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Functions for the aboveground woody biomass in Small-leaved lime (*Tilia cordata* Mill.)

Funkce pro hodnocení biomasy nadzemních částí lípy malolisté (*Tilia cordata* Mill.)

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Abstract
The Small-leaved lime (*Tilia cordata* Mill.) is currently not commercially important species, therefore the knowledge of biomass partitioning in a tree is rather incomplete. Moreover, lime biomass is estimated mostly using biomass functions designated for other species, without the knowledge of limits of such a use. For these reasons, we developed functions for the estimation of lime biomass in the aboveground woody parts. The functions were parameterized using 81 tree samples collected in two plots in the Czech Republic. In addition, we compared the biomass estimates produced by our functions with estimates produced by a function for beech, which have been obviously used as a surrogate for missing lime models in the Czech Republic and Slovakia.

On average, 78% of lime aboveground biomass was found to account for tree stem, 20% for branches and 2% for stump. Average biomass density was 374 kg m^{-3} and no significant differences between tree compartments were found. Accuracy of all models in terms of the Root Mean Square Error (RMSE) significantly differed between tree diameter classes; in case of total aboveground biomass, the RMSE was ca. 20% of the average biomass weight in a given class up to a diameter of 45 cm, and then it rose sharply. The RMSE was higher in case of compartments with variable dimensions, such as branches and stump. RMSE was slightly higher in case of estimates produced using a beech-specific function than using that developed in the current study (average RMSE 27.95 and 29.42%, respectively); at the same time, beech-specific function overestimated lime stem biomass by ca 12%. The almost equal RMSE implies the usability of both parameterisations for lime biomass estimation, though the correction of the mentioned overestimation should be applied.
Key words: biomass weight and volume; wood density; temperate forests; tree compartments

Abstrakt
Lípa malolistá (*Tilia cordata* Mill.) v současnosti nepředstavuje hospodářsky významnou dřevinu, což je jeden z důvodů proč jsou poznatky o distribuci její biomasy v rámci stromu značně nekompletní. Kromě toho, biomasa lípy je většinou hodnocená pomocí rovnic navrhnutých pro jiné dřeviny, přičemž možné nedostatky tohoto postupu jsou ve značné míře neznámé. Z těchto důvodů jsme na základě údajů získaných z 81 stromů na dvou plochách v České republice vytvořili parametrizace rovnic pro odhad dřevnatých částí nadzemní biomasy lípy. Následně jsme porovnali odhady objemu biomasy lípy získané pomocí námi navrhnutých modelů s odhadem získaným modelem parametrizovaným pro buk, který je v České republice a na Slovensku pro hodnocení biomasy lípy obvykle používaný.

V průměru připadalo 78% nadzemní biomasy na kmen stromu, 20% na korunu a 2% na pařez. Průměrná hustota biomasy činila 374 kg na m^{-3} a nebyl zjištěn signifikantní rozdíl mezi hustotou jednotlivých kompartmentů. Přesnost všech modelů v intencích procentuální RMSE (Root Mean Square Error) byla vyšší do tloušťkové třídy 45 cm, následně se zhoršila. V případě celkové nadzemní biomasy se pohybovala kolem 20% z průměrných hodnot dané třídy, vysokých hodnot dosahovala při stromových komponentech s variabilními dimenzemi jako koruna a pařez. Rozdíly v hodnotě RMSE při odhadu biomasy kmene lípy pomocí námi navržených funkcí a na základě funkce pro odhad biomasy buku byly minimální (průměrné hodnoty RMSE 27.95 a 29.42%). Biomasa vzorníků lípy určena pomocí rovnice parametrizované pro buk nadhodnotila biomasu o přibližně 12%. Z hodnot RMSE vyplývá vhodnost využití obou typů funkcí, avšak uvedené systematické nadhodnocení by mělo být zohledněno.
Klíčová slova: objem a hmotnost biomasy; hustota dřeva; lesy mírného pásma; stromové komponenty

1. Introduction

An assessment of amount of timber and woody biomass accumulated in forests has been of high importance in forestry community for a long time (e.g. Burger 1937; Vyskot 1976; Wirth et al. 2004; Wutzler et al. 2008; Dong et al. 2014). Recently, with a growing realization of forest importance in global carbon cycle (Nabuurs et al. 1997, 2013), also the evaluation of forest carbon stocks become an important part of forestry research (e.g. Eggers et al. 2008; Rötzer et al. 2009; Tatarinov & Cienciala 2009; Zierl & Bugmann 2007; Hlásny et al. 2011, 2014). In response to national commitments on carbon accounting and needs of the precise assessment of timber and biomass resources, numerous regional parameterizations of allometric functions (Zianis et al. 2005) and biomass expansion factors (Lehtonen et al. 2007) have been developed for most of Central European countries and tree species (Cienciala 2005, 2006, 2008; Seifert et al. 2006; Neuman & Jandl 2005; Hochbichler et al. 2006; Konôpka & Žilinec 1999). Tree biomass equations allow the calcula-

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tion of tree biomass on the basis of straightly measurable tree dimensions, such as stem diameter, tree height, crown dimensions, etc. (Cienciala et al. 2008). Although biomass equations are mostly applied at tree scale, also methods addressing the aggregated stand level data have been developed (e.g. Lehtonen et al. 2007; Somogyi et al. 2007).

Despite the long-term research on biomass quantification, there are still unexplored areas, such as the biomass allocation in species with minor occurrence, commercially less important species or in early developmental stages (Pajtík et al. 2008; Pajtík et al. 2011; Vahedi et al. 2014; Uri et al. 2014). One of such species groups is Tilia, which is the genus comprising 40 species growing in the temperate forests of the northern hemisphere (Větvička 2000). Five species occur in the Czech Republic, two of them being considered as commercially important – Small-leaved Lime (*Tilia cordata* Mill.) and Large-leaved Lime (*Tilia platyphyllos* Scop.). Only the latter two species will be considered in this study, and, because of their ecological and morphological resemblance, they will not be differentiated further. A share of lime in the Central Europe varies among countries (e.g. 1.1% in the Czech Republic; 0.4% in Slovakia). Species share has substantially decreased during the recent decades in the Czech Republic, from 6.5% in 1970–1990 to the current share of ca. 1%, mainly as a consequence of low interest in the species in forestry practice in 80`s and 90`s. However, growing interest in forest non-productive functions, which lime is capable to provide (e.g. soil ammelioration, honey production, aesthetics, recreation etc.), promotion of the concept of multifunctional forestry (Schmithüsen 2007) as well as growing realization of the importance of forest diversity in climate change adaptation (e.g. Hlásny et al. 2014), indicate increasing importance of lime and similar species. Moreover, the species has substantial regeneration capacity and can be potentially exploited for biomass production (Radoglou et al. 2008).

This paper aims at the assessment of biomass allocation in the aboveground tree compartments of *T. cordata* and the parameterization of allometric functions applicable for the assessment of dry matter content and biomass volume on the basis of tree heights and diameters. As lime biomass is obviously calculated using biomass functions parameterized for other species with similar morphology, most frequently those for European beech (*Fagus sylvatica* L.), we compared the performance of functions developed in this study with biomass function parameterized for European beech, which is commonly used for lime biomass assessment in the Czech Republic and Slovakia. Such a comparison is supposed to indicate the importance of further research on lime biomass allocation, or may confirm the validity of approaches which have been used so far.

2. Material and methods

2.1. Empirical material

The 81 lime trees in two forest plots in the Czech Republic were sampled (Table 1). The first plot „Dražíč“ (50°17'3.1''N; 13°03'47.3''E), lied in the so-called Natural Forest Region (NFR) Central Bohemia in elevation 406 m a.s.l. The stand is classified as acidophilous oak-beech forest type. The stand contained 70% of lime and 30% of spruce, with mean age 58 years. Stand density was 10, mean stem diameter 16.1 cm, and site index 24. The second plot „Doupov“ (49°17'57.0''N; 14°20'29.1''E) was situated in the NFR Doupov Mts., in elevation 550 m a.s.l., in stony-colluvial lime-oak beech forest type. The stand contained mature lime trees with mean age 118 years, mean diameter 41.7 cm, and site index 28. The both stands are single-layered. The 60 trees were sampled in the stand "Dražíč", and 21 trees in the stand "Doupov".

Tree sampling was conducted in the period of vegetation quiescence in 2011 in the plot Dražíč and in 2013 in the plot Doupov. Stem diameter of felled trees was measured in $d_{0.0}$, $d_{1.0}$, $d_{1.3}$ and $d_{1,5}$, and then in two-meter step up to the top of a tree. Branches thinner than 7 cm were measured only at $d_{0.1}$ a d_{max}, while branches with diameter above 7 cm were measured in a two-meter step.

A weight of small branches (i.e. those with diameter thinner than 1.5 cm) was determined using the field scales with 1 kg accuracy.

Biomass moisture was determined on the basis of 26 samples (Eq. 1); 19 samples were used for the determination of biomass density (Eq. 2) (wood and bark). The 9 samples were taken from tree stem (mean volume 386; minimum 96.1; maximum 746.4 cm³), and 15 samples from branches (mean volume 120.9; minimum 7.2; maximum 278.8 cm³). The samples were weighted in the field using laboratory scales (1 gram accuracy). At the same time, sample dimensions were measured to determine the volume of fresh biomass (V_{max}). Next, samples were dried in a laboratory oven under a constant air temperature of 95°C until their weight stopped to decrease.

$$W_{rel} = \frac{m_{max} - m_0}{m_{max}} \times 100 \qquad [1]$$

W_{rel} – Relative biomass moisture in %; m_{max} – fresh mass weight; m_0 – dry mass weight

$$\rho = \frac{m_o}{V_{max}} \qquad [2]$$

ρ – wood density kg m^{-3}; m_0 – dry mass weight kg; V_{max} – fresh wood volume m³.

In case of small branches, where only the fresh wood weight was measured, the following equation was used to calculate the dry mass weight m_0:

$$m_0 = \frac{m_{\max} \times (100 - W_{rel})}{100} \qquad [3]$$

m_0 – dry mass weight kg; m_{max} – fresh mass weight kg; W_{rel} – relative moisture %.

Volume of stem and branches was calculated using the Smalian equation.

Data on mean moisture and wood density of all samples were used for biomass calculation. To avoid producing biased biomass estimates due to different moisture and density in stem and branches, t-test was used to evaluate whether the samples taken from the respective compartments differ in their mean values. In case of small branches, where only the information on weight of fresh mass was available, the volume was calculated using the Eq. 4.

$$V_{brn} = \frac{m_{max} \times (100 - W_{rel\%})}{\rho \times 100} \quad [4]$$

V_{brn} – volume of small branches with bark in m^3; m_{max} – weight of small branches in kg; $W_{rel\,\%}$ – relative small branches moisture in %; ρ – wood density.

Dry mass weight of tree compartments, for which the volume data were available, was calculated using the Eq. 2.

In addition, volume and weight of stump was evaluated. The volume calculation was based on the basis of stump height and basal area calculated from d_0. As a result, a total aboveground biomass was determined for all sampled trees, consisting of stem, branch and stump biomass.

2.2. Statistical analyses

We used Eq. 5 for the approximation of the relationship between tree dimensions and tree biomass, which is the equation which has been repeatedly found suitable for tree biomass estimation (Cienciala et al. 2008; Hochbichler et al. 2006; Bollandsås et al. 2009):

$$ln(Y) = a + b_1 \, ln(X_1) + b_2 ln(X_2) ... b_n \, ln(X_n) + \varepsilon \quad [5]$$

where Y is biomass of a tree compartment; a, b_1–b_n are estimated parameters, $X_1 – X_n$ are predictors (tree height and diameter in the current study), and ε is the error term.

Tree heights and diameters were used as biomass predictors; and predictive power of both diameter and the combination of height and diameter was tested. Models for biomass volume and dry mass of the total above-ground biomass, stem, branches and stump were parameterized; altogether, 16 models were developed and tested.

The following equations were used for the final biomass estimates:

$$B = e^{(b_0 + b_1 \ln d)} \lambda \quad [6]$$

$$B = e^{(b_0 + b_1 \ln d + b_2 \ln h)} \lambda \quad [7]$$

where B is the biomass estimate, d is tree diameter, h is tree height, λ is a correction coefficient described below.

A correction factor λ was introduced into the equations above (Marklund 1987) as the back-transformation of the logarithmically transformed values causes a bias:

$$\lambda = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} e^{\ln \hat{Y}_i}} \quad [8]$$

where n is the sample size, Y_i denotes empirical values, and $\hat{Y}_i$ predicted values.

To perform a robust validation of the models, the set of 81 sampled trees was randomly split 20-times into parameterisation (n=61) and validation (n=20) sample. While the former dataset was used for the estimation of model parameters, the latter dataset was used for the calculation of the root mean square error (RMSE), which is an estimate of models accuracy. The RMSE represents the sample standard deviation of the differences between the predicted and observed values:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(\hat{Y}_i - Y_i\right)^2}{n}} \quad [9]$$

where $\hat{Y}$ is a vector of n predictions, Y is the vector of the true values, and n is the sample size.

In addition to the mean RMSE calculated using all samples, we also calculate the RMSE per diameter class, which can provided useful information supporting the use of the proposed parameterisations. Both RMSE in terms of original units (kg, m^3) and in terms of per cent of the predicted values was calculated.

The final biomass models were parameterized using all 81 samples.

The analyses were conducted in Statistica v.12 (StatSoft 2013).

3. Results

3.1. Exploratory analysis of the empirical material

Diameters $d_{1.3}$ of sampled trees ranged from 7.3 to 58.6 cm, with mean 22.2 cm. Tree heights ranged from 11.7 to 31.2 m, with mean 21.1 m (Table 1). Average biomass density (ρ) was 374 kg m^{-3}, and relative biomass moisture (W_{rel}) was 54.1%. Biomass moisture and density were not found to differ significantly between the stem and branches, hence the mean values were used in all calculations.

On average, dry mass weight of the stem, branch and stump biomass accounted for 78, 20 and 2% of the total aboveground biomass, respectively. In terms of volume, these compartments accounted for 80, 18 a 2% of the total aboveground biomass.

An average branch to trunk (stem + stump) biomass weight ratio in sampled trees was 0.26, though this relationship changes along tree diameters (Fig. 1). While the ratio is highly variable in diameters up to 15 cm, for bigger diameters the ratio is stable at ca 0.23.

Table 1. Descriptive statistics of the empirical material used for the parameterisation of lime biomass functions.

	Tree dimensions [cm, m]		Tree biomass [kg in dry matter]				Volume [m^3]			
	Diameter ($d_{1.3}$)	Height	Stem	Branches	Stump	Above-ground	Stem	Branches	Stump	Above-ground
Average	22.2	21.1	211.8	55.9	8.7	276.4	0.57	0.12	0.023	0.70
Median	17.0	20.4	81.4	14.9	1.4	97.1	0.22	0.04	0.004	0.26
Maximum	58.6	31.2	1060.1	541.6	67.0	1422.9	2.84	1.32	0.179	3.64
Minimum	7.3	11.7	9.6	6.1	0.1	17.5	0.03	0.02	0.000	0.05
St. deviation	12.3	5.0	286.1	98.2	15.4	387.7	0.77	0.21	0.041	0.98

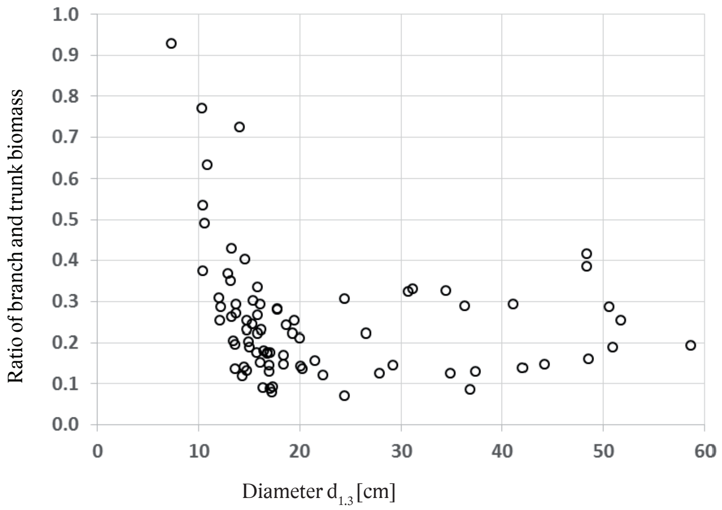

Fig. 1. A ratio of branch and trunk biomass weight along tree diameter classes in sampled lime trees. Trunk biomass was calculated as stem plus stump biomass.

3.2. Biomass functions

In biomass weight estimation, the RMSE produced on the basis of 20-randomly generated validation samples (n=20) reached 29 to 127% of the measured values (Table 2–3). The error was higher in case of compartments with variable dimensions such as stump and branches. An estimation based on biomass functions with two predictors (*d*, *h*) produced lower RMSE in all cases; the magnitude of such a difference however largely differed between the compartments and depending on whether the biomass volume or biomass weight was estimated.

An effect of tree height was higher in volume than in biomass weight estimates. In case of stem volume, the RMSE was 28.8 and 33.3% in case when *d*, *h* and *d* where used as predictors. In case of the total aboveground volume, the errors were 33.0 and 38.9% respectively. In case of biomass weight estimation, the improvement due to height inclusion was up to 2% in all compartments.

Accuracy of all models in terms of the RMSE significantly differed between diameter classes, therefore the informative value of the above described RMSE, which was calculated using all samples, is limited. We found out that in case of the total aboveground biomass weight and stem biomass weight, the RMSE reached 10–30% of the average biomass weight in a given class up to a diameter of 45 cm, and then it rose sharply (Fig. 2–3, Appendix A). The effect of diameter class on the RMSE was weaker in case of biomass volume estimates; in case of stem volume, the RMSE was stable in all classes, ranging between 12–29%. In case of the aboveground biomass volume, model which used only *d* as predictor was performing better and RMSE was stable in the range of 12–34%. Generally, errors associated to branch and stem biomass estimations were significantly higher in all diameter cases as compared with the above mentioned estimates. Differences in R–square were between functions with one (*d*) or two (*d*, *h*) predictors were negligible in most of cases.

Table 2. Parameters of functions for the estimation of lime biomass volume in main tree compartments as well as of the whole aboveground biomass.

	Tree compartment	b_0*	b_1*	b_2*	R^2	λ	RMSE	RMSE in %
Volume [m^3]	aboveground	−8.926 0.310	2.071 0.081	0.562 0.157	0.970	1.019	0.28	33.04
	branches	−8.414 0.834	1.968 0.218	−0.114 0.423	0.753	1.138	0.14	112.13
	stem	−9.653 0.298	2.074 0.078	0.726 0.151	0.974	1.019	0.18	28.76
	stump	−15.157 0.623	2.966 0.163	0.410 0.316	0.936	1.08	0.02	−83.24
	aboveground	−7.935 0.150	2.309 0.050	— —	0.965	1.022	0.30	38.90
	branches	−8.614 0,373	1,920 0,124	— —	0,753	1,139	0,16	127,60
	stem	−8.375 0.152	2.381 0.050	— —	0.966	1.024	0.2	33.25
	stump	−14.436 0.282	3.139 0.093	— —	0.935	1.081	0.02	83.58

Abbreviations: b_0, b_1, b_2 – parameters, RMSE – Root Mean Square Error, λ – corrections factor (explanation is given in the text), *first number denotes the estimated coefficient, second number denotes coefficient`s standard error.

Table 3. Parameters of functions for the estimation of biomass weight in main tree compartments as well as of the whole aboveground biomass.

	Tree compartment	b_0*	b_1*	b_2*	R^2	λ	RMSE	RMSE %
Dry mass weight [kg]	aboveground	−3.032	2.115	0.538	0.969	1.020	100.74	35.32
		0.318	0.083	0.161				
	branches	−2.936	2.228	−0.175	0.799	1.135	59.24	101.64
		0.819	0.214	0.415				
	stem	−3.728	2.074	0.726	0.974	1.019	62.21	28.57
		0.298	0.078	0.151				
	stump	−9.233	2.966	0.410	0.936	1.079	8.27	89.28
		0.623	0.163	0.316				
	aboveground	−2.086	2.342	—	0.965	1.023	109.44	38.37
		0.152	0.050	—				
	branches	−3.245	2.154	—	0.799	1.135	67.50	115.82
		0.367	0.122	—				
	stem	−2.451	2.381	—	0.966	1.024	68.14	31.30
		0.152	0.050	—				
	stump	−8.512	3.139	—	0.935	1.081	8.65	93.39
		0.282	0.093	—				

Abbreviations: b_0, b_1, b_2 – parameters, RMSE – Root Mean Square Error, λ – corrections factor (explanation is given in the text), *first number denotes the estimated coefficient, second number denotes coefficient`s standard error.

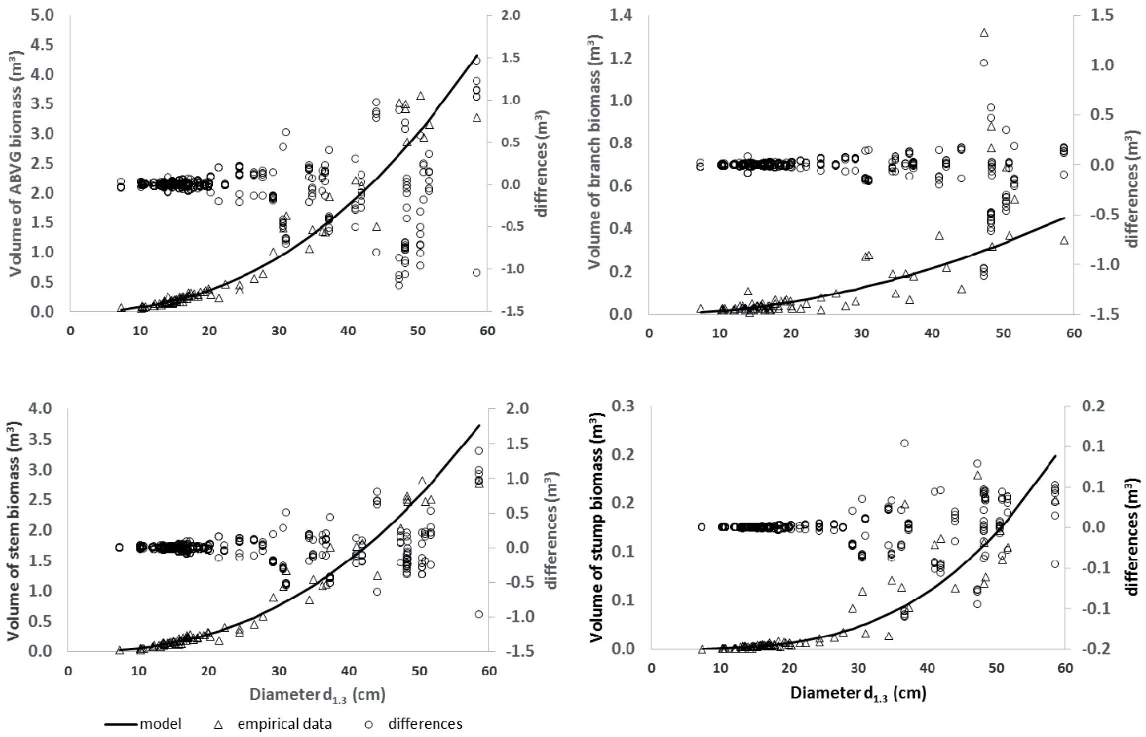

Fig. 2. Fitted empirical data of lime biomass volume in selected tree compartments (triangles) and differences between observed and fitted data (circles) which are indicative of models` quality.

3.4. Lime biomass estimation using a beech-specific function

We compared the lime biomass estimates produced using the equations parameterized in the current study with estimates produced using biomass functions for beech proposed by Petráš & Pajtík (1981) (PP); such equations have been obviously used for lime biomass estimation in the Czech Republic and Slovakia. However, as the definition of tree compartments used by the latter authors differed from that used in our study, we compared only the estimates of stem biomass weight.

Assuming that the estimates produced by the lime model are the reference, the PP model overestimated lime biomass weight by 12% (Fig. 4). We found no significant differences between the RMSEs produced using the PP model and lime-specific functions. While stem biomass weight estimated using the function with *d* as predictor was 0.17 (30.21%) and with *d* and *h* 0.16 (27.95%), the PP model (*d*, *h*) produced RMSE 0.17 (29.42%). This finding implies that both parameterisations can be used for lime biomass estimation, though the earlier mentioned overestimation could be subjected to correction. R–square was almost identical in both models.

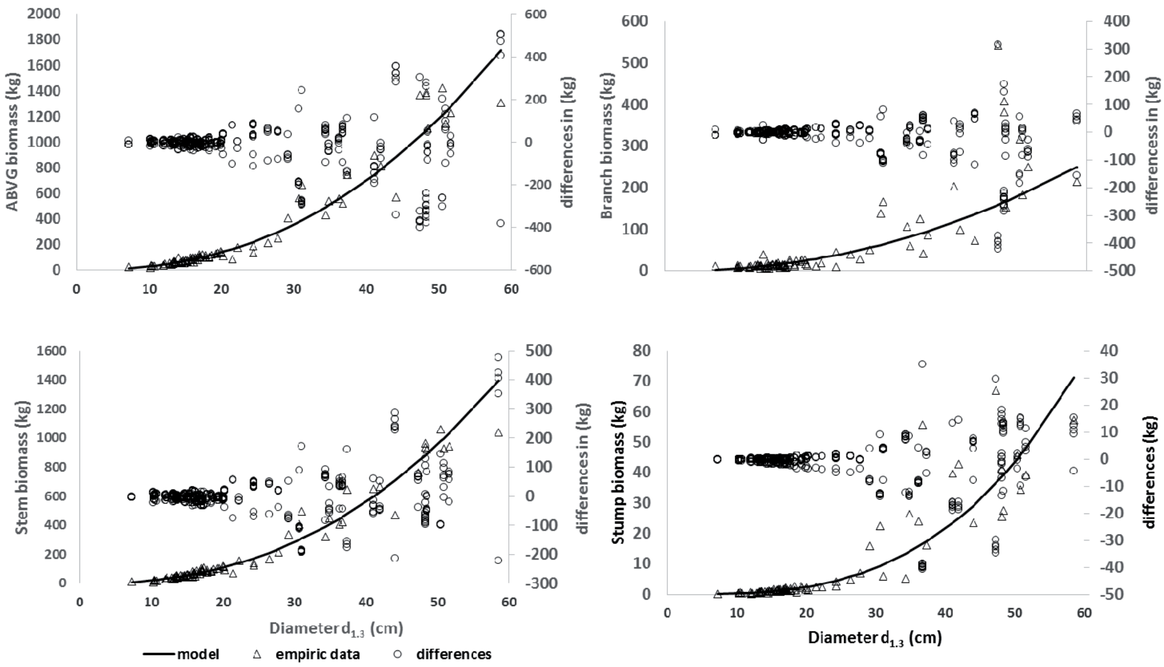

Fig. 3. Fitted empirical data of lime biomass weight in selected tree compartments (triangles) and differences between observed and fitted data (circles) which are indicative of models` quality.

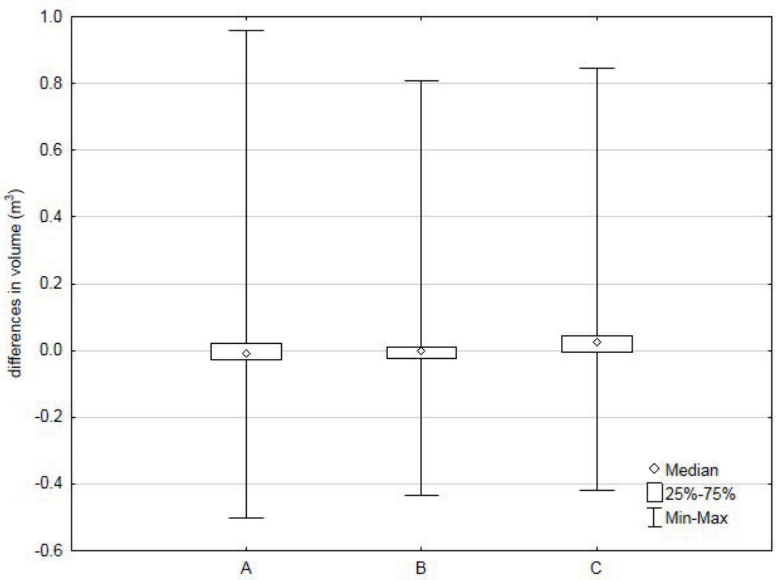

Fig. 4. Differences between the empirical data on lime stem biomass volume and stem biomass volume estimates produced using the biomass functions parameterized in the current study for lime (A – *d* as predictor; B – *d, h* as predictors), and those produced using the model for beech biomass estimation (C – *d, h* as predictors).

4. Discussion and conclusions

Biomass estimation of commercially less important species has been receiving only a marginal attention so far, however, the importance of carbon accumulation in and biomass production of these species can be expected to increase as a consequence of efforts to support the diversity of current forests. Lime biomass is obviously estimated using functions parameterized for other morphological similar tree (CzechTerra 2014; Jenkins et al. 2003). Lime biomass estimates are rare in the Central Europe at all. An exception is, for example, the study by Vyskot (1976), who estimated the biomass of a floodplain forest, though using a very limited number of sampled trees; or the study by Tokár (1986), who analysed a biomass of mixed stand of black walnut and lime. A model of lime aboveground biomass was proposed by Bunce (1968), the author however used only 10 sample trees with diameter range from 3.2 to 15 cm. In general, low tree age and diameter is typical of most of available studies; hence the limited applicability of the designated functions. Another model was proposed by Lambert et al. (2005), who used 80 sample trees with mean diameter 26.5 cm. However, as the model was developed for the *Tilia americana* L. using samples collected in Ontario (USA), such model`s applicability is limited in the Central Europe.

Mean wood density of lime trees found in our study was 374 kg m^{-3}, which is the value in the range reported by other authors. For example, lime wood density by IPCC (2004) is 430 kg m^{-3}. Gschwantner & Schadauer (2006) suggested the value of 490 kg m^{-3} for lime branch biomass, and mean wood density of 320 kg m^{-3} was found for *T. americana* and *Tilia heterophyla* Vent., which occur in the North America. Such differences can be attributed to several factors, for example the inter-species and inter-compartment differences as well as the differences in measuring methods. For example, while we calculated wood and bark biomass together, Bunce (1968) evaluated wood without bark, and used trees of smaller dimension; hence the limited comparability with our study.

Lime biomass functions parameterized in the current study showed much lower accuracy of stump and branch biomass estimation as compared with stem; this is valid for both biomass weight and volume. Such uncertainties were propagated to the total biomass estimate, however, as the stump and branch biomass accounted for ca. 20% of the total biomass, this effect was not substantial. On the other hand, relatively low errors were associated with stem biomass estimation, especially in lower diameter classes, what implies the reliability of our functions for the assessment of lime timber weight and volume. Similarly to other studies, effect of the use of two predictors (d, h) did not induce any substantial improvement as compared with the use of d only. Therefore, the effect of including tree height should be carefully considered as increased cost of data collection does not need to be compensated by an increased accuracy of estimation.

The comparison of biomass estimates based on lime-specific functions parameterized in our study with available function for beech showed quite good match between the two models in terms of RMSE, although only the stem estimates were compared. However, the 12% overestimation of lime stem biomass estimate produced using a beech specific function should be considered. Of course, relatively limited extent of empirical material used in this study could question the general applicability of such a finding.

Biomass partitioning in lime seems to be slightly different than that in beech, mainly in small diameters. While we found the mean crown to stem ratio 0.26, Cienciala et al. (2005) found such ratio to be 0.18 in beech (85% stem, 15% branches). The difference was however pronounced in small diameters only, in diameters above 20 cm both tree species showed similar values around 0.2. Such findings suggest differences in biomass allocation between lime and beech in small diameters, which is the fact supporting the use of functions developed in this study.

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Appendix A: Results of the validation of lime biomass functions.

DBH class [cm]	RMSE	Biomass weight [kg] (*d*)				Biomass weight [kg] (*d, h*)			
		Stem	Branches	Stump	ABG	Stem	Branches	Stump	ABG
0–15	%	17.8	46.9	125.4	16.8	16.4	47.7	35.6	15.7
	kg	6.1	5.3	0.8	7.7	5.6	5.4	0.2	7.2
15.1–20	%	17.3	36.4	80.5	11.9	13.8	36.7	30.9	10.1
	kg	14.1	5.9	1.2	11.8	11.3	5.9	0.5	10.0
20.1–25	%	27.1	88.3	70.6	34.6	23.0	92.5	36.7	30.9
	kg	31.9	18.8	1.9	49.0	27.1	19.7	1.0	43.8
25.1–30	%	27.1	82.0	28.6	18.8	18.1	82.6	50.2	14.5
	kg	51.4	32.2	2.6	54.1	43.5	32.5	4.6	41.7
30.1–35	%	29.8	82.0	28.6	18.8	25.7	56.1	78.5	29.8
	kg	122.5	32.2	2.6	54.1	106.6	64.9	8.5	161.1
35.1–40	%	17.1	72.7	10.4	12.2	17.9	72.9	73.0	14.9
	kg	77.7	55.9	4.0	69.2	81.1	56.1	28.1	84.9
40.1–45	%	25.0	62.5	14.8	27.9	23.9	63.4	41.6	28.2
	kg	146.8	80.3	5.1	209.4	140.2	81.3	14.3	211.5
45.1–50	%	8.9	63.9	15.6	20.2	13.8	63.2	43.4	22.6
	kg	79.7	226.9	6.2	261.8	123.8	224.4	17.3	292.4
50.1 >	%	24.6	32.1	16.6	21.0	19.4	32.5	22.3	17.7
	kg	242.4	74.6	7.2	264.9	190.8	75.5	9.7	222.4

RMSE – Root Mean Square Error; *d* – diameter in breast height; *h* – tree height; ABG – aboveground biomass.

Appendix B: Results of the validation of lime volume functions.

DBH class [cm]	RMSE	Biomass volume [m^3] (*d*)				Biomass volume [m^3] (*d, h*)			
		Stem	Branches	Stump	ABG	Stem	Branches	Stump	ABG
0–15	%	16.69	56.35	35.54	17.86	16.71	57.11	36.39	25,82
	m^3	0.02	0.02	0.001	0.02	0.02	0.02	0.001	0.04
15.1–20	%	17.00	43.85	35.80	12.17	12.31	43.66	36.83	18,02
	m^3	0.04	0.02	0.001	0.03	0.03	0.02	0.001	0.05
20.1–25	%	27.12	86.02	36.08	34.37	24.31	86.90	33.77	39,63
	m^3	0.09	0.04	0.003	0.13	0.08	0.04	0.002	0.15
25.1–30	%	21.30	88.00	50.83	17.39	19.30	88.49	50.24	20.97
	m^3	0.15	0.06	0.015	0.14	0.14	0.06	0.014	0.17
30.1–35	%	29.07	46.37	69.40	31.04	23.78	46.62	66.94	27.96
	m^3	0.32	0.10	0.027	0.42	0.26	0.10	0.026	0.38
35.1–40	%	23.90	41.78	72.27	19.95	21.43	41.77	71.74	25.66
	m^3	0.34	0.06	0.056	0.33	0.31	0.06	0.056	0.43
40.1–45	%	25.11	48.10	39.55	27.21	23.30	47.72	39.20	37.16
	m^3	0.40	0.11	0.038	0.53	0.38	0.11	0.038	0.72
45.1–50	%	22.15	72.42	41.82	22.70	13.36	74.48	40.63	60.86
	m^3	0.54	0.58	0.043	0.76	0.32	0.58	0.041	2.01
50.1 >	%	23.26	45.02	25.16	22.59	19.92	45.06	23.63	69.99
	m^3	0.63	0.23	0.031	0.75	0.54	0.23	0.029	2.33

RMSE – Root Mean Square Error; *d* – diameter in breast height; *h* – tree height; ABG – aboveground biomass.