

## Allometric equations for predicting aboveground biomass of beech-hornbeam stands in the Hyrcanian forests of Iran

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**ABSTRACT:** A better understanding of the carbon biomass from forests is needed to improve both models and mitigation efforts related to the global C cycle and greenhouse gas mitigation. Despite the importance of Hyrcanian forests for biodiversity conservation, no study with biomass destruction has been done to predict biomass and carbon pools from this forest. Mixed-specific regression equations with 45 sample trees using different input variables such as diameter, height and wood density were developed to estimate the aboveground biomass of beech-hornbeam stands. All the sample trees were harvested and the diameter at breast height (DBH) spanned from 31 to 104 cm so as to represent the diameter distribution reported in the beech-hornbeam stand management. Using only diameter as an input variable, the stands regression model estimates the aboveground biomass of the stand with an average deviation of 19% ( $R^2_{adj} = 0.92$ ;  $SEE = 0.22$ ). Adding height as the second explanatory variable slightly improved the estimation with an average deviation of 18% ( $R^2_{adj} = 0.95$ ;  $SEE = 0.17$ ). Adding only height or wood density did not improve significantly the estimations. Using the three variables together improved the precision of bole biomass prediction of stands with an average deviation of 10.3% ( $R^2_{adj} = 0.965$ ;  $SEE = 0.167$ ). 68% of the observed variation in the aboveground biomass of beech-hornbeam stands was explained only by diameter.

**Keywords:** climate change mitigation; carbon stock

The tree biomass from forest ecosystems plays a key role in the sustainable management of natural resources and also for the contribution of forests in the global C cycle (BROWN 2002; ZIANIS, MENCUCINI 2003). Hyrcanian forests which are located in the north of Iran stretch up to an altitude of 2800 m above sea level. They are constituted of different forest stands with about 80 woody species (ROUHI-MOGHADDAM et al. 2008). The communities of oriental beech (*Fagus orientalis* Lipsky) forests are the most important parts of the Hyrcanian forests due to their valuable ecological characteristics and their commercial value. The proportion of oriental beech reaches up to 30% of

total volume in the Hyrcanian forests and is the best-known industrial commercial tree species among the broadleaved trees and shrubs (IUFRO 2004). Oriental beech appears in the stands usually in a mixture with hornbeam (*Carpinus betulus* Lipsky) and constitutes beech-hornbeam stands in the Hyrcanian forests. Hornbeam is the most abundant tree species in the Hyrcanian forests and sometimes reaches a height of 25–30 m and a diameter at breast height (DBH) of 120 cm in these stands (MARVI-MOHAJER 2004). The beech-hornbeam stands are characterized by a two-layer structure with beech in the upper storey and hornbeam in the lower storey (IUFRO 2004).

Thus, the knowledge of aboveground biomass related to these stands in the Hyrcanian forests may help to reduce the uncertainty associated with carbon accounting on a regional and/or national level.

Biomass studies are a very costly, time-consuming and destructive method, which is generally restricted to small areas and small sample trees (KETTERINGS et al. 2001; FEHRMANN, KLEINN 2006), is the most appropriate method that has been used by many researchers (KETTERINGS et al. 2001; DJOMO et al. 2010; HENRY et al. 2010) for biomass estimations and carbon accounting from forests. Thus, to predict biomass and carbon storage of the forests, allometric models are the powerful tools widely applied (YEN, LEE 2011; ALVAREZ et al. 2012). The most important variable used in these models is diameter at breast height (DBH) (ZIANIS, MENCUCINI 2004; YEN et al. 2010; SHACKLETON, SCHOLDS 2011). The most common allometric model used to predict biomass is the power function  $Y = a \times X^b$ , where  $Y$  – dry biomass weight,  $a$  is the integration factor,  $b$  is the scaling factor and  $X$  is the diameter at breast height (KETTERINGS et al. 2001; ZIANIS, MENCUCINI 2003, 2004; FEHRMANN, KLEINN 2006; PILLI et al. 2006; DJOMO et al. 2010). This function is considered as the best applicable mathematical model for biomass studies because it has long been noted that growing plants maintain the weight proportion between different parts (PILLI et al. 2006; DJOMO et al. 2010).

Allometric biomass equations have been developed for tree species in different ecological regions of the world, which are related to species-specific and stand-specific biomass models (TER-MIKAELIAN, KORZUKHIN 1997; ZIANIS, MENCUCINI 2003, 2004; JOOSTEN et al. 2004; XIAO, CEULEMANS 2004; CHAVE et al. 2005; PEICHL, ARAIN 2007; DJOMO et al. 2010; REBEIRO et al. 2011). These equations are not actually available for Hyrcanian forests resulting in higher uncertainties of biomass estimations. This study focuses on the aboveground biomass of beech and hornbeam which are the dominant and most abundant tree species in Hyrcanian forests. Therefore, the main objectives are to use destructive biomass data to (1) develop allometric models for beech and hornbeam tree species; (2) evaluate the accuracy of each model presented; (3) choose the best allometric equation from each model for the estimation of the beech-hornbeam stand biomass in the Hyrcanian forests.

## MATERIAL AND METHODS

**Study area.** The study was carried out in Glandrood Forest District (36°27'30"–36°32'15"N and

51°53'25"–51° 57'25"E) located in northern forests of Iran. The study land has a total area of 1,521 ha with altitudes which range between 940 and 1,520 m a.s.l. The studied forests belong to the beech community widely distributed in most parts of the district. The abundant tree species in the studied forests are *F. orientalis* L. and *C. betulus* L. The bedrock is of limestone and the soil texture ranges from silty clay loam to clay. According to data of the Nowshahr Meteorological Station, the mean annual precipitation and temperature of this area were 1,293.5 mm and 16.1°C, respectively.

**Destructive sampling and biomass data.** A total of 45 sample trees belonging to *F. orientalis* L. (21 individuals) and *C. betulus* L. (24 individuals) were harvested for biomass estimation and allometric equation parameterization of beech-hornbeam stands in the study area. All the trees were selected following lines of exploitation carried out by the forestry department of Nowshahr. We took samples from the trees in the beech-hornbeam stands which exhibited similar structure and site conditions in the Glandrood forest. Selection of each individual tree was based on diameter at breast height (1.3 m above the ground). The individuals were grouped into three DBH classes: 30–60, 60–80 and  $\geq 80$  cm, which is the diameter classification system commonly used in the Hyrcanian forests of Iran. The diameter (DBH) range of the felled trees spanned from 31 to 104 cm so as to represent the diameter distribution reported in the beech-hornbeam stands. For each sample tree the DBH and total height ( $H$ ) of the stand trees were first recorded. Then, trees were felled at the DBH level and separated into bole and branches (ZIANIS, MENCUCINI 2003). Because the trees were felled in the winter, the leaves were not measured. For trees with multiple stems, the bole biomass of one single stem was considered as the sum of weights of each stem of this tree (REBEIRO et al. 2011). The boles were cut and divided into 2-m sections and weighed in the field using a steelyard of 650 kg capacity (ABOAL et al. 2005; HENRY et al. 2010; ZHU et al. 2010). A sample of 2-cm thick disk was cut from the base of each stem section (PEICHL, ARAIN 2006; ZHU et al. 2010) and two sub-samples of  $3 \times 3 \times 3$  cm were extracted from the opposite sides of disks and oven-dried at 105°C to constant mass. The dry mass was determined with an electronic balance in the laboratory and was used to estimate the moisture content and the wood density (HENRY et al. 2010; ZHU et al. 2010; REBEIRO et al. 2011; ALVAREZ et al. 2012). The basic wood density (WD) was calculated as an average of the two measurements per disk (REBEIRO et al. 2011). The wet

volume (cm<sup>3</sup>) and the dry mass (g) were measured to calculate the wood density (g·cm<sup>-3</sup>) as dry mass divided by wet volume. The biomass of each bole section was calculated by multiplying the wet mass of each component by the dry/wet ratio of each disk. The total biomass of a tree was calculated by summing the dry mass of the branches and the various sections of bole.

**Data analysis and modelling.** A general nonlinear mathematical model  $Y = a \times X^b$  with  $X$  being the DBH is the most frequently used for biomass prediction because it has long been noted that growing plants maintain the weight proportion between different parts (ZIANIS, MENCUCCINI 2003; PILLI et al. 2006; DJOMO et al. 2010). The DBH is the most commonly used parameter because it can be easily measured from the field with a great precision. In addition to the fact that the height and other parts such as crown length and volume are not easy to measure from the field, there is a good correlation between diameter and these other parameters (SANTA REGINA 2000). Different independent variables such as DBH, height, wood density and several combinations (DBH<sup>2</sup>, DBH<sup>2</sup>× $H$ ,  $H$ /DBH, DBH/ $H$ , DBH<sup>2</sup>× $WD$ , DBH<sup>2</sup>× $H$ × $WD$ ) were tested to select the best combined variables having a high correlation with biomass (SANTA REGINA et al. 2000; ZIANIS, MENCUCCINI 2003; ABOAL et al. 2005; CHAVE et al. 2005; DJOMO et al. 2010). The models were fitted to data using the ordinary least squares regression analysis. Because of heteroscedasticity of the data, the power function was logarithmically transformed into the linear form  $\ln Y = \ln a + b \times \ln (D)$ . The systematic bias introduced by this log-transformation was corrected with the correction factor CF depending on the standard error of the estimate SEE (CHAVE et al. 2005; PILLI et al. 2006; DJOMO et al. 2010; REBEIRO et al. 2011) using the formula  $CF = \exp(SEE^2/2)$ . In order to obtain the most accurate biomass predictions, the most common and empirical regression models proposed in the literature were tested (BROWN et al. 1989; CHAVE et al. 2005; DJOMO et al. 2010; REBEIRO et al. 2011). First, only diameter as an independent variable was used to develop the allometric equations and subsequently height and wood density stepwise were introduced in the models and their effects were analyzed to determine the best goodness of fit and predictive model. Model comparison and selection were based on adjusted  $R^2$  that corrects the coefficients of determination, and also on other parameters such as standard error of estimate (SSE),  $T$ -test statistical significance, correction factor (CF), average deviation and Akaike information criterion (AIC). AIC was measured by the equation:

$$AIC = 2k - 2 \ln L \quad (1)$$

where:

- $k$  – number of parameters in the regression model,
- $L$  – likelihood of the fitted regression model (NELSON et al. 1999; BASUKI et al. 2009; DJOMO et al. 2010; RAZAKAMANARVIO et al. 2012).

The models having smaller AIC, average deviation, standard error and correction factor CF were selected as the best estimator (DJOMO et al. 2010). The precision of regression equation was calculated after the prediction was back-transformed to the unit values and corrected with CF using the average deviation method. The average deviation to the regression model was estimated by the equation:

$$S(\%) = \frac{100}{n} \cdot \sum_{i=1}^n \frac{|y_{pi} - y_i|}{y_i} \quad (2)$$

where:

- $S$  – average deviation,
- $y_{pi}$  – predicted dry weight,
- $y_i$  – observed dry weight,
- $n$  – number of observations.

In order to identify the multicollinearity associated with log-transformed models having multiple independent variables, a collinearity diagnostic test was carried out using a variance inflation factor (BIHAMTA, CHAHOUKI 2011). The variance inflation factor ( $VIF$ ) measures the severity of multicollinearity in the regression model and is calculated as follows:

$$VIF = \frac{1}{1 - R_i^2} \quad (3)$$

where:

- $R_i^2$  – coefficient of determination.

This index shows how much the variance of an estimated regression coefficient increases because of collinearity. A value greater than 10 ( $VIF > 10$ ) is an indication of potential multicollinearity among independent variables. Thus, according to the smaller variance inflation factor ( $VIF < 10$ ) the predictive model either can be valid and applicable or can be compared to other predictive models (BIHAMTA, ZARE CHAHOUKI 2011).

## RESULTS AND DISCUSSION

### Tree variables

The mean values of DBH, height and wood density as measurable characteristics related to the subset of trees that was destructively sampled for branch and bole biomass estimation are sum-

Table 1. Pearson's correlation between diameter, height, wood density and branches, bole mass, total aboveground biomass and measurable parameters of destructive biomass

	Pearson's correlation			Mean (CV)	Range
	DBH (cm)	H (m)	WD (g·cm <sup>-3</sup> )		
Branch biomass (t)	0.718**	0.515**	0.101 <sup>ns</sup>	1.07 (54.6%)	0.078–2.46
Bole biomass (t)	0.923**	0.652**	0.448**	2.72 (69%)	0.31–6.81
Total aboveground biomass (t)	0.942**	0.667**	0.375**	3.79 (61%)	0.38–8.43
DBH (cm)	1	0.588**	0.269 <sup>ns</sup>	69.22 (31%)	30.87–104.35
H (m)	0.588**	1	0.043 <sup>ns</sup>	16.62 (24%)	9.15–25
WD (g·cm <sup>-3</sup> )	0.269 <sup>ns</sup>	0.043 <sup>ns</sup>	1	0.62 (4.7%)	0.57–0.69

CV – coefficient of variation, \*\* $P < 0.01$ , ns –  $P > 0.05$

marized in Table 1. The minimum and maximum weight of dry branches and of dry bole mass was 78–2,460 kg and 310–6,810 kg, respectively, with coefficient of variation of 54% and 69% (Table 1). Among all the variables measured, the coefficient of variation of wood density (4.7%) was the smallest compared to others (Table 1). The results also show that there was a strong significant correlation ( $P < 0.01$ ) between bole biomass and diameter, bole height, wood density (Table 1). However, the wood density was not correlated with branch biomass, diameter and height significantly ( $P > 0.05$ ).

### Modelling and developing allometric equations

**One-way biomass model: breast height diameter D.** We first tested the species-specific allometric equation of beech and of hornbeam separately with only diameter at breast height (Table 2). Also, the mixed-species allometric equations related to the beech-hornbeam stands were tested with only diameter at breast height (Table 5). The analysis of species-compartment-specific allometric equations showed that using only diameter in the basic functional model Eq. (1) and Eq. (10) predicted the branch biomass of beech and of hornbeam respectively with adjusted  $R^2$  of 0.58 and 0.62 with average deviation of 47.5% and of 58% and Akaike information criterion (AIC) of –127 and of –92 (Table 2). Using only diameter as a predictor in the regression Eq. (4) and Eq. (13) estimated the bole biomass of beech and of hornbeam respectively with adjusted  $R^2$  of 0.91 and 0.94, average deviation of 16% and 17%, AIC of –55 and –156.5. The total biomass of beech and of hornbeam was predicted using only diameter at breast height. The prediction accuracy was similar and close to the bole biomass of each species (Table 2). It implies that the bole biomass of

beech and of hornbeam has a majority contribution to the total biomass goodness of fit data because the majority of total weight of trees belongs to the bole. Using only diameter in the allometric equation predicted bole biomass and total aboveground biomass of the stand with more accuracy and better goodness of fit of data compared to branch biomass (Figs 1, 4 and 9). Moreover, the goodness of fit showed that 68% of the observed variation in aboveground biomass was explained just only by diameter (Fig. 9). Similar to our findings, NAVAR (2009) indicated that in the allometric equations related to the tree species of northwestern Mexico forests in most cases more than 67% of the observed variation in biomass was explained by diameter at breast height. DBH is the common and best predictor for biomass in allometric models because it is strongly correlated with biomass; in addition, DBH can be easily measured in the field and is always available in forest inventories data (ZIANIS, MENCUCINI 2003; SEGURA, KANNINEN 2005; REBEIRO et al. 2011). Table 1 also shows that there is a strong correlation between DBH and bole biomass ( $r = 0.92$ ;  $P < 0.01$ ), total aboveground biomass ( $r = 0.94$ ;  $P < 0.01$ ), confirming the prominent effect of diameter on the aboveground biomass prediction. Most of the studies on tree allometry with the power function  $Y = a \times X^b$  including only diameter showed the value of  $b$  as the scaling factor to be between 2.36 and 2.67 or between 2 and 3; this value varies with species, stand age, site quality, climatic conditions and stocking of stands (ENQUIST 2002; NIKLAS 2004; ULRICH 2004; ZIANIS, MENCUCINI 2004; DJOMO et al. 2010; ALVAREZ et al. 2012). However, some authors underlined that the use of a universal value of  $b$  is not acceptable, implying that the ratio of aboveground biomass and diameter for trees growing in different environmental conditions cannot be constant (ZIANIS, MENCUCINI

2004; NIKLAS 2006; PILLI et al. 2006). Nevertheless, there is a general convergence of the scaling exponents despite the multitude of factors affecting tree growth in different sites (PILLI et al. 2006). For this study, the average value of the scaling parameter  $b$  of bole and aboveground biomass was almost ranging between 2.36 and 2.67; this shows that a relative fixed scale coefficient was also observed for biomass estimation associated with beech-hornbeam stands in the Hyrcanian forests. The scaling parameter of branch biomass did not range between 2.36 and 2.67, implying that the ability to predict the biomass of large woody components such as boles and total aboveground biomass tends to be more stable than that of smaller, shorter-lived

components such as branches (NAVAR 2009). Models based only upon diameter  $D$  may underestimate the aboveground biomass especially for mature trees and may have greater uncertainty than the models integrating height and wood density (ALVAREZ et al. 2012). Thus, adding height and wood density in addition to diameter in the allometric models can significantly improve the aboveground biomass prediction (BAKER et al. 2004; CHAVE et al. 2005, 2006; DJOMO et al. 2010; REBEIRO et al. 2011; ALVAREZ et al. 2012).

**Biomass model: diameter  $D$  and height  $H$ .** We introduced the height in the allometric models and tested its effects in addition to diameter. Adding  $H$  slightly improved the branch biomass

Table 2. Model description based on only diameter, diameter and height for the estimation of branch, bole and total biomass of oriental beech and hornbeam

Species	Eq. No.	Allometric model	$a$	$b$	$c$	SEE	CF	Adj. $R^2$	$SD_{avg}$ (%)	AIC	VIF
<i>Fagus orientalis</i>	<b>Branch biomass</b>										
	1	$\ln(Y) = a + b \times \ln(D)$	1.53	1.29	–	0.358	1.058	0.579	47.55	–126.91	–
	2	$\ln(Y) = a + b \times \ln(D^2 \times H)$	1.28	0.507	–	0.332	1.056	0.638	42.85	–133.65	–
	3	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	1.33	0.899	0.664	0.339	1.058	0.621	45.11	–131.80	1.93
	<b>Bole biomass</b>										
	4	$\ln(Y) = a + b \times \ln(D)$	–2.72	2.49	–	0.255	1.032	0.909	16.24	–54.98	–
	5	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–2.9	0.94	–	0.170	1.014	0.965	12.57	–72.11	–
	6	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	–3.002	1.9	0.92	0.174	1.015	0.959	13.07	–67.19	1.93
	<b>Total biomass</b>										
7	$\ln(Y) = a + b \times \ln(D)$	–0.582	2.048	–	0.204	1.020	0.917	15.14	–177.51	–	
8	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–0.816	0.791	–	0.123	1.007	0.971	9.81	–222.87	–	
9	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	–8.17	1.58	0.784	0.126	1.008	0.968	11.93	–218.57	1.93	
<i>Carpinus betulus</i>	<b>Branch biomass</b>										
	10	$\ln(Y) = a + b \times \ln(D)$	–0.558	1.73	–	0.492	1.128	0.622	57.92	–91.83	–
	11	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–1.33	0.719	–	0.484	1.123	0.634	55.33	–93.26	–
	12	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	–1.16	1.55	0.484	0.492	1.128	0.621	58.14	–91.02	1.43
	<b>Bole biomass</b>										
	13	$\ln(Y) = a + b \times \ln(D)$	–2.80	2.51	–	0.240	1.029	0.937	17.02	–156.57	–
	14	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–3.95	1.04	–	0.193	1.018	0.959	16.76	–178.27	–
	15	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	–3.74	2.23	0.750	0.187	1.017	0.961	16.59	–168.39	1.43
	<b>Total biomass</b>										
16	$\ln(Y) = a + b \times \ln(D)$	–1.52	2.28	–	0.233	1.027	0.929	16.55	–151.84	–	
17	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–2.57	0.950	–	0.194	1.018	0.951	16.08	–176.88	–	
18	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	–2.38	2.032	0.684	0.188	1.017	0.953	15.76	–177.92	1.43	

$Y$  – species-compartment-specific biomass,  $D$  – diameter,  $H$  – bole height,  $a$ – $c$  – model's fitted parameters, SEE – standard error of estimation, Adj  $R^2$  – adjusted value of the coefficient of determination,  $SD_{avg}$  – average deviation, AIC – Akaike information criterion, VIF – variance inflation factor

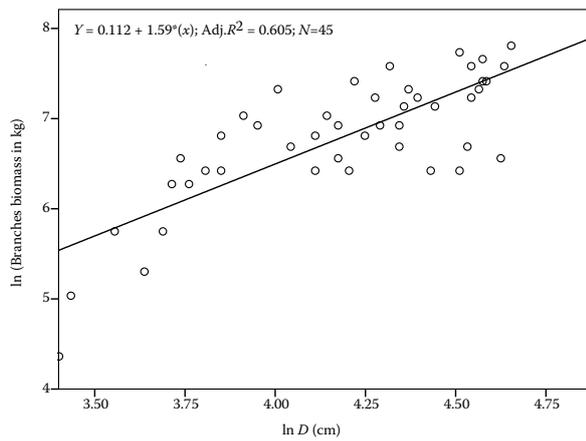


Fig. 1. Regression between the natural logarithm of branch biomass (kg) and the natural logarithm of diameter at breast height (cm)

prediction of beech, of hornbeam (Table 2) and of mixed-species stands (Table 5). Figs 2 and 3 show the goodness of fit of data on the branch biomass of mixed-species stand type. As indicated in Table 2, the equations that included height in addition to diameter were the optimal estimative regression of each tree species' bole biomass and total biomass.

We compared the biomass prediction of each best estimative regression of beech and of hornbeam using the paired *t*-test presented in Table 3. The results showed that there was no significant difference ( $P > 0.05$ ) between predictions of Eq. (2) and Eq. (11), which are related to beech branch biomass and to hornbeam branch biomass, respectively (Table 3). Moreover, the lower and the upper limit of confidence interval of the difference of Eq. (5) and Eq. (14) was similar to the range of Eq. (8) and Eq. (17) according to the mean residual and *t*-value of estimations (Table 3).

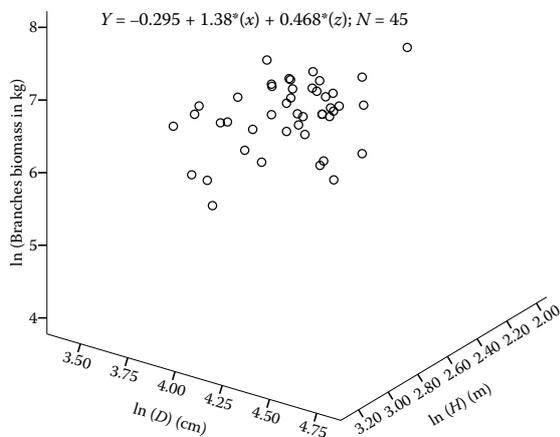


Fig. 3. Multivariate regression between the natural logarithm of branch biomass (kg) and the natural logarithm of diameter (*x*) (cm), natural logarithm of height (*z*) (m)

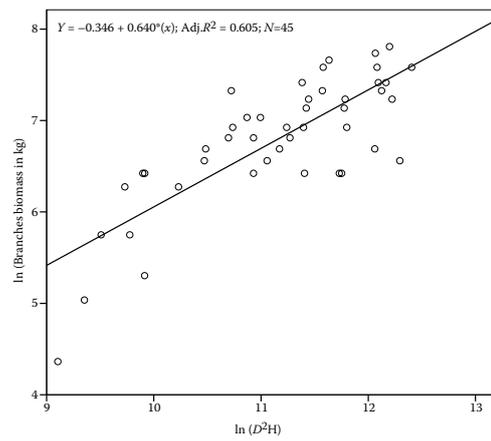


Fig. 2. Regression between the natural logarithm of branch biomass (kg) and the natural logarithm of the product of square diameter and height

Adding the height as incorporated variable ( $D^2 \times H$ ) or second variable improved the bole biomass and total aboveground biomass of beech-hornbeam stands (Table 5). Adding the height to the square of diameter in Eq. (26) and Eq. (36) ameliorated the bole biomass and aboveground biomass prediction significantly with an adjusted  $R^2$  of 0.95 and 0.92, an average deviation of 16.9% and 18.2%, an AIC of  $-145.5$  and  $-154$  as shown in Table 5. The interaction term ( $D^2 \times H$ ) is more appropriate than  $D \times H$  to estimate biomass because the biomass is a product of volume ( $\pi/4 \times D^2 \times H \times \text{form factor}$ ) and wood density. Figs 5 and 10 show the observed values and the prediction line using the interaction term of *D* and *H*. We further tested the effects of height in the allometric models with independent variables *D* and *H* using Eq. (27) and Eq. (37) (Table 5). The results showed that adding *H* as an independent second variable in the regression models can improve the accuracy of bole biomass and aboveground biomass prediction very slightly compared to

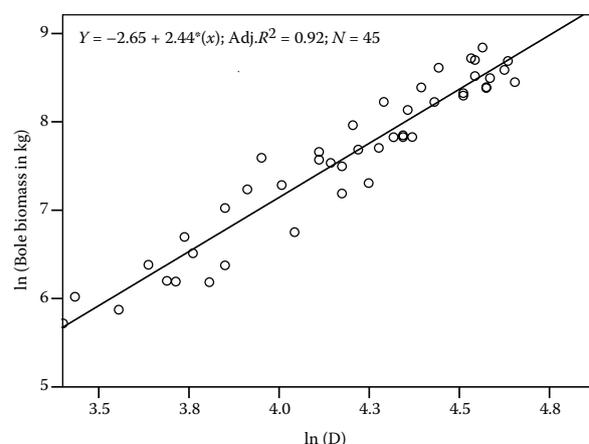


Fig. 4. Regression between the natural logarithm of total bole biomass (kg) and the natural logarithm of diameter at breast height (cm)

Table 3. Paired *t*-test at 95% confidence interval of the mean of branch, bole and total aboveground biomass (kg) for oriental beech and hornbeam (the optimal models were compared)

Pair Allometric Models	Mean residual (95% conf. int.)	<i>t</i>	<i>P</i>
Model 2–model 11 (branch biomass)	–102.31 (–343.51 to 138.88)	–0.885	0.387
Model 5–model 14 (bole biomass)	–495.66 (–910.67 to –80.64)	–2.49	0.022
Model 8–model 17 (total biomass)	481.64 (9.24 to 954.03)	2.12	0.043

the regression model including the interaction term ( $D^2 \times H$ ). Fig. 11 shows the observed values and the prediction line using a multivariate linear model Eq. (37). In accordance with this result other researches in different biomes found that adding height to diameter in the allometric modelling as interaction term or independent predictor slightly ameliorated the accuracy of aboveground components of tree biomass (KETTERINGS et al. 2001; CHAVE et al. 2005; BASUKI et al. 2009; NAVAR 2009; DJOMO et al. 2010; YEN, LEE 2010, 2011; REBEIRO et al. 2011). Furthermore, incorporating *H* in the regression model may increase the potential applicability of the equation to different sites since the height is often used as an index for the site growing conditions; it will also help to explain some of the variations in bole weight (VANN et al. 1998; KETTERINGS et al. 2001; NAVAR 2009). Also, PEICHL and ARAIN (2007) reported that the inclusion of height as second variable would be necessary in equations that are applied to trees from different social classes (e.g. seedlings, young, co-dominant, dominant, etc.). Table 1 shows a significant correlation between diameter and height; therefore, a multicollinearity test was performed. The result in Eq. (27) and in Eq. (37) ( $VIF = 1.61 < 10$ ) showed that in this case diameter and height are individual predictors of bole biomass and aboveground biomass when log-transformed.

#### Height regression model

Tree height is laborious to measure in the field and many forest inventories data do not include these values (KETTERINGS et al. 2001; NAVAR 2009).

A height regression model with diameter at breast height as an input variable can be applied in the biomass allometric equation including diameter and height to increase the precision of estimations (DJOMO et al. 2010). For development of height – diameter regression equations, we measured the height of 144 trees, especially of beech and hornbeam, which represented the diameter classes in the studied stands. We tested three models (Table 3) which have been reported by different authors to give a good fit of the height diameter relationship (DJOMO et al. 2010). The regression equation from model Eq. (21)  $\ln(H) = 2.962 - 17.07/D$  estimates better the relationship between the two variables with adjusted  $R^2$  of 0.22, SEE of 0.30 and average deviation of 14.63 %. The linear regression from model Eq. (19)  $\ln(H) = 1.287 + 0.344 \ln(D)$  estimates the height with very slightly different accuracy compared to model Eq. (21) with correlation coefficient of 0.22, SEE of 0.25 and average deviation of 14.67 % (Table 4). Although there is a correlation between DBH and *H* (Table 1), a large variance was observed around this general relationship that can be seen in Fig. 6, and a lower value of adjusted  $R^2$  in the three models. The results showed the multicollinearity between independent variables in model Eq. (20) because the value of *VIF* was much higher than 10 (Table 4), showing that this model may not be suitable to predict tree height in the studied area. MARSHAL et al. (2012) and FELDPAUSCH et al. (2011) reported that precipitation, dry season length, stem density and mean annual temperature are all key drivers of

Table 4. Height-diameter regression models for the total bole biomass of beech-hornbeam stands (n = 144)

Eq. No.	Mixed-species model	<i>a</i>	<i>b</i>	<i>c</i>	SEE	CF	Adj. $R^2$	SD <sub>avg</sub> (%)	AIC	VIF
19	$\ln(H) = a + b \times \ln(D)$	1.287	0.334	–	0.253	1.032	0.215	14.67	–393.67	–
20	$\ln(H) = a + b \times \ln(D) + c \times \ln(D)^2$	–0.923	1.454	–0.14	0.253	1.032	0.214	14.77	–392.56	518.46
21	$\ln(H) = a + b/D$	2.962	–17.07	–	0.251	1.031	0.217	14.63	–394.07	–

*D* – diameter, *H* – bole height, *a*–*c* – model's fitted parameters, SEE – standard error of estimation, CF – correction factor, Adj  $R^2$  – adjusted value of the coefficient of determination, SD<sub>avg</sub> – average deviation, AIC – Akaike information criterion, VIF – variance inflation factor

Table 5. Model description based on diameter, height and wood density for the estimation of branch, bole and total aboveground biomass of beech-hornbeam stand

Eq. No.	Mixed-species equation type	<i>a</i>	<i>b</i>	<i>c</i>	<i>k</i>	SEE	CF	Adj. $R^2$	SD <sub>avg</sub> (%)	AIC	VIF
<b>Branches</b>											
22	$\ln(Y) = a + b \times \ln(D)$	0.112	1.59	–	–	0.449	1.05	0.605	49.21	–69.76	–
23	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–0.346	0.640	–	–	0.439	1.099	0.621	48.08	–71.58	–
24	$\ln(Y) = a + b \times \ln(D) + c \ln(H)$	–0.295	1.38	0.468	–	0.442	1.102	0.614	48.97	–69.89	1.61
<b>Bole biomass</b>											
25	$\ln(Y) = a + b \times \ln(D)$	–2.65	2.44	–	–	0.256	1.033	0.918	21.46	–123.52	–
26	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–3.4	0.986	–	–	0.201	1.020	0.950	16.89	–145.46	–
27	$\ln(Y) = a + b \times \ln(D) + c \ln(H)$	–3.34	2.08	0.79	–	0.198	1.019	0.951	16.49	–144.98	1.61
28	$\ln(Y) = a + b \times \ln(D^2 \times H \times WD)$	–2.85	0.97	–	–	0.179	1.016	0.960	10.34	–155.56	–
29	$\ln(Y) = a + b \times \ln(D) + c \times \ln(WD)$	–1.48	2.38	1.91	–	0.243	1.029	0.926	20.89	–126.64	1.06
30	$\ln(Y) = a + b \times \ln(D) + c \times \ln(D^2 \times H \times WD)$	–2.88	0.23	0.89	–	0.180	1.016	0.959	10.48	–153.65	19.41
31	$\ln(Y) = a + b \times \ln(D^2 \times H) + c \times \ln(WD)$	–1.92	0.95	2.47	–	0.167	1.013	0.965	10.28	–160.22	1.04
32	$\ln(Y) = a + b \times \ln(D^2 \times WD) + c \times \ln(H)$	–2.77	1.02	0.808	–	0.177	1.015	0.961	12.14	–155.09	1.59
33	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H) + k \times \ln(WD)$	–1.94	1.98	0.85	2.38	0.168	1.014	0.965	11.90	–156.46	1.73
34	$\ln(Y) = a + b \times \ln(D) + c \times \ln(D^2 \times H) + k \times \ln(WD)$	–1.94	0.26	0.85	2.38	0.168	1.014	0.965	10.56	–156.46	19.43
<b>Total biomass</b>											
35	$\ln(Y) = a + b \times \ln(D)$	–1.11	2.71	–	–	0.219	1.024	0.925	19.12	–134.28	–
36	$\ln(Y) = a + b \times \ln(D^2 \times H)$	–1.75	0.875	–	–	0.176	1.015	0.951	18.23	–154.05	–
37	$\ln(Y) = a + b \times \ln(D) + c \times \ln(H)$	–1.69	1.87	0.668	–	0.172	1.014	0.953	18.01	–154.60	1.61

*Y* – species-compartment-specific biomass, *D* – diameter, *H* – bole height, *a–c* – model’s fitted parameters, *k* – ???, SEE – standard error of estimation, Adj  $R^2$  – adjusted value of the coefficient of determination, SD<sub>avg</sub> – average deviation, AIC – Akaike information criterion, VIF – variance inflation factor

variation in height-diameter relationships and may also explain the variations in these relationships in the Hyrcanian forests.

**Biomass model: diameter *D*, height *H* and wood density *WD***

We included the wood density as an incorporated variable to diameter and height ( $D^2 \times H \times WD$ ). The regression analysis showed that the wood density was not an effective variable on the improvement of accuracy and goodness of fit of data for the prediction of aboveground biomass in beech-hornbeam stands. Moreover, as shown in Table 2, the wood density was excluded to develop species-specific regressions because it did not change within species. Even if the wood density might change within the different trees organs, we tested introducing the wood density in mixed species-compartment-specific regressions and found no considerable pre-

cision of biomass prediction in regression analysis. Introducing the wood density (*WD*) as an interaction term with diameter and height in the linear models improved the bole biomass prediction more accurately than the other mentioned allometric equations (Table 5). The results showed that adding the wood density to Eq. (28) increased  $R^2_{adj}$  and reduced the value of SEE and of average deviation and lowered the value of AIC (Table 5). Linear equation Eq. (31) had the highest accuracy with  $R^2_{adj}$  of 0.97, SEE of 0.17, average deviation of 10.3 and AIC of –160.2 (Table 5). Eq. (34) had the same accuracy compared to Eq. (31) with a higher VIF of 19.43 (Table 5). Introducing the wood density only with height or diameter like Eq. (29) did not improve the model; it was then concluded that the wood density can improve certainty of the model prediction when adding both diameter and height. Fig. 7 shows the observed values of bole biomass

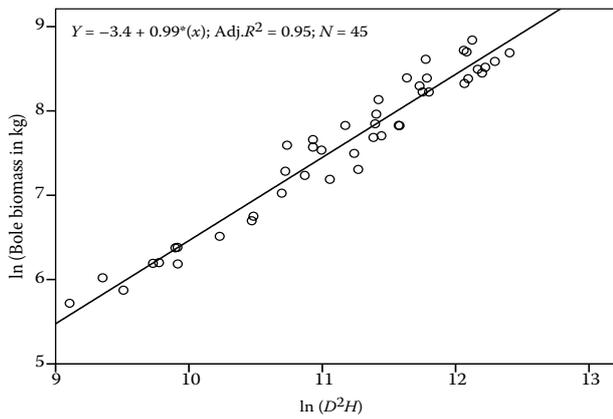


Fig. 5. Regression between the natural logarithm of total bole biomass (kg) and the natural logarithm of the product of diameter (cm) and height (m)

and the prediction line using model Eq. (28) that includes  $(D^2 \times H \times W)$  as an independent variable. Also, Fig. 8 shows the goodness of fit between the observed values of bole biomass and multivariate model Eq. (31) that includes  $(D^2 \times H)$  and  $WD$  as different explanatory variables.

Wood density is an important factor for converting forest volume data to biomass data; it may depend on location, climate, management scenarios, and is a good indicator for life history strategy for tree species (MANI, PARTHASARATHY 2007). Thus, introducing wood density and height as well as diameter may explain the site variations, species variations and increase the precision of the estimations. ALVAREZ et al. (2012) indicated that for the Amazonian watershed, the inclusion of wood density and tree height revealed spatial biomass and carbon patterns in these forests. Moreover, CHAVE et al. (2005) included  $D$ ,  $H$  and  $WD$  within their models and proposed a global forest classification

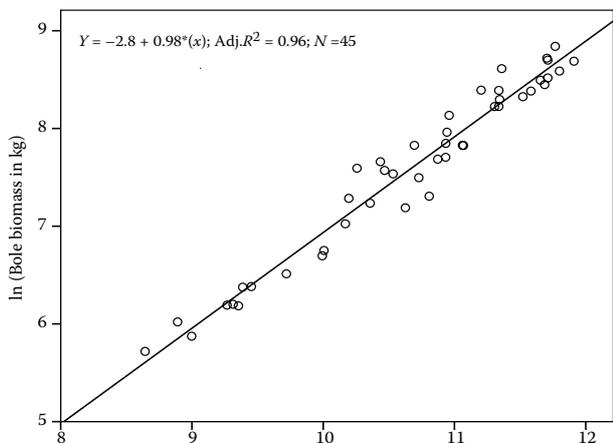


Fig. 7. Regression between the natural logarithm of total bole biomass (kg) and the natural logarithm of the product of square diameter, height and wood density ( $\text{g}\cdot\text{cm}^{-3}$ )

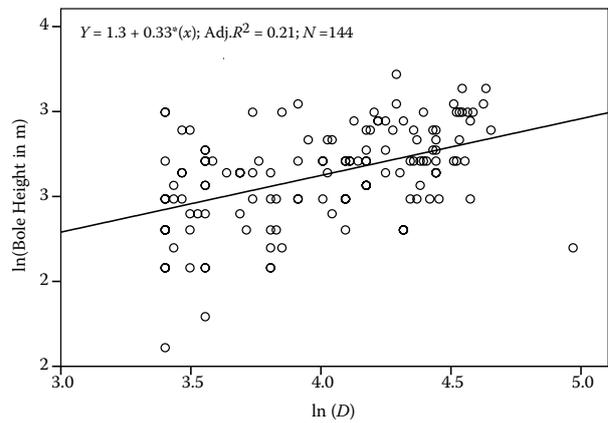


Fig. 6. Regression between the natural logarithm of total bole biomass (kg) and the natural logarithm of the product of square diameter and height

system that contains three climatic categories (dry, moist, and wet) to account for climatic constraints in the aboveground biomass variation.

## CONCLUSIONS

In the presence of complex environmental gradients, allometric equations can provide additional information to improve the knowledge of biomass distribution (CHAVE et al. 2005; ALVAREZ et al. 2012). MANI and PARTHASARATHY (2007) reported that variation in environmental factors such as topography and edaphic characteristics (e.g. soil nutrient availability) may also complicate attempts to generalize aboveground biomass on a regional or landscape scale. Allometric equations presented in this study associated with beech-hornbeam stands, the most common stand in the Hyrcanian forests, may bring

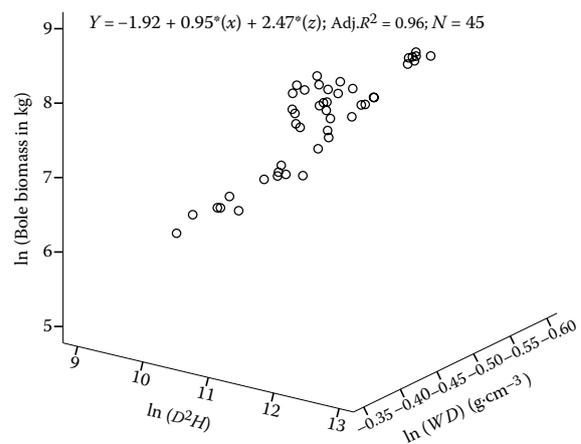


Fig. 8 Multivariate regression between the natural logarithm of total bole biomass (kg) and the natural logarithm of the product of square diameter and height ( $x$ ) and logarithm of wood density ( $z$ ) ( $\text{g}\cdot\text{cm}^{-3}$ )

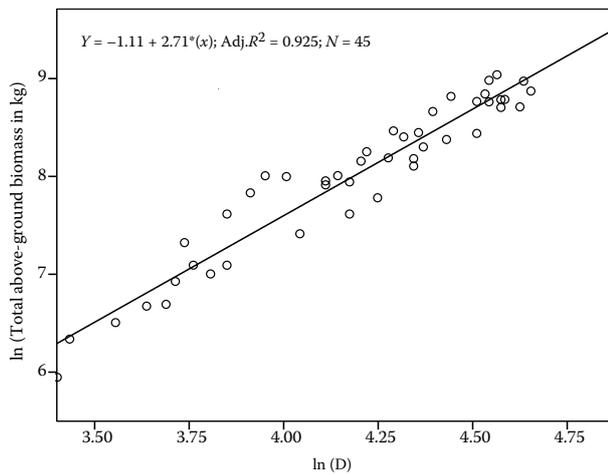


Fig. 9. Regression between the natural logarithm of total aboveground biomass of the stands (kg) and the natural logarithm of diameter at breast height (cm)

additional information for the aboveground biomass patterns and distribution. Measuring height ( $H$ ) and wood density ( $WD$ ) requires additional work, increases project time and costs (ALVAREZ et al. 2012). The allometric model including  $D$  and  $H$  as incorporated terms or two different explanatory variables was the best estimator for the total aboveground biomass prediction for each single species. For the mixed species beech and hornbeam, the allometric models including  $D$ ,  $H$  and  $WD$  had a higher precision than the models including only diameter or only diameter and wood density or only diameter and height. A lot of researches confirmed that the role of wood density in the allometric equations is more prominent for mixed species than for species-specific allometric equations because trees of different species differ greatly in tree architecture and wood density (KETTERINGS et al. 2001; BAKER et al. 2004; CHAVE et al.

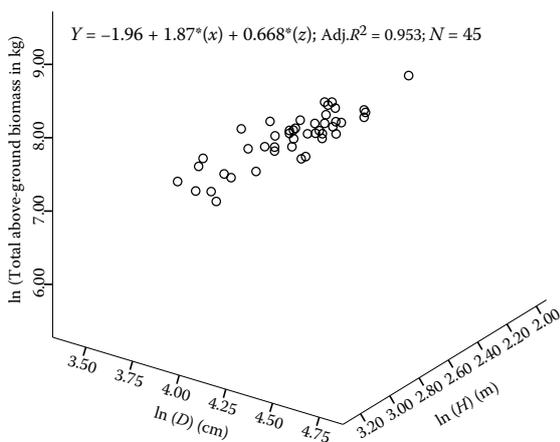


Fig. 11. Multivariate regression between the natural logarithm of total aboveground biomass of the stands (kg) and the natural logarithm of diameter ( $x$ ) (cm), natural logarithm of height ( $z$ ) (m)

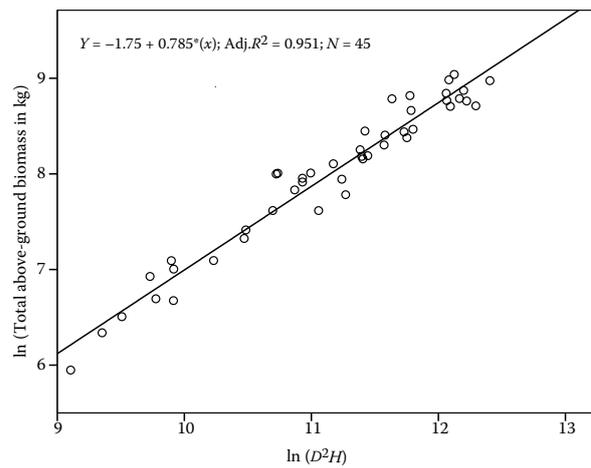


Fig. 10 Regression between the natural logarithm of total aboveground biomass of the stands (kg) and the natural logarithm of the product of square diameter and height

2005; BASUKI et al. 2009; DJOMO et al. 2010; REBEIRO et al. 2011; ALVAREZ et al. 2012). Here, we considered beech-hornbeam stands including *F. orientalis* L. and *C. betulus* L. as the majority of tree species within this ecological area. Despite the low number of species in the stand, there was still a variation in average wood density that explained the need of adding wood density as another parameter in the prediction when it is possible. Although there was no need of wood density for the total aboveground biomass prediction, allometric equations related to the beech-hornbeam stands as mixed-species stands predicted bole biomass much more accurately through introducing  $WD$  as well as  $D$  and  $H$ . The branch biomass of species-specific and of mixed-species was not well fitted as those of bole biomass and aboveground biomass (Figs 1–3). For aboveground biomass, this study recommended using Eq. (35) when only diameter is considered, Eq. (37) when only diameter and height are included. Furthermore, for bole biomass estimation Eq. (28) and Eq. (31) are recommended when diameter, height and wood density are the input parameters. This study also shows that  $D$  is the most prominent explanatory variable for biomass prediction and simple equation ( $\ln Y = a + b \times \ln D$ ) can be used in the absence of height and wood density as concluded by studies (ZIANIS, MENCUCINI 2003, 2004; DIAS et al. 2006; ZIANIS 2008; DJOMO et al. 2010; SHACKELTON, SCHOLLES 2011; ALVAREZ et al. 2012)

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