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Biomass functions applicable to European beech

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ABSTRACT: This material describes parameterization of allometric functions applicable to biomass estimation of European beech trees. It is based on field data from destructive measurements of 20 full-grown trees with diameter at breast height (dbh) from 5.7 to 62.1 cm. The parameterization was performed for total tree aboveground biomass (*AB*; besides stump), stem and branch biomass, respectively. The allometric functions contained two or three parameters and used dbh either as a single independent variable or in combination with tree height (*H*). These functions explained 97 to 99% of the variability in the measured *AB*. The most successful equation was that using both dbh and *H* as independent variables in combination with three fitted parameters. *H*, as the second independent variable, had rather a small effect on improving the estimation: in the case of *AB*, *H* as independent variable improved prediction accuracy by 1–2% whereas in the case of branch biomass by about 5%. The parameterized biomass equations are applicable to tree specimens of European beech grown in typically managed forests.

Keywords: allometry; aboveground tree biomass; branch; stem; carbon; wood density

An interest in total tree biomass assessment is growing. It is mainly due to the importance of forests to mitigate climate change, i.e. specifically for the capacity of trees to sequester and store carbon. The national inventories and international commitments (United Nations' Framework Convention on Climate Change, Kyoto Protocol) require a more accurate assessment of carbon stock change in forests. This in turn requires a quantification of total tree aboveground biomass. The available data on forests have traditionally been focused on production indices. Specifically in the Czech Republic, production is expressed in merchantable volume defined as stem and branch biomass above a threshold diameter of 7 cm. Hence, data on the stand or tree level must be recalculated to total aboveground biomass using expansion factors (stand-aggregated data) or allometric functions (single-tree level data). Specific attention requires tree-level data because statistical forest inventory provides data on this level. The most important tree species in the Czech Republic are European beech, English and sessile oak, Scots pine and Norway spruce. While rather an extensive scientific literature dealing with allometric equations for spruce is available (e.g. Wirth et al. 2004), the reported allometry of other tree species, specifically of deciduous ones, is far less frequent. A rigorous quantification of total tree biomass for certain region requires locally parameterized allometric equations. Therefore an experiment with destructively measured components of full-grown beech trees was conducted. The aim of this paper was to parameterize a set of allometric equations for European beech (*Fagus sylvatica* L.) that could be used for quantification of total aboveground biomass and of its individual components, i.e. branch and stem biomass.

MATERIAL AND METHODS

Sample trees

The selected sample beech trees represent a set of 20 trees from four different stand localities (Table 1).

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Table 1. Basic information on four stand localities where sample trees were selected. Stand ID, stand age, forest type group (FTG) and management unit (MU) according to the country-specific (Czech) forestry practice is noted

Locality	Stand ID	Age	FTG	MU
Jílové u Prahy (1)	440 X 12	112	3J1	401
Jílové u Prahy (2)	439 E 6	40	2K5	233
Trhanov FD	427 E 06	106	6S5	541
Horšovský Týn FD	119 C 12a	114	6N1	556

Table 2. The measured samples of beech trees ($n = 20$) and fundamental data used for parameterization of allometric equations. The given mass values represent oven-dry conditions for the individual components (stem, branch) and total aboveground biomass (*AB*)

ID	Age (years)	dbh (cm)	*H* (m)	Stem (kg)	Branch (kg)	*AB* (kg)
1	112	35.3	22.3	600.5	187.3	787.8
19	112	40.3	24.0	753.3	368.3	1,121.6
101	106	26.5	32.7	552.4	57.5	609.9
102	106	30.7	32.0	612.8	96.2	709.0
103	106	34.7	33.4	848.8	155.9	1,004.7
104	106	39.4	33.9	1,216.1	152.2	1,368.3
105	106	34.5	32.3	913.2	111.4	1,024.6
106	106	29.3	29.6	593.0	49.0	642.0
107	106	26.2	30.5	503.7	21.4	525.1
108	114	41.4	28.6	1,175.6	85.8	1,261.4
109	114	46.2	26.7	1,469.8	273.7	1,743.5
110	114	40.7	28.3	1,099.5	305.2	1,404.7
111	114	39.5	29.1	848.3	105.4	953.7
112	114	47.7	27.2	1,348.3	286.1	1,634.4
113	114	30.9	25.2	578.8	48.5	627.3
114	114	62.1	29.1	2,574.3	541.9	3,116.2
115	40	15.0	14.5	66.3	26.3	92.6
116	40	8.1	12.8	23.5	2.9	26.4
117	40	5.7	9.2	5.7	0.9	6.6
220	112	30.3	24.1	446.9	79.2	526.1

Three sample trees with diameters at breast height (dbh) from 30 to 40 cm, 112 years old, were selected in Jílové u Prahy locality (1). Other three sample trees with dbh from 6 to 15 cm, 40 years old, were selected in Jílové u Prahy locality (2). A 106-year old beech stand prepared for selective logging was selected in the Forest District Trhanov. It provided trees of smaller dimensions, namely trees with dbh from 26 to 39 cm. Finally, 120-year old beech trees with dbh from 31 do 62 cm were available in the Forest District Horšovský Týn.

All sample trees and fundamental biometric data used in this study are listed in Table 2. Fig. 1 shows the dbh-*H* relation for all sample trees ($n = 20$).

Stem and branch biomass estimation

The measured data of sample trees included total stem volume, stem volume located in the crown, weight of stem section located in the crown and fresh weight of branches. The volume of stem and branch samples was obtained xylometrically. The weight of the above components was measured *in situ* and represented fresh weigh with unknown moisture content. Dry weight was estimated in the lab after oven-drying. In this study, only conventional wood density is used. It is defined as dry weight at zero moisture content (oven-dried samples) divided by the corresponding volume as measured *in situ* (fresh state).

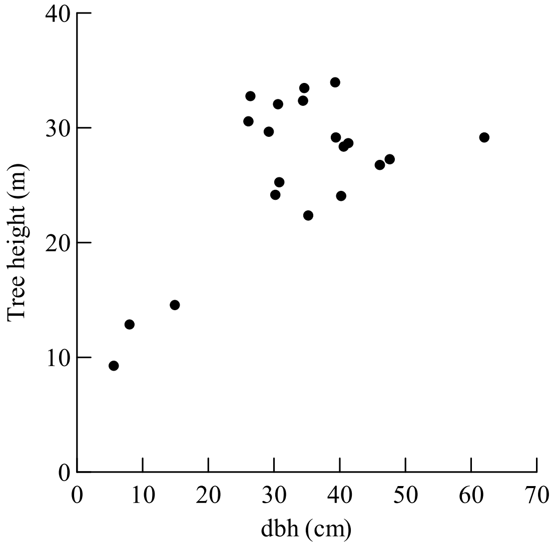

Fig. 1. Scatter graph of tree height and dbh of the selected sample trees used for destructive mass and volume measurements needed for establishing the data set used for parameterization of allometric equations

Allometric equations

The dependence of total aboveground biomass (AB) on the basic measurable biometric variables, i.e. dbh and total tree height (H), was estimated using three different functions, namely

$$AB = a \times dbh^b \quad (1)$$

$$AB = a \times (dbh^2 \times H)^b \quad (2)$$

$$AB = a \times dbh^b \times H^c \quad (3)$$

Equation (1) is a classical exponential function that is most commonly used in biometric studies (e.g. Zianis, Mencuccini 2004). It contains two parameters (a, b) and a dependence of AB on dbh only. Equation (2) also contains two parameters, but the dependence of AB is expressed as a composition of two independent variables, dbh and H, in the form dbh^2 × H, which basically indicates volume. Equation (2) was earlier successfully deployed for spruce allometry e.g. by Černý (1990). Finally, Equation (3) contains three parameters (a, b, c). This equation is often parameterized in its linearized form by logarithmic transformation of both independent variables (e.g. Hochbichler 2002). It must be stressed that although linearization may lead to a simplified parameterization procedure by avoiding nonlinear regression, it requires a reverse transformation that may produce a bias that must be statistically treated (e.g. Zar 1968; Sprugel 1983). It is hence advisable to avoid a possible estimation bias by applying a standard nonlinear fitting procedure directly using the form of Equation (3).

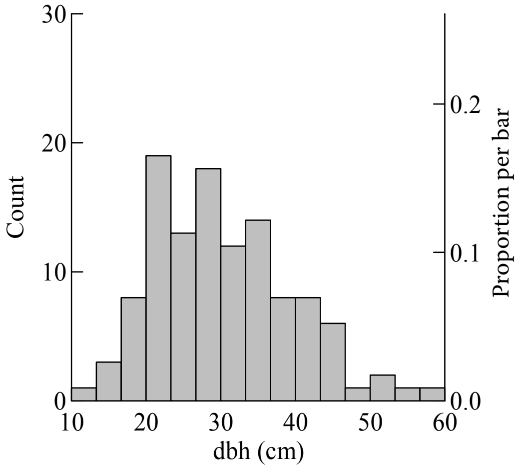

Fig. 2. Histogram of tree dbh measured in the selected permanent research plot of beech stand in 1998

Research plot to compare allometric functions

A permanent research plot of beech stand was selected for a comparison of the tested allometric equations with other equations applicable to beech as published in literature. Plot No. 501118 was selected from the databank of permanent research plots in the Czech Republic, which is currently administered by the Forest Management Institute, Brandýs nad Labem. The plot is located in Natural Forest Area 6 at the elevation of 565 m. It is a monospecific beech stand, 89 years old in 1998. At that time the last measurement on the tree level was

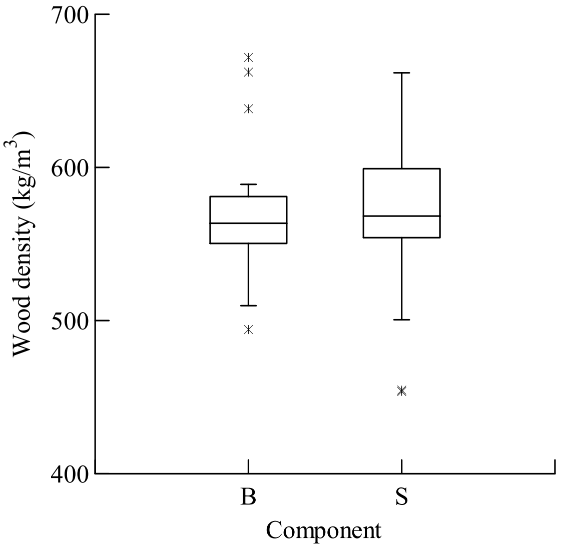

Fig. 3. Box plot of wood density estimated from the samples of branches (B, n = 23) and stems (S, n = 56). The difference between the density values estimated for branch and stem wood statistically insignificant (t-test, P = 0.054)

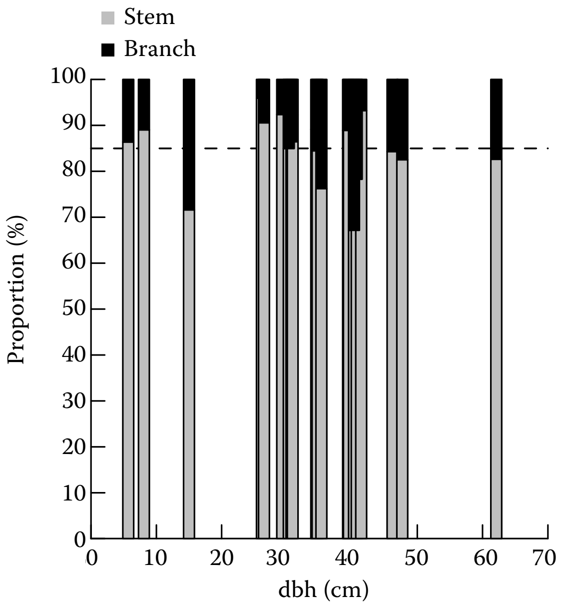

Fig. 4. The proportion of stem and branch volume in the total aboveground biomass estimated in the sampled beech trees. No significant dependence on dbh was found; the average proportion of stem in the total tree biomass was 85% (dashed line on the y-axis)

performed and used in this study. The frequency distribution of dbh in this experimental stand is shown in Fig. 2. Tree stocking of this stand was 550 trees/ha.

RESULTS

Wood density

Conventional wood density estimated for the wood of stem was 575.5 kg/m^3 (SD ± 32.8, n = 56). As for the branch wood, conventional wood density was estimated at 560.1 kg/m^3 (SD ± 29.1, n = 23), i.e. a slightly lower value as compared to the density of stem wood (Fig. 3). These differences were statistically insignificant (t-test, P = 0.054). However, since the found test values were just marginally above the level of statistical significance (P = 0.05), the individually estimated density values were used for the specific components of aboveground biomass. The corresponding moisture content in wood at fresh condition was assessed to be 42.3% for tree stems and 45.7% for branch wood.

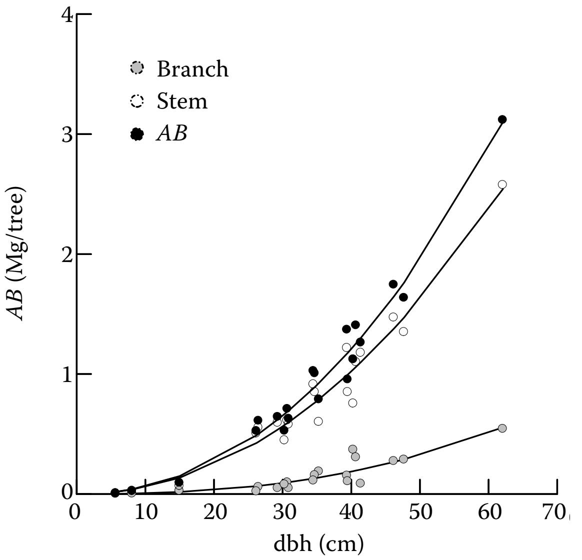

Fig. 5. The dependence of total aboveground biomass (AB) and individual components (branch and stem) on dbh according to Equation (1) (lines) and the measured data used for parameterization (symbols)

Proportion of stem and branch biomass

The proportion of branch and stem biomass assessed from the destructive experiment amounted to 15% and 85% of the total aboveground biomass, respectively (Fig. 4). There was no dependence of

Table 3. The final parameter values of Equations (1, 2, 3), asymptotic standard errors (A.S.E.) and the mean corrected r^2 of the regression estimated for the total aboveground biomass and individual components

Biomass component	Equation	Parameter values (A.S.E.)			r^2
		a	b	c	
	1	0.453 (0.157)	2.139 (0.090)	–	0.974
AB	2	0.015 (0.006)	1.054 (0.036)	–	0.983
	3	0.047 (0.033)	2.121 (0.068)	0.697 (0.189)	0.986
	1	0.494 (0.224)	2.070 (0.118)	–	0.954
Stem	2	0.017 (0.006)	1.027 (0.034)	–	0.984
	3	0.014 (0.010)	2.053 (0.071)	1.084 (0.199)	0.984
	1	0.021 (0.025)	2.471 (0.311)	–	0.806
Branch	2	0.001 (0.001)	1.192 (0.180)	–	0.736
	3	5.137 (11.96)	2.665 (0.320)	–1.878 (0.806)	0.849

these fractions on dbh, the linear regression of the dependence of stem proportion on dbh was insignificant ($P = 0.574$, $r^2 = 0.02$).

Allometric equations for biomass estimation

The simple exponential dependence of aboveground biomass (*AB*) on dbh according to Equation (1) explained 97% of the variability in the measured data ($r^2 = 0.97$, Table 3). The application of Equation (1) to express the dependence of the individual biomass components on dbh resulted in $r^2 = 0.95$ for stem and $r^2 = 0.81$ for branch wood. The parameterized Equation (1) for all biomass components is shown in Fig. 5.

As expected, the forms of Equation (2) and (3), which deploy also tree height (*H*) as an independent variable, were more successful (Table 3). As for *AB*, the parameterized functions reached $r^2 = 0.98$ (Equation (2)) and $r^2 = 0.99$ (Equation (3)). The graphical comparison of the measured *AB* and estimations by Equations (1, 2, 3) is shown in Fig. 6.

Equation (3) was also the most successful form of dependence for stem ($r^2 = 0.98$) and branch biomass ($r^2 = 0.85$).

The asymptotic standard errors of parameter values were relatively largest for parameter *a* whereas they were smallest for parameter *b*, which is mostly associated with dbh (Table 3). However, the effect of all parameters in the analyzed equations was always significant.

DISCUSSION

It is important to note that a detailed destructive analysis of full-grown beech trees *in situ* is very time- and labour-consuming, and hence also costly. It is unlikely that extensive destructive studies similar to those compiled in Pařez et al. (1990) will be conducted again. The set of data analyzed in this study reflects the available resources. Although it does not allow to do allometry analysis differentiated according to growth conditions, it still represents a very valuable set of data for constructing robust allometric equations.

A necessary step for preparation of the final set of data required for parameterization of allometric equation was the assessment of conventional wood density. The estimated density found here for stem wood corresponds well to the value of 580 kg/m^3 recommended by Intergovernmental Panel on Climate Change in its Good Practice Guidance (IPCC 2003). A slightly higher density for stem wood as compared to that of branches likely reflects the relatively lower proportion of bark and phloem tissues in stems relative to branches.

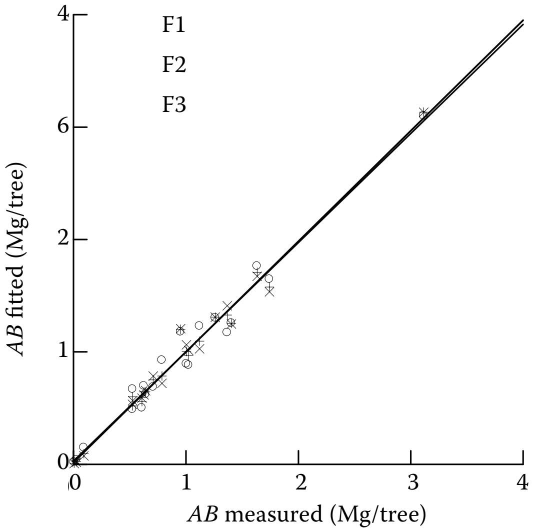

Fig. 6. Aboveground biomass derived from *in situ* measurements against the assessment by the individual parameterized functions (Equations 1, 2, 3)

Tree height (*H*) as the second independent variable used in Equations (2, 3) improved the estimation relative to basic Equation (1) involving dbh only (Table 3) only slightly, namely by about 1 or 2% for *AB* and by 3 and 4% for stem and branch biomass. A similar or even less significant contribution of *H* was reported for beech allometry by Bartelink (1997) and Corbyn et al. (1988).

The performance of the parameterized equations can be appraised by comparison with other available biomass functions published elsewhere. This was performed on selected research plot of beech No. 501118. The allometric equations for aboveground biomass (*AB*) of European beech were published by Bartelink (1997), Pretzsch (2000) and Hochbichler (2002). These studies were based on data from the experiments in the Netherlands, Germany and Austria. Additional resource represents a generalized equation applicable to broadleaved species of temperate regions (Schroeder et al. 1997). It was estimated from an extensive empirical material collected in the Northeast of the USA. As it is obvious from Fig. 7, the last named equation shows the smallest values of *AB* relative to other functions, which probably reflects a different character of forest ecosystems in the American Northeast as compared to the more intensively managed beech stands in Central Europe. Other equations were more similar in their quantification of *AB*. Specifically important is the agreement of Equation (3), which was the most successful in parameterization on the data collected for this study, with that of Bartelink (1997) and

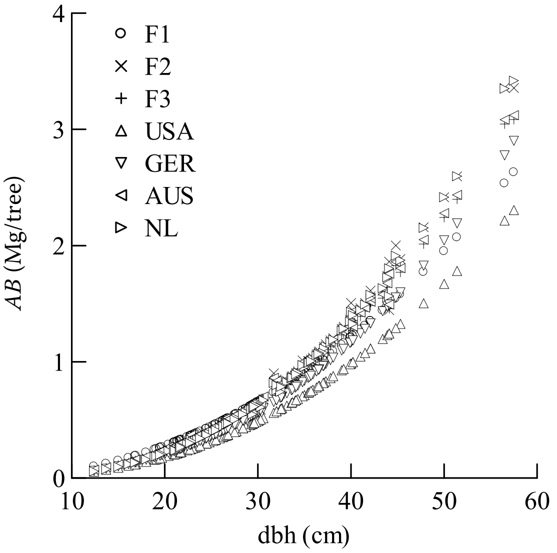

Fig. 7. The application of the parameterized equations (1 – F1, 2 – F2, 3 – F3) and other published equations applied to trees of the selected research plot: USA – Schroeder et al. (1997); GER – Pretzsch (2000); AUS – Hochbichler (2002); NL – Bartelink (1997)

Hochbichler (2002). These equations have basically identical forms and differ only in their specific parameter values.

The differences observed in Fig. 7 imply different estimation of total *AB*. For example, in the selected test stand of beech, *AB* density as estimated by parameterized Equation (3) would be 422 t/ha. Relative to this estimate, parameterized Equations (1, 2) and the functions of Bartelink (1997) and Hochbichler (2002) would quantify *AB* within 3%. The application of the generalized function according to Schroeder et al. (1997) would underestimate *AB* by almost 25%. Note, however, that the actual difference in quantifications by different equations would also be affected by the specific distribution of trees in the stand.

The parameterization of branch biomass was less tight as compared to the parameterization applied to stem biomass (Table 3). Still, the explained variability in the empirical data can be considered high, namely as for Equation (3) that explained 85%. This equation used a combination of two independent variables and three parameters. On the other hand, Equation (2) was shown to be least useful for the application to branch biomass. This is likely due to its specific form intended to approximate the volume of simple bodies. This apparently works well on tree stems, but not on the complex structure of branches.

This paper analyzed only the allometric functions involving the two fundamental measurable characteristics of trees, i.e. dbh and *H*. However, it is likely that other biometric parameters and their specific combinations may be needed for a more accurate quantification of stem and branch biomass. The analysis of effective parameters for remote crown biomass quantification will be the subject of our next study.

Another important point to mention concerns the terminology usage. The term aboveground biomass (*AB*) is not always clearly defined. Here, *AB* includes that part of aboveground tree biomass that excludes foliage and stump. While the foliage of broadleaves is not usually considered as a "long-term" biological storage, the treatment of stump should always be mentioned in the definition of *AB*. A rare quantification of stump is included in the paper of Pařez et al. (1990), who defined the proportion of stump volume in relation to the volume of merchantable wood and dependent on mean tree dbh in the stand. This approximation may also be applied to the level of individual trees. According to Pařez et al. (1990), the proportion of stump is relatively most important for the smallest dbh, where stump accounts for ca. 3% of the stem volume. Stump volume becomes relatively less important for dbh close to 20 cm and accounts for about 1.5% of the stem volume. For larger dbh, the proportion of stump slowly increases and reaches values slightly above 2% of the stem volume for the largest trees.

The demonstrated parameterization of three basic allometric functions for assessment of aboveground biomass and its major components was optimistic in terms of large percentage of explained variability in the empirical data. Still, these equations must be applied cautiously. It cannot be expected that a trustable estimation will be obtained for trees growing in extreme site conditions and specifically for trees growing as solitaires. Such tress will contain a significantly higher proportion of wood biomass allocated in branches. Therefore, the recommended usage of the parameterized equations is limited to beech trees growing in the standard conditions of classically managed forest stands excluding extreme sites.

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Stanovení alometrických rovnic pro buk lesní

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ABSTRAKT: Příspěvek popisuje parametrizaci alometrických vztahů pro biomasu buku lesního na základě údajů zjištěných destruktivním měřením souboru 20 vzrostlých stromů v rozpětí výčetní tloušťky (dbh) 5,7–62,1 cm. Byly hledány vztahy vyjadřující celkovou nadzemní biomasu (*AB*) stromu (mimo pařez), biomasu kmene a biomasu větví. Pro parametrizaci vztahů byly zvoleny tři alometrické rovnice o dvou nebo třech parametrech, využívající nezávislou proměnnou dbh a kombinaci dbh a výška (*H*). Vybrané rovnice vysvětlily 97–99 % variability v případě *AB*, přičemž marginálně nejúspěšnější byl vztah s použitím dbh a *H* v kombinaci se třemi parametry rovnice. V případě jednotlivých komponentů biomasy – tj. kmene a větví – parametrizovaná rovnice vysvětlila 98 % a 85 % variability měřených údajů. Výška jako druhá nezávislá proměnná měla poměrně malý význam pro zpřesnění vztahu – v případě nadzemní biomasy přispěla ke zlepšení predikce o 1–2 %, v případě komponenty větví pak o necelých 5 %. Výsledné parametrizované vztahy jsou aplikovatelné pro jedince buku lesního rostoucího v klasickém hospodářském lese.

Klíčová slova: alometrie; nadzemní biomasa stromu; větve; kmen; uhlík; hustota dřeva

V posledních letech narůstá zájem o celkovou kvantifikaci biomasy dřevin. Je to především v souvislosti s významem lesů v rámci klimatických změn, tj. specificky pro kapacitu lesů vázat uhlík. V rámci národních inventur a mezinárodních závazků republiky (UNFCCC – Úmluva OSN o změně klimatu, Kjótský protokol) je požadováno stále přesnější vykazování změn zásob uhlíku v lesích. K tomu je nutná kvantifikace celkové nadzemní biomasy. Dostupné údaje o lesích se dosud zaměřovaly především na produkční charakteristiky. Specificky v České republice se produkce vztahuje k hroubí, které je definované jako objem kmene a větví s průměrem nad 7 cm. Údaje na porostní nebo stromové úrovni je nutné přepočíst, a to pomocí expanzních faktorů v případě prvním (agregovaná data na porostní úrovni) a pomocí alometrických rovnic v případě druhém (data na stromové úrovni). Především stromové úrovni je nutné věnovat pozornost, protože statistická inventarizace lesa poskytuje primární data o jednotlivých stromech. Důležité z tohoto pohledu jsou především hlavní hospodářské dřeviny, tj. borovice, buk, dub a smrk. Zatímco v evropské vědecké literatuře existuje poměrně velký zdroj spolehlivých alometrických vztahů pro smrk mírného pásma, u ostatních dřevin je situace horší. Především u listnatých dřevin může být biomasa větví důležitým komponentem celkových zásob uhlíku v lesích. Ke kvantifikaci celkové biomasy listnatých dřevin je potřebná spolehlivá sada rovnic, která je odvozena na základě lokálních růstových podmínek. K tomu byl využit experiment s destruktivním měřením komponentů biomasy listnatých stromů. Cílem práce je popsat parametrizační soubor a vlastní parametrizaci vybraných alometrických vztahů pro výpočet celkové nadzemní biomasy, biomasy kmene a biomasy větví buku lesního.

Vzorníkové stromy byly vybírány tak, aby zachycovaly široké spektrum dimenzí stromů. Celková sestava vzorníků představuje 20 jedinců pocházejících ze tří oblastí a zahrnujících rozsah tloušťky kmene od 6 do 62 cm.

Z měřených údajů biomasy vzorníků byly využity údaje o celkovém objemu kmene, objemu korunové části kmene, hmotnosti korunové části kmene a korunové a celkové hmotnosti větví. Hmotnost uvedených komponentů byla změřena *in situ*, představuje tedy čerstvou váhu vzorků s neznámou vlhkostí. Objem vzorků kmene a větví byl zjišťován xylometrickým měřením. Vzorky kmene a větví pak byly vysušeny v laboratoři pro stanovení sušiny a konvenční hustoty dřeva studovaných komponentů.

Pro vyjádření závislosti celkové nadzemní biomasy (*AB*) na základních měřitelných biometrických veličinách, tj. výčetní tloušťce (dbh) a celkové výšce (*H*) stromu, byly použity tři nelineární vztahy: 1. klasickou exponenciální funkci o dvou parametrech a vyjadřující závislost *AB* pouze na výčetní tloušťce; 2. rovnici o dvou parametrech, ale závislost vyjádřenou kompozicí nezávislých proměnných dbh a *H*; 3. rovnice obsahující tři parametry a exponenciální závislost na obou nezávislých proměnných.

Jednoduchá exponenciální závislost celkové nadzemní biomasy (*AB*) na dbh podle rovnice (1) vysvětlila 97 % celkové variability v měřeném souboru údajů. Aplikace této rovnice pro závislost komponentů biomasy vysvětlila 95 % variability v případě biomasy kmene a 81 % v případě biomasy větví. Závislost vztahů (2) a (3), které využívají jako nezávislou proměnnou i výšku, byla podle očekávání těsnější. Pro *AB* parametrizovaný vztah vysvětlil v případě rovnice (3) 99 % variability měřených údajů. Rovnice (3) byla také nejúspěšnější pro kvantifikaci biomasy větví.

Je nutné si uvědomit, že podrobná destruktivní analýza vzrostlých jedinců *in situ* vyžaduje poměrně značné nasazení lidské práce. Soubor dostupných empirických dat shromážděný pro tuto studii je odrazem reálných možností, ale není dostatečný pro diferencovanou klasifikaci vztahů podle růstových podmínek. Přesto znamená cenný materiál k sestavení robustních alometrických vztahů. Věrohodnost parametrizovaných rovnic lze posoudit srovnáním s dostupnými zahraničními zdroji. To ukázalo poměrně těsnou shodu parametrizovaných rovnic s rovnicemi odvozenými na základě Evropských experimentů, zatímco robustní rovnice odvozená na základě rozsáhlého empirického materiálu ze severovýchodních oblastí USA se lišila výrazněji. To pravděpodobně odráží jiný charakter lesních ekosystémů severovýchodu USA ve srovnání s intenzivním hospodářstvím buku ve středoevropských podmínkách.

Ačkoliv jsou demonstrované výsledky parametrizace alometrických rovnic pro nadzemní biomasu a její hlavní komponenty optimistické, nelze očekávat uspokojivou predikci pro stromy rostoucí na extrémních stanovištích a především pro stromy rostoucí jako solitéry, které budou mít signifikantně výraznější podíl dřeva alokovaného ve větvích. Proto lze uvedené rovnice doporučit pouze pro stromy rostoucí v podmínkách hospodářského lesa na neextrémních stanovištích. Podle dostupnosti údajů lze použít rovnici s jednou (dbh) nebo dvěma (dbh, *H*) nezávislými proměnnými.

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