

ALLOMETRIC EQUATION FOR PREDICTING ABOVEGROUND BIOMASS OF THREE TREE SPECIES

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EBUY J, LOKOMBE JP, PONETTE Q, SONWA D & PICARD N. 2011. Allometric equation for predicting aboveground biomass of three tree species. Allometric equations, which predict the aboveground dry biomass of a tree from its diameter and/or height, are needed to estimate carbon stocks in forests. Although pantropical multispecies biomass equations have been developed for tropical rain forests, very few tree biomass measurements are available for central Africa, and none of these measurements were used to fit the pantropical equations. We measured the biomass of 12 trees belonging to three species at Yangambi in the Democratic Republic of Congo. Using these data, we developed a site-specific biomass equation and checked whether the pantropical equations were consistent with it. The pantropical equations were within the 95% confidence interval of the fitted site-specific equation, but with a bias for measurements that ranged from 26 to 32%. Although the pantropical biomass equations were consistent with the biomass measurements at Yangambi, larger data sets (including larger trees and more species) and more precise estimate of the wood specific gravity would be required to confirm the result.

Keywords: Carbon stock, central Africa, Congo Basin, destructive sampling, site-specific equation

EBUY J, LOKOMBE JP, PONETTE Q, SONWA D & PICARD N. 2011. Persamaan alometrik untuk meramal biojisim atas tanah bagi tiga spesies pokok. Persamaan alometrik yang meramal biojisim kering atas tanah sesuatu pokok daripada diameter dan/atau ketinggiannya diperlukan untuk menganggar stok karbon di dalam hutan. Walaupun persamaan biojisim pelbagai spesies pantropika telah dibangunkan untuk hutan hujan tropika, data biojisim pokok bagi Afrika tengah tidak banyak didapati dan data ini tidak dipadankan kepada persamaan pantropika. Kami menyukat biojisim 12 pokok daripada tiga spesies di Yagambi di Republik Demokratik Congo. Kami menggunakan data ini untuk membangun persamaan biojisim tapak spesifik dan menyiasat sama ada persamaan pantropika konsisten dengannya. Persamaan pantropika adalah dalam selang keyakinan 95% persamaan tapak spesifik tetapi lebih kepada data dalam julat antara 26% hingga 32%. Walaupun persamaan biojisim pantropika konsisten dengan biojisim yang disukat di Yagambi, set data yang lebih besar (termasuk pokok besar dan lebih spesies) dan anggaran graviti tentu yang lebih tepat bagi kayu diperlukan untuk mengesahkan keputusan ini.

INTRODUCTION

Estimating the carbon stocked in forests is important to assess the mitigation effect of forests on global change and to predict the potential impact of mechanisms to reduce carbon emission. Although many techniques exist to estimate carbon stocks in forests at different scales (Gibbs et al. 2007), all techniques ultimately rely on ground measurement of tree biomass. Measuring the biomass of a tree is tedious and time consuming. Moreover, it is destructive. This is why biomass equations have been developed. These are

equations that predict the biomass of a tree from dendrometrical characteristics such as diameter or height that are easier to measure. Species-specific biomass equations have been developed for temperate forests (Zianis et al. 2005). In highly diverse ecosystems such as tropical rainforests, either specific, local equations with good precision but narrow range of application (Araújo et al. 1999, Basuki et al. 2009) or general multispecies pantropical equations (Brown 1997, Chave et al. 2005) have been developed.

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Although the Congo Basin is the second largest block of tropical forest in the world after Amazon, it has contributed little to the development of pantropical biomass equations. It is symptomatic; for instance the pantropical biomass equations Chave et al. (2005) relied on data from the neotropics and South-East Asia but not from central Africa. Biomass equations for tropical rainforests in the neotropics or South-East Asia have been developed (Lescure et al. 1983, Brown et al. 1995, Nelson et al. 1999, Chave et al. 2001, Basuki et al. 2009). Biomass equations for African tropical dry forests are common because the supply of fuelwood is a long lasting issue in these areas. Specific biomass equations can be found for most species of the Soudano–Sahelian and miombo woodlands (Tietema 1993, Smehtala et al. 2002, Chamshama et al. 2004, Hofstad 2005). On the contrary, in African tropical rainforests where the issue is classically to build volume equations to predict timber volume, biomass measurements are scarce. Allometric equations for indigenous species of the rainforests of central Africa have been constructed from biomass data collected in plantations (Ola-Adams 1993, Pendje 1993, Onyekwelu 2007) or secondary forests (Deans et al. 1996).

As a consequence of the scarcity of data on tree biomass in central Africa, most of the current estimates of the carbon stocks in central Africa (Baccini et al. 2008, Lewis et al. 2009) are paradoxically based on pantropical biomass equations that do not rely on any data from Africa. There is debate whether this paradoxical situation is a shortcoming or not a problem given the precision of the pantropical biomass equations. Some authors such as Gibbs et al. (2007) considered species-specific or site-specific allometric equations as not needed to generate reliable estimate of forest carbon stocks. It would not improve accuracy with respect to general pantropic equations. On the contrary, authors such as Basuki et al. (2009) is of the opinion that pantropical biomass equations lead to significantly biased estimates of carbon stocks. Thus, specific relationships are needed.

The problem with central Africa is the effort required to sample trees for biomass. If pantropical equation defenders are correct, measuring tree biomass in central Africa is useless. On the contrary, if they are wrong, destructive sampling of trees in central Africa is needed urgently. A compromise would be to

measure a few trees to assess if the pantropical biomass equations are consistent with them. This research was aimed at assessing the biomass of 12 trees and studying if the data were consistent with biomass values predicted using pantropical equation. A site-specific biomass equation for these 12 trees was developed.

MATERIALS AND METHODS

Study site

This study was conducted in the agronomic research station of Yangambi, 100 km to the west of Kisangani, in the Oriental province of the Democratic Republic of Congo (DRC). The Yangambi research station was established in 1933. It covers 6297 km², including 737 ha of tree plantations. The climate is equatorial of the Af type according to Köppen's classification (Bultot 1971), with mean annual temperature of 25.2 °C and mean annual rainfall of 1837 mm.

We selected 11 plantation stands with establishments ranging from 1937 till 1974. The sizes of the stands were between 2500 m² and 1 ha. Five of the stands were planted with *Gilbertiodendron dewevrei*, five with *Austranella congolensis*, and the eleventh with a combination of *Austranella congolensis* and *Drypetes likwa*.

Focal species

Two of the selected species, *G. dewevrei* (Fabaceae, Caesalpinioideae) and *A. congolensis* (Sapotacea) were studied for their potential to store carbon.

Gilbertiodendron dewevrei is a large timber tree species that is found from Nigeria to the DRC (CTFT 1975, 1992). It can reach 40 m in height and above 2 m in diameter at breast height (dbh). It is often found in monodominant stands on terra firme sandy soils, although it can also be found in swampy forest or close to rivers. The specific wood gravity ranges from 0.684 to 0.728 g cm⁻³, with mean of 0.707 g cm⁻³ (Zanne et al. 2009).

Austranella congolensis is a large timber tree species that is found in equatorial Africa, from Cameroon to Kasai and from the central African Republic to the Mayombe (CTFT 1954). Its stem can reach 30 m in height and above 1.5 m in dbh. Its specific wood gravity ranges from 0.585–0.869 g cm⁻³, with mean of 0.777 g cm⁻³ (Zanne et al. 2009).

The third species, *D. likwa* (Euphorbiaceae) was also studied because it was planted in combination

with *A. congolensis* in one of the stands. It can reach 25 m in height and 1.2 m in dbh. It is found in primary forests in the whole Congolese area. No specific wood gravity was reported for this species. The wood gravity of the genus *Drypetes* ranges from 0.530–0.850 g cm⁻³, with mean of 0.707 g cm⁻³ (Zanne et al. 2009).

Biomass measurement

All trees in the 11 stands were first inventoried for dbh. The average tree basal area for each species in each stand was then computed. One tree with basal area similar to the average value was selected in each plot for destructive measurement, provided it was at least 10 m from the border of the plot. Twelve trees ranging from 24.4 to 52.2 cm dbh were thus sampled (two trees from the mixed *A. congolensis*–*D. likwa* stand and one tree each from the other stands).

Biomass data consisted of field and laboratory measurements. Field measurements took 12 days. Once felled, the total height and stem height of the trees were measured. The trees were divided into six compartments: stem (without bark), bark, gross branches (small end diameter ≥ 8 cm), thin branches (small end diameter < 8 cm), leaves, and fruits. As we focused on the aboveground biomass, stumps were not considered. The stem was divided into logs that could be regarded as approximately cylindrical, with length between 2 and 5 m. The length and diameter at each end of the logs were measured. Between three and five discs were removed from each stem. The length and diameter at each end of the discs were also measured. The total weights of these discs were measured using a hanging scale. Gross branches were treated in the same way as the stem. The fresh biomass of thin branches, leaves and fruits was weighed using a hanging scale. Then a sample of each compartment was taken. Fresh weights were measured as quickly as possible after felling to prevent moisture loss.

The discs removed from the stem and gross branches, and the samples of thin branches, leaves and fruits were brought to the laboratory. Woody samples were oven dried at 105 °C for 48 hours, whereas leaves and fruits were oven dried at 70 °C for 24 hours. All samples were finally weighed using an electronic balance.

The final step of biomass estimation consisted of computations from the measured data. The volume *V* of each log and each disc was computed

from its length *L* and diameters *d*₁ and *d*₂ at each end using Smalian's formula (Pardé & Bouchon 1988): $V = \pi L (d_1^2 + d_2^2) / 8$. The volume of the stem and gross branches were then computed by summing the volumes of the logs that composed them. The fresh volume $V_{\text{fresh, sample}}$ and fresh weight $W_{\text{fresh, sample}}$ of the discs were used to compute an average fresh wood density $\rho_{\text{fresh}} = W_{\text{fresh, sample}} / V_{\text{fresh, sample}}$. The fresh weight W_{fresh} of the stem and gross branches was obtained from their volume V_{fresh} and this average fresh wood density as $W_{\text{fresh}} = \rho_{\text{fresh}} \times V_{\text{fresh}}$. The fresh weight $W_{\text{fresh, sample}}$ and the dry weight $W_{\text{dry, sample}}$ of the discs and samples were used to compute an average moisture content for each compartment as $\mu = W_{\text{dry, sample}} / W_{\text{fresh, sample}}$. Finally, the dry biomass W_{dry} of each compartment was obtained from its fresh weight W_{fresh} and this average moisture content as $W_{\text{dry}} = \mu \times W_{\text{fresh}}$.

Statistical analyses

Following Chave et al. (2005), three multispecies equations were fitted:

$$\ln B = \alpha + \beta_1 \ln(\rho D^2 H) \quad (1)$$

$$\ln B = \alpha + \beta_1 \ln D + \beta_2 \ln H + \beta_3 \ln \rho \quad (2)$$

$$\ln B = \alpha + \beta_1 \ln D + \beta_2 (\ln D)^2 + \beta_3 (\ln D)^3 + \beta_4 \ln \rho \quad (3)$$

where \ln is the natural logarithm, *B* is the dry biomass in kg, *D* is dbh in cm, *H* is total height in m and ρ is the specific wood gravity in g cm⁻³. Equation 1 is equivalent to $B = \alpha' (\rho D^2 H)^{\beta_1}$ where $\alpha' = \exp(\alpha)$, and thus corresponds to an allometry between dry biomass and the volume proxy $D^2 H$. Equation 2 is an extension of equations 1, since 2 simplifies to 1 if $\beta_1 = 2\beta_2 = 2\beta_3$. Contrary to equations 1 and 2, equation 3 does not depend on height. All equations were fitted by linear regression, using for ρ the mean value reported by Zanne et al. (2009). They were compared on the basis of the Akaike information criterion (AIC) for small samples: $AIC = -2 \ln L + 2p + 2p(p+1)/(n-p-1)$, where *L* is the likelihood of the fitted equation, *p* is the total number of parameters in the equation and *n* is the sample size (Burnham & Anderson 2004). The best equation is the one with the lowest AIC.

The best fitted equation for total aboveground dry biomass was compared with the two pantropical equations recommended by Chave et al. (2005) for moist forests:

$$B = 0.0509 \times \rho D^2 H \tag{4}$$

$$B = \rho \times \exp[-1.499 + 2.148 \ln D + 0.207(\ln D)^2 - 0.0281(\ln D)^3] \tag{5}$$

where D is expressed in cm, H in m, ρ in g cm⁻³ and B in kg. We checked whether the predictions using equations by Chave et al. (2005) were within the confidence interval of the predictions of the best equation fitted to our data. The confidence interval of the predictions was computed using the classical formula:

$$X_0 \hat{\beta} \pm t(n - p; 1 - \alpha/2) \hat{\sigma} \sqrt{1 + X_0(X^T X)^{-1} X_0^T} \tag{6}$$

where n is the number of observations used for equation fitting (n = 12), p is the number of parameters, $\hat{\beta}$ is the estimate of the p-vector of the parameters of the model, t(df; x) is the x quantile of the Student distribution with df degrees of freedom, α is the level of the confidence interval (α = 5%), $\hat{\sigma}$ is the estimate of the residual standard error, X is the n × p design matrix of the fitted model and X₀ is the n' × p design matrix for the n' new values to predict (so that X₀ $\hat{\beta}$ is the n'-vector of predictions).

RESULTS

Table 1 shows the biomass measurements. Table 2 shows the fit of equations 1–3 to the

aboveground dry biomass of trees. All equations were significant at 5% level and the best equation according to the AIC was equation 1. Fitting a linear regression on log-transformed data and then turning back to initial (i.e. untransformed) units introduces a bias in predictions that can be corrected using the correction factor exp(σ²/2), where σ is the residual standard error of the linear equation on log-transformed data (Parresol 1999). The best uncorrected equation to predict total aboveground dry biomass was (Table 2):

$$B = 1.560 \times (\rho D^2 H)^{0.657} \tag{7}$$

with residual standard error σ = 0.2319, where D is expressed in cm, H in m, ρ in g cm⁻³ and B in kg. Thus the best bias-corrected equation to predict total aboveground dry biomass was:

$$B = 1.603 \times (\rho D^2 H)^{0.657} \tag{8}$$

The bias between measured total aboveground dry biomass and its prediction was 19% on average, whether one uses equation 7 or 8. This bias reached 26% on average when using Chave et al.'s equation 4 and 32% when using Chave et al.'s equation 5. Figure 1 compares the biomass predicted by the fitted equations 7 and 8 with the biomass predicted by Chave et al.'s equations 4 and 5. Although Chave et al.'s equations yielded

Table 1 Biomass measurements for the 12 trees at Yangambi

Species	D (cm)	Age (years)	H (m)	B _{stem} (kg)	B _{bark} (kg)	B _{branch} (kg)	B _{thinbr} (kg)	B _{leaf} (kg)	B _{fruit} (kg)	B _{tot} (kg)
<i>Gilbertiodendron dewevrei</i>	28.0	35	26.1	633.9	91.2	122.1	61.7	93.7	0.0	1002.6
<i>G. dewevrei</i>	28.8	35	26.9	638.3	110.8	125.1	13.5	54.3	9.3	951.4
<i>G. dewevrei</i>	36.5	62	24.0	990.4	95.6	97.7	24.3	43.4	0.0	1251.3
<i>G. dewevrei</i>	47.0	70	32.1	1040.9	152.4	248.3	44.2	43.2	0.0	1528.9
<i>G. dewevrei</i>	52.2	70	25.1	1269.4	195.5	514.0	185.4	120.5	0.0	2284.8
<i>Austranella congolensis</i>	26.2	60	23.8	536.5	144.5	19.2	3.6	1.8	0.0	705.6
<i>A. congolensis</i>	34.0	60	28.8	773.5	88.0	0.0	18.0	10.6	0.0	890.0
<i>A. congolensis</i>	44.0	70	39.2	2329.4	329.1	111.5	41.4	21.4	0.0	2832.8
<i>A. congolensis</i>	28.1	68	22.2	889.1	122.2	0.0	1.9	0.0	0.0	1013.2
<i>A. congolensis</i>	36.5	68	29.3	1033.6	195.5	8.2	18.0	10.7	0.0	1266.0
<i>A. congolensis</i>	32.4	72	25.9	607.5	65.9	43.3	14.3	10.6	0.0	741.7
<i>Drypetes likwa</i>	24.4	71	26.1	611.5	24.7	56.0	31.9	31.4	0.0	755.5

D = diameter at breast height, H = total height, B_{stem} = dry biomass of stem, B_{bark} = dry biomass of bark, B_{branch} = dry biomass of gross branches, B_{thinbr} = dry biomass of thin branches, B_{leaf} = dry biomass of leaves, B_{fruit} = dry biomass of fruits, B_{tot} = total dry biomass

Table 2 Results of the fit of three allometric equations to predict aboveground dry biomass using dataset of 12 trees at Yangambi, DRC

Equation	α	β_1	β_2	β_3	β_4	F	p	r ²	AIC
1	0.445	0.657				29.52	< 0.001	0.75	5.79
2	-0.021	1.313	0.677	-0.683		8.91	0.006	0.77	15.67
3	234.310	-191.093	53.008	-4.848	0.193	5.46	0.026	0.76	25.10

The best significant equation has the lowest AIC (Akaike information criterion)

lower biomass predictions for small trees ($\rho D^2 H < 2000$ kg) and higher predictions for large trees ($\rho D^2 H > 4000$ kg) than the fitted equations 7 and 8, their predicted biomass remained within the 95% confidence interval of the predictions of the fitted equations. Hence, the best fitted equation using the total aboveground biomass data of the 12 trees at Yangambi was consistent with the pantropical equations by Chave et al. (2005).

DISCUSSION

Site-specific biomass equations were developed for Yangambi. Although the number of trees used for equation fitting was low, this is often the case with biomass studies due to the amount of labour required to weigh trees. For instance, Russell (1983) weighed 15 trees in Pará (Brazil), Brown et al. (1995) weighed 8 trees in Rondônia (Brazil) or Deans et al. (1996) weighed 14 trees in Cameroon. Larger biomass datasets, including the one used by Chave et al. (2005) which comprises 2410 trees, are most often obtained through the compilation of smaller datasets. This is why we included in this study the biomass data (Table 1), so that they will be available for future studies.

The fitted biomass equations 1–3 are the ones identified as most relevant by many researchers (Araújo et al. 1999, Brown 1997, Chambers et al. 2001). However, most of these studies (Brown 1997, Chambers et al. 2001) did not include wood specific gravity as a predictor, which was the case here. Although significant relationships can be found between biomass and diameter, using wood specific gravity as a predictor is considered as significantly improving the biomass equation when dealing with a multispecies dataset (Deans et al. 1996, Chave et al. 2005). Moreover, as extensive databases on wood gravity are now available (Zanne et al. 2009), using it as a predictor does not necessarily require additional measurements. Accordingly, we compared our

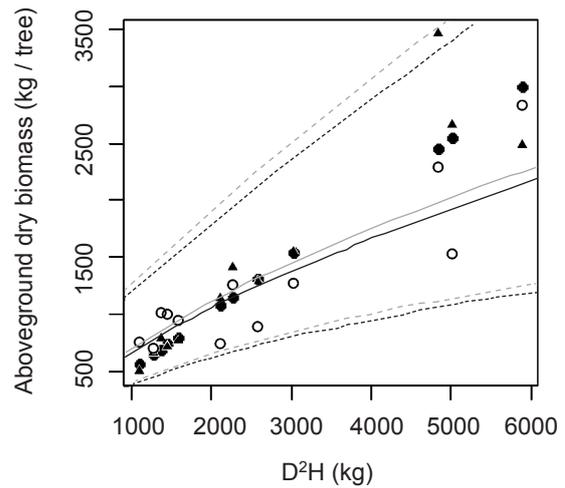


Figure 1 Measured and predicted aboveground dry biomass of 12 trees at Yangambi. White dots are measurements; black dots are predictions according to Chave et al.’s model $B = 0.0509 \times \rho D^2 H$; triangles are predictions according to Chave et al.’s model $B = \rho \times \exp[-1.499 + 2.148 \ln D + 0.207(\ln D)^2 - 0.0281(\ln D)^3]$; black solid line is the prediction according to the fitted model $B = 1.560 \times (\rho D^2 H)^{0.657}$ with its confidence interval in dashed black lines; grey solid line is the prediction according to the corrected model $B = 1.603 \times (\rho D^2 H)^{0.657}$ with its confidence interval in dashed grey lines.

fitted equations with the pantropical equations of Chave et al. (2005), which also used wood specific gravity as a predictor. The other pantropical equations that are most used are the ones by Brown (1997) but they depend on only diameter.

Equations 1 and 2 use total height as a predictor, which limit their use. Equation 3 which depends on diameter only is more appropriate when dealing with forest inventory data. However, equation 3 was the worst model in this study according to the AIC (Table 2). The minimum AIC value was obtained for equation 1, AIC_{min}

= 5.79. The difference, $AIC - AIC_{\min}$, is the only quantity that is interpretable. They were 9.88 for equation 2 and 19.31 for equation 3. These differences are elevated, meaning that equations 2 and 3 have essentially no support (Burnham & Anderson 2004). Hence, although other criteria could be used to assess the goodness-of-fit of the equations (see Parresol 1999), we did not find them useful.

As $(\pi/4)D^2H$ is the volume of the cylinder with diameter D and height H , and assuming some allometry between canopy biomass and basal area, ρD^2H is expected to be a good predictor of total aboveground biomass. Most studies using ρD^2H or D^2H as a predictor found a value for the β_1 coefficient (see equation 1) close to one (Deans et al. 1996, Chave et al. 2005). The value of $\beta_1 = 0.657$ found here thus seemed quite low. This small estimated value of β_1 explains why the fitted equation 1 yielded lower predictions than the pantropical equation of Chave et al. (2005).

The low estimated value of β_1 can be explained in two ways. Firstly, it can indicate that the measured trees have low biomass for their size. This could be related to the conformation of trees that grew in plantations rather than in natural forests. Secondly, as the standard error of the estimator of β_1 is proportional to $n^{-1/2}$ (where n is sample size, see equation 6), the low estimate of β_1 can simply be the consequence of sampling variability due to the small dataset size. As the standard error of β_1 is high, chance alone can bring a value that is much smaller than the true unknown value of β_1 . To check the latter assertion, we compared the measured biomass of the 12 trees at Yangambi with a compilation of 773 trees that were measured in the neotropics or in South-East Asia (Figure 2). Our measurements fall within the range of other biomass measurements, thus suggesting that the low value of β_1 is simply a consequence of sampling variability. Equation 6 also shows that the standard error of the estimator of β_1 is inversely proportional to the standard deviation of the predictor variable, meaning that a larger range of tree size in the dataset would bring a lower standard error for β_1 . Figure 2 shows that the range of tree size in our study ($24.4 \leq dbh \leq 52.2$ cm) is quite small as compared with other datasets. Thus, a better accuracy of the parameter estimates would have been obtained if both smaller and larger trees had been measured.

Our study showed that the pantropical equations of Chave et al. (2005) were consistent

with the biomass estimates at Yangambi, thus supporting the use of pantropical equations. However, this conclusion requires two conditions. Firstly, more tree biomass measurements are needed in central Africa including large trees ($dbh > 50$ cm) and more species that are representative of the central African rainforests. Secondly, uncertainties in biomass estimates should be more carefully addressed (Parresol 1999, Keller et al. 2001). In this study, the biomass predictions according to Chave et al.'s equations were compared with the 95% confidence interval of the predictions of the fitted equations. It would have been more interesting to compare our measurements with the confidence interval of the predictions of Chave et al.'s equations but as the design matrix X for Chave et al.'s data is unknown, this cannot be achieved using equation 6. An approximate confidence interval for the predictions of Chave et al.'s models could be computed as the predictions $\pm t(n - p; 1 - \alpha/2)\hat{\sigma}$, but this would be equivalent to disregarding the uncertainty on parameter estimates and would thus lead to artificially too narrow intervals.

Another source of uncertainty in predictions that has not been addressed properly in the literature is the one that comes from specific wood gravity ρ . Specific wood gravity was used as a predictor as if it was a constant for each species, whereas it varied across individuals within

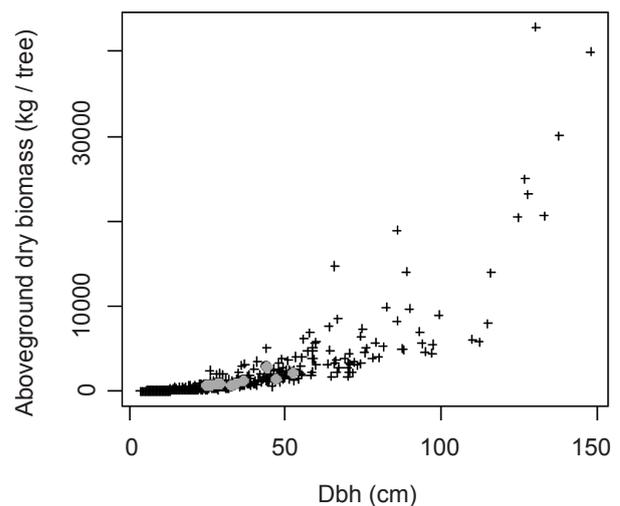


Figure 2 Aboveground dry biomass versus diameter at breast height for 773 trees recorded in the literature (crosses) and for the 12 trees at Yangambi (grey dots). Data were compiled from Brown et al. (1995), Brown (1997), Araújo et al. (1999), Ketterings et al. (2001), Nogueira et al. (2008).

a species, and even across compartments within an individual (Zanne et al. 2009). This is not a statistical shortcoming as long as the ρ value used for predictions is the same as the one used for equation fitting, but it becomes a problem when the biomass equation is extrapolated to species not used for equation fitting. In the present case, the two African species *G. dewevrei* and *A. congolensis* were presumably not part of the dataset used by Chave et al. (2005) for fitting their equations (since this dataset did not include any data from Africa), and thus, we *a priori* do not know which ρ value should be used to make predictions for these two species using equation 4 or 5. In this case, the range of values reported for ρ in the literature could be used to get a lower and a higher predicted value of the biomass.

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