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Allometric Formulas to Predict *Haematostaphis barteri* Biomass Above and Below Ground in Cameroon

Dr. Awé Djongmo Victor[1]* and Prof. Noiha Noumi Valery[2]

[1]Department of Plant Production, Higher Institute of Agriculture, Wood, Water Resources and Environment of Belabo, University of Bertoua, P.O. Box 60, Belabo, Cameroon

[2]Department of Life Science, Higher Teacher Training College of Bertoua, University of Bertoua, Cameroon

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Author : Dr. Awé Djongmo Victor, Ph.D.

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***Correspondence:**
Dr. Awé Djongmo Victor, Department of Plant Production, Higher Institute of Agriculture, Wood, Water Resources and Environment of Belabo, University of Bertoua, P.O. Box 60, Belabo, Cameroon,
E-mail: awevictor920@gmail.com

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Abstract

This study used a destructive approach to develop species-specific allometric equations for *H. barteri* in Cameroon. A sample of 30 individuals was chopped, measured, and weighed, and six prediction models were created for leaves, branches, trunks, roots, and total above-ground biomass. The best models were chosen using Akaike's information criterion, residual standard error, root mean square error, and adjusted coefficients of determination. The total biomass above ground was $\ln(B) = 2.832 + 0.981 * \ln(dbh^2 \times H \times WD) * (1.0008)$; the trunks were $\ln(B) = 1.101 + 0.106 * \ln(dbh \times WD) * (1.0003)$; the branches were $\ln(B) = 0.065 + 0.010 * \ln(dbh \times WD) * (1.0008)$; the leaves were $\ln(B) = 0.065 + 0.010 * \ln(dbh^2 \times H) * (1.0008)$, and the roots were $\ln(B) = 0.758 + 0.035 * \ln(dbh) * (1.0009)$. The equations offer important information for scaling up biomass estimations and evaluating carbon sequestration potential in *H. barteri* stands in Cameroon.

Keywords: ***Haematostaphis barteri*; Cameroon, Biomass, Allometric Formulas**

Introduction

Haematostaphis barteri Hook. F. is a forest tree species with regional significance found in savannas of Guinea and Sudan in tropical Africa [1-3]. Its fruits are marketed fresh in local marketplaces and consumed by people in North Cameroon, Togo, and northern Cameroon. *H. barteri* contains protein, vitamins, and trace elements in its fruits and leaves. Its natural range is limited to tropical Africa, including Ghana, Togo, Benin, Nigeria, Cameroon, and Chad [4]. Forests play a significant role in the global carbon cycle, and REDD+ programs aim to estimate carbon stored in forests [5]. Local allometric models are essential for estimating biomass in various land uses, such as nitrogen cycle, energy, and environmental impacts. Forests are considered a means of mitigating climate change [5].

Wood basic density (WD) is a crucial explanatory element for biomass estimation, calculated from wood samples by dividing dry mass by green volume [5-12]. Tree dbh and ht are often used as explanatory variables in biomass allometric models [5, 7, 13]. However, the dbh range, unequal distribution, and ecological zones limit their applications in Africa [14]. Some sub-Saharan African nations rely on pantropic models to estimate local AGB, but these models cannot solve the increasing demand for local allometric models [15, 16].

Despite its importance, little information exists about its potential for carbon storage. Understanding biomass could help rural populations become more resilient to climate change and aid carbon sequestration initiatives like the REDD + Mechanism biomass [17-22]. The study aims to create allometric formulas to calculate the aboveground and root biomass of *H. barteri* in Cameroon's Sudano-Sahelian zone.

Materials and Methods

Research site

The research was conducted in Central Africa, namely in the North region of Cameroon. This area lies between latitudes 9° 18'N and 8° 10'N and longitudes 13° 23'E and 12° 16'E [23] (Figure 1). Between the Adamawa Plateau to the south and the Mandara Mountains (1442 m) to the north, the relief is a sizable pedi-plain. There are two distinct seasons in the Sudano-Sahelian climate: a six-month dry season (November–May) and a six-month rainy season (June–October) [24]. Between August and March, the average monthly temperature ranged from 26°C to 40°C. The ferruginous kind of soil is distinguished by its poor cation exchange capacity and acidity (pH = 5.5–6) [25]. Around the villages, the vegetation is a clear and degraded Sudanian savannah, with shrubby vegetation [26].

Data Collection

The study used a direct method to investigate *H. barteri* trees, selecting individuals based on availability and absence of signs of human abuse. Circumferences were measured and three diameter classes 5–10 cm, 10–20 cm, and 20–30 cm were chosen, with thirty trees in the North Cameroon region marked.

Ten individuals were divided into classes and separated into three sections: leaves, branches, and trunks. Roots were excavated to determine biomass. Large branches, trunks, and roots were chopped into small pieces, bagged, and weighed. Samples were dried in an oven set to 70°C for leaves and 105°C for trunk, branches, and root discs. The following formula will be used to determine the water content of the leaf, branch, and trunk samples:

WC (%) = ((WM-DM) / DM) * 100 [27, 28]

where WM and DM stand for the sample's wet mass (Kg) and dry mass (Kg), respectively, and WC is the water content of the samples expressed as a percentage. The following formula was used to determine the total dry masses of the fractions based on the samples' water content: 100 * TWM / (100 + WC) = TDM [27, 28], TDM stands for total dry mass. The total wet mass is TWM (Kg). Known as biomass, the total dry masses are measured in kilograms (Kg).

Wood samples from trunks and branches were harvested to calculate *H. barteri's* wood density. They were weighed, labeled, and stored in a laboratory. To calculate volume, samples were soaked in water and calibrated on a balance following Archimedes' principle [29]. Samples were dried in an oven at 105°C for 72 hours, then weighed every six hours until a consistent weight was achieved, with data stored after achieving complete evaporation of water [22, 30]. Using the dry weight to volume ratio and the calculation from [29] below, the density of the wood was determined: WDi = Mi / Vi, where WDi is the wood density I, Mi is the species I's dry weight, and Vi is its water content. We determined the root:shoot ratio (RS) for each tree by simply dividing the values of leaves, branches, trunk, and AGB by the matching BGB value after estimating AGB and BGB as previously said.

Data Analysis

The leaf, trunk, branch, root biomass, and total AGB of *H. barteri* were found to be allometrically related to the tree's physical characteristics, including height (H), wood density (WD), and diameter at breast height (dbh) [27]. The power model and the polynomial model are the two types of models commonly used in the literature to forecast these biomasses [7]. Since the polynomial model frequently displays aberrant behavior outside of its region of validity, the power model was employed in this investigation [27].

B = a * Db is the mathematical formula frequently used to modify biomass [27, 31], where B is the biomass, D is the diameter, and a, b are the regression coefficients. The formula is frequently altered using the logarithmic transformation using the relation ln (B) = a + b * In (D) [21, 28, 31] in order to account for the heteroskedasticity of the data [21, 27]. The following six models were used to fit the biomasses in this investigation [5, 7, 31]:

$$\ln(B) = a + b \times \ln(dbh) \quad (1)$$

$$\ln(B) = a + b \times \ln(dbh \times \rho) \quad (2)$$

$$\ln(B) = a + b \times \ln(dbh^2 \times H) \quad (3)$$

$$\ln(B) = a + b \times \ln(dbh^2 \times H \times \rho) \quad (4)$$

$$\ln(B) = a + b \times \ln(dbh) + c \times \ln(H) \quad (5)$$

$$\ln(B) = a + b \times \ln(dbh) + c \times \ln(H) + d \times \ln(\rho) \quad (6)$$

In this case, B stands for biomass (kg), Dbh for tree diameter, H for total height (m), ρ or WD for wood density, and a, b, c, and d for regression coefficients.

A correction is consequently required, which entails multiplying the estimated Biomass by a correction factor (CF), which is computed as follows: The logarithmic processing of the data typically results in a bias in the calculation of Biomass [31]. [21, 27] CF = exp ($RSE^2/2$); the CF is always bigger than 1 [31]. The models' accuracy and robustness in estimating above-ground biomass were evaluated using four criteria [31]. They are listed in priority order: i) Adjusted R2, or adjusted coefficient of determination, where SRS stands for sum of residual squares and STS for sum of total squares. ii) The Akaike Information Criterion, or AIC, was calculated using the formula below: AIC = -2ln (L) + 2p, where p is the total number of model parameters and L is the "Likelihood," or probability, at which the predicted model is accurate to the unknown true. iii) Residual standard error, or RSE, is calculated as follows: RSE = ln (AGB obs) - ln (AGB pred), where AGB obs is the measured above-ground biomass, Pred AGB is the predicted above-ground biomass. iv) Root mean squared error, or RMSE:

$$RMSE = \frac{\sqrt{\sum(\ln(AGBobs) - \ln(AGBpréd))^2}}{\sqrt{n-k}}$$

in which: n: the total number of observations that the model uses;

AGB obs: Above-ground biomass measurement;

Predicted above-ground biomass, or Pred AGB.

K: the total number of model parameters.

A number of statistical characteristics were taken into consideration while choosing the optimum allometrics created for predicting the biomass of the various *H. barteri* components. Therefore, the better the model, the lower the mean square error (RMSE), residual standard error (RSE), Akaike information criterion (AIC), and the strong adjusted R2 [31]. R i386 3.1.2 and Excel 2020 were used to perform the statistical analyses.

Results

Height, Diameter, Wood Density, and Leaves, Branches, Trunk, Roots, Total Aboveground Biomass, and Measurable Destructive Biomass Parameters Pearson's Correlation

Table 1 shows the distribution of biomasses and dendrometric characteristics in a forest. The dbh ranged from 5.09 to 29.93 cm, with heights from 3.5 to 9.5 meters. The wood density ranged from 0.390 to 0.670 g/cm^3. The biomass's AGB ranged from 164.02-298 kg, with trunks acquiring more biomass than other compartments. The biomass of leaves, trunks, branches, roots, total aboveground biomass, and H showed a positive association with the dbh, while the dbh and wood density showed a positive but non-significant link.

Regression Relationship between Diameter-Height

Individual height and diameter have been found to correlate

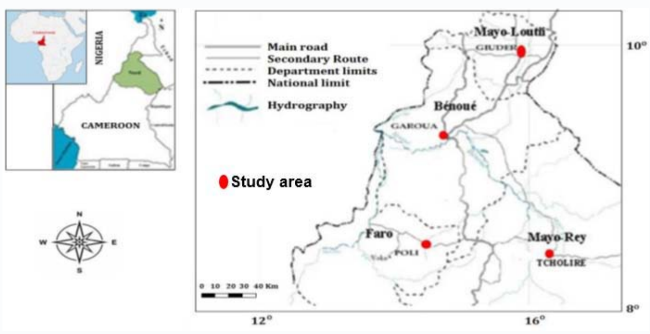

Figure 1: Study area's geographic location within the North Cameroon Region.

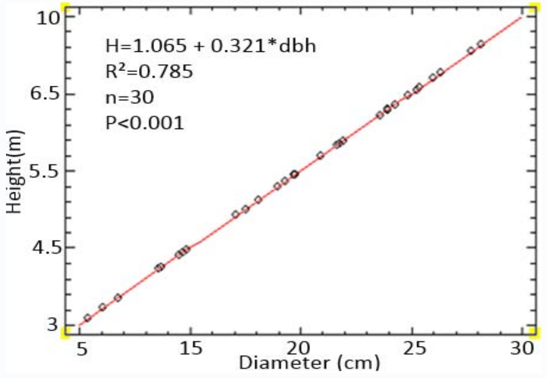

Figure 2: Diameter-height regression connection.

significantly ($r^2 = 0.785$; $P < 0.001$) (Figure 2).

Allometric Equation Development and Modeling

The regression coefficients of the examined models are statistically significant, with coefficients varying between compartments. The adjusted coefficients of determination range from 94.58 to 99.87 percent, indicating positive and significant connections between biomass and various characteristics (Table 2).

Choosing the Best Models

Leaf biomass was best predicted using $dbh^2 \times H$, with adjusted R2 (98.98%) and RSE (0.201 kg). Branch and trunk biomass had higher adjusted R2 values and lower RSE.

The best prediction for total above-ground biomass is achieved using $dbh^2 \times H \times WD$, with an adjusted R2 of 99.87%, RSE of 0.31 kg, AIC of 10.01, and RMSE of 0.143 kg. Table 3 displays these optimal equations, and their modifications are displayed in Figures 3 (a, b, c, d, e).

The proportions of total above-ground biomass, biomass from other above-ground compartments, and biomass from roots

The dug individuals' root biomass varied between 40.90 and 95.02 kg. The average root biomass to various tree parts ratios were then calculated (Table 4). Root biomass to other tree components has an average ratio between 0.29 and 1.66. Nonetheless, the overall biomass is the most significant biomass in the calculations.

Discussion

Accurate biomass models are crucial for estimating forest carbon stocks and providing verifiable information to decision-makers [27]. The diameter-height relationship indicates species' ecological growth conditions [28]. The height of a tree is predicted by its diameter, indicating variations among species due to their specific structures, competition, or environmental conditions affecting growth rate [32].

The study calculates an average base wood density of 0.53 g/cm^3 for *H. barteri*, similar to other species like Anacardium occidentale [33] and Mangifera indica [34]. However, this density is lower than previous estimates for Tectona grandis plantations [35]. In addition, [36] reported an average value of 0.54 g/cm^3 from 123 species in the tropical forest of Panama and [37] reported an average value of 0.60 g/cm^3 for 470 species from tropical America. The differences between the study and database values suggest potential errors in biomass estimates. Field measurements can improve allometric equation precision.

The study found that trunk biomass contributed the most to aboveground biomass, accounting for 52.35%, while leaf biomass made up the smallest part, aligning with previous literature [38, 39]. The reason for this is that the leaves are pushed onto the younger branches rather than the older ones [40]. The study involved 30 individuals, a variable sample size in allometric model development, considering resources and time allocated to the study [27]. Some allometric biomass equations have been constructed from a limited number of individuals, 26 trees [35]; 20 trees [41]; 38 trees [42]; 17 trees [27]; 20 trees [28]. Others incorporate very few large diameter trees, 1 to 79 cm in diameter [17]. Dendrometry range is a condition for model use, variable depending on objectives, species, populations,

Table 1: Height, wood density, leaves, branches, trunks, roots, total aboveground biomass, belowground biomass, and quantifiable damaging biomass factors are correlated.

Person correlation						
Item		dbh	H	WD or ρ	Mean (CV)	Range
Leaves (kg)		0.875**	0.654**	0.265ns	40.90 (39.95)	20.93-60.88
Branches (kg)		0.954**	0.503**	0.554**	85.52 (41.68)	64.68-106.36
Trunk (kg)		0.812**	0.696**	0.587**	104.58 (52.35)	78.41-130.76
TAGB (kg)		0.987**	0.785**	0.502**	2 31(133.98)	164.02-298
Roots (kg)		0.765**	0.453ns	0.328ns	67.96 (54.12)	40.90-95.02
dbh (cm)		1	0.785**	0.213ns	17.51 (24.84)	5.09-29.93
H (m)		0.785**	1	0.276ns	6.50 (10.48)	3.50-9.50
WD (g/cm^3)		0.213ns	0.276ns	1	0.530 (28)	0.390-0.670

CV: Coefficient of variation, **P < 0.01, ns: P > 0.05, Diameter (D), Height (H), wood density (WD), Aboveground biomass (AGB)

Table 2: Dry biomass prediction allometric equation models based on various *H. barteri* components.

Allometric models										
Compartment	**Regressions of coefficient's**				**Performance of model**					
	a (sd)	**b (sd)**	**c (sd)**	**d (sd)**	**Adj.R² (%)**	**RSE**	**AIC**	**RMSE**	***P***	**CF**
Leaf biomass										
ln (B) = a +b×ln (dbh)	0.845(0.05)	0.203(0.03)			95.96	0.251	15.94	0.128	<0.001	1.0004
ln (B) = a +b×ln (dbh×*WD*)	1.105(0.14)	0.103(0.02)			95.88	0.228	13.27	0.124	<0.001	1.0001
ln(B) = a + b ×ln (dbh²×H)	2.005(0.16)	1.035(0.01)			98.98	0.201	10.94	0.101	<0.001	1.0002
ln(B) = a + b ×ln (dbh²×H×*WD*)	0.205(0.02)	0.630(0.04)			95.97	0.244	16.28	0.124	<0.001	1.0006
ln(B) = a + b× ln (dbh) + c×ln (H)	0.518(0.08)	0.205 (0.03)	0.020(0.02)		95.98	0.254	18.94	0.141	<0.001	1.0003
ln(B) = a + b× ln (dbh) + c×ln (H) + d×ln (*WD*)	0.408(0.03)	0.105 (0.02)	0.010(0.01)	0.005(0.00)	94.58	0.258	14.26	0.154	<0.001	1.0005
Branch biomass									0,181	
ln (B) = a +b×ln (dbh)	0.404(0.02)	0.006(0.00)			97.98	0.204	14.14	0.120	<0.001	1.0006
ln (B) = a +b×ln (dbh×*WD*)	0.065(0.01)	0.010(0.00)			99.65	0.102	12.94	0.100	<0.001	1.0008
ln(B) = a + b ×ln (dbh²×H)	0.657(0.03)	0.202 (0.01)			98.08	0.118	15.28	0.114	<0.001	1.0001
ln(B) = a + b ×ln (dbh²×H×*WD*)	0.708(0.04)	0.307(0.02)			96.07	0.218	15.94	0.134	<0.001	1.0005
ln(B) = a + b× ln (dbh) + c×ln (H)	0.902(0.05)	0.408(0.03)	0.005(0.00)		95.16	0.144	19.20	0.152	<0.001	1.0002
ln(B) = a + b× ln (dbh) + c×ln (H) + d×ln (*WD*)	0.705(0.04)	0.205(0.01)	0.201(0.01)	0.102(0.00)	95.73	0.285	17.94	0.178	<0.001	1.0003
Trunk biomass										
ln (B) = a +b×ln (dbh)	0.706(0.02)	0.326(0.04)			97.56	0.258	15.65	0.184	<0.001	1.0002
ln (B) = a +b×ln (dbh×*WD*)	1.101(0.04)	0.106(0.01)			97.88	0.212	11.01	0.112	<0.001	1.0003
ln(B) = a + b ×ln (dbh²×H)	1.306(0.05)	0.406(0.02)			97.58	0.268	13.29	0.128	<0.001	1.0006
ln(B) = a + b ×ln (dbh²×H×*WD*)	1.017(0.01)	0.506(0.03)			97.36	0.344	16.19	0.134	<0.001	1.0005
ln(B) = a + b× ln (dbh) + c×ln (H)	2.013(0.07)	0.702(0.05)	0.068(0.01)		97.52	0.318	15.05	0.120	<0.001	1.0008
ln(B) = a + b× ln (dbh) + c×ln (H) + d×ln (*WD*)	3.085(0.09)	0.004(0.00)	0.002(0.00)	0.001(0.00)	97.63	0.254	13.53	0.194	<0.001	1.0004
Total aboveground biomass										
ln (B) = a +b×ln (dbh)	1.876(0.05)	0.406(0.02)			98.98	0.312	17.59	0.189	<0.001	1.0007
ln (B) = a +b×ln (dbh×*WD*)	1.986(0.06)	0.657(0.03)			98.75	0.328	13.59	0.152	<0.001	1.0005
ln(B) = a + b ×ln (dbh²×H)	1.806(0.04)	1.030(0.05)			98.74	0.344	12.01	0.148	<0.001	1.0001
ln(B) = a + b ×ln (dbh²×H×*WD*)	2.832(0.08)	0.981(0.04)			99.87	0.310	10.01	0.143	<0.001	1.0008
ln(B) = a + b× ln (dbh) + c×ln (H)	2.302(0.07)	0.068(0.02)	0.062(0.02)		98.94	0.344	16.32	0.180	<0.001	1.0004
ln(B) = a + b× ln (dbh) + c×ln (H) + d×ln (*WD*)	1.089(0.03)	0.049(0.01)	0.004(0.00)	0.001(0.00)	98.72	0.378	13.05	0.179	<0.001	1.0003
Root biomass										
ln (B) = a +b×ln (dbh)	0.758(0.02)	0.035(0.01)			97.96	0.154	14.15	0.119	<0.001	1.0009
ln (B) = a +b×ln (dbh×*WD*)	2.206(0.08)	0.495(0.03)			95.95	0.180	18.61	0.152	<0.001	1.0001
ln(B) = a + b ×ln (dbh²×H)	1.806(0.05)	0.205 (0.02)			95.78	0.244	17.52	0.148	<0.001	1.0006
ln(B) = a + b ×ln (dbh²×H×*WD*)	0.721(0.02)	0.208(0.03)			96.78	0.218	18.15	0.184	<0.001	1.0004
ln(B) = a + b× ln (dbh) + c×ln (H)	0.550(0.01)	0.062(0.01)	0.004(0.01)		96.06	0.264	15.61	0.180	<0.001	1.0008
ln(B) = a + b× ln (dbh) + c×ln (H) + d×ln (*WD*)	1.008(0.04)	0.452(0.03)	0.043(0.00)	0.002(0.00)	97.43	0.268	16.52	0.179	<0.001	1.0003

The coefficients at p <0.001 are significantly different from zero; Standard deviation (sd), Coefficient of regression model (a, b, c and d), Diameter at breast height (dbh), Height (H), wood density (WD), Biomass (B), logarithm (ln), adjusted coefficient of determination (adj. R^2), correction factor (CF), residual standard error (RSE), Root mean squared error (RMSE) and Akaike information criteria (AIC)

and sampling plans [43]. Logarithmic transformation is used to reduce residual heterogeneity and approach linearity [44].

Allometric equations were developed using breast height, height, and wood density, considering Akaike information criterion, residual standard error, and root mean square error. Five models were selected, with Eq.4 being the best for determining total aboveground biomass and Eq. 3 for leaf biomass estimation [31]. This result corroborates those of [27] and [28] who showed respectively that the best model for the prediction of the foliar biomass of 17 feet of *Daniella oliveri* and 20 feet of *Faidherbia albida* in Cameroon is the one taking into account the diameter squared multiplied by the height ($dbh^2 \times H$). The optimal model for estimating branch and trunk biomass is model Eq. 2, which has the lowest AIC, RMSE, and RES values, and the highest adjusted coefficient of determination for root biomass, considering only diameter. The dbh alone is a good predictor for estimating the roots biomass. This result is similar to that of [27] who worked on 17 individuals of *Daniellia oliveri* in Cameroon.

Table 3: Top allometric model selections by compartment.

Compartment biomass (kg)	Allometric models	R^2 (%)	RSE	RMSE	AIC
Leaves	ln(B)= 2.005+ 1.035*ln(dbh²×H)*(1.0002)	98.98	0.201	0.101	10.94
Branch	ln(B)= 0.065+ 0.010*ln(dbh×*WD*)*(1.0008)	99.65	0.102	0.100	12.94
Trunk	ln(B)= 1.101+ 0.106*ln(dbh×*WD*)*(1.0003)	97.88	0.212	0.112	11.01
AGB	ln(B)= 2.832+ 0.981*ln(dbh²×H×*WD*)*(1.0008)	99.87	0.310	0.143	10.01
Roots	ln(B)= 0.758 + 0.035*ln(dbh)*(1.0009)	97.96	0.154	0.119	14.15

Diameter at breast height (dbh), Height (H), wood density (WD), Biomass (B), logarithm (ln), adjusted coefficient of determination (adj. R^2), residual standard error (RSE), Root mean squared error (RMSE) and Akaike information criteria (AIC)

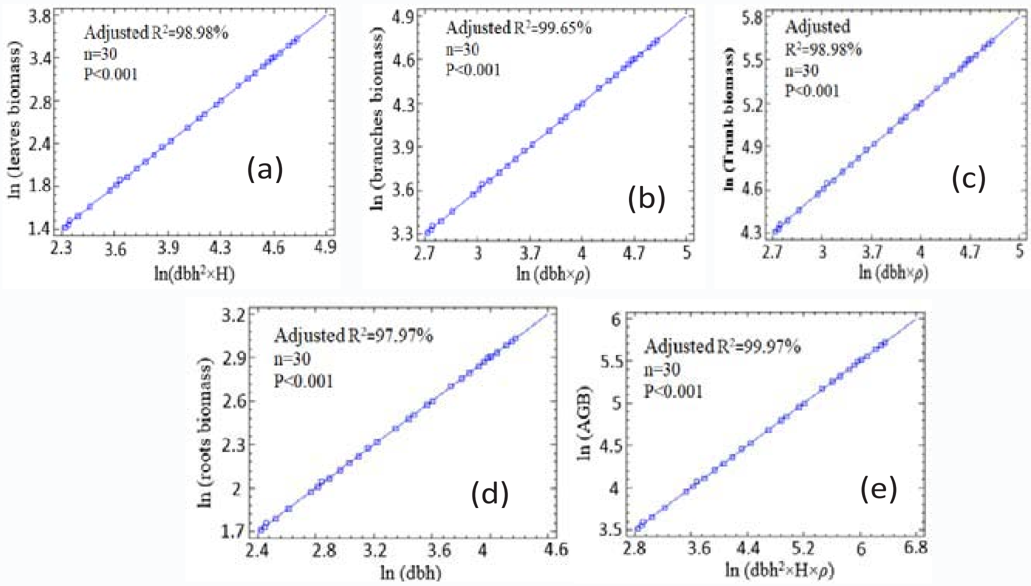

Figure 3: Regression of the best models chosen. (a) ln (leaves biomass) and ln(dbh2×H), (b) ln (branches biomass) and ln (dbh× WD), (c) ln (trunk biomass) and ln (dbh×WD), (d) ln (roots biomass) and ln (dbh), (e) ln (AGB) and ln (dbh2×H ×WD).

Table 4: Average ratios by compartment.

Ratios	Roots biomass /Leaves biomass	Roots biomass /Branches biomass	Roots biomass/ Trunk biomass	Roots biomass/ AGB
Mean (sd)	1.66 (0.83)	0.79 (0.32)	0.64 (0.21)	0.29 (0.12)

Standard deviation (sd), Aboveground biomass (AGB)

Logarithmic CF is a statistical tool for eliminating biases, but it's generally small compared to biomass estimate variation, making it omitted [27, 32]. The study found low CF values for all biomass equations, indicating minimal errors when fitting logarithmic transformations to biomass data.

The ratio established in our study is in line with other results found in the literature such as those of [27]. We did not find results for *H. barteri* in particular, but for woody plants in general, [7] determined a ratio of 0.28 which is close to the value found in our study. The small difference observed could be due, on the one hand, to the architectural forms [27] between the species used in this study and those studied by [27] and on the other hand, to the environmental conditions which are different in the two studies.

Conclusion

This study developed allometric relationships for estimating biomass for socio-economically important species like *H. barteri* in Central Africa's Sudano-Sahelian savannah zone of Cameroon. The study used data from thirty trees to build allometric mathematical models based on diameter, height, and wood density. The models showed varied performance, with the best model for predicting total above-ground biomass being 2.832+ 0.981 * ln (dbh^2 × H × WD) * (1.0008) and the roots were ln (B) = 0.758 + 0.035 * ln (dbh) * (1.0009). The models can also serve as benchmarks for formulating conservation strategies. However, new allometric models should be used cautiously when estimating biomass of trees outside their range of data and site conditions.

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