy města Písku s.r.o.), and Training Forest Enterprise Hůrky [Školní polesí Hůrky; organisation part of the Secondary School of Forestry in Písek (Lesnická škola v Písku)]. The basic characteristics of the individual research plots are shown in Table 1. The basic statistical characteristics of selected tree variables measured on the sample trees are shown in Table 2.

Sample trees measurement. The volume of the felled stem over bark was determined by measuring the diameter of segments with an absolute length of 1 m. The beginning of the first segment was located at the cut point separating the stem from the stump, and the end of the last segment was at the point where the diameter of the stem over bark was 7 cm. The diameter at breast height, the stump height and the total length of the felled tree were also measured. Stump height was measured from the soil surface to the height of the main cut. The total height of the tree was calculated as the sum of the height of the stump and the length of the felled tree. The diameters measured at individual segments were arranged into stem profiles.

Table 1. Basic characteristics of the research plots

Research plot No.	Owner	Age (years)	Number of sample trees	Mean *DBH*	Mean *h*	Mean *v*
1	TFEM	33	73	22.6	22.0	0.46
2	TFEM	44	16	27.1	23.9	0.71
3	TFEM	21	10	15.8	16.2	0.15
4	SSF	100	16	45.8	36.5	2.68
5	PMF	28	7	14.7	16.3	0.13
6	PMF	100	1	47.6	32.0	2.29
7	PMF	113	17	60.4	39.6	5.07
8	PMF	64	1	40.5	31.0	1.80
9	PMF	104	7	46.3	35.8	2.40
10	TFEM	95	4	47.6	31.8	2.34
11	TFEM	19	33	14.6	14.3	0.11

DBH – diameter at breast height of a tree; *h* – total height of a tree; *v* – merchantable stem volume of a tree; TFEM – Training Forest Enterprise Masaryk Forest Křtiny (organisation part of Mendel University in Brno); SSF – Training Forest Enterprise Hůrky (organisation part of the Secondary School of Forestry in Písek); PMF – Písek Municipal Forests (Lesy města Písku s.r.o.)

Table 2. Basic characteristics of selected tree variables

Variable	Minimum	Maximum	Mean value	Standard deviation
Age (years)	19.00	113.00	48.32	33.24
Total height (m)	10.14	44.86	23.97	8.73
Diameter at breast height (cm)	8.00	86.40	28.06	16.00
Merchantable stem volume (m^3)	0.017	10.993	1.135	1.710

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Length measurements were made using a tape measure with 1 cm accuracy. Stem diameters were measured using a calliper. The diameter in each measuring point was calculated as the arithmetic mean of two perpendicular measurements of partial diameters with 1-millimetre accuracy. The cross-sectional area of the segment was calculated from the diameter of the segment. The volume of each sample tree was determined by the sum of the volumes of the individual segments, the volumes of which were calculated using the Smalian formula that uses the cross-sectional areas of the stem at the beginning and at the end of the given segment, see Equation (1).

$$v_{ij} = \frac{g_{oij} + g_{nij}}{2} l_{ij} \tag{1}$$

where:

v_{ij} – merchantable stem volume of section j on a tree i;

g_{oij} – cross-sectional area at the beginning of the stem segment j on a tree i;

g_{nij} – cross-sectional area at the end of the stem segment j on a tree i;

l_{ij} – length of stem segment j on a tree i.

Data analysis. Four volume equation models were tested to model the relationship between the merchantable stem volume over bark (dependent variable) and the diameter at breast height of a tree and the total height of the tree (independent variables). We tested models by Petráš and Pajtík (1991), as shown by Equation (2):

$$v_i = a_1\left(d_{1.3i} + 1\right)^{a_2} h_i^{a_3} - a_4\left(d_{1.3i} + 1\right)^{a_5} h_i^{a_6} \tag{2}$$

Valenta and Šešulka (2015), which are both used for merchantable stem volume estimation of silver fir in the Czech Republic:

$$v_i = \left[a_1\left(d_{1.3i} + 1\right)^{a_2} h_i^{a_3} - a_4\left(d_{1.3i} + 1\right)^{a_5} h_i^{a_6}\right]0.8467 \tag{3}$$

A third model was from Omule et al. (1987) for Douglas fir in British Columbia:

$$v_i = e^{\left[a_1 + a_2 \ln\left(d_{1.3i}\right) + a_3 \ln\left(h_i\right)\right]} \tag{4}$$

and model according to Vallet et al. (2006) for Douglas fir in France:

$$v_i = \left(\frac{d_{1.3i}}{200}\right)^2 \pi h_i \left(a_1 + a_2 \frac{h_i}{d_{1.3i}}\right) \tag{5}$$

where:

$a_1, a_2, a_3, a_4, a_5, a_6$ – model parameters;

$d_{1.3i}$ – diameter at breast height of a tree i;

h_i – total height of a tree i;

v_i – merchantable stem volume of a tree i.

All four tested models were parametrized using nonlinear regression using the nonlinear least square (NLS) method. The following goodness of fit characteristics were used as evaluation criteria for choosing the best model, as shown in Equations (6–11):

Mean value of residuals

$$\bar{e} = \frac{\sum_{i=1}^{n} e_i}{n} \tag{6}$$

Residual standard deviation

$$\sigma_e = \sqrt{\frac{\sum_{i=1}^{n} (e_i - \bar{e})^2}{n}} \tag{7}$$

Residual standard error

$$SE_e = \frac{\sigma_e}{\sqrt{n}} \tag{8}$$

Akaike's information criterion (Akaike 1973)

$$AIC = n \ln\left(\frac{\sum_{i=1}^{n} e_i^2}{n}\right) + 2m \tag{9}$$

Root mean square error

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n - m}} \tag{10}$$

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Index of determination

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \tag{11}$$

where:

$\bar{e}$ – mean value of residuals;
e_i – residual value of a tree i;
y_i – measured value of a tree i;
n – sample size;
m – number of model parameters;
$\hat{y}_i$ – fitted value of a tree i;
$\bar{y}$ – mean value of all measured trees.

Based on these criteria, a model was selected, which was then used for the next phase of modelling the merchantable stem volume over bark. This was the model according to Omule et al. (1987). This model was further developed into a nonlinear model with mixed effects (NLME) and also into a variant of the nonlinear model using the weighted least square (WLS) method. These two mentioned variants were tested because a high degree of heteroscedasticity was detected in the classic NLS model in the graphical analysis of the residuals (Figure 1A). For the NLME model, different combinations of random effects of parameters and also different variance functions were tested to eliminate heteroscedasticity. For the WLS model, different types of weights were tested in relation to tree variables in different weighting functions also to eliminate heteroscedasticity. For the tested models, the relative error of the model was also calculated according to the formula shown in Equation (12):

$$e_{\%} = \frac{e_i}{y_i}100 \tag{12}$$

where:

$e_{\%}$ – relative error;
e_i – residual value of a tree i;
y_i – measured value of a tree i.

All statistical analyses were performed at a significance level of α = 0.05 in R software (Version 4.3.0, 2023).

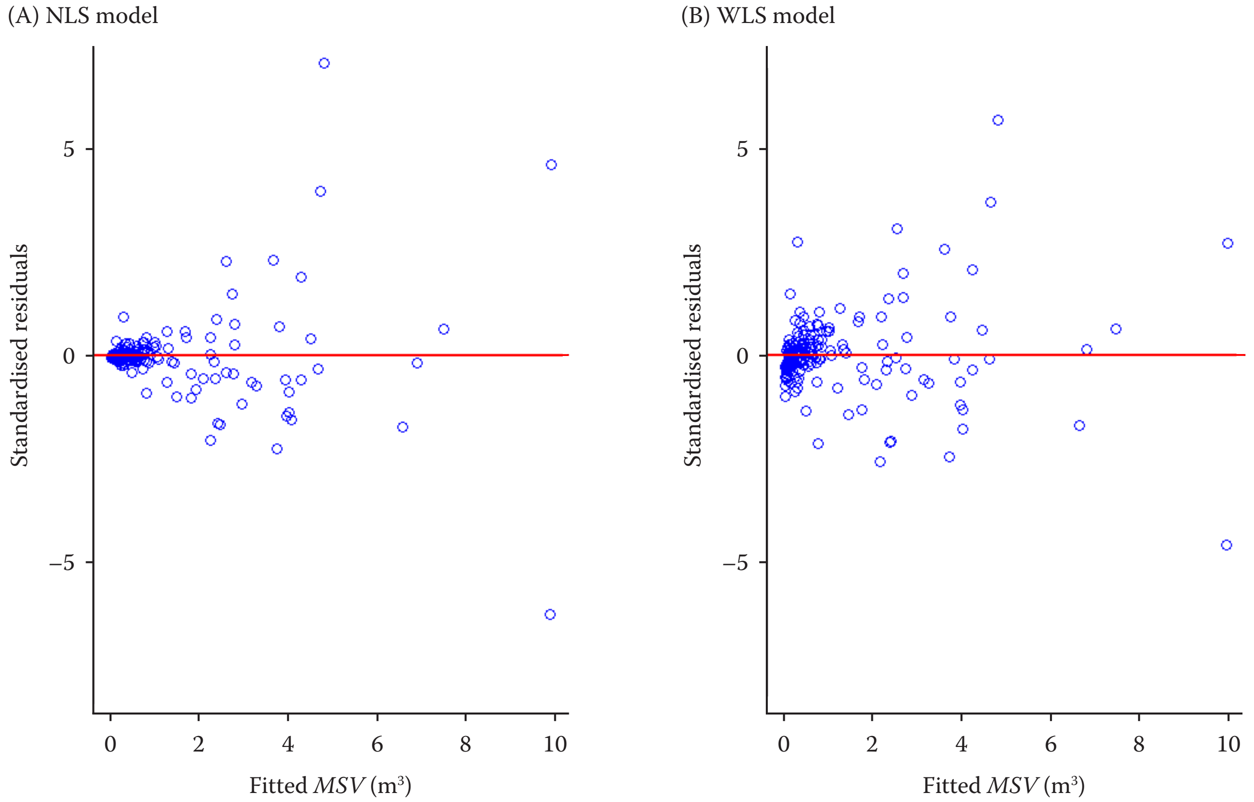

Figure 1. Plot of standardised residuals against fitted values of merchantable stem volume (*MSV*) from the Omule et al. (1987) model: (A) Nonlinear least squares (NLS) model; (B) Weighted least squares (WLS) model

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Table 3. Goodness of fit characteristics of tested NLS models

Model	*MR*	*SD*	*SE*	*AIC*	*RMSE*	R^2
Petráš and Pajtík (1991)	0.000162	0.232572	0.017099	–528.668	0.23580	0.963362
Valenta and Šešulka (2015)	0.000192	0.232567	0.017099	–528.676	0.23579	0.963364
Omule et al. (1987)	–0.003789	0.232363	0.017084	–534.951	0.23367	0.963418
Vallet et al. (2006)	–0.008060	0.234215	0.017220	–533.843	0.23499	0.962804

MR – mean value of residuals; *SD* – residual standard deviation; *SE* – residual standard error; *AIC* – Akaike's information criterion; *RMSE* – root mean square error; R^2 – index of determination

RESULTS

All four tested models were parametrized using the NLS method. The final values of the goodness of fit characteristics for all the compared models are shown in Table 3. From these values, it can be seen that all the compared models have a similarly high level of quality of fit, with the model according to Omule et al. (1987) being the most precise one. However, heteroscedasticity was detected in all the tested models in the graphical analysis of the residuals. Therefore, for the selected model according to Omule et al. (1987), the model was further developed in the variants of the NLME model and the WLS model.

For the NLME model, a random effect at the property level was tested. Although different variants of combinations of random effects as well as different variance functions were tested, it was not possible to find a final NLME model that would significantly reduce the degree of heteroscedasticity. The reason is apparently that the data comes only from three properties, which is not sufficient for the NLME model to work effectively.

On the other hand, for the model that used the WLS method for parameter estimation, it was possible to find a suitable weighting function from various combinations, which successfully reduced the degree of heteroscedasticity. The final weight function can be written as Equation (13):

$$w_i = \frac{1}{\frac{v_i}{\sigma_v^2}} \tag{13}$$

where:

w_i – weight of measured value of tree *i* in WLS method;

v_i – merchantable stem volume of a tree *i*;

σ_v^2 – variance of merchantable stem volume of all trees.

The estimated parameters of the final WLS model of Omule et al. (1987) are shown in Table 4. The goodness of fit characteristics of the final WLS model are shown in Table 5. Fitted values of merchantable stem volume over bark in relation to *DBH* of a tree and total height of a tree are shown in Figure 2.

When comparing the goodness of fit criteria of the best WLS model and NLS model, it can be seen that the results of the WLS model are numerically only slightly worse. However, when the results of the graphical analysis of the residuals

Table 4. Estimated parameters of final WLS model of Omule et al. (1987; $P < 0.0001$)

Parameter	Estimation	Standard error	*t*-value
a_1	10.20575	0.13778	74.07
a_2	1.74011	0.05081	34.25
a_3	1.24779	0.08562	14.57

Table 5. Goodness of fit characteristics of final WLS model of Omule et al. (1987)

WLS model	*MR*	*SD*	*SE*	*AIC*	*RMSE*	R^2
Omule et al. (1987)	0.012723	0.234227	0.017221	–531.497	0.23586	0.962735

MR – mean value of residuals; *SD* – residual standard deviation; *SE* – residual standard error; *AIC* – Akaike's information criterion; *RMSE* – root mean square error; R^2 – index of determination

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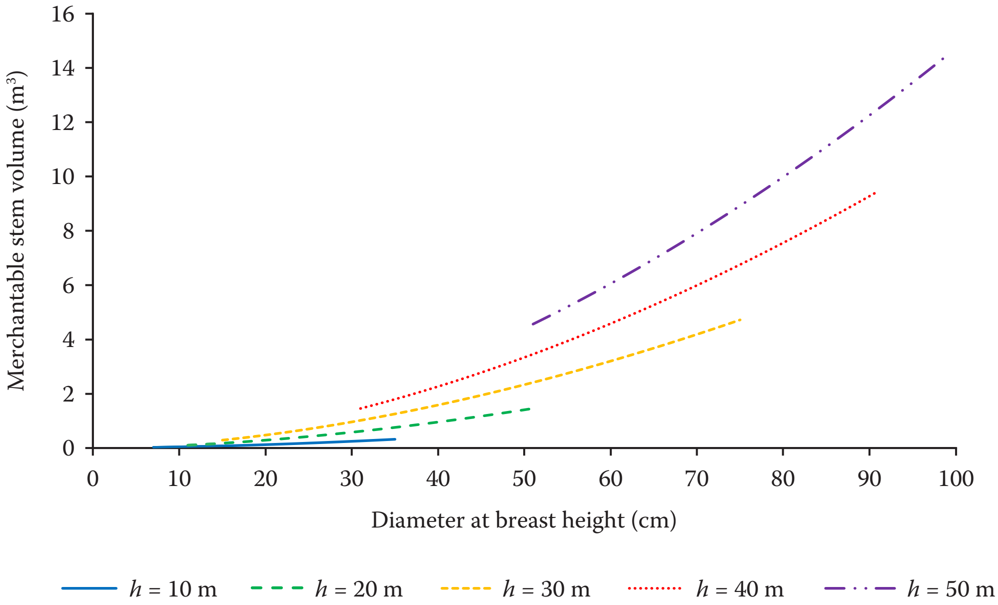

Figure 2. Fitted values of merchantable stem volume related to diameter at breast height of a tree and total height (*h*) of a tree [Weighted least squares (WLS) method – the Omule et al. (1987) model]

are compared, it can be seen that the WLS model significantly reduced the heteroscedasticity of the residuals (Figure 1B) and removed the statistically significant bias of the model. This is evident from the boxplots of the relative errors of the models (Figure 3). It is clearly visible that the confidence interval of the median of the relative errors of the WLS model (Figure 3B, D) contains 0 (the estima-

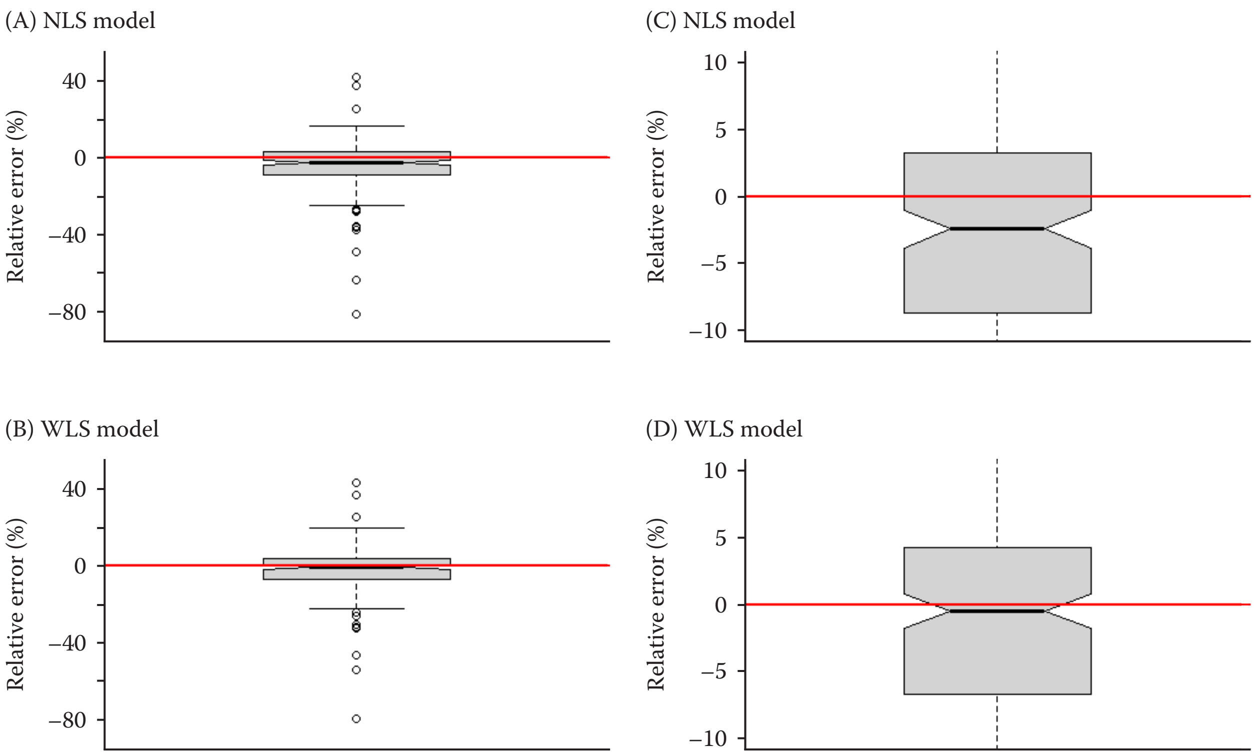

Figure 3. Boxplots of relative errors of the Omule et al. (1987) model: (A) Nonlinear least squares (NLS) model – full data range; (B) Weighted least squares (WLS) model – full data range; (C) Nonlinear least squares (NLS) model – detail for interval <–10,10>; (D) Weighted least squares (WLS) model – detail for interval <–10,10>

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tion of the median is –0.53%) in contrast to the NLS model (Figure 3A, C), which has a statistically significant bias (median estimation is –2.44%). However, the slightly worse values of the numerical model quality criteria are clearly complemented by better results of the graphical analysis of the residuals and also by the removal of the model bias, which is decisive for the resulting quality of the model. Based on the showed results it can be concluded that the model developed with the use of the WLS method to estimate the values of the model parameters should be used to determine the merchantable stem volume of Douglas fir depending on the *DBH* of a tree and total height of a tree.

DISCUSSION

We found that the model of Omule et al. (1987) has the smallest relative error. We try to demonstrate the accuracy of the final model in comparison of a currently used method for tree volume estimation in the Czech Republic. We selected a sample tree with the *DBH* and total height closest to the mean values (*DBH* = 33 cm, total height = 23.95 m, measured merchantable stem volume = 0.874 m^3). We fitted the volume for this tree by the Omule et al. (1987) model: 0.853 m^3, by the Petráš and Pajtík (1991) model: 0.819 m^3, and by the ÚLT (1951) model: 0.970 m^3, respectively. It is evident that the Omule et al. (1987) model has really the smallest deviation from the real volume calculated by section method in combination with the Smalian formula.

The choice of the optimal volume equation does not depend only on the regression analysis, but it is also necessary to evaluate the suitability of the equation based on the difference between the real volume of the sample trees and the calculated volume according to the selected equation (Stolariková et al. 2014). The choice of the size of the segments and the selection of the stereometric formula for determining the volume of the stem is also related to the accuracy of the models. The Smalian formula used in this study was also used by Mbangilwa et al. (2020). A simple rule of thumb regarding segment length is that shorter segments allow for better description of the stem shape. For example, Petráš and Pajtík (1991) used 2 m segments for developing volume equations, while Vallet et al. (2006) used 1 m segments, the same segment length was used in this study.

Some authors of volume equations do not use only easily measurable variables such as tree height and diameter at breast height, but also use tree or stand age, for example in the study by Gonzalez-Benecke et al. (2021) of Monterey pine (*Pinus radiata* D. Don) in Chile. Gonzalez-Benecke et al. (2014) state that the inclusion of other variables such as tree age, stand density or site index can improve the accuracy of the models. Gonzalez-Benecke et al. (2021) reported that the accuracy of stem volume prediction improved when stand age was included in the model. In the current conditions of the Czech Republic, this variable is quite easy to determine (e.g. from the Forest management plan), but in the future, when forest stands will be conversed to uneven-aged stands, it might be more difficult to determine it.

On the contrary, Bjarnadottir et al. (2007) used only one independent variable (diameter at the height of 50 cm) while developing volume equations for Siberian larch (*Larix sibirica* Ledeb.). They found that the use of the second independent variable (tree height) does not significantly improve the quality of the prediction.

On the other hand, Bjarnadottir et al. (2007) presume that this was a result of the fact that the felled trees used for the study came from local population with similar site conditions and the ratio between tree height and *DBH* varied little, thus confirming the results of Parresol (1999). However, it is also advisable to use the height of the tree as a second independent variable to reduce the error estimation of generic functions based on only one independent variable (most often diameter at breast height; Bjarnadottir et al. 2007). Lee et al. (2017) state in the study for *Pinus densiflora* Siebold & Zucc., *Pinus koraiensis* Siebold & Zucc., and *Larix kaempferi* (Lamb.) Carriére, that the volume equation that uses only the *DBH* as an independent variable is very similar to the equation that uses the *DBH* and tree height, and also further state that the forest manager should decide in the forest stand which equation to use to determine the volume. It is worth mentioning that in their study, the error of determining the volume using only the *DBH* increased with the increasing volume. Other attempt to use only one independent variable (*DBH*) in volume equations include the study of Sönmez et al. (2023) that dealt with sample trees of Turkey oak (*Quercus cerris* L.). This study demonstrated that using two independent variables, namely *DBH* and tree height, improved the accuracy of the stem volume estimation, as opposed to using only *DBH*.

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Some equations use tree circumference at 1.3 m as an independent variable instead of *DBH*, such as the equations developed by Vallet et al. (2006).

CONCLUSION

All the four tested models were successfully reparametrized, and their evaluation showed the high quality of the merchantable stem volume over bark prediction. The model according to Omule et al. (1987) was evaluated as the best one since its parametrization using NLS method showed the best values of goodness of fit characteristics. However, this model still had to be reparametrized using the WLS method to remove the heteroscedasticity of the residuals. The NLME model was also tested to eliminate this problem, but was unsuccessful. The use of the WLS method helped to reduce the relative error of the model too and get an estimation of the median as low as –0.53% for its final version. However, this value was not statistically significant, so the final model could be considered as a model without a systematic error. This is a significant improvement compared to the model with an estimated 4% relative error used in the Czech Republic up until now. Our reparametrized WLS model according to Omule et al. (1987) could therefore replace the other models (Petráš, Pajtík 1991; Valenta, Šešulka 2015) currently used in the Czech Republic when modelling the merchantable stem volume over bark of Douglas fir.

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