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Full Length Article

Estimation of Diameters by Stump Measurements for Natural and Artificial Small-Leaved Linden (*Tilia cordata*)

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Abstract

This study aimed at to assess the relationship between stump diameter (DST) at the height of 0.1 m above ground level and diameter at 1.3 m (DBH – diameter at breast height) for eight different age classes (IV–XI); of plantings of small-leaved linden (*Tilia cordata* Mill.). From 4,523 pairs of DBH and DST measurements, several simple linear models representing the DBH – DST relationship have been developed and evaluated. The field data processing was carried out using the methods generally accepted in forest inventory and variation statistics. For the dependence DBH = b×DST for each trial plot and pooled samples, the values of the coefficients b, significance, errors (standard, relative, systematic and random) were established. Age classes were compared according to the F-criterion, it was concluded that they differ significantly from each other. Verification of the data obtained with the standards developed in the 1980s showed that their accuracy is acceptable for forest managers when assessing tree volume removed in local conditions. However, for an accurate assessment, for example, scientific research, tracking forest management history, etc., a differentiated assessment is necessary, considering the origin, age and conditions of the habitats. The research results can help model and plan management in stands of the same age with trees removed for various reasons. © 2021 Friends Science Publishers

Keywords: Forecast; Tree diameter; Small-leaved linden; Diameter at 1.3 m; Diameter at stump height; Linear model; F-criterion

Introduction

In forestry, volumetric tables are used to determine the stock of forest stands. Depending on the number of parameters, they are divided into three types: one, two and several indicators. In tables with one input, it is enough to know the diameter at the height of 1.3 m (DBH), with two inputs – DBH and the tree's height (or the category of heights) with an average shape of the trunk. With several inputs and the previous indicators, the form factor is considered, and in exceptional cases and other forest biological characteristics of the tree (Verkhunov and Chernykh 2007; Sağlam *et al.* 2016).

The volumetric tables with one input are used more often because DBH is easy to measure. The variability of the volumes of the trunks within the same diameter when using local assortment tables is taken into account due to the group of diameters represented by 4 cm steps of thickness, the group of heights in grades of heights with an average shape factor.

Various reasons may require the restoration of diameters and heights of already felled trees: a description of the structure (Costa *et al.* 2019) and restoration of the taxation characteristics of the stand before felling (Kulla *et al.* 2017). This may be an assessment of the damage caused by illegal felling (Abdullaeva and Khairov 2019) or the results of catastrophic events (Di Cosmo and Gasparini 2020). This may require tracking the history of management activities (García-Cuevas *et al.* 2017; Paramonov *et al.* 2020), and a review of the intensity of fell, the acquisition of skills in eye taxation at the preparatory stage of forest inventory etc. (Milios *et al.* 2016; Asrat *et al.* 2020; Mugasha 2021). In such cases, only the stump parameters have to be used. A high correlation dependence allows models for finding the DBH of felled trees by stump diameter (DST) at the height of 0.1 m as an independent variable (Ercanli *et al.* 2015).

The number of studies in many world countries on DBH/DST ratios of various woody species is not decreasing. Research in this direction is being conducted over many parts of the earth including North (Westfall 2010; Pond and Froese 2014; García-Cuevas *et al.* 2017) and South (Costa *et al.* 2019) America; Western (Diéguez-Aranda *et al.* 2003), Southern (Milios *et al.* 2016; Di Cosmo and Gasparini 2020), Central (Bruchwald 2001; Kulla *et al.* 2017) and Eastern (Abdullaeva and Khairov 2019;

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Paramonov *et al.* 2020) Europe, Western Asia (Sasanifar *et al.* 2015; Şahin *et al.* 2019; Şenyurt *et al.* 2020) and Africa (Asrat *et al.* 2020; Chukwu *et al.* 2020; Mugasha 2021). In Turkey alone, about two dozen studies have been conducted on the relationships between DST and DBH (Şahin *et al.* 2019). These works considered one (Weiss 2013; Chukwu *et al.* 2020) to 30 common tree species (Asrat *et al.* 2020; Di Cosmo and Gasparini 2020) in the studied regions. Both coniferous (Şenyurt *et al.* 2020) and deciduous (Sasanifar *et al.* 2015) trees, which have primary and secondary commercial value were studied (Costa *et al.* 2019; Paramonov *et al.* 2020). Özdemir *et al.* (2020) determine the DST/DBH ratio for pure stands of rock oak (*Quercus petraea* (Matt.) Liebl), and Sakici and Özdemir (2017) for mixed stands of oriental beech (*Fagus orientalis*) and Kazdag fir (*Abies nordmanniana subsp. equi-trojani*) plant. To solve the problem of finding DBH depending on DST, many authors considered the possibility of using both simple linear and nonlinear equatins (Milios *et al.* 2016; Sağlam *et al.* 2016; Özdemir *et al.* 2020). They also used the stump height's effect on the accuracy of DBH determination (Diéguez-Aranda *et al.* 2003; Pond and Froese 2014; Sakici and Özdemir 2017) and artificial neural networks to model the relationship and differentiate DBH from DST (Sakici and Ozdemir 2018; Şenyurt *et al.* 2020).

Lack of empirical information on the size of felled trees can impede the conviction of illegal loggers. In the legal proceedings in the Russian Federation, the assessment of damage by volume of wood is carried out at 4 cm steps of thickness and the first category of heights in the bark (Abdullaeva and Khairov 2019). To describe the structure of stands and restore their inventory characteristics before logging, more precise values of the diameters and heights of the removed trees are needed (Bruchwald 2001; Kulla *et al.* 2017). It is noted that biases in the definition of DBH lead to distortions in the assessment of growing stock (Pond and Froese 2014).

Based on regression models, diagrams or tables (VNIITslesresurs 1991; Corral-Rivas *et al.* 2007; Milios *et al.* 2016), works on DBH estimation by DST are applied both everywhere and locally. Simultaneously, the lack of accuracy is noted since the conditions of growing stands, the category of heights, the entirety of stands etc., are not considered. Consequently, the most suitable option for different geographic regions is developing local models and standards for assessing the felled stock that meet the existing requirements and conditions for tree growth (Westfall, 2010; Sağlam *et al.*, 2016; Kulla *et al.* 2017).

Small-leaved linden (*Tilia cordata* Mill.) is a widespread species; its stands occupy 22% of the forested lands of the territory of the Republic of Bashkortostan (1148.4 thousand hectares) with a total reserve of 209.3 thousand m^3 (Sultanova *et al.* 2020). Linden is widespread not only in Russia but also in the temperate zone of Europe. However, no previous scientific studies have been traced in the literature that would show a DST – DBH relationship, which creates uncertainty in obtaining biometric parameters of trees removed from the forest and urban environment. For this reason, our study aimed at to determine the relationship between DST and DBH for eight different age classes of natural and artificial stands of linden and to develop a predictive model for DBH based on DST measurements of distant trees. The tasks undertaken to achieve this goal were to a) develop a simple linear model with a single coefficient for the transition from DST to DBH; b) evaluate the significance and errors of regression models; c) tabulate the generalized model for the definition of DBH from DST and d) verify the existing regulations.

Materials and Methods

The studies were carried out in the territory of Ufa and the Ufa municipal district. The area is characterized on an average by coordinates 54°70′ N 55°90′ E etc.; at an altitude of 150 m above sea level (Fig. 1), the climate is quite humid-continental. Average annual air temperature is 3.0°C, January is characterized by an average temperature of -14.5°C, July 19.5°C with an absolute maximum of 40°C and an absolute minimum of -50°C. The average annual precipitation is in the range of 500–600 mm, during the growing season about 350 mm. Under these conditions of growth, the small-leaved linden grows according to quality classes I to III. In this work, natural and artificial stands of small-leaved linden ten temporary test plots (TPs) of various age classes (III-XI) were studied. Also, trees of VII class of age of free growth, planted on the streets of Ufa, were studied (Martynova *et al.* 2020). The duration of age classes for small-leaved linden was ten years.

The TPs were planted with a size of 0.1 ha or more, depending on the stand's specific entirety, so that each of them was a homogeneous plantation. At each site, DBH and DST of all growing trees were >3.9 cm with bark in two mutually perpendicular directions, which were measured with an accuracy of 1 cm. The stump height was considered to be no more than 10 cm when cutting trees with DBH thinner than 30 cm (for thicker ones - no more than one-third of DST) from the soil surface and when the roots are exposed - from the root collar. Heights were measured according to the data of taxation descriptions and lists of forest cultures. The age was determined by counting the annual rings of the model trees. The rest of the forest stands were calculated using the counted trees (Verkhunov and Chernykh 2007).

The main densitometric characteristics of the investigated plantations are shown in Table 1. A total of 4994 trees were measured. Statistical processing of the obtained research results was carried out using computer programs Microsoft Excel and Statistica. A simple linear function without a free coefficient was tested by the least-squares method for each TP, for each age class as a whole (III–XI) and pooled samples to estimate DBH by DST.

The applicability of the obtained equations was assessed by the coefficient of determination (R^2), standard (S_e), relative (S_o), systematic (Q_p) and random (Q_s) errors (formulas 1–5):

$$R^2 = 1 - \frac{n-1}{n-p} * \left(\frac{\Sigma(y_i - \hat{y}_i)^2}{\Sigma(y_i - \bar{y}_i)^2}\right) \quad (1)$$

$$S_e = \pm\sqrt{\frac{\Sigma(y_i - \hat{y}_i)^2}{n-p}} \quad (2)$$

$$S_o = \pm\sqrt{\frac{1}{n}\Sigma\left(\frac{y_i - \hat{y}_i}{y_i}\right)^2} \quad (3)$$

$$Q_p = \frac{1}{n}\Sigma\left(\frac{y_i - \hat{y}_i}{y_i} 100\%\right) \quad (4)$$

$$Q_s = \pm\sqrt{\frac{1}{n}\Sigma\left(\frac{y_i - \hat{y}_i}{y_i} 100\% - Q_p\right)^2} \quad (5)$$

where y_i - are actual DBH;
$\hat{y}_i$ – are calculated DBH values calculated by substituting DST values into the regression equations;
$\bar{y}$ - is the arithmetic mean of y_i;
n - is the sample size;
p - is the number of equation parameters (in our case, p = 1).

A "nonlinear complementary sum of squares" method was used to determine the likelihood of differences in the equation DBH = f (DST) between age classes. This method is based on creating complete and reduced models, which is used to detect differences between tree species and geographic regions (Corral-Rivas *et al.* 2007; Özçelík *et al.* 2010), age classes (Özdemir *et al.* 2020). Each age class is defined using a different set of parameters in the full model, while in the shorthand model, all age classes are defined with the same parameters. The equality of the complete and reduced models is checked using the F-test:

$$F = \frac{SSE_R - SSE_F}{df_R - df_E} \div \frac{SSE_F}{df_F} \quad (6)$$

where SSE_R and df_R are the errors sums and the freedom degree of the reduced model, and SSE_F and df_F are the sums of the squares of the errors and the degree of freedom of the entire model.

The null hypothesis of the model`s equality is rejected if the F, calculated by formula 6, takes a higher value than the tabular F_{st} with a probability of 95% and the corresponding number of degrees of freedom. Consequently, there is a statistical difference between the age classes for the models. Conversely, suppose the null hypothesis is adopted. In that case, it is concluded that there is no significant difference between the age classes for the DST to DBH models, and a single equation can describe this relationship.

Additionally, the comparison of the series was carried out by calculating the standard deviation (σ, %):

$$\sigma = 200\sqrt{\frac{\sum_{i=1}^{n}\left(\frac{a_i - b_i}{a_i + b_i}\right)^2}{n-1}} \quad (7)$$

where a_i and b_i are pairwise compared DBH data;
n - is the number of compared pairs, pcs.

Results

Statistical processing of the starting material is presented in Table 2. The study range is for DST from 4 to 66 cm and from 3 to 55 cm - for DBH. The distribution series of DBH stands for SP to corresponded to the normal distribution: the coefficients of asymmetry and kurtosis were within their main twofold errors (except for the stands for SP 2, 14). A normal distribution characterizes DST for 13 stands, for seven - by nominal values of extension (kurtosis - negative) and rows' asymmetry. The volume of material was sufficient for a reliable characterization of the average values since the experiment's accuracy did not exceed 3%. The coefficient of variation for TPs varied from 20 to 44% for DBH and from 20 to 45% for DST.

The obtained statistical indicators testified the reliability of the empirical material and gave the right, on their basis, to reveal the dependencies and patterns of changes in DBH on DST. Based on empirical data, simple linear functions of the transition from DST to DBH were calculated for all test plots, age groups and altitude categories (Table 3). The gradation of the heights categories was adopted following the current assortment tables for forest stands of the Cis-Urals.

All equations were characterized by relatively high coefficients of determination ($R^2 > 0.7$), except for the model for trees of open growth of the urban environment (0.45). Coefficient b was in the range of 0.8167–0.8727 for natural stands, 0.7787–0.8561 for artificial stands, and 0.7917 for free growth trees. It was significant for all models (p <0.01). The Fisher criterion's calculated values significantly exceeded the critical ones ($F > F_{st}$), indicating the models' reliability. The S_e value was in the range of 0.9–2.9 cm, S_o - 0.07–0.15, Q_p varies from –5.6 to 3.4%, and Q_e did not exceed 15%. It also testified the adequacy of the obtained equations.

Graphical analysis and similar values of the b coefficients showed uniformity in plots for trial plots - they merge into one line, despite the difference in the heights. A dense correlation field and a visible form of connection gave the basis to combine data by age classes, two categories of heights, and a single sample. Simple linear equations were also compiled, and their statistical indicators were found (Table 3).

The results of comparing the equations by age class using the F-test are shown in Table 4. Comparison of the equations of each pair of TPs by age classes and in general showed that there was a statistical difference between them at the significance level α = 0.05 ($F > F_{st} = 3.9$), except for natural stands VIII (TP3 and TP4) and X (TP6 and TP8; TP6 and TP9), as well as forest cultures of VI (TP15 and TP16) age classes.

The DBH/DST ratio depends significantly on the shape of the trunk in the butt part, not on the entire shape of the trunk and the tree's age. Despite the differences in the model's age classes, we used the generalized equation.

Table 1: Main dendrometric characteristics of TPs

TP number	Age (years)	Average height (m)	Average diameter (cm)	Total basal area ($m^2 ha^{-1}$)	Height class
			Natural forest stand		
1	28	14.0	12.4	25.56	2
2	38	15.0	10.4	24.12	1
3	70	19.8	24.8	33.09	2
4	75	21.5	25.2	38.73	2
5	85	19.8	26.0	40.91	2
6	97	22.1	32.5	33.79	2
7	100	23.4	30.6	37.43	1
8	100	22.6	29.0	42.90	1
9	100	24.4	32.0	36.25	1
10	110	21.0	26.0	32.52	2
			Artificial forest stand		
11	39	16.0	14.2	42.07	2
12	48	15.0	12.6	27.58	1
13	50	18.7	16.1	31.81	1
14	52	17.0	14.1	33.92	1
15	55	13.9	13.3	17.49	2
16	55	18.7	14.6	25.24	1
17	63	20.0	19.3	32.89	1
18	63	20.0	19.6	36.71	1
19	71	22.0	22.2	38.62	1
20	79	26.0	25.2	34.11	1
			Open urban trees		
21	65	13.6	36.4	-	<4

Table 2: Summarized descriptive statistics of tree diameters on TPs

Parameters		Distribution series statistics*					
		X, cm	S	X_{min}, cm	X_{max}, cm	As	Ex
				Natural forest stand			
DST	min	11,7	4,42	4	22	-0,78	-0,82
	max	37,2	11,21	16	66	0,62	1,04
DBH	min	9,6	3,79	3	19	-0,33	-0,73
	max	31,6	10,34	15	55	0,59	0,19
				Artificial forest stand			
DST	min	12,8	4,02	4	25	0,06	-0,30
	max	30,4	7,63	12	51	1,01	6,11
DBH	min	10,7	3,53	4	21	0,03	-0,42
	max	24,7	6,35	12	42	1,93	5,61
				Open urban trees			
DST		44,5	9,25	10	70	-0,22	0,92
DBH		35,6	7,43	9	65	-0,10	1,55

Notes. X is the arithmetic mean, cm; S - standard deviation, cm; X_{min} - minimum value, cm; X_{max} - maximum value, cm; As is the coefficient of asymmetry; Ex - kurtosis coefficient

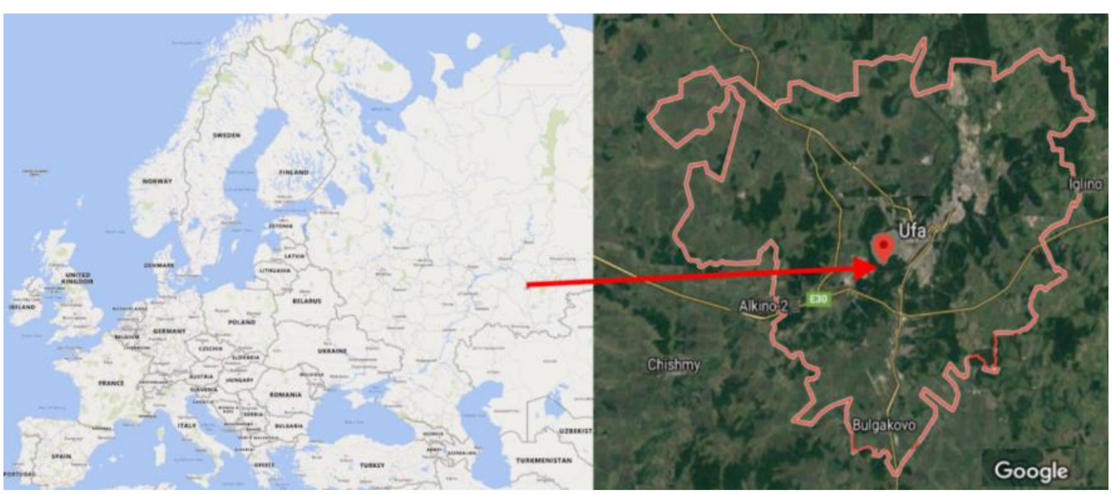

Fig. 1: The spatial location of the data collection area

Table 3: Statistical indicators of the relationship model DBH = b×DST*

TP number / age class	n, pcs	b	R^2	Errors of equations for TPs, sampling by the height category of and combined sampling												σ	
				S_e			S_o			Q_p			Q_s				
				TP	h.c.	total	TP	h.c.	total	TP	h.c.	total	TP	h.c.	total	h.c.	total
Natural forest stand																	
1/III	176	0.8223	0.932	1.1	1.1	1.1	0.08	0.08	0.08	-0.8	1.5	1.1	8.4	8.2	8.3	5.0	4.9
2/IV	228	0.8254	0.949	0.9	0.9	0.9	0.10	0.10	0.10	0.6	2.3	2.4	9.6	9.4	9.4	3.8	4.0
3/VIII	169	0.8290	0.902	1.9	1.9	1.9	0.07	0.07	0.07	-0.8	0.6	0.6	7.5	7.4	7.4	3.2	3.1
4/VIII	243	0.8167	0.789	2.2	2.3	2.3	0.09	0.09	0.09	-0.9	2.0	2.0	9.0	8.8	8.8	6.6	6.4
3+4/VIII	412	0.8216	0.847	2.1	2.7	2.2	0.09	0.08	0.08	-0.9	1.5	1.4	8.5	8.3	8.3	5.2	5.1
5/IX	235	0.8501	0.871	1.9	1.9	1.9	0.07	0.08	0.07	-0.6	-1.6	-1.7	7.3	7.3	7.3	2.1	2.3
6/X	108	0.8579	0.851	2.6	2.7	2.7	0.08	0.08	0.09	-0.4	-2.4	-2.4	8.2	8.4	8.4	4.0	4.1
7/X	177	0.8277	0.864	2.8	2.9	2.9	0.09	0.08	0.08	-1.5	-0.1	0.1	8.5	8.4	8.4	3.2	3.4
8/X	141	0.8606	0.881	2.1	2.2	2.2	0.07	0.08	0.08	0.3	-2.2	-2.1	7.3	7.5	7.4	5.0	4.7
9/X	149	0.8405	0.825	2.9	2.9	2.9	0.09	0.09	0.09	-0.1	-0.1	0.1	9.2	9.2	9.2	0.2	0.1
6+7+8+9/X	575	0.8442	0.854	2.7	-	2.7	0.08	-	0.08	-0.6	-	-0.9	8.4	-	8.5	-	0.8
10/XI	146	0.8727	0.974	1.7	1.9	1.9	0.08	0.09	0.09	1.7	-1.9	-2.0	8.3	8.6	8.6	7.3	7.4
1 height category	695	0.8399	0.960	-	2.3	2.3	-	0.09	0.09	-	0.3	0.4	-	8.9	8.9	-	-
2 height category	1077	0.8415	0.942	-	1.9	1.9	-	0.07	0.07	-	-0.3	-0.3	-	7.6	7.6	-	-
Total (1-10)	1772	0.8409	0.952	-	-	1.5	-	-	0.06	-	-	-0.2	-	-	5.9	-	-
Artificial forest stand																	
11/IV	145	0.7787	0.695	2.1	21	2.3	0.15	0.15	0.14	-2.2	-0.9	3.4	14.7	14.6	13.9	19.5	12.3
12/V	173	0.8322	0.886	1.2	1.2	1.2	0.10	0.10	0.10	-0.1	-0.5	-1.2	9.7	9.7	9.8	0.9	2.2
13/V	236	0.8561	0.968	1.1	1.2	1.2	0.07	0.08	0.08	0.1	-3.2	-3.9	7.3	7.6	7.6	6.5	7.8
12+13/V	409	0.8484	0.953	1.1	1.2	1.2	0.08	0.09	0.09	0.3	-2.1	-2.7	8.4	8.7	8.7	4.8	6.1
14/VI	263	0.8250	0.935	1.2	1.2	1.2	0.10	0.10	0.10	-1.9	-1.5	-2.1	10.1	10.0	10.1	0.8	0.6
15/VI	341	0.7933	0.923	1.5	1.4	1.5	0.12	0.12	0.12	-1.5	-2.2	2.2	12.1	12.1	11.6	1.3	8.3
16/VI	263	0.7859	0.923	1.5	1.7	1.7	0.11	0.10	0.10	-3.2	2.1	1.5	10.7	10.1	10.2	12.1	10.5
14+15+16/VI	867	0.7975	0.927	1.4	-	1.5	0.12	-	0.11	-2.6	-	0.6	11.2	-	10.9	-	7.0
17/VII	267	0.8165	0.853	2.4	2.4	2.4	0.12	0.12	0.12	-1.3	0.2	-0.4	11.7	11.6	11.6	3.2	1.8
18/VII	204	0.8528	0.860	2.2	2.2	2.3	0.10	0.11	0.11	-1.9	-4.9	-5.6	9.4	9.7	9.7	5.8	7.0
17+18/VII	471	0.8318	0.851	2.4	2.3	2.4	0.11	0.11	0.11	-1.6	-2.0	-2.7	11.0	11.1	11.2	0.8	2.1
19/VIII	333	0.8469	0.861	2.1	2.1	2.2	0.09	0.10	0.10	-1.3	-3.5	-4.2	9.2	9.4	9.4	4.4	5.7
20/VIII	152	0.8067	0.756	2.6	2.7	2.6	0.11	0.11	0.11	-1.5	1.2	0.6	10.9	10.6	10.7	5.9	4.4
19+20/VIII	485	0.8311	0.834	2.3	2.3	2.3	0.10	0.10	0.10	-1.7	-2.0	-2.7	10.0	10.0	10.1	0.6	2.0
1 height category	1891	0.8287	0.924	-	1.9	1.9	-	0.10	0.10	-	-1.4	-2.0	-	10.1	10.2	-	-
2 height category	486	0.7884	0.882	-	1.7	1.8	-	0.13	0.13	-	-1.8	2.5	-	12.9	12.4	-	-
Total (11-20)	2377	0.8233	0.922	-	-	1.9	-	-	0.11	-		-1.1	-	-	11.7	-	-
Total (1-20)	4149	0.8339	0.949	-	-	1.9	-	-	0.10	-	-	-1.0	-	-	9.8	-	-
Open urban trees																	
21/VII	374	0.7917	0.451	5.5	-	-	0.15	-	-	-2.3	-	-	14.6	-	-	-	-
17+18+21/VII	845	0.8016	0.857	4.1	-	-	0.13	-	-	-3.5	-	-	13.0	-	-	-	-
Total (11-21)	2751	0.8097	0.921	-	-	2.7	-	-	0.12	-		-2.4	-	-	11.5	-	-
Total (1-21)	4523	0.8242	0.935	-	-	2.5	-	-	0.10	-		-1.1	-	-	10.4	-	-

*Notes. b - is the value of the coefficient of the linear equation; h.c. – height cate*gory

The validity of combining empirical material was confirmed by minor errors of the compared equations and analytically - by calculating the standard deviation of the series: the degree of difference between series was non-significant. It did not exceed 4% on average, except for TP11 and TP16 (Table 3). However, comparing free growth trees in urban conditions with natural and artificial stands revealed a significant difference (14 and 105%, respectively).

Discussion

This study was carried out using mathematical-statistical analysis and descriptive interpretation of the DBH and DST indices in tree bark of linden small-leaved. On an average, for TP, the DST variation coefficients were 26.9 and 32.3%, and for DBH they were 27.6 and 31.8% for natural and artificial stands, respectively. The greater variation in trunk diameters in forest cultures is explained by their rare density and, accordingly, less pronounced differentiation processes.

The results of the regression analysis showed a linear relationship between these metrics, which can be applied to assess small trees. Some authors reported that simple linear models, taking into account the fit statistics, are most suitable for modeling the DBH – DST relationship (Özçelík *et al.* 2010; García-Cuevas *et al.* 2017). It was found that the coefficients of all models in age classes and generalized samples were quite closer to each other and explained the change in DBH by 70–97% for natural and artificial stands. Kulla *et al.* (2017) in their species-specific models showed an overall DBH variance of 95% for European beech, 96% for Norway spruce and 97% for Silver fir and Scots pine. Ercanli *et al.* (2015) used mixed-effects models to predict DBH according to DST *Fagus Orientalis* Lipsky with a

Table 4: The results of the F test, which determine the differences in age classes, describing the relationship DBH = b×DST

TP numbers	Age classes	n	SSE_R	SSE_F	F
1+2	III+IV	304	377	377	0.1
3+4	VIII	412	1782	1768	3.2
1+3+4	III+VIII	588	1988	1974	4.1
1+5	III+IX	411	1046	1020	10.3
6+7	X	285	2234	2149	11.2
6+8	X	249	1368	1368	0.1
6+9	X	257	2032	2004	3.4
7+8	X	318	2169	2066	15.9
7+9	X	326	2721	2004	115.8
6+7+8+9	X	575	4210	4070	19.7
1+6+7+8+9	III+X	751	4433	4275	27.6
1+10	III+XI	322	688	611	40.2
1+3+4+5+6+10	III+VIII+IX+X +XI	1077	4061	3715	100.2
2+3+4	IV+VIII	640	1954	1939	4.8
2+5	IV+IX	463	1004	986	8.5
2+6+7+8+9	IV+X	803	4392	4241	28.6
2+7+8+9	IV+X	695	3627	3515	21.9
2+10	IV+XI	374	638	577	39.1
3+4+5	VIII+IX	647	2709	2583	31.4
3+4+6+7+8+9	VIII+X	987	6121	5838	47.8
3+4+10	VIII+XI	558	2438	2174	67.5
5+6+7+8+9	IX+X	810	5030	4885	24.1
5+10	IX+XI	381	1262	1221	12.8
6+7+8+9+10	X+XI	721	4705	4643	9.6
Total (1-10)	III+IV+VIII+IX+X+XI	1772	4062	3715	165.6
12+13	V	409	526	511	12.1
11+12+13	IV+V	554	1353	1172	85.3
14+15	VI	604	1110	1077	18.5
14+16	VI	526	1034	984	26.7
15+16	VI	604	1345	1342	1.1
14+15+16	VI	867	1754	1702	26.8
11+14+15+16	IV+VI	1012	2430	2363	28.5
11+15	IV+VI	486	1385	1379	2.3
12+13+14+15+16	V+VI	1276	2488	2212	158.6
12+13+14+16+17+18+19+20	V+VI+VII +VIII	1891	6951	6493	133.1
17+18	VII	471	2607	2526	15.1
11+17+18	IV+VII	616	3381	3187	37.3
12+13+17+18	V+VII	880	3156	3036	34.4
14+15+16+17+18	VI+VII	1338	4504	4232	85.9
19+20	VIII	485	2617	2473	28.1
11+19+20	IV+VIII	630	3394	3134	52.0
12+13+19+20	V+VIII	894	3171	2984	55.9
14+15+16+19+20	VI+VII	1352	4533	4179	114.3
17+18+19+20	VII+VIII	956	5224	4999	43.0
Total (11-20)	IV–VIII	2377	8533	7877	197.7
12+13	V	409	526	511	12.1
11+12+13	IV+V	554	1353	1172	85.3
2+11	IV+IV	373	876	832	19.4
3+4+19+20	VIII+VIII	897	4416	4241	36.8
Total (1-20)	III–XI	4149	16634	15308	359.3
17+18+21	VII	845	14235	13847	23.6
Total (11-21)	IV–VIII	2751	20294	19193	157.6
Total (1-21)	III–XI	4523	29014	26629	404.9

coefficient of determination of 0.99. Diéguez-Aranda *et al.* (2003) developed a linear model for the *Eucalyptus globulus* Labill and *Betula alba* L., explaining 92 and 81%, respectively, of the total variance of DBH. Extrapolation of large stump diameters of linden trees in free growth conditions should be approached cautiously, as their forecasts were more volatile (R^2=45%). The linear models created in our study allow the DBH to be estimated with standard error values ranging from 0.9 to 2.9 cm for trees growing in the forest and 5.5 cm for free growing trees. Errors Q_p do not exceed 6%, and Q_s in most cases is below 10%. This indicates that the models with the R^2 coefficient of more than 0.7 give quite satisfactory estimates for the corresponding age group and the origin of the stands.

The R^2 variability is inversely correlated with the sum of the cross-sectional areas of stands and is –0.63 (p = 0.053) for natural lime forests and –0.60 (p = 0.068) for artificial ones. It is due to the trees' conicity, depending on the density of the stands and the trees cenotic position. The DBH/DST ratio varies from one stand to another because the conditions and structures of the stand are site-specific, i.e., in terms of stand density, site and soil properties, with significant variability (Ercanli *et al.* 2015). It is also consistent with Milios *et al.* (2016), who indicated that higher tree conicity results from low forest density. Free growing trees or large dominant trees have more wood increment at the base, while oppressed trees or trees growing in stands with high completeness, without being dominant, have a smaller trunk thickness.

A significant correlation was noted between the age and the coefficient *b* of the linear equation for natural lime forests ($r = 0.685$; $p = 0.029$). This also indicates an increase in the taper of tree trunks with the age of the stands. However, for artificial stands such a relationship is not found ($r = 0.076$; $p = 0.835$). Apparently in forest crops with a regular planting step and row spacing the taper is not pronounced.

In our study, the stump height was not considered a predictive variable; it was assumed that all trees at the cut height have the correct trunk; that is, they are not strongly deformed due to root butt swell. There are conflicting reports in the literature on this subject. Pond *et al.* argue that in cases where the stump height is not included in the model, and there is high variability in the stump height, the model's predictive power is low (Pond and Froese 2014). Research by Diéguez-Aranda *et al.* (2003) showed that the stump height did not significantly improve the forecasts for the five studied species. Only in the case of features at the base of the birch trunk was it advisable to consider this variable.

Comparison of DBH/DST ratios between TP, age classes, altitude categories based on the whole, and reduced models found that, with a few exceptions, there was a significant difference between them. Therefore, each age class should be represented by separate regression equations, and caution must be exercised when applying the obtained regression equations to estimate DBH/DST ratios in natural and artificial stands, especially free-growing trees. The results may not be applicable due to differences in origin, density and habitat.

Even though the results of the F tests revealed significant differences between the equations for assessing DBH by age classes and the origin of stands, the resulting generalized model DBH = 0.8339 DST ($R^2 = 0.95$, which is relatively higher) was used for comparison with the data of the forests of Urals (VNIITslesresurs 1991). It is the only regulatory document in Russia on the translation of DBH from DST for small-leaved linden. Verification of theoretical data of generalized model with the reference book data showed an overestimation of the results of entire range of diameters for the latter. At the same time, the maximum differences were observed in the group of small-sized trunks, not exceeding 5%, and for others, <2.5%. In absolute terms, for the thickest trunks (56 cm), the difference did not exceed 1 cm, while the predicted DBHs remained identical in thickness steps for the entire standard range.

Conclusion

Analysis of simple linear equations without a free parameter indicated their high adequacy, indicating no need to use complex models. When evaluating models between age classes and natural and artificial stands, trees of free growth, the presence of a statistically significant difference according to the F-criterion was revealed. Despite this, the generalized equation DBH = 0.8339•DST explained 95% variability of DBH versus DST. The values of errors for the combined material varied within acceptable limits and indicated a similar pattern of DBH changes for I and II categories of heights. Verification of the data obtained with the standards developed in the 1980s showed that their accuracy was acceptable for forest managers when assessing the volume of illegally removed trees in local conditions. However, for an accurate assessment, a differentiated assessment is necessary, considering the origin, age and conditions of habitats. Lack of previous work on DBH and DST allometry on this species indicates that this is actually the first study of its kind.

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Author Contributions

AG devised and supervised the project, formulated the main conceptual ideas and proof outline, and performed the computations. AG, IM and IS established the test plots and planted the trees. LB and RB wrote the manuscript and revised it after peer review. All authors discussed the results and contributed to the final manuscript

Conflict of Interest

The authors declare that they have no conflicts of interest.

Data Availability

Data will be available on a reasonable request.

Ethics Approval

The authors declare that the work is written with due consideration of ethical standards. The study was conducted in accordance with the ethical principles approved by the Ethics Committee of Federal State Budgetary Educational

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