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Biomass functions and expansion factors for young trees of European ash and Sycamore maple in the Inner Western Carpathians

Biomassefunktionen und Expansionsfaktoren für junge Europäische Eschen und Bergahorne in den Inneren Westlichen Karpaten

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Schlüsselworte: Biomassemodelle, Biomassestruktur, Baumkomponenten, Baumhöhe, Stammdurchmesser

Summary

Forest tree biomass models are important, not only for estimating total tree biomass but also for estimating biomass structure by components. Thus, we developed allometric equations, biomass conversion and expansion factors (BCEF) for young European ash (*Fraxinus excelsior*) and Sycamore maple (*Acer pseudoplatanus*). New data, including 100 sample of each tree species, were collected from central Slovakia. Stem diameter, volume and length were measured and individual tree components; roots, stem, branches and foliage were dried and weighed. Biomass models were constructed using diameter at stem base and/or tree height as independent variables and biomass structure in ash and maple were compared with existing European beech (*Fagus sylvatica*) data obtained previously from the same region. While relatively few interspecific differences were recorded in whole tree biomass, there is evidence of structural diversity in component biomass. The main differences were found in percentages of stem and branch biomass with beech results contrasting with ash and

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maple. Contributions of tree components to structural biomass change relative to tree size. These changes are possibly a consequence of progressive growth strategy from early to later tree growth stages. Proportions of stem and branches to whole tree biomass increase with tree size, while foliage and roots decrease. For instance, the smallest trees have a root to shoot ratio of nearly 1.0 while trees with a stem diameter of 70 mm demonstrate proportions of around 0.2. We showed differences between allometric equations and BCEF in both European ash and Sycamore maple. Moreover, our allometric models were compared with other models from Germany and UK.

Zusammenfassung

Forstliche Biomassemodelle für Bäume sind nicht nur bedeutsam für die Bestimmung der gesamten Biomasse eines Baumes, sondern auch für die Kompartimentsstruktur der Biomasse. Daher entwickelten wir allometrische Gleichungen und Umwandlungs- und Expansionsfaktoren der Biomasse (biomass conversion and expansion factors - BCEF) für junge Europäische Eschen (*Fraxinus excelsior*) und Bergahorne (*Acer pseudoplatanus*). Neue, für jede Baumart 100 Proben umfassende Daten wurden in der Zentralslowakei aufgenommen. Stammdurchmesser, Volumen und Länge wurden gemessen und die individuellen Baumkomponenten Wurzel, Stamm, Zweige und Belaubung wurden getrocknet und gewogen. Biomassemodelle wurden aufbauend auf die unabhängigen Variablen des Durchmessers am Stammfuß und/oder der Baumhöhe konstruiert. Die Biomassestruktur von Esche und Ahorn wurde mit existierenden Daten der Europäischen Buche (*Fagus sylvatica*) in derselben Region verglichen. Während relativ wenige interspezifische Differenzen bei der Biomasse des Gesamtbaumes festgestellt wurden, gibt es Anzeichen für strukturelle Differenzen in den Komponenten der Biomasse. The Hauptgegensätze ergaben sich bei den Anteilen der Biomasse von Stamm und Zweigen zwischen den Ergebnissen von Buche verglichen mit denen von Esche und Ahorn. Die Beiträge der Baumkomponenten zur strukturellen Biomasse ändern sich relativ zur Baumgröße. Diese Änderungen begleiten progressive Wachstumsstrategien von frühen zu späteren Wachstumsstufen der Bäume. Anteile des Stammes und der Zweige an der Biomasse des Gesamtbaumes steigen mit Baumgröße, während die Anteile von Belaubung und Wurzeln sinken. Zum Beispiel hat der kleinste Baum eine Relation von Wurzel zu Sproß von 1,0 während Bäume mit Stammdurchmesser von 70 mm Anteile von 0,2 aufweisen. Wir zeigten Unterschiede zwischen allometrischen Gleichungen und Konversion- und Expansionsfaktoren der Biomasse für beide Europäische Esche und Bergahorn. Darüber hinaus wurden unsere allometrischen Modelle mit anderen aus Deutschland und Großbritannien verglichen.

1. Introduction

The importance of carbon sequestration in forest ecosystems as a complex measure to mitigate climate change is an established concept (e.g. Vogt, 1991; Dixon, 1994). On a global scale, European forests are an important carbon sink, currently accumulating biomass. They are also significant soil carbon stores highlighting their importance for carbon store in the future (Janssens et al., 2003; Karjalainen et al., 2003). In central Europe, the amount of carbon stored in tree biomass exceeds soil carbon storage (Brunner and Godbold, 2007). At the same time, the quantity of carbon fixed in forest biomass is more dynamic than that in the forest soils. Thus, accurate estimates of forest tree biomass are important to develop a clear understanding of biomass carbon storage. Traditionally, only biomass estimates of merchantable wood; stem and coarse branches with diameter over 7 cm (in some countries over 5 cm), were conducted in forestry practice and subsequently a wide range of methods were developed for its inventory. However, biomass allocation among tree components influence the residence time of carbon fixation and therefore plays a critical role in the carbon cycle in forest ecosystems (e.g. Helmisaari et al., 2002; Konôpka et al., 2013). Two basic tree component groups are considered important for biomass carbon storage: long-term fixed carbon storage (e.g. stem, branches and coarse roots) that contain carbon for decades or longer; and short-term carbon storage (e.g. foliage and fine roots) that store carbon for months to a few years maximum (e.g. Yuste et al., 2005). Consequently, there is an urgent need to improve the existing methods for reliable assessments of non-stem components on both the tree and stand levels (Lehtonen, 2005).

In general, during the past couple of decades, focus has centered on tree biomass models with particular emphasis based on allometric equations or biomass expansion factors (e.g. West, 2009). Allometric equations or biomass functions express biomass calculations of various parts of individual trees based on measurable characteristics (e.g. stem diameter or tree height). Biomass expansion factors are used to expand the available tree stem biomass data to estimate the total tree biomass or specific tree component. Integrating biomass expansions and conversion components (Tobin and Nieuwenhuis, 2007) into one biomass factor expressed as a biomass conversion and expansion factor (BCEF) converts the most commonly available data on stem volume directly to whole tree or component biomass (Schroeder et al., 1997) and this can be further up-scaled to the forest stand level (e.g. Jalkanen et al., 2005; Šmelko et al., 2011). At the same time, the choice of method and the sample material might have a strong impact on the biomass/carbon results (Thurnher et al., 2013).

A lack of research focusing on young trees identifies the requirement to find allometric relations to enable biomass calculations for juvenile carbon storage potential (Wirth et al., 2004; Pajtík et al., 2008, 2011). This is further supported by the fact that the tree biomass component proportions are height (age) dependant and reflect different growth strategies in young and old stages (Claesson et al., 2001; Lehtonen et al., 2004). Similarly, Wirth et al. (2004) further suggested that it is necessary to establish biomass models for small trees as the existing models for large tress are non-transferable due to contrasting biomass allocation patterns.

The Good Practice Guidance for land use; Land Use Change and Forestry (IPCC, 2003) suggests direct field measurements in young stands because current biomass models originate from large trees only. Pajtík et al. (2008) stressed the importance of biomass models for small trees due to a rise in the area covered by even-aged young forests in the last decade as a consequence of afforestation and salvage cuttings. Further, recent changes in the forestry policy towards preference from even-aged monocultures to mixed-age forests can be documented in most of the European countries and in practice increases the percentage of young trees within forest stands.

In Slovakia the contribution of "other" broadleaved species (the term expresses all broadleaves excepting the main commercial species; European beech, Pedunculate oak, Sessile oak and Common hornbeam) to standing stock in young stands is much higher than in older stands (Konôpka et al., 2012b). For instance, the National Forest Inventory (NFI) in Slovakia performed in 2005 – 2006 (unpublished data) showed that Sycamore maple (*Acer pseudoplatanus*) represented approx. 8.2% of the entire forest cover when considering the first age class (up to 20 years). On the other hand, this species made up only 3.0% and 1.5% in the stands aged 40 – 80 years and over 100 years, respectively. European ash (*Fraxinus excelsior*) made up ca. 3.2%, 2.0% and 0.6% of the forest cover considering stands with ages 0 – 20, 40 – 80, and over 100 years, respectively. The percentage cover of these tree species decrease gradually with stand age, most probably due to interspecific competition, intentional forest management (thinning) and external factors such as red deer (*Cervus elaphus*) browsing.

After reviewing literature (e.g. Zianis et al., 2005; Muukkonen, 2007; Teobaldelli et al., 2009) we can state that only few studies have previously focused on biomass models in European ash and Sycamore maple. For instance in Slovakia, Petráš and Pajtík (1991) constructed models for stem and coarse branch volume in European ash, Albert et al. (2014) in Germany and Bunce (1968) in UK developed models for biomass allocation of aboveground woody parts (i.e. stem and branches) in both European ash and Sycamore maple. Hence, biomass models expressing all tree compartments and total tree biomass are lacking for both species.

The specific aims of this paper are summarized as follows:

1. Construct both allometric equations as well as BCEF for tree components in young European ash and Sycamore maple
2. Demonstrate the differences between allometric equations and BCEF in young European ash and Sycamore maple
3. Compare our biomass models for European ash and Sycamore maple to models for European beech from our previous work (Pajtík et al. 2011).

2. Material and Methods

2.1 Site and stand description

Our research focused on the forested mountain area of the Slovak Central Mountains which belongs to the sub-province of the Inner Western Carpathians. The mountains are volcanic in origin and the predominantly andesitic bedrock is covered by Cambisol. The forest composition is dominated by European beech with a mixture of other broadleaf species at lower altitudes such as Common hornbeam, European ash and Sycamore maple. In higher altitudes, coniferous species such as Norway spruce (*Picea abies*), Silver fir (*Abies alba*) and isolated populations of European larch (*Larix decidua*) are present.

A preliminary screening of forest stands containing European ash or Sycamore maple was conducted using a forest database (Programs of Forest Management by Stand Units in Slovakia; available on: http://gis.nlcsk.org/lgis/) with specific information on tree species composition and age class (defined within a 10 year interval). The main criteria was to select forest stands with a minimum composition of 80% of the target tree species (ash or maple) and a stand age of up to 20 years. The final selection of 20 forest stands (10 x ash and 10 x maple; Figure 1; Table 1 and 2) were identified for their exclusively natural regeneration. The altitudinal range was between 710 m – 950 m a.s.l. for ash stands and 700 m – 980 m a.s.l. for maple forest stands. The area thus belonged to two altitudinal vegetation zones categorised by the native dominant forest tree species; beech and fir-beech. In this region the total mean annual precipitations is 950 mm and average annual temperature 5.5˚C.

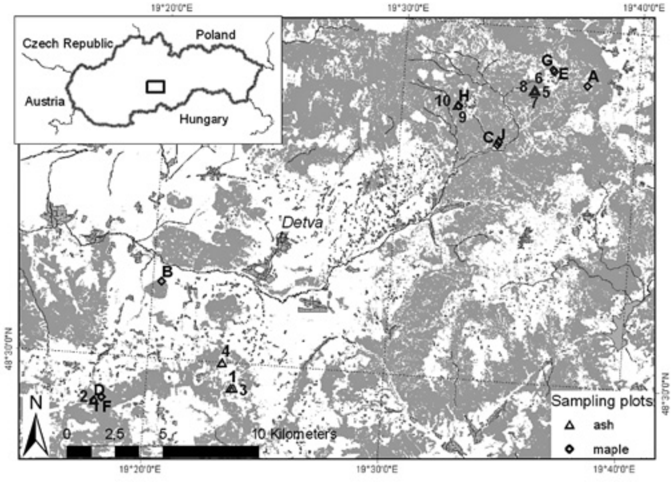

Fig. 1: Localization of the sampling plots for European ash (codes 1-10) and Sycamore maple (codes A-J)

Table 1: Basic characteristics of stand properties in research plots used for study of European ash

Plot code	Canopy cover (%)	Percentage of ash (%)	Number of trees* per 100 m²	Mean stem diameter d_0* (mm)	Lorey's height* (m)	Age* (years)
1	45	90	358	14.7	0.80	2
2	35	90	390	15.5	0.96	3
3	55	100	454	15.6	1.03	3
4	70	100	920	15.8	1.22	3
5	60	100	222	27.9	2.05	5
6	40	100	183	36.8	2.94	6
7	85	100	207	36.1	4.17	6
8	75	100	223	39.7	4.20	7
9	90	100	239	31.3	4.25	5
10	90	100	366	32.5	4.59	6

Explanatory note: * characteristics for ash trees

Table 2: Basic characteristics of stand properties in research plots used for study of Sycamore maple

Plot code	Canopy cover (%)	Percentage of maple (%)	Number of trees* per 100 m²	Mean stem diameter d_0* (mm)	Lorey's height* (m)	Age* (years)
A	40	100	1047	5.5	0.30	1
B	45	90	679	12.3	0.94	2
C	70	80	271	22.1	1.53	4
D	50	80	358	25.5	2.40	4
E	35	100	271	27.8	2.79	5
F	30	95	280	21.1	3.81	4
G	95	100	430	36.0	4.80	6
H	80	85	188	39.5	5.81	7
I	90	90	305	38.4	6.09	7
J	70	95	158	46.6	6.86	8

Explanatory note: * characteristics for maple trees

2.2 Tree measurements and sampling

Circle-like plots with radius of between 1 and 2 m were established in each of the 20 selected stands during the second half of the growing season in 2012 and 2013. The size of each plot was determined with regards to stand density to include approximately 40 trees for further analysis. Tree height, diameter at stem base (diameter d_0), diameter at breast height (dbh) and number of individual trees (ash, maple or other species) were recorded on each plot and divided into five height classes of equal interval. Then, ten trees were identified and sampled to represent each of the five height classes (two trees per class) for both ash and maple. A total of 200 trees, 100 individual trees of each species, were excavated including roots with a diameter of over 1 mm. By using a handsaw and garden shears the trees were separated into roots, stem and branches with foliage. The borderline between roots and stem was the ground level (marked prior to tree excavation) and to separate stem and branches the branch base was identified (i.e. the area of each branch closest to the stem surface). The samples of roots, stems and branches with foliage were packed and transported to the laboratory.

In the laboratory, diameters d_0 and dbh were measured in two perpendicular directions and tree height was recorded. Stems were divided into approximately 50 cm-long sections and if trees were under 150 cm in height they were divided into three equal sections. Three diameters were measured on each section; the middle point and the diameter at both ends. The volume of each section was calculated according to Newton's formula (e.g. West, 2009):

$$V = \frac{L(A_b + 4A_m + A_s)}{6} \tag{1}$$

where V is the volume, L is the section length, A_b the cross-sectional area at the large end of section, A_m the cross-sectional area at midpoint of section and A_s is the cross-sectional area at smallest end of section. The total sum of volumes of all three sections was calculated to represent the total stem volume (over bark).

Table 3: Descriptive statistics of the sampled trees

Species	Tree parameter	Mean	Median	S.D.	S.E.	Min	Max	Lower quartile	Upper quartile	Skewness	Kurtosis
Ash	Diameter d_0 (mm)	23.44	21.45	11.61	1.29	5.35	51.25	13.35	31.75	0.42	-0.73
	Height (m)	2.09	2.09	1.18	0.13	0.19	4.24	1.02	2.96	0.12	-1.17
	ABVG biomass (g)	369.10	204.38	421.27	47.10	2.45	1806.50	41.43	546.15	1.42	1.40
	Total biomass (g)	508.01	292.15	586.19	65.95	5.25	3064.50	65.90	701.30	1.80	3.95
	Stem volume (cm³)	502.06	261.63	571.05	63.45	2.10	2239.89	52.31	771.21	1.33	0.90
Maple	Diameter d_0 (mm)	31.30	27.85	22.09	2.21	5.70	104.50	12.48	43.78	1.01	0.50
	Height (m)	3.36	2.93	2.46	0.25	0.24	9.87	0.85	5.17	0.59	-0.45
	ABVG biomass (g)	1053.05	282.29	1921.50	194.10	3.07	14098.13	27.21	1122.59	3.96	21.81
	Total biomass (g)	1368.72	408.78	2383.58	243.27	5.67	16932.93	59.98	1509.65	3.68	18.95
	Stem volume (cm³)	1750.72	489.56	3188.91	318.89	2.28	23114.93	28.04	1883.24	3.85	20.46

After a few days under room temperature foliage was separated from the branches. Tree components were then oven dried at a temperature of 105˚C until they reached a constant weight. Volume, size and weight measurements were subsequently used for alometric relations and BCEF. Descriptive statistics for the sampled trees are presented separately for ash and maple in Table 3.

2.3 Construction of biomass models

For calculations of biomass, whole tree or specific tree components, the most frequent allometric equation is in the form:

$$Y = aX^{b} \tag{2}$$

where Y is the dependent variable, X is independent variable and a and b are parameters of the biomass model. Due to its flexibility, a variety of applications of this formula have been established, since it can easily be expanded into the following multiple form:

$$Y = a_0 . X_1^{b_1} . X_2^{b_2} . X_3^{b_3} ..... X_n^{b_n} . \theta \tag{3}$$

where Y is the dependent variable, X_1-X_n are independent variables, a_0-b_n are model coefficients and θ represents the multiplicative error term. We implemented the function in its logarithmic form as it allows for linear regression to be used to estimate the coefficients:

$$\ln Y = b_0 + b_1 . \ln X_1 + b_2 . \ln X_2 + b_3 . \ln X_3 + ... + \ln X_n + \varepsilon \tag{4}$$

where $b_0 = \ln a_0$ and $\varepsilon = \ln \theta$. It is relevant to point out that the logarithmic transformation of the dependent variable does cause a bias which occurs during reverse transformation of the logarithmic form (e.g. Baskerville, 1972). Hence, it is necessary to use a correction factor for re-transformation which is calculated using the method suggested by Marklund (1987) as follows:

$$\lambda = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} e^{\ln \hat{Y}_i}} \tag{5}$$

where n is the sample size.

Since some trees in the sample set were smaller than 130 cm, we could not use the standard tree mensuration parameter dbh. Instead we implemented diameter d_0 as the independent variable which is considered useful for all tree heights. Moreover, we used tree high as an individual parameter and in combination with diameter d_0 because this characteristic is rather easy to measure in young forest stands.

The predictive power of the following functions was tested:

$$B = e^{(b_0 + b_1 \ln d_0)} \lambda \tag{6}$$

$$B = e^{(b_0 + b_1 \ln h)} \lambda \tag{7}$$

$$B = e^{(b_0 + b_1 \ln d_0 + b_2 \ln h)} \lambda \tag{8}$$

where B is the total dry biomass per tree, d_0 the diameter at stem base, h is the tree height and b_0, b_1, b_2 are the coefficients.

Biomass allocated in a tree can be calculated by regression equations or by using biomass factors. We used BCEF (e.g. Lehtonen et al., 2004) which is expressed as:

$$BCEF_i = \frac{W_i}{V} \tag{9}$$

where W_i is the biomass (dry matter) of a tree component (i.e. roots, stem, branches, foliage, above-ground parts and whole tree) and V is stem volume. In fact, BCEF of the stem is the stem density.

Stem volume was calculated as described above (Equation 1) and the point cloud was fitted through the function (2) transformed in the forms:

$$V = e^{(b_0 + b_1 \ln d_0)} \lambda \tag{10}$$

$$V = e^{(b_0 + b_1 \ln h)} \lambda \tag{11}$$

$$V = e^{(b_0 + b_1 \ln d_0 + b_2 \ln h)} \lambda \tag{12}$$

where V is the stem volume.

For expressing dry weight, Wi, we have used the basic allometric formula (Equation 2) which fits for the calculation of volume, V. We can therefore expand Equation 9 into the form:

$$BCEF_i = \frac{a_1 X^{b_1}}{a_2 X^{b_2}} = aX^b \text{, where } a = \frac{a_1}{a_2} \text{ and } b = b_1 - b_2 \tag{13}$$

and use the allometric equation to calculate the BECFs of all tree biomass components. Therefore, three functions, similar to Equations 6 – 8 were tested:

$$BCEF = e^{(b_0 + b_1 \ln d_0)}\lambda \tag{14}$$

$$BCEF = e^{(b_0 + b_1 \ln h)}\lambda \tag{15}$$

$$BCEF = e^{(b_0 + b_1 \ln d_0 + b_2 \ln h)}\lambda \tag{16}$$

Since stem volume is an exclusive independent variable for calculating tree component biomass by means of BCEF method, we found a simple estimation method where we utilised an equation for the calculation of a cone volume and compared the result with stem volume expressed as a sum of section volumes (Newton's formula). We compared the two volumes for all of the sampled trees; ash, maple and beech data that was implemented from our previous work (see Pajtík et al., 2011) and fitted a linear relationship. All statistical analyses were carried out using the least squares method using Statistica 7.0 (StatSoft, Oklahoma, USA).

3. Results

3.1 Allometric equations

Through combining these results with the previous study focusing on biomass studies in young stands of European beech in the same region (Pajtík et al., 2011), biomass results for three broadleaved species; beech, ash and maple are combined. The main motivation of this research is based on the fact that beech is the regional dominant species and together with ash and maple made up mixture in the stands. Since diameter d_0 is not a common characteristic in forestry practice, we showed the relationship between diameter d_0 and tree height (Fig. 2a) and further between diameter d_0 and dbh (Fig. 2b). Relatively large interspecific differences existed in the relationship between diameter d_0 and tree height. For example, if we consider ash and maple with the same diameter d_0, ash trees were in general shorter while maple trees were tall and slender. In this aspect, beech trees were more closely related to ash than to maple. Formulas for their relationship were calculated as follows:

ash: $h = \frac{d_0^2}{125.858 + 0.395 d_0 + 0.193 d_0^2}$, $R^2 = 0.861$

maple: $h = \frac{d_0^2}{72.728 + 3.890 d_0 + 0.069 d_0^2}$, $R^2 = 0.895$

beech: $h = \frac{d_0^2}{1.166 + 11.157 d_0 + 0.018 d_0^2}$, $R^2 = 0.784$

As for the relationship between diameters d_0 and $d_{1.3}$, a linear relationship was considered suitable for all species:

ash: $d_{1.3} = -3.446 + 0.664 d_0$, $R^2 = 0.827$

maple: $d_{1.3} = -3.142 + 0.680 d_0$, $R^2 = 0.956$

beech: $d_{1.3} = -4.878 + 0.654 d_0$, $R^2 = 0.808$

Interspecific differences for correlation between diameter d_0 and dbh were negligible with maximum values in maple and minimum in beech.

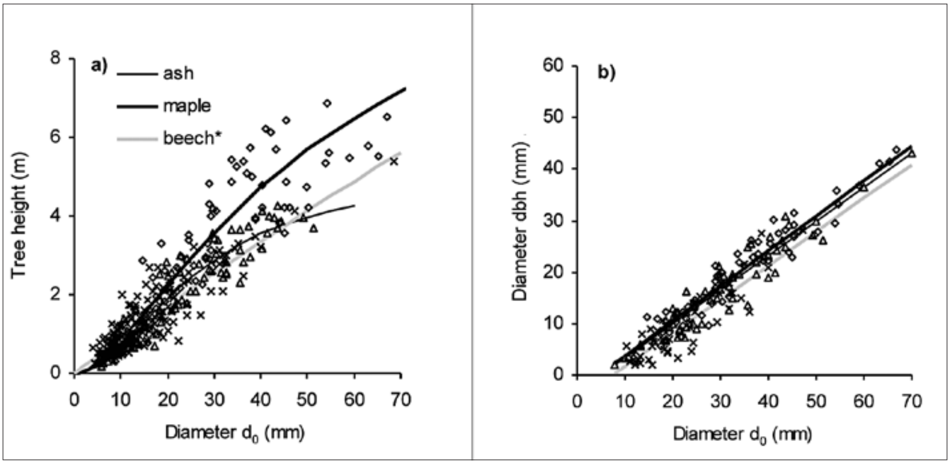

Fig. 2: Relationship between (a) diameter d_0 and tree height and (b) diameter d_0 and dbh in ash (triangles), maple (diamonds) and beech (crosses; *data from Pajtík et al., 2011)

Estimated coefficients and statistic characteristics of allometric equations for ash are presented in Table 4 and for maple in Table 5. It is evident that diameter d_0 is a statistically more suitable variable than tree height for predicting the biomass of all tree components in both species. As for ash trees, while diameter d_0 explained 84 – 95 % of sample variability in particular component quantity, the tree height explains 75 – 94 %. As for maple, the precision of the models were slightly higher with diameter d_0 explained 93 – 98 % of sample variability and tree height explaining 85 – 97 %. Models are even more precise when estimating whole tree biomass. Using diameter d_0 we reached 96% and 98% confidence in ash and maple respectively, and by using tree height we obtained 92% and 94% in ash and maple. Through combining the independent variables, diameter d_0 and tree height, the allometric models are only slightly improved, by between 1 – 2% compared to the model based solely on diameter d_0.

Table 4: Regression coefficients (b_0, b_1, b8), their relative standard errors (S.E.) and p-values; coefficient of determination (R^2); mean squared errors (MSE); logarithmic transformation bias (λ) and standard deviation (S.D.) for equations 6 – 8 (allometric relationships) in ash trees

Eq.	Ash component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
(6)	Stem	-4.374	0.229	<0.001	2.997	0.075	<0.001				0.954	0.140	1.072	0.430
	Branches	-9.108	0.624	<0.001	3.738	0.197	<0.001				0.835	0.562	1.256	0.792
	Leaves	-3.969	0.255	<0.001	2.388	0.083	<0.001				0.912	0.174	1.085	0.435
	Roots	-3.301	0.243	<0.001	2.454	0.079	<0.001				0.925	0.146	1.077	0.452
	ABVG	-3.839	0.209	<0.001	2.925	0.068	<0.001				0.959	0.117	1.057	0.360
	Whole tree	-2.999	0.200	<0.001	2.769	0.065	<0.001				0.959	0.099	1.049	0.332
(7)	Stem	3.523	0.056	<0.001	2.206	0.061	<0.001				0.944	0.171	1.096	0.601
	Branches	0.698	0.168	<0.001	2.785	0.189	<0.001				0.753	0.841	1.433	1.174
	Leaves	2.345	0.070	<0.001	1.721	0.077	<0.001				0.864	0.270	1.129	0.554
	Roots	3.171	0.075	<0.001	1.780	0.084	<0.001				0.853	0.288	1.156	0.719
	ABVG	3.874	0.057	<0.001	2.140	0.062	<0.001				0.938	0.178	1.093	0.522
	Whole tree	4.279	0.062	<0.001	2.048	0.069	<0.001				0.920	0.193	1.100	0.525
(8)	Stem	-0.906	0.372	0.017	1.667	0.139	<0.001	1.052	0.103	<0.001	0.980	0.060	1.038	0.399
	Branches	-6.807	1.152	<0.001	2.830	0.431	<0.001	0.795	0.339	0.022	0.847	0.529	1.244	0.782
	Leaves	-2.219	0.596	<0.001	1.717	0.223	<0.001	0.531	0.165	0.002	0.923	0.156	1.075	0.411
	Roots	-2.043	0.562	<0.001	1.968	0.211	<0.001	0.394	0.160	0.016	0.931	0.137	1.073	0.450
	ABVG	-0.795	0.355	0.028	1.757	0.133	<0.001	0.923	0.099	<0.001	0.981	0.055	1.031	0.315
	Whole tree	-0.589	0.372	0.117	1.838	0.140	<0.001	0.754	0.106	<0.001	0.976	0.060	1.032	0.301

The allometric models show that the quantity of the specific tree components is similar in ash and maple (Fig. 3a, 3b) with slightly higher values in all tree components recorded in ash. Interspecific differences were minimal between ash, maple and beech, when concerning above-ground biomass (Fig. 4a), whole tree biomass (Fig. 4b) and root (below-ground biomass) to shoot (above-ground biomass) ratio (Fig. 4c). In both above-ground biomass and whole tree biomass the largest values were found for ash and lowest for maple with beech values most similar to ash. For root to shoot ratio, all species recorded a decrease with tree size (diameter d_0). While the smallest trees had a root to shoot ratio of nearly 1:1, trees with diameter d_0 of 70 mm recorded values of around 0.2. This indicates that the total tree biomass was composed of approximately 17% below- and 83% above-ground biomass.

Table 5: Regression coefficients (b_0, b_1, b_2), their relative standard errors (S.E.) and p-values; coefficient of determination (R^2); mean squared errors (MSE); logarithmic transformation bias (λ) and standard deviation (S.D.) for equations 6 – 8 (allometric relationships) in maple trees

Eq.	Maple component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
(6)	Stem	-4.169	0.150	<0.001	2.914	0.046	<0.001				0.976	0.112	1.064	0.421
	Branches	-8.107	0.342	<0.001	3.351	0.101	<0.001				0.926	0.443	1.225	0.800
	Leaves	-2.650	0.173	<0.001	1.950	0.053	<0.001				0.933	0.162	1.082	0.473
	Roots	-2.595	0.153	<0.001	2.226	0.047	<0.001				0.960	0.119	1.060	0.370
	ABVG	-3.342	0.127	<0.001	2.755	0.039	<0.001				0.981	0.088	1.044	0.324
	Whole tree	-2.432	0.115	<0.001	2.583	0.035	<0.001				0.983	0.067	1.034	0.276
(7)	Stem	3.194	0.051	<0.001	2.273	0.040	<0.001				0.971	0.149	1.077	0.435
	Branches	0.386	0.135	0.005	2.583	0.101	<0.001				0.882	0.708	1.335	0.959
	Leaves	2.329	0.079	<0.001	1.459	0.062	<0.001				0.853	0.357	1.182	0.705
	Roots	3.109	0.085	<0.001	1.648	0.066	<0.001				0.868	0.391	1.205	0.753
	ABVG	3.632	0.056	<0.001	2.133	0.044	<0.001				0.960	0.1832	1.0942	0.482
	Whole tree	4.140	0.066	<0.001	1.969	0.051	<0.001				0.941	0.234	1.120	0.552
(8)	Stem	-0.832	0.174	<0.001	1.577	0.068	<0.001	1.094	0.053	<0.001	0.996	0.023	1.011	0.153
	Branches	-5.912	0.775	<0.001	2.463	0.301	<0.001	0.741	0.237	0.002	0.934	0.402	1.195	0.709
	Leaves	-2.626	0.466	<0.001	1.941	0.181	<0.001	0.008	0.142	0.956	0.934	0.164	1.082	0.473
	Roots	-2.797	0.404	<0.001	2.307	0.157	<0.001	-0.066	0.122	0.589	0.960	0.120	1.059	0.367
	ABVG	-0.783	0.194	<0.001	1.729	0.075	<0.001	0.840	0.059	<0.001	0.994	0.028	1.014	0.167
	Whole tree	-0.784	0.241	0.002	1.923	0.094	<0.001	0.539	0.073	<0.001	0.989	0.043	1.021	0.218

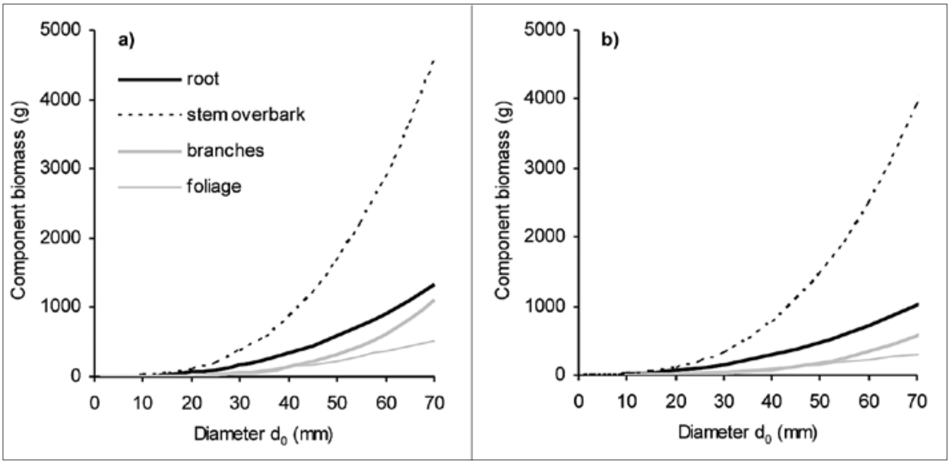

Fig. 3: Biomass of roots, stem (overbark), branches and foliage in (a) ash and (b) maple against diameter d_0

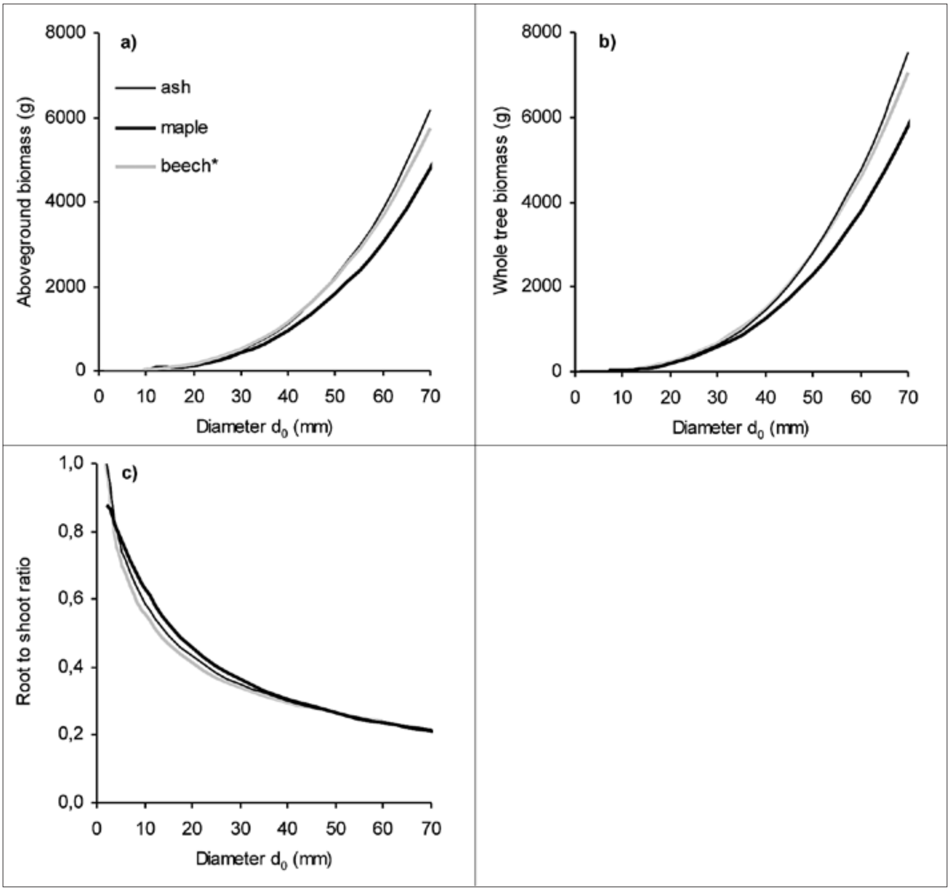

Fig. 4: Ash, maple and beech (a) above-ground biomass (b) whole tree biomass and (c) root to shoot ratio against diameter d_0 (* data from Pajtík et al., 2011)

While relatively little interspecific differences were recorded in whole tree biomass, there is evidence of differences existing in biomass structure (Fig. 5a-d). The largest differences were recorded in the percentage biomass of stem and branches. In these parameters, beech contrasted with ash and maple specifically with beech having a much higher proportion of branch biomass but lower percentage of stem biomass than the other species. If considering the largest trees (diameter d_0 of 70 mm), contribution of beech branches was approx. 23% while in ash and maple branch biomass contribution was 14% and 10% respectively. At the same time, total biomasses of the largest trees were composed by around 49% (beech), 60% (ash) and 67% (maple) of stem biomass.

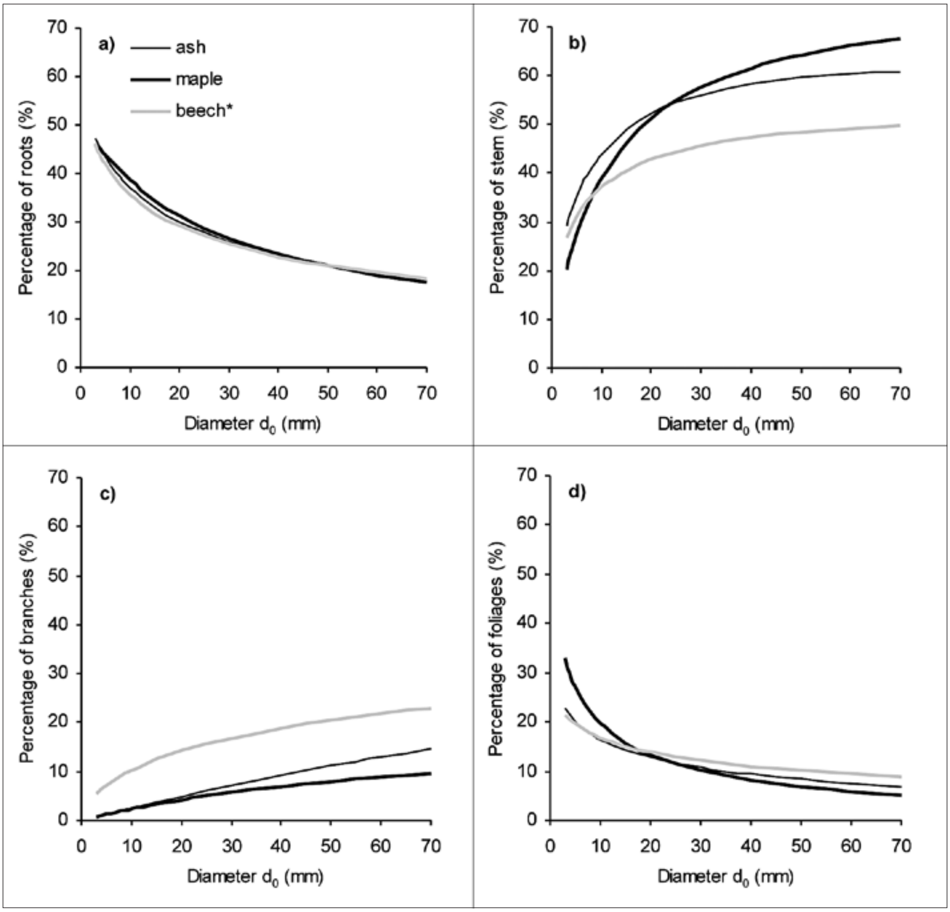

Fig. 5: Contribution of (a) roots, (b) stem, (c) branches and (d) foliage to whole tree biomass against diameter d_0 in ash, maple and beech (* data from Pajtík et al., 2011)

3.2 Biomass expansion and conversion factors

Estimated coefficients and statistic characteristics for stem volume in both ash and maple species are presented in Table 6. The results show that both variables; diameter d_0 and tree height explain sample variability with a very high precision. The highest values; 0.991% in ash and 0.997% in maple for coefficient of determination R^2 was recorded for model results when implementing both diameter d_0 and tree height as independent variables. Estimated coefficients and statistic characteristics for models of BCEFs for ash are in Table 7 and for maple in Table 8. Values of coefficients of determinations are much lower than for allometric models. It is proposed that for these models, both variables should be utilised. Doing so, a very precise model (R^2=0.832) was constructed for whole tree biomass in maple.

Table 6: Regression coefficients (b_0, b_1, b_2), their relative standard errors (S.E.) and p-values; coefficient of determination (R^2); mean squared errors (MSE); logarithmic transformation bias (λ) and standard deviation (S.D.) for equations 10 – 12 (stem volume) in ash and maple trees

Eq.	Species	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
(4)	Ash	-4.100	0.230	<0.001	3.093	0.075	<0.001				0.956	0.141	1.071	0.402
	Maple	-3.890	0.169	<0.001	3.028	0.052	<0.001				0.972	0.155	1.080	0.456
(5)	Ash	4.041	0.046	<0.001	2.299	0.051	<0.001				0.963	0.117	1.057	0.351
	Maple	3.747	0.045	<0.001	2.375	0.035	<0.001				0.979	0.119	1.060	0.377
(6)	Ash	0.040	0.252	0.874	1.505	0.094	<0.001	1.257	0.070	<0.001	0.991	0.028	1.014	0.170
	Maple	0.081	0.137	0.553	1.436	0.053	<0.001	1.302	0.042	<0.001	0.997	0.14	1.007	0.118

Table 7: Regression coefficients (b_0, b_1, b_2), their relative standard errors (S.E.) and p-values; coefficient of determination (R^2); mean squared errors (MSE); logarithmic transformation bias (λ) and standard deviation (S.D.) for equations 14 – 16 (BCEF) in ash trees

Eq.	Ash component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
(14)	Stem	-0.324	0.073	<0.001	-0.087	0.024	<0.001				0.147	0.014	1.007	0.120
	Branches	-5.411	0.590	<0.001	0.766	0.186	<0.001				0.192	0.502	1.246	0.865
	Leaves	0.131	0.254	0.607	-0.705	0.083	<0.001				0.478	0.172	1.080	0.408
	Roots	0.702	0.254	0.007	-0.609	0.082	<0.001				0.412	0.159	1.080	0.444
	ABVG	0.270	0.116	0.022	-0.173	0.038	<0.001				0.212	0.036	1.020	0.255
	Whole tree	0.957	0.138	<0.001	-0.282	0.045	<0.001				0.336	0.051	1.027	0.265
(15)	Stem	-0.545	0.016	<0.001	-0.078	0.017	<0.001				0.215	0.013	1.006	0.115
	Branches	-3.310	0.137	<0.001	0.439	0.154	0.006				0.102	0.558	1.272	0.885
	Leaves	-1.696	0.050	<0.001	-0.579	0.055	<0.001				0.588	0.136	1.064	0.363
	Roots	-0.850	0.048	<0.001	-0.544	0.053	<0.001				0.576	0.115	1.058	0.374
	ABVG	-0.168	0.023	<0.001	-0.160	0.026	<0.001				0.333	0.030	1.017	0.233
	Whole tree	0.235	0.027	<0.001	-0.251	0.029	<0.001				0.486	0.039	1.021	0.230
(16)	Stem	-0.785	0.171	<0.001	0.090	0.064	0.164	-0.140	0.048	0.004	0.235	0.013	1.006	0.114
	Branches	-6.886	1.112	<0.001	1.348	0.416	0.002	-0.509	0.327	0.124	0.219	0.492	1.228	0.791
	Leaves	-2.260	0.557	<0.001	0.212	0.209	0.313	-0.726	0.155	<0.001	0.593	0.136	1.063	0.362
	Roots	-2.107	0.498	<0.001	0.475	0.187	0.013	-0.879	0.141	<0.001	0.608	0.107	1.053	0.350
	ABVG	-0.806	0.254	0.002	0.240	0.095	0.014	-0.326	0.070	<0.001	0.384	0.028	1.016	0.222
	Whole tree	-0.528	0.288	0.071	0.287	0.108	0.010	-0.450	0.080	<0.001	0.530	0.036	1.019	0.216

Table 8: Regression coefficients (b_0, b_1, b_2), their standard errors (S.E.) and p-values; coefficient of determination (R^2); mean squared errors (MSE); logarithmic transformation bias (λ) and standard deviation (S.D.) for equations 14 – 16 (BCEF) in maple trees

Eq.	Maple component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
(14)	Stem	-0.279	0.048	<0.001	-0.113	0.015	<0.001				0.374	0.013	1.006	0.116
	Branches	-4.311	0.335	<0.001	0.349	0.009	<0.001				0.124	0.425	1.207	0.739
	Leaves	1.235	0.235	<0.001	-1.075	0.072	<0.001				0.698	0.299	1.155	0.671
	Roots	1.314	0.232	<0.001	-0.807	0.071	<0.001				0.577	0.275	1.144	0.611
	ABVG	0.544	0.080	<0.001	-0.271	0.025	<0.001				0.557	0.035	1.018	0.195
	Whole tree	1.473	0.128	<0.001	-0.448	0.039	<0.001				0.582	0.084	1.043	0.313
(15)	Stem	-0.553	0.013	<0.001	-0.103	0.010	<0.001				0.502	0.010	1.005	0.102
	Branches	-3.365	0.108	<0.001	0.207	0.081	0.012				0.070	0.452	1.213	0.736
	Leaves	-1.417	0.055	<0.001	-0.916	0.043	<0.001				0.827	0.171	1.093	0.565
	Roots	-0.647	0.053	<0.001	-0.722	0.041	<0.001				0.761	0.155	1.077	0.421
	ABVG	-0.115	0.019	<0.001	-0.242	0.015	<0.001				0.729	0.021	1.011	0.152
	Whole tree	0.384	0.029	<0.001	-0.401	0.023	<0.001				0.770	0.046	1.023	0.226
(16)	Stem	-0.913	0.110	<0.001	0.141	0.043	0.001	-0.208	0.034	<0.001	0.552	0.009	1.005	0.097
	Branches	-5.856	0.780	<0.001	0.974	0.303	0.002	-0.521	0.239	0.032	0.170	0.408	1.199	0.734
	Leaves	-2.702	0.460	<0.001	0.503	0.179	0.006	-1.292	0.140	<0.001	0.841	0.159	1.088	0.569
	Roots	-2.891	0.398	<0.001	0.876	0.154	<0.001	-1.373	0.120	<0.001	0.822	0.117	1.057	0.358
	ABVG	-0.859	0.151	<0.001	0.291	0.059	<0.001	-0.460	0.046	<0.001	0.785	0.017	1.009	0.137
	Whole tree	-0.871	0.215	<0.001	0.490	0.083	<0.001	-0.766	0.065	<0.001	0.832	0.034	1.017	0.197

The results related to BCEFs show a large difference between the tree components in both ash and maple species (Fig. 6a, 6b). Comparing BCEFs with tree size (diameter d_0), values decreased with increasing diameter d_0 which is particularly evident for biomass components, foliage and roots. On the other hand, the opposite was found for tree size (diameter d_0) and branches. In fact, BCEF for stem is equal to density (wood and bark together) thus, it is not surprising that the highest values of stem density in both species were found for the smallest trees (nearly 0.70 g.cm^{-3}) with the lowest values in the largest trees (around 0.50 g.cm^{-3}). Considering all tree species, large differences were found for BCEFs in above-ground (Fig. 7a) and whole tree biomass (Fig. 7b). For BCEF expressing above-ground biomass, maple differed (lower values) from ash and beech. BCEF for whole tree biomass differed in beech (higher values) from those of ash and maple. In all trees, the values of these BCEFs decreased with increasing tree size (diameter d_0) however, the values for trees with diameters of approximately 30 mm changes only moderately.

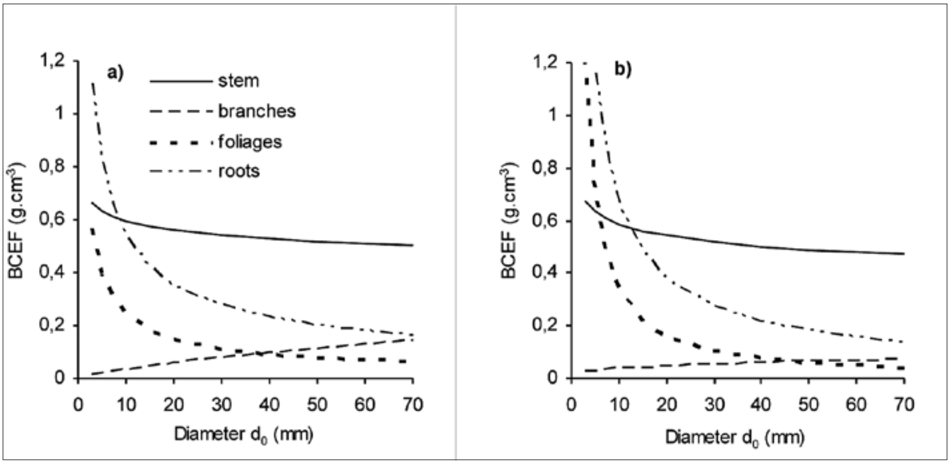

Fig. 6: BCEF for tree compartments in (a) ash and (b) maple against diameter d_0

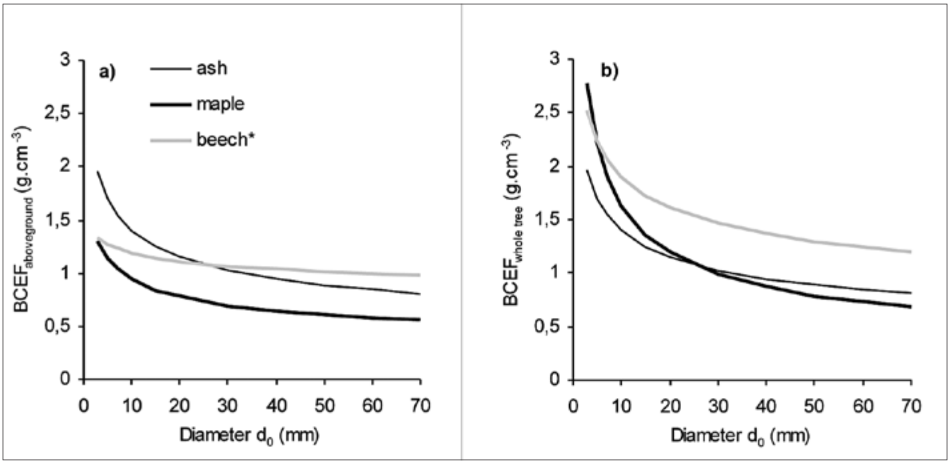

Fig. 7: BCEF for (a) above-ground biomass and (b) whole tree biomass against diameter d_0 in ash, maple and beech (* data from Pajtík et al., 2011)

Comparisons of the two methods, i.e. alometric relation and BCEF, for biomass estimates suggested just moderately different results in both species (Fig. 8a, 8b). As for the precision of the models, BCEF (residual standard deviations for BCEF using modeled and measured stem volume was 237.1 and 149.1, respectively) performed better than alometric relation (252.9) for ash trees. In contrast, alometric relationship (453.11) was more precise than BCEF (594.5 and 549.5, respectively for BCEF using modeled and measured stem volume) for maple trees. Here, the equation for modeling stem volume in ash was $V = 0.257139DAB^{2.31126}$ and in maple was $V = 0.026715DAB^{2.92014}$, where DAB is diameter d_0.

Finally, our alometric models for both species were compared with other available relationships from Germany (Albert et al., 2014) and UK (Bunce, 1968). Unfortunately, these models for European ash and Sycamore maple were expressed for above-ground woody biomass only. The comparison showed that our model outputs recorded "average" values compared to the other models in the case of both tree species (Fig. 9; see also Table 9 and 10). Specifically, while our models and the models from Germany recorded larger above-ground woody biomass compared to dbh in both ash and maple, the models from UK estimated less biomass.

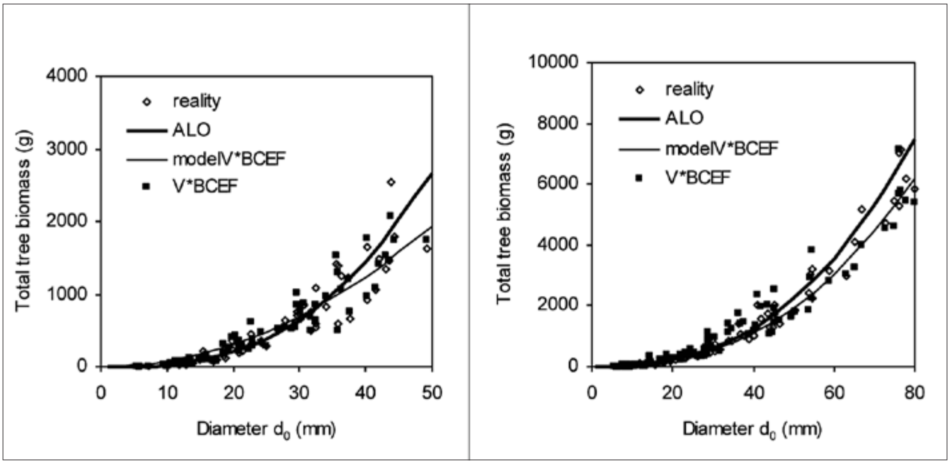

Fig. 8: Comparison of total tree biomass estimated by alometric relation (ALO) and BCEF (as for modeled stem volume - modelV*Bcef and mesaured stem volume – V*BCEF) in (a) ash and (b) maple trees. Open circles represent really weighted tree biomass (reality).

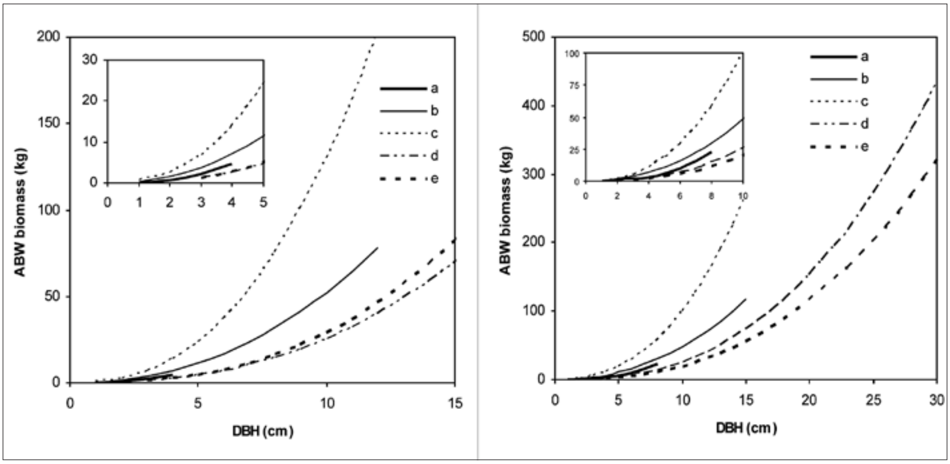

Fig. 9: Comparison of our models with some other alometric models for ash (upper plate) and maple (lower plate) aboveground woody biomass. The letters in the legends represents: a – our model; b and c – models of Albert et al., 2014; d and e – models of Bunce, 1968

Table 9: Comparison of equations for aboveground woody biomass based on dbh as a predictor in European ash (a – our model; b and c – models of Albert et al., 2014; c and d – models of Bunce, 1968)

	n	dbh (cm)	Region	Equation
a	100	0 – 3.5	Slovakia	$ABW = e^{\left(-4.511+3.075*\ln\left(\frac{DBH+3.4462}{0.664}\right)\right)} *1.069$
b	178	0.1 – 12.1	Germany (Liebenburg)	$ABW = 0.2292 * DBH^{2.1799}$
c	21	1.0– 14.8	Germany (Barterode)	$ABW = 0.1757 * DBH^{2.4351}$
d	15	2.9 – 33.0	United Kingdom	$\ln ABW = -2.5 + 2.49 * \ln DBH$
e	15	3.0 – 18.0	United Kingdom	$\ln ABW = -2.5 + 2.55 * \ln DBH$

Table 10: Comparison of equations for aboveground woody biomass based on dbh as a predictor in Sycamore maple (a – our model; b and c – models of Albert et al., 2014; c and d – models of Bunce, 1968)

	n	dbh (cm)	Region	Equation
a	100	0 – 8.0	Slovakia	$ABW = e^{\left(-4.203+2.951*\ln\left(\frac{DBH+3.1418}{0.6798}\right)\right)}*1.063$
b	148	0.1 – 15.5	Germany (Liebenburg)	$ABW = 0.2286*DBH^{2.1639}$
c	20	1.2 – 14.6	Germany (Barterode)	$ABW = 0.1349*DBH^{2.4361}$
d	15	3.5 – 28.0	United Kingdom	$\ln ABW = -2.7 + 2.58*\ln DBH$
e	10	3.7 – 31.0	United Kingdom	$\ln ABW = -2.8 + 2.52*\ln DBH$

4. Discussion and conclusion

The results indicate that allometric equations are more suitable for expressing biomass and structural components of small trees than BCEFs. Although, we did not find differences between these two approaches for accuracy of biomass estimates, alometric equations are more practical for implementation than BCEFs in young trees. Specifically, it is simpler to use only stem characteristic (diameter and/or height) as a predictor for allometric relations than stem volume (due to complicated measurement or calculation) for BCEF. On the other hand, we suppose that BCEF is suitable for large trees where the stem volume (predictor) is generally better known than for small trees. Moreover, while the value of BCEF is near constant in large trees (Lehtonen et al. 2004), its value is sensitive to tree dimensions in small trees (Pajtík et al., 2011). The use of stem diameter as the most precise independent variable for alometric equations is supported in previous work (e.g. Johansson, 1999; Hochbichler et al., 2006; Pajtík et al., 2008). As for diameter d_0, practical measurement might be difficult in young, often dense stands and may be further complicated by deformations on stem bases. Since dbh is applicable exclusively for trees with height over 130 cm, a compromise between model precision and practical measurement can be achieved by using tree height as a variable. This further creates compatibility between small and large tree results.

The results show little interspecific difference between young ash, maple and beech trees in whole tree biomass with regard to diameter d_0. At the same time, minimum interspecific differences exist for root to shoot ratio. Previous work conducted in Slovak forest (Konôpka et al., 2010) indicated a large differences in root to shoot ratio among the four most abundant tree species; European beech, Norway spruce, Scots pine (*Pinus sylvestris*) and Sessile oak. Specifically, substantial differences were observed between the broadleaved (higher value of root to shoot ratio) and coniferous trees (lower value). This sort of information is highly relevant to understand carbon cycling in young stands. Since young stands often grow under high competition stress, they typically record a high mortality rate (e.g. Lutz and Halpern, 2006). At the same time, the proportion of carbon emitted or stored by the above- and belowground biomass, after tree mortality, is determined by the root to shoot ratio. For instance, King et al. (2007) established linear models for root to shoot ratio compared to tree size in a variety of species. However, the focus was on older growth stands than observed during this study. Our results indicate that ash, maple and beech with diameter d_0 between 40 and 70 mm manifest values of root to shoot ratio from between 0.3 and 0.2. These values agree with the results of Harris (1992), who showed that, under normal conditions, root to shoot ratio in most adult trees vary between 0.16 and 0.20.

Large interspecific differences between young ash, maple and beech trees were found for biomass structure, specifically for stem and branch components. Beech has evidently higher proportion of branches than ash and maple, and in contrast, ash and maple manifested higher contributions of stem biomass than beech. These results might have some implication for the understanding of interspecific competition. If we neglect possible interspecific differences in growth rate, especially in height, and also ecological demands, higher competition potential might be predicted for beech with larger proportion of branches (this species occupies a relatively bulky space in canopy layer) than for ash and maple. On the other hand, minimum differences were found in the contribution of foliage to total biomass. This knowledge would be useful for instance in terms of modeling carbon cycling through foliage or growth efficiency, expressing production of biomass in stem or all woody components based on foliage mass unit (Gersonde and O'Hara, 2005). Another implication of foliage and branch quantity or their contribution to whole tree biomass, might be related to feed potential for ruminating ungulate game (e.g. Konôpka et al., 2012a; Pajtík et al., 2015) or competition for light with weed (Ceacero et al., 2014).

Our results show that structure of biomass as a contribution of tree components changes dramatically with tree size with the most significant changes found for smallest trees (diameter d_0 up to approx. 30 mm). These changes perhaps relates to alternating changing growth strategy from early (primary intention to occupy sufficient soil space) to later stages (to compete neighbouring trees for light). Proportion of stem on whole tree biomass increased with tree growth is generally acknowledged (e.g. Kozlowski and Pallardy, 1997). In young ash, maple and beech trees, contrasting tendencies with increasing size were recorded, increasing for branches and decreasing for foliage. This phenomenon is also evident in Norway spruce stands at least until the development of a closed canopy (Kantola and Mäkelä, 2006). At this stage the level of branch contribution to whole tree biomass stabilizes and percentage of foliage continues to decrease. This is most probably related to limited light resources under closed canopy conditions and as a consequence the constraints for foliage survival.

There is the potential for future studies on European ash and Sycamore maple to focus on biomass models for larger trees. At the same time, the models should include all tree components in the above-ground and below-ground parts of trees, especially for the purpose of biomass/carbon stock estimates in forest stands. The biomass models for the most frequent tree species can be implemented in combination with data from the NFI (in Slovakia, the first NFI was in 2005 – 2006 and the second will be in 2015 – 2016; see Šmelko et al., 2014). Since all trees with height over 0.1 m are registered in NFI in Slovakia, our biomass models for small ash and maple trees can be incorporated. Thus, after the second NFI and the potential construction of models for the full range of tree dimensions, not only biomass/carbon stock, but also biomass production can be estimated on the national level.

Acknowledgements

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