

Estimating diameter at breast height from basal diameter of plantation-grown Scots pine (*Pinus sylvestris* L.) trees in Bulgaria

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Abstract

Our study aimed to develop and provide forest practitioners with a reliable tool for estimating the breast height diameters of the plantation-grown Scots pine trees for restoration of their dimensions when the stems have been removed or destroyed. We applied a number of modelling approaches and developed a simple and a multiple fixed-effects models, a mixed-effects model, and a mixed-effects model with calibrated random parameter components. We compared their goodness of fit and contrasted the accuracy of their predictions with that of the currently applied table. A fixed-effects linear function of the basal tree diameter and the respective linear mixed-effects relationship showed an overall best model performance. Specifying the mixed-effects model to the particular stand by calibrating the random-parameter components with a breast height-basal diameter pair of measurements of one average-sized tree, was recommended. Our models perform better than the currently applied table, which systematically overestimates the breast height diameter, and consequently the volume of the largest portion of the tree trunk. Both model versions are executable in a few simple steps in the user-friendly environment of the MS Excel-based simulator DbhRestore, which is distributed free of charge on the Internet.

Key words: forest simulator, linear function, mixed-effects model, model calibration, Scots pine plantations, stump diameter.

Introduction

Volume tables provide data on individual-tree volume as a function of one or more quantitative tree characteristics

(Mihov 2005). Such a characteristic is the diameter at breast height (DBH), the variable most frequently recorded in forest inventories, which is closely related to stand height, stem volume, and tree bio-

mass (Vanclay 1994, Ercanli et al. 2014, Horvath and Popa 2021). Although easily measurable, there are cases in which DBH measurement is not possible, e.g., following illegal logging or natural disturbances (Horvath and Popa 2021). At the same time, a need to estimate the tree volume when only stumps are left arises in some situations, such as valuation of timber for sale, checking harvesting practices following tree extraction, certification of felling sites, assessment of damages caused by natural disasters, and calculation of the losses from illegally harvested timber (Hampf 1954, Corral-Rivas et al. 2007, Özçelik et al. 2010).

Even if the trees have been removed, their breast height diameter dimensions can still be restored, with the primary source of information being the tree stump. Therefore, the relationship between breast height and basal (d_0) tree diameters is of practical importance in forestry and derives the need to investigate options for estimating the breast height stem diameter from tree stump measurements. The functional relationship and its inverse function between diameter at breast height and diameter at the stem base were analysed to serve the National Forest Inventory in Hungary (Hungarian Ministry of Agriculture 2010). Stump height was defined at 20 cm above the ground, and the linear function was chosen to develop five pairs of models, which were generalised at the level of species groups: black locust, beech and alder, poplars, oaks, and pines. Generalised one-predictor relationships by species groups – coniferous and broadleaves – were developed and used during the first Italian National Forest Inventory in 1985 (IFN185), as well (Di Cosmo and Gasparini 2020). Large-scale studies on predicting DBH from stump diameter have been reported for a range of tree species in the

Northeastern (Hampf 1954, 1955a–e, 1957a–b; Wharton 1984; Westfall 2010) and the Southern USA (Bylin 1982), British Columbia (Demaerschalk and Omule 1982), and Italy (Di Cosmo and Gasparini 2020). Most of them considered variable stump height which, along with the stump diameter, was related linearly (Hampf 1954, 1955a–e, 1957a–b) or non-linearly (Demaerschalk and Omule 1982, Westfall 2010, Di Cosmo and Gasparini 2020) to the DBH. The studies in the USA paid particular attention on the dependencies to the basal diameter under bark (Hampf 1954; 1955a–e, 1957a–b; Bylin 1982; Wharton 1984) and the reported accuracy was within an error range from 0.3 to 1.19 inches (0.76–3.03 cm) and from 0.2 to 0.7 inches (0.51–1.78 cm) obtained for the various species (Hampf 1954, 1955a–e, 1957a–b) or species groups (Westfall 2010).

Except for some early studies (e.g., Wharton 1984), most of the investigations explore a number of linear and non-linear functions as candidate models for the breast height–basal diameter relationship (Corral-Rivas et al. 2007, Ercanli et al. 2014, Milios et al. 2016, Sakici and Unal 2017). Although a linear model is often derived (e.g., Bylin 1982, Corral-Rivas et al. 2007, Özçelik et al. 2010), power (Ercanli et al. 2014, Sakici and Unal 2017, Şahin et al. 2019) and second-degree polynomial functions (Milios et al. 2016, Şahin et al. 2019) have also been reported. One-predictor model formulations are usually considered when stump diameter is defined and measured at a particular height above the ground (e.g., Johnson and Weigel 1990, Corral-Rivas et al. 2007, Ercanli et al. 2014, Milios et al. 2016), or when the measuring height is disregarded (e.g., Wharton 1984). However, numerous studies developing two-predictor relation-

ships, by adding the stump height as a second independent variable to the basal diameter, have also been reported (Curtis and Arney 1977, Kozak and Omule 1992, Chhetri and Fowler 1996, Westfall 2010, Pond and Froese 2014, Di Cosmo and Gasparini 2020). The DBH- d_0 models are usually specified at the species level, but a higher level of generalisation, as well as a higher degree of localisation of the dependencies, have also been investigated. Chhetri and Fowler (1996) developed a model for the lower temperate broad-leaved forest type of Nepal, including data from 17 tree species, while Westfall (2010) suggested DBH-predicting functions for 18 species groups in the Northeastern USA, aggregating the species in groups according to taper. Demaerschalk and Omule (1982), on the other hand, differentiated their species-specific models according to age classes and geographic regions.

Around the middle of the last century, a table was developed in Bulgaria for determining breast height diameter from the stump diameter of Scots pine, Norway spruce, and silver fir trees, which was first published in the Forest Inventory Worker's Handbook (Duhovnikov et al. 1955) and was included in its original form in later published reference books (Nedyalkov et al. 1983, Krastanov and Raykov 2004), as well. There is no accompanying publication for this table that would provide information on the range of the data used, the methodology applied, the mathematical expressions of the obtained relationships, and the accuracy attained. This raises certain doubts about how adequate and useful the application of this table would be in the current practice and under the disturbances and climate change nowadays. Therefore, addressing the needs of the forest inventory practitioners, control

bodies, and certification auditors, the main objective of this study was to develop an adequate predictive model, together with a simulator for its practical implementation, to describe the relationship between the diameters at breast height and at the stem base of plantation-grown Scots pine trees in Bulgaria.

Materials and Methods

Data sets

The data used in this study were composed of training and validation subsets. The information for model derivation and parameterisation (training subset) was collected in 29 experimental units (referred hereafter as 'plots') of permanent sample plots (PSP) at 15 locations in Scots pine plantations throughout the mountainous range of Bulgaria (Fig. 1). Diameters at the stem base and at breast height were determined as averages from two mutually perpendicular measurements taken at each of these points on the stems of the sampled trees with the digital calliper Haglöf Digitech DP II. Following the current Bulgarian forest regulations – Regulations for the implementation of the Forestry Act, art. 93(1) (Bulgarian Council of Ministers 1998), Ordinance 8 on felling in forests (Ministry of Agriculture, Food and Forests 2011), and Ordinance 18 on inventory and planning in forest areas (Ministry of Agriculture, Food and Forests 2015) – basal tree diameter measurements were taken at up to 5 cm heights from the ground surface for stump diameters less than 20 cm and up to 10 cm for larger stumps, at the upper side of the stump on inclined terrain. These stump heights have been established as the maximum heights above ground needed to avoid butt swell. Fifteen

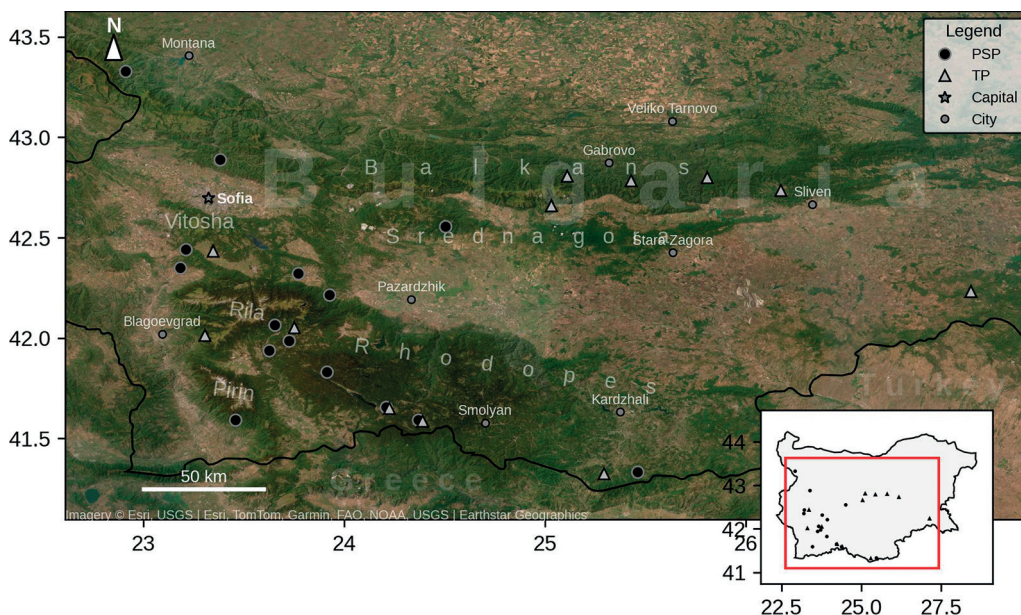


Fig. 1. Locations of the permanent sample plots (PSP) and temporary plots (TP).

Note: the mountain ranges Vitosha, Balkans, Sredna gora, Rhodopes, Rila and Pirin are indicated.

to 211 trees per experimental unit were measured depending on the plot size. The stand-level parameters of the sampled plantations were obtained from the inventory records (Stankova et al. 2024). Validation data were gathered from 60 destructively sampled Scots pine trees in 12 temporary plots (TP). The number and range of the records in both data subsets are included in Table 1, and the locations of the plots are shown in Fig. 1.

Derivation of base DBH – d_0 model

Based on the graphical analysis of the parameterisation data, and considering the findings of previous investigations (e.g., Özçelik et al. 2010, Ercanli et al. 2014, Sakici and Unal 2017), nine one-predictor functions were selected and tested for modelling the breast height – basal diameter relationship of Scots pine trees.

Five of the models were polynomials of the 1st and 2nd degree (formulae 1 to 5 in Table 2), and the others included power, exponential, and logarithmic relationships (formulae 6, 7 and 9 in Table 2, respectively), as well as a function known as Schumacher or Michailoff function (formula 8 in Table 2, Gadow and Hui 1999). The models were fitted to the entire training data set, as well as by plots, and their predictive abilities were compared using 2 sets of criteria, which were based on the residual values. The first group of criteria characterises model accuracy at the stand level and includes 3 test statistics (Stankova and Diéguez-Aranda 2013): the mean bias, estimated as an average of the different plot biases, mean squared error (MSE), calculated per plot and aggregated to a single value for each model, and the 90th percentile of the absolute values of the relative biases evaluated for

Table 1. Experimental data used for derivation and for validation of a relationship between the breast height and the basal stem diameter of the plantation-grown Scots pine trees.

Data set	Variable	Number of units	Mean	Standard deviation	Range	
					min	max
Training	At stand level	QMD	26.61	6.77	15.21	38.65
		H_m	24.7	5.5	14.8	37.3
		A	67	11	50	89
		N	1024	632	313	2688
	At tree level	DBH	24.31	8.29	7.80	52.10
		d_0	30.50	9.82	11.10	67.25
Validation	At stand level	QMD	28.59	5.07	19.12	35.20
		H_m	24.51	3.73	19.05	31.12
		A	58	10	40	75
	At tree level	DBH	28.24	6.56	14.95	44.65
		d_0	34.91	8.14	19.15	56.90

Note: QMD – quadratic mean diameter, cm; H_m – mean height, m; A – age, years; N – density, trees·ha⁻¹; d_0 – basal tree diameter, cm; DBH – diameter at breast height, cm.

Table 2. Goodness of fit and comparison of the examined functional relationships.

Model		By plots			For total data			
		Mean bias, cm	Aggregated MSE	90th percentile of ARB	ME	RMSE, cm	AIC	AICw
1	DBH = $a_0 + a_1 d_0$	$-7.75 \cdot 10^{-19}$	45.572	0.053	0.972	1.386	8,258	0.779
2	DBH = $a_1 d_0$	$-1.25 \cdot 10^{-02}$	47.332	0.054	0.970	1.425	8,387.38	0
3	DBH = $a_0 + a_1 d_0 + a_2 d_0^2$	$-1.30 \cdot 10^{-17}$	44.275	0.053	0.972	1.386	8,259.89	*
4	DBH = $a_1 d_0 + a_2 d_0^2$	$-3.14 \cdot 10^{-03}$	45.358	0.053	0.972	1.392	8,279.44	0
5	DBH = $a_0 + a_2 d_0^2$	$8.92 \cdot 10^{-18}$	59.176	0.058	0.938	2.057	10,125.16	0
6	DBH = $a_0 d_0^{a_1}$	$-1.32 \cdot 10^{-03}$	45.460	0.053	0.972	1.387	8,260.53	0.221
7	DBH = $a_0 \exp(a_1 d_0)$	$1.18 \cdot 10^{-03}$	59.109	0.053	0.943	1.970	9,921.08	0
8	DBH = $a_0 \exp(a_1/d_0)$	$1.54 \cdot 10^{-02}$	54.459	0.058	0.933	2.138	10,306	0
9	DBH = $a_0 + a_1 \ln d_0$	$-2.61 \cdot 10^{-09}$	56.037	0.059	0.932	2.167	10,371.1	0

Note: d_0 – basal tree diameter, cm; DBH – diameter at breast height, cm; a_0 , a_1 , a_2 – model parameters; MSE – mean squared error, cm²; ARB – absolute relative bias at plot level ($0 < \text{ARB} < 1$); ME – model efficiency ($0 < \text{ME} < 1$); RMSE – root mean squared error, cm; AIC – Akaike information criterion; AICw – Akaike weights ($0 < \text{AICw} < 1$). *The second-degree polynomial was excluded from comparison due to a non-significant parameter a_2 ($p = 0.739$).

the plots. These three characteristics were chosen since they account for both the magnitude and the range of model errors,

with lower values indicating better model performance. The second group of criteria assesses model accuracy for the param-

eterisation data as a whole and includes model efficiency (ME), which indicates what part of the variation in the data is explained by the model ($0 < ME < 1$), root mean squared error (RMSE), and Akaike Information Criterion (AIC) (Gadow and Hui 1999, Sileshi 2014). The goodness of fit of the function that showed the best predictive potential is further checked graphically and analytically regarding normality and homoscedasticity of the residuals. The model was also tested for bias using a *t*-test for a mean error equal to zero and a simultaneous *F*-test for a slope of 1 and an intercept 0 in the linear regression connecting experimental and predicted values. Final model selection at this and the following derivation steps was done according to Akaike weights that can be interpreted as the relative likelihood that a model is the best among the set considered (Wagenmakers and Farrell 2004, Sileshi 2014).

Derivation of stand-specific model formulations

The potential for improvement of the derived DBH- d_0 model was further tested within the mixed-effects modelling framework. The mode of expansion with additional predictor variables was derived by presenting model parameters separately and together as being composed of fixed and random components and by comparing the prediction potential of the resulting formulations according to Akaike weights.

We tested 3 stand-level variables as additional predictors in the model: plantation age, density (number of trees per hectare) and average basal diameter (estimated as a quadratic mean) since they can be measured for any partially or completely harvested stand. Such confidence

cannot be guaranteed for either mean and dominant heights or for quadratic mean breast height diameter, if they are calculated on the basis of the remaining stand. For example, trees that have been damaged by fire will be removed from the Scots pine plantation and consequently their dimensions (except for the basal diameter) will not be reflected in the average parameters of the undisturbed stand. The candidate multiple regression models were derived by stepwise backward selection. Collinearity of the regression models was assessed and controlled by the condition number (<30) and the variance inflation factor (<10) and when the thresholds were exceeded, reduced-form model combinations were tested and proposed instead, taking into account the correlation matrix of the predictor variables.

In addition, calibration of the random parameter components of the mixed-effects model that performed best with a breast height-basal diameter measurement of one tree at each occasion, following the procedure described by Trincado et al. (2007), was also attempted. Since the mixed-effects model was developed using all trees in the training data set, calibration of the random parameter components was done over the validation data set. For each validation plot, the calibration procedure was carried out using consequently all sampled trees. The mean error, the ranges of the minimum and maximum errors in the DBH predictions produced by the different trees for calibration, as well as the averages of these extreme values were assessed.

Model comparison and software development

The best simple and multiple fixed-effects models, the mixed-effects model,

the mixed-effects model with calibrated random parameter components, and a table-derived model (Table 5.21 in Nedyalkov et al. 1983) were compared through error test statistics evaluated for the relevant, training and/or validation, data subset. The range (0th, 25th, 50th, 75th and 100th percentiles of the relative errors) and the magnitude (Bias, cm; mean absolute relative errors – MARE, %) of the errors were assessed. Finally, a simulator for calculating the breast height diameter from the basal stem diameter of the trees in the Scots pine plantations, based on macros in MS Excel, was elaborated, incorporating the best models developed in this study. The data management, statistical analyses, and some of the graphical representations were carried out in the R software environment (R Core Team 2024), and the results were also illustrated employing the graphical tools of Microsoft Excel (Microsoft Corporation 2021).

Results

Base DBH – d_0 model

The two sets of statistical criteria used to compare the candidate functions for describing the relationship between the breast height and the basal diameter

showed a better predictive potential for the power function and for some of the first- and second-degree polynomials (Table 2). The three-term second-degree polynomial was excluded from the final comparison using the Akaike weights (AICw), despite its superiority over the other estimates, because one of its coefficients was not significantly different from zero. The final test (AICw) showed a higher predictive potential of the linear model compared to the other examined functions, with a nearly fourfold better suitability for describing the relationship than the next best – the power function (e.g., AICw = 0.779 vs 0.221, Table 2).

The table for DBH determination currently employed in practice (Table 5.21 in Nedyalkov et al. 1983) is readily fitted by a linear function of d_0 (adj. $R^2 = 0.9999$). When the predictions of the obtained in this study linear relationship were collated with those of the table-derived linear model (Model M2 in Table 3), the results showed that the table systematically overestimated the breast height diameters over the entire data range, although the deviations from the newly developed model did not exceed 4.5–6 % (Table 3, Fig. 2a). Considering the main volume calculation formula based on the basal area, height and form factor of the tree, this deviation of the table-predicted DBH

Table 3. Comparison of the derived simple linear model with the model based on Table 5.21 in Nedyalkov et al. (1983).

Model	Deviation	MARE, %	Q0, %	Q25, %	Q50, %	Q75, %	Q100, %
M1: DBH = $0.832 \cdot d_0 - 1.081$	according to data	4.79	-40.0	-3.9	0.1	3.8	20.9
M2: DBH = $0.869 \cdot d_0 - 1.012$	according to data	6.51	-47.2	-9.1	-4.8	-0.9	16.6
	according to M1	4.96	-5.9	-5.1	-4.9	-4.8	-4.6

Note: M1 – simple linear model developed in this study, M2 – linear model according to Table 5.21 in Nedyalkov et al. (1983); MARE, % – mean absolute relative error ($0 < \text{MARE, \%} < 100$); Q0–Q100, % – 0th, 25th, 50th, 75th and 100th percentiles of the relative errors.

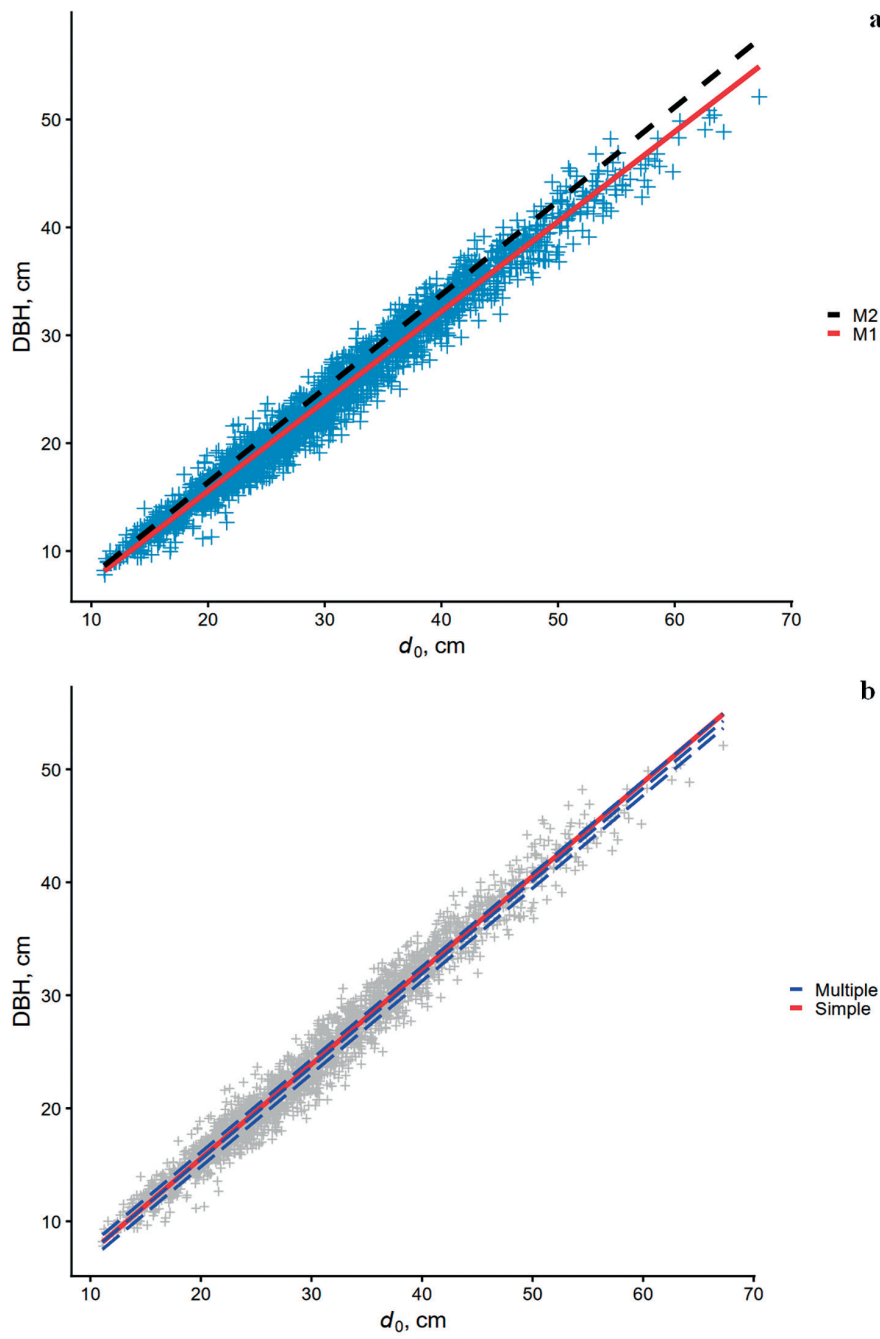


Fig. 2. Comparison of the fixed-effects linear models: (a) Simple linear model of this study (M1) vs. the table-based linear model (M2) (Table 5.21 in Nedyalkov et al. 1983); (b) Simple vs. multiple linear regression model for ages 10, 50 and 90 years.

will produce volume overestimation of 9.2 to 12.4 % as compared to our model.

Localised model formulations, model validation and application software

When fitted within the mixed-effects modelling framework, the simple linear relationship derived here revealed its potential for improvement if parameter estimates are specified at stand level, and such op-

tions were distinguished for both the slope and the intercept (Table 4).

Therefore, we formulated and examined multiple regression models expanding both the slope and the intercept through functions of the selected predictor variables. Ten adequate multiple regression models were derived, but only 3 of them showed better goodness of fit than the simple linear function (Table 5). The strongest improvement was manifested by

Table 4. Comparison of linear mixed-effect model formulations for the relationship between the breast height and the basal tree diameter.*

Equation	Mixed-effects model	AIC	AICw
Eq. 1	$a_0 + a_1 \cdot d_0$	8258.00	0
Eq. 2	$(a_0 + u) + a_1 \cdot d_0$	7830.87	0
Eq. 3	$u + (a_1 + v) \cdot d_0$	7809.07	0.171
Eq. 4	$(a_0 + u) + (a_1 + v) \cdot d_0$	7806.38	0.653
Eq. 5	$a_0 + (a_1 + v) \cdot d_0$	7809.00	0.176
Eq. 6	$(a_0 + u) + v \cdot d_0$	7967.34	0

Note: d_0 – basal tree diameter, cm; DBH – diameter at breast height, cm; AIC – Akaike information criterion; AICw – Akaike weights ($0 < \text{AICw} < 1$); a_0 , a_1 – fixed parameter components; u , v – random parameter components. * All possible parameter combinations were tested and compared, including the cases of random intercept only (u) and random slope only (v).

Table 5. Multiple regression models for the relationship between the breast height and the basal tree diameter.*

	Regression model	AIC	AICw
M1	$\text{DBH} = a_0 + a_1 \cdot d_0$	8,258.0	0
MR1	$\text{DBH} = a_0 + a_1 \cdot d_0 + a_2 \cdot \text{QMD}_0$	8,241.4	0.022
MR2	$\text{DBH} = a_0 + a_1 \cdot d_0 + a_2 \cdot A$	8,233.8	0.933
MR3	$\text{DBH} = a_0 + a_1 \cdot d_0 + a_2 \cdot \text{QMD}_0 \cdot A$	8,239.9	0.045
MR4	$\text{DBH} = a_1 \cdot A + a_2 \cdot d_0 + a_3 \cdot d_0 \cdot A$	8,270.2	0
MR5	$\text{DBH} = a_0 + a_1 \cdot A + a_2 \cdot d_0 \cdot \text{QMD}_0$	11,279.7	0
MR6	$\text{DBH} = a_0 + a_1 \cdot d_0 \cdot \text{QMD}_0 + a_2 \cdot d_0 \cdot A$	11,442.0	0
MR7	$\text{DBH} = a_1 \cdot \text{QMD}_0 + a_2 \cdot d_0 \cdot A$	12,686.2	0
MR8	$\text{DBH} = a_0 + a_1 \cdot d_0 \cdot \text{QMD}_0 + a_2 \cdot A$	11,279.7	0
MR9	$\text{DBH} = a_0 + a_1 \cdot d_0 \cdot \ln(N) \cdot A + a_2 \cdot d_0 \cdot \ln(N)$	10,189.6	0
MR10	$\text{DBH} = a_0 + a_1 \cdot d_0 \cdot \ln(N) \cdot A + a_2 \cdot d_0 \cdot \ln(N) + a_3 \cdot N$	9,118.4	0

Note: d_0 – basal tree diameter, cm; DBH – diameter at breast height, cm; QMD_0 – quadratic mean of the basal diameters, cm; A – age, years; N – density, trees $\cdot \text{ha}^{-1}$; AIC – Akaike information criterion; AICw – Akaike weights ($0 < \text{AICw} < 1$). * The simple linear model is in the top row, with the multiple regression models of higher prediction power (AICw) beneath, separated from the rest of the tested multiple regression models by a line.

the two-predictor model MR2 expanding the intercept as a linear function of age: $a_0 + a_2 \cdot A = 0.016 \cdot A - 1.757$ (slope parameter $a_1 = 0.821$). However, this improvement, although statistically significant, did

not yield a substantial increase in prediction accuracy as compared to the simple linear model with fixed and mixed regression parameters (Fig. 2b, Fig. 3, Table 6). Therefore, we examined another ap-

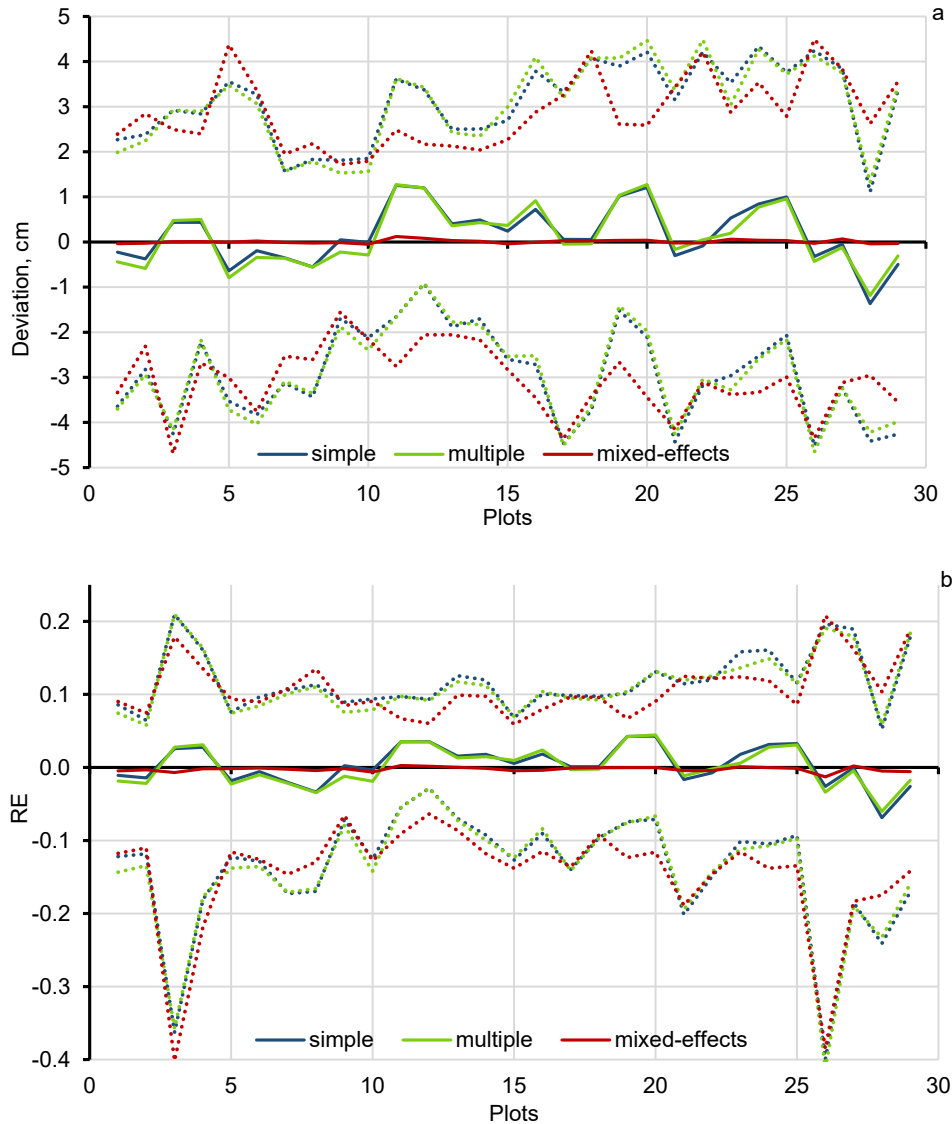


Fig. 3. Comparison of the simple and multiple linear fixed-effects models and the linear mixed-effects model by plots (training data set) according to absolute (a) and relative errors (b).

Note: RE – relative errors. * The mean errors are presented with solid lines, while the range of the errors (min-max) is indicated with dotted lines.

Table 6. Comparison between the three derived models and the table model for the relationship between the basal and the breast height tree diameter.

Data set	Statistical parameter	Simple linear model (M1)	Mixed-effects model	Multiple linear regression model
Parameterisation data	ME	0.97	0.98	0.97
	Q0, %	-39.97	-40.15	-41.23
	Q25, %	-3.90	-3.44	-3.90
	Q50, %	0.15	0.07	0.13
	Q75, %	3.83	3.26	3.77
	Q100, %	20.93	20.79	20.95
	MARE, %	4.79	4.15	4.76
		Simple linear model (M1)	Mixed-effects model with calibrated random components	Table model (M2)
Validation data	ME	0.95	0.96	0.92
	Q0, %	-9.23	-8.74	-14.47
	Q25, %	-6.14	-5.47	-11.27
	Q50, %	-2.06	-2.17	-6.96
	Q75, %	1.13	1.13	-3.71
	Q100, %	4.22	3.36	-0.37
	MARE, %	4.00	3.57	5.03

Note: M1 – simple linear model developed in this study; M2 – linear model according to Table 5.21 in Nedyalkov et al. (1983); ME – model efficiency ($0 < ME < 1$); MARE, % – mean absolute relative error ($0 < MARE, \% < 100$); Q0–Q100, % – 0th, 25th, 50th, 75th and 100th percentiles of the relative errors.

proach for calibration of the random parameter components: the use of an additional measurement of the DBH- d_0 dimensions of one tree from the stand, with the fixed parameter components estimated according to Eq. 4 (Table 4): $a_0 = -0.512$, $a_1 = 0.818$. This approach was tested with the validation data, utilising consecutively all trees in the plots as calibration trees.

The results showed that the additional calibration measurement leads to a decrease in the prediction errors and an increase in model efficiency (Table 6). The application of the table-derived model to the validation data confirmed once again that the table systematically overestimates

the diameters at breast height, in some cases by up to 15 % (Table 6, Fig. 4). In 10 of 12 plantations, the average errors of the table model were larger than those of the linear models derived in this study, both with and without calibration. Only in 1 of 12 plantations did the average errors of the two newly derived models exceed 5 %, while for the table model this occurred in 5 plantations. There was variation in the prediction errors produced by the calibrated model depending on the tree used to specify the random parameter components (figs 4b and 4d), which also indicated the possibility to reduce the errors nearly by half as compared to the

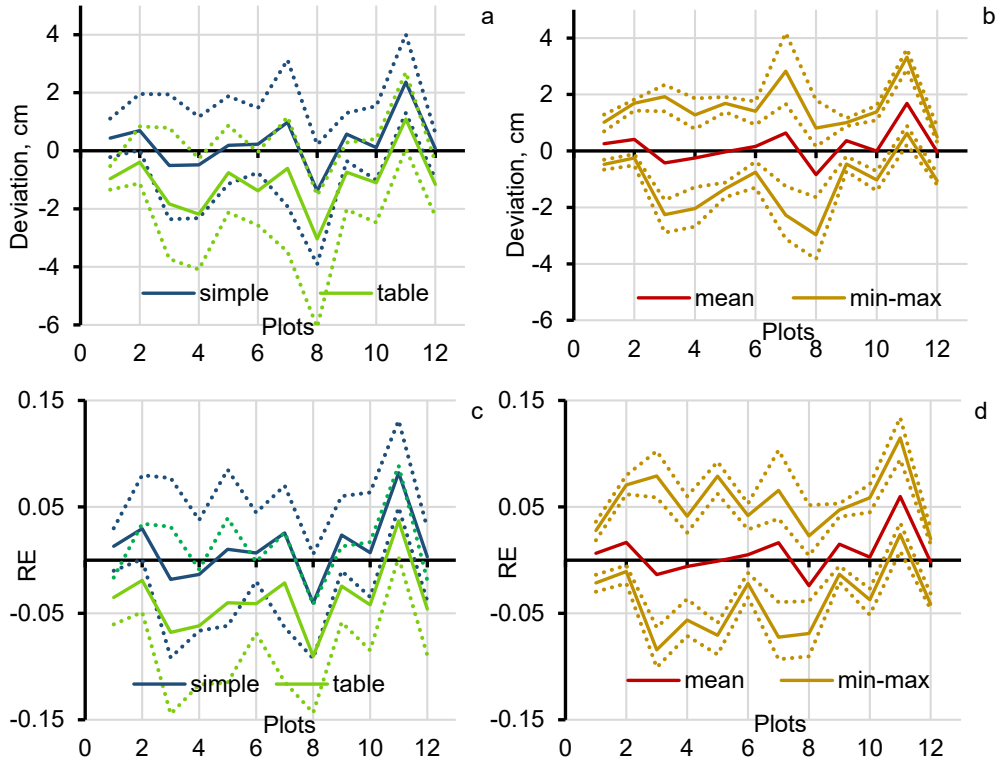


Fig. 4. Comparison of the simple fixed-effects model, the table model (a, c) and the calibrated mixed-effects model (b, d) by plots (validation data set).

Note: RE – relative errors. * a, c: The mean errors are presented with solid line, while the range of the errors (min-max) is indicated with dotted lines. b, d: The overall mean errors are shown with a red solid line, and the range of the errors (min-max) is shown with yellow lines: solid for the averaged min-max prediction errors from all calibration trees, and dotted for the extremes.

simple linear model (figs 4a vs. 4b, figs 4c vs. 4d), if the calibration tree is chosen properly (i. e. of extreme prediction errors corresponding to the innermost dotted lines in figs 4b and 4d).

With the training data set, that was larger and encompassing all DBH classes represented in the stands, we examined the effect of the calibration tree size, expressed as the breast height diameter relative to the stand quadratic mean diameter, on the accuracy of the predictions (Fig. 5). The outcome of the comparison

suggested that calibration with trees of average breast height diameter (0.7–1.1 of the basal area-weighted mean diameter) would yield prediction errors of no practical importance.

To facilitate the application of the newly derived DBH-prediction model, with or without additional calibration, we developed the simulator DbhRestore, which is based on macros in MS Excel. It is organised into two worksheets, for each of the model variants, and runs in a few simple steps. The simulator is available free of

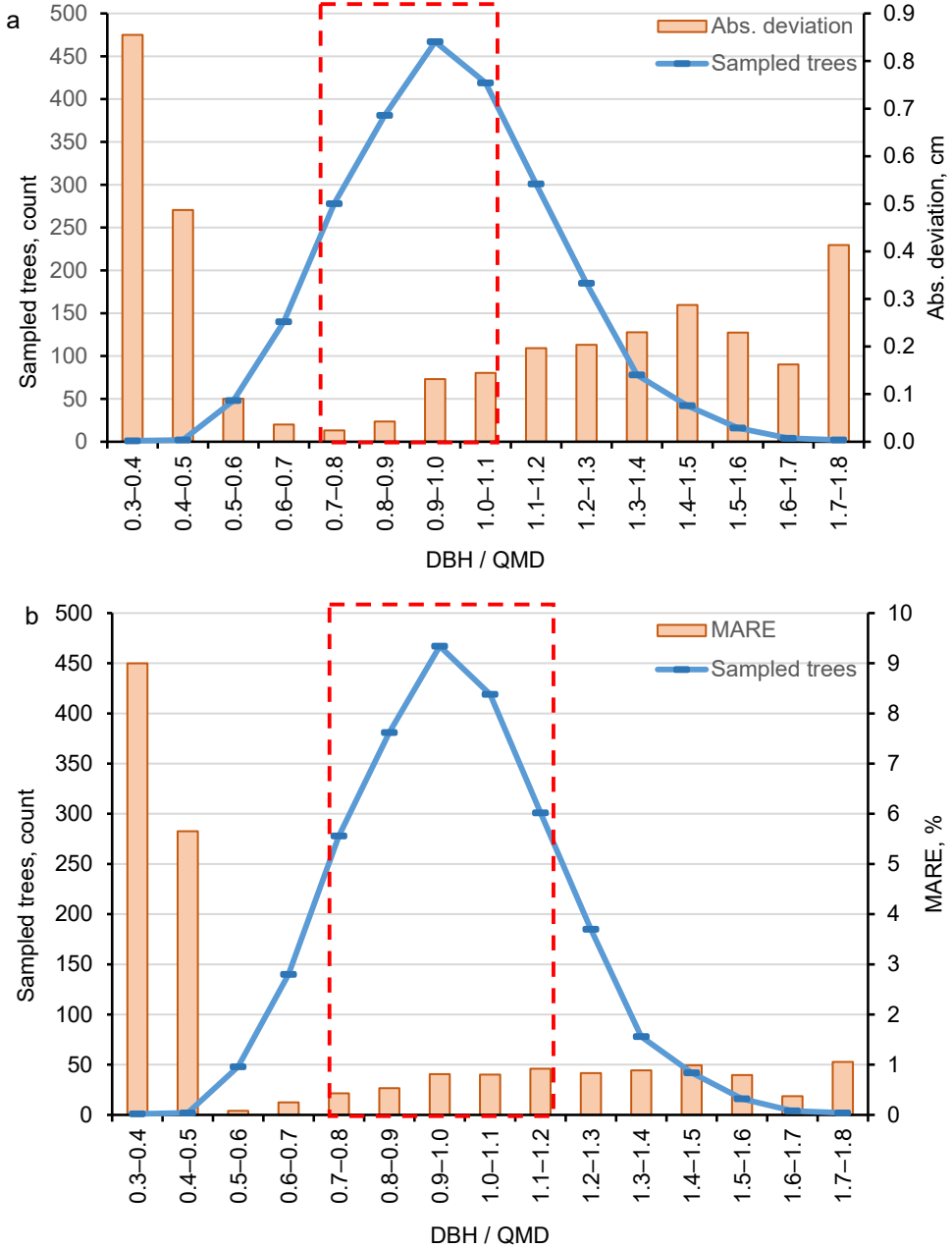


Fig. 5. Error ranges according to the breast height tree diameter of the calibration tree as relative to the mean stand diameter (DBH/QMD): (a) Absolute values of the average deviations, cm; (b) Averages from the absolute values of the relative errors (MARE), %.

Note: The red rectangle indicates the optimal range of DBH/QMD, defined by the lowest errors estimated from sufficiently large sample (> 200 trees).

charge and can be downloaded from the websites of the ClimGYM Project and the Forest Research Institute – Bulgarian Academy of Sciences (Stankova et al. 2025a,b).

Discussion

Pond and Froese (2014) concluded that the inclusion of stump height is a key difference between classes of published models on the DBH- d_0 relationship. Since stump-to-breast-height modelling shares strong similarities with tree taper modelling, in cases where stump height varies, the height at which a stump is measured may be important in estimating the amount of taper between that point and breast height (Pond and Froese 2014). Chhetri and Fowler (1996) pointed out that the reference height, at which DBH is measured, is generally better established than the reference height, at which d_0 is measured. Indeed, the relevant literature provides information on a variety of reference heights for measuring d_0 : 15 cm (Johnson and Weigel 1990), 20 cm (Milios et al. 2016), 30 cm (Corral-Rivas et al. 2007, Ercanli et al. 2014). Sakici and Unal (2017), who developed DBH- d_0 relationships for 10 cm and 30 cm stump heights, concluded that the models at 30 cm stump height were more accurate. Horvath and Popa (2021) conducted a comparative study deriving linear DBH- d_0 models for Norway spruce from the Gheorgheni Forest District in Romania, considering 3 variants of stump height: 0 cm (ground level), 10 cm and 30 cm. They also concluded that 30 cm for measuring basal diameter ensures the highest accuracy, while the other two options lead to overestimation of predictions for the smaller trees ($d_0 < 20$ –25 cm). Our inquiry revealed that his-

torically, the definition of stump height in Bulgaria has not been changed in the official national regulations and ordinances; therefore, different measurement heights for basal stem diameter cannot explain the observed overestimation by the currently applied table. However, given the lack of information on the range and origin of the data used in table construction, we assume that the measurements could have been collected in both natural stands and plantations of Scots pine, which in turn may differ in the size and the variation of their stem taper due to different plant origin and applied management practices. Such an assumption also suggests that stand origin must be considered when applying the DBH- d_0 model.

In our study, three stand-level variables were also tested as predictors in addition to the basal stem diameter. Although no models including such variables have been previously reported, their importance in differentiating the DBH- d_0 relationship has been recognised in some studies. In an investigation on *Quercus frainetto* Ten. in the region of Evros in Northeastern Greece, Milios et al. (2016) derived different breast height–basal diameter models for sparse and dense stands, with the rationale that this relationship is determined by tree taper, which depends on the competition between trees, higher in dense stands. They pointed out that higher tree taper is expected at low densities, while trees from dense stands would exhibit a high variability of form factors. In agreement with the study by Demaerschalk and Omule (1982) on estimating breast height diameters from stump measurements for commercially important forest tree species in British Columbia, which differentiated the models by age classes, our investigation also supports considering plantation age as a second predictor in the model.

Similar to a number of studies (Bylin 1982, Wharton 1984, Corral-Rivas et al. 2007, Özçelik et al. 2010, Horvath and Popa 2021), our investigation also derived the linear model as the most adequate functional form for the explored relationship. In an attempt to improve the goodness of fit by localising the model to particular stands, we tested both fixed-effects multiple regression and mixed-effects modelling approaches. Mixed-effects modelling has also been applied by Westfall (2010), who developed new models for predicting diameter at breast height from stump dimensions for 18 species groups with data from 13 states of the Northeastern USA. The author suggested that, most commonly, the model will be applied by setting the random-effects parameters to zero (mean-response model), and provided evidence with independent validation data that the accuracy will be sufficiently high with the fixed-effects model form. Our study also revealed high predictive ability of the global one-predictor relationship, which would be an acceptable option when no trees for random-component calibration are available for measurement. However, given the various and changing stand conditions (e.g., altered taper due to climate change, management regimes), specifying the relationship for the particular stand in the particular moment by a random-component calibrating measurement should be preferred when possible. Ercanli et al. (2014) applied mixed-effects modelling as well, when deriving the DBH- d_0 relationship for Oriental beech stands from Northeastern Turkey. The authors examined and compared options for calibration of the random parameter components using samples of 3 to 5 trees of various sizes (smallest, largest, medium, random). Based on the error statistics, they concluded that the highest predictive

ability was yielded when the four largest trees were used for calibration, and the lowest – with the smallest and medium-size trees. Our study examined model calibration with only one tree, considering that finding a sufficient number of representative individuals might be an obstacle. Contrary to the result of Ercanli et al. (2014), we found that average-size trees should be preferred when the DBH- d_0 model for Scots pine plantations in Bulgaria is calibrated locally.

Conclusions

Our study aimed to provide a reliable tool for estimating the breast-height diameters of plantation-grown Scots pine trees to allow restoration of their dimensions when the stems are removed or destroyed. Following the current Bulgarian forest regulations, we considered basal diameter at fixed stump height and we focused on the comparison of one-predictor functional forms. We derived a linear function of the basal tree diameter (d_0 within the range 11.1–67.3 cm), which expansion to a multiple regression model with additional stand-level variables did not yield a substantial increase in its prediction accuracy. The model performs better than the currently applied table and can be used even more accurately if it is specified for the particular stand by calibrating it with a DBH- d_0 pair of measurements (DBH within the range 7.8–52.1 cm) from one average-size tree. Both model versions are executable in a few simple steps in the user-friendly environment of the MS Excel-based simulator DbhRestore. The simulator is available in both Bulgarian and English and can be found on the websites of the ClimGYM Project (Stankova et al. 2025a) and the Forest Research In-

stitute – Bulgarian Academy of Sciences (Stankova et al. 2025b).

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