Site-specific allometric equations for biomass prediction of *Moringa oleifera* **Lam. in the northern zone of Cameroon**

ABSTRACT

Aims: *Moringa oleifera* is a species of socio-economic interest with multivariate uses. Despite its socio-eological importance in the northern part of Cameroon, it remains undervalued. Understanding its contribution to the fight against climate change requires precise quantification of its biomass. However, there is a lack of site-specific allometric equations for estimating this biomass. The development of site-specific allometric equations for *M.oleifera* is therefore imperative to facilitate this effort.
Study design: To achieve this objective, a sample of fourteen individuals of *M.oleifera* was taken in the area and divided into diameter classes between 5 and 13 cm.
Place and Duration of Study: Sample: Agroecological zones of High guinean savannahs and Sudano-sahelian zone of Cameroon between April 2009 and July 2021.
Methodology: The diameter at breast height of these individuals and their height were measured. After tree cutting, biomass of compartments of leaves, branches and trunks were determined after drying and weighing. Various allometric equations between biomasses and two parameters of the tree (the diameter and the height) were tested. The adjusted coefficient of determination (R^2adj), the residual standard error (RSE) and the Akaike Information Criteria were used for choosing the best models.
Results: The different analyses showed that diameter at breast height (DBH) is the variable that offers the best correlation for global above-ground (AGB) and below-ground (BGB) biomass in contrast to the other compartments. Thus, the best models for predicting total above-ground biomass of *M. oleifera* are -3.653-0.250lnD+5.119lnH (Sudano-Sahelian), -3.916 + 2.982lnD (High guinean Savannahs), -2.340 + 2.117lnD (Global) and finally for roots -6.426 + 2.182lnD.
Conclusion: These mathematical models could help in estimating the biomass of *Moringa oleifera* in agroforestry systems under the ecological conditions of Cameroon.

Keywords: allometric equations, biomass, M. oleifera, agroforestry systems, northern Cameroon

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1. INTRODUCTION

A major challenge in agroforestry is the choice of high-performance plant species. This issue is attracting more attention lately due to changing climatic conditions. *Moringa oleifera* represents a promising species to meet such challenges [1]. Indeed, *M. oleifera* has its origins in the regions of Agra and Oudh in northeastern India and those of Chenab in the south of the Himalayan mountain range [2,3]. This plant is now cultivated and acclimatized in

many tropical and subtropical regions around the world [4,5]. *M. oleifera* is a species of socio-economic interest [6] which adapts well to local conditions [7]. The use of all its parts makes this plant an asset in contributing to the fight and prevention of malnutrition [8,9,10,11]. Several factors contribute to this widespread interest: its cultivation in a variable range of climatic and geographical conditions, its high production yields, nutritional relevance for humans and animals [12]. This shrub, belonging to the Moringaceae family, is widely exploited for its preventive and curative properties for several diseases [13]. The exploitation of the products of this plant makes it possible to improve the diet as well as the health of the populations and to generate very interesting income for the producers [14]. However, knowledge on the biomass produced by this species is very limited in the ecological conditions of the northern zone of Cameroon. Yet, biomass provides important information on the ecological and economic performance of agrosystems [15,16]. Moreover, biomass provides information on the potential for atmospheric carbon sequestration by a species. This issue is particularly relevant to the global concern of climate change mitigation due to greenhouse gas emissions [17]. Indeed, climate change has received increasing attention, particularly with regard to the sustainable management of forest ecosystems [18]. These ecosystems, including sustainably managed agroforestry systems, can contribute to climate change mitigation [19,20,21,22]. It is with this in mind that economic incentives such as REDD+ (Reduction of emissions from deforestation and forest degradation + conservation and sustainable management of forests) have been designed to offset carbon inputs by reducing emissions from deforestation and forest degradation [23]. The success of REDD+ thus relies on robust, reliable and efficient procedures for assessing carbon stocks [24]. Data on species of socio-economic importance such as *M.oleifera* must therefore be documented [25] to build a database to predict biomass and, in turn, carbon stocks. Specific biomass estimation models must be formulated. In the tropical forests of Africa, biomass estimates are hampered by the lack of accurate allometric equations [26,27]. Therefore, many biomass estimates in Africa have relied on pantropical models [28, 29]. However, the applicability of these general equations in tropical African ecosystems is questionable [30,26,27]. Species- and site-specific allometric equations are therefore needed for reliable monitoring and verification of carbon stocks [18]. The objective of this study is to develop allometric equations to accurately predict the biomass of *M. oleifera* in agrosystems, thus addressing Goal 13 of the Sustainable Development Goals (to take urgent action to address climate change and its impacts) as well as the opportunities offered by the Clean Development Mechanism (CDM) and REDD+.

2. MATERIAL AND METHODS

2.1. Study sites

This study was carried out in the northern zone more precisely in the High guinean savannahs (HGS) and the Sudano-Sahelian zone (SS) of Cameroon. These areas are located between 6° and 8° North latitude, 10° and 16° East longitude for the HGS savannahs and between 7° and 10° North latitude and between 12° and 16° East longitude for the SS zone (Fig.1) [31]. The climate of the HGS has two distinct seasons (the rainy season followed by the dry season). The dry season extends from November to March [32]. The rainy season from April to October. During this period, the rhythm of the rains is sustained with more than 200 mm of monthly rain for five months and 1600 to 1800 mm/year. The SS zone is characterized by annual rainfall reaching 1290 mm/year. It is characterized by 6 to 7 months of rain (April to October) and 5 to 6 months of drought (November to March) [33]. SS type are ferruginous with a predominantly sandy texture, clayey horizon at depth [34,35]. Concerning the vegetation, the HGS are covered at more than 90% by a shrubby savannah or open tree whose dominant species are *Daniellia oliveri* and *Lophira lanceolata* [36]. As for the SS zone, it abounds in shrubby to wooded or tree savannahs and even open forests in the Bénoué basin. The main plant formations are: gregarious formations with *Isoberlinia doka* and *Isoberlinia tomentosa*, formations with *Boswellia odorata*, *Sclerocarya birrea*, *Prosopis africana* [37]. Livestock raising predominates peasant activities in the HGS [35,38]. The SS zone is marked by a dominant production system based on cotton and food crops [39].
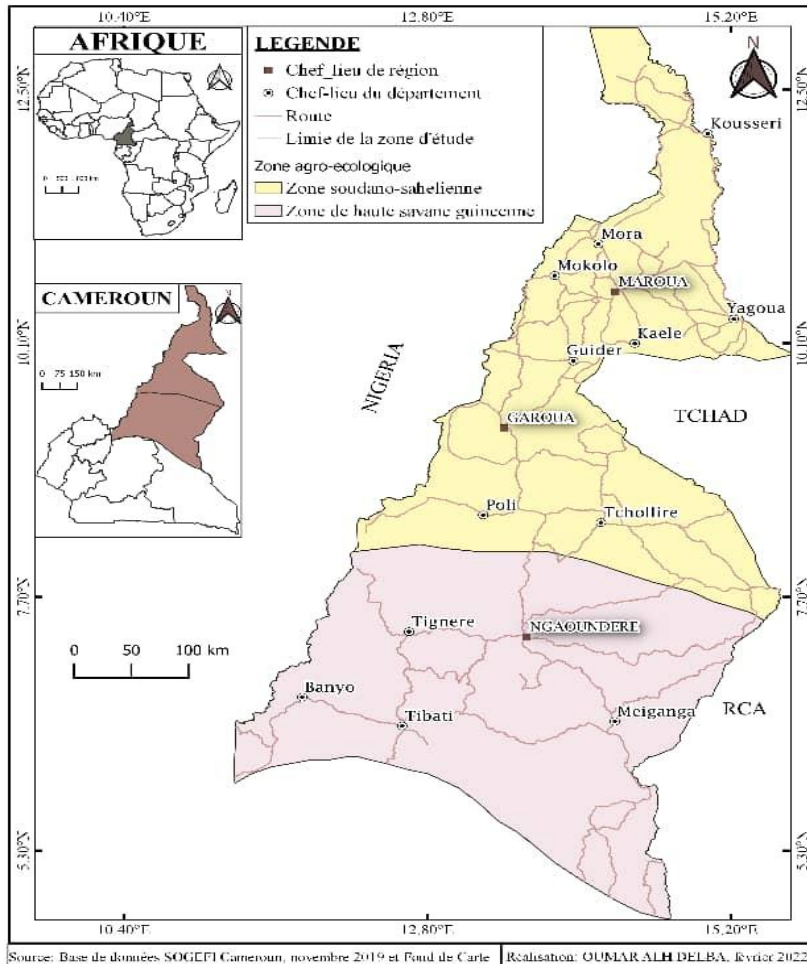
Figure 1: Location of the study site

2.2. Sampling and data collection

2.2.1. Selections of individuals

After having identified the *Moringa oleifera* trees and selected the healthiest (the least anthropized possible), the first step consisted in obtaining from the operators, an authorization to carry out research on their trees. A total of fourteen *M.oleifera* trees were cut in the two agro-ecological zones. A distribution of individuals into diameter at breast height (DBH) classes was carried out beforehand, by measuring the circumferences of selected trees in the field [40]. Four diameter classes have been selected: class I (]1;5]cm), class II (]5;9]cm), diameter class III (]9;13]cm) and diameter class IV (]13; 17]cm). Of the fourteen trees felled, seven were by zone.

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2.2.2. Data collection for the establishment of allometric models

The felling of trees is preceded by the measurement of their DBH. After determining their height after felling, each tree was separated into trunk, branches and leaves as well as small twigs, following the method described by Picard et al. [41]. The different trunk compartments, branches and leaves were weighed using a 50 kg capacity scale. The total wet weight of each compartment of the tree was determined in the field. Trunks, roots and large branches were cut into discs. A disc sample from the trunk, a branch and a leaf sample were taken and weighed. At the root level, after clearing the roots of mud, disc samples were taken at random. All these samples taken were immediately stored in plastic bags and brought back to the National school of agro-industrial sciences of the University of Ngaoundere physico-chemical analysis laboratory to determine their dry mass. In the laboratory, samples of leaves, trunks and branches were oven-dried at a constant temperature of 75°C to constant weight after 72 hours. The water content (WC) in the different compartments (leaves, branches, trunk) was determined after drying the samples according to the formula WC (%) = ((FM-DM)/DM)*100, with WC being the water content of the sample, FM and DM are respectively the fresh and dry mass (Kg) of the sample. From the water content of the samples, the total dry mass (TDM) of each compartment was calculated according to the French standard NF M 03-002 using the following formula: TDM = 100*TFM/(100+ WC), where TFM and TDM are respectively the total fresh mass and the total dry mass (kg) [42]. The total dry mass of each tree was estimated by adding the dry mass of the different compartments of the trees.

2.3. Data analysis

Allometric equations have been established between the physical parameters of the tree, namely diameter at breast height (DBH), height (H), and tree biomass (B) [43]. Prior to this step, since allometric relationships are influenced by growth stages [44], the relationship between tree height (H) and diameter (D) (H–D) was initially analyzed by plotting H (m) versus D (cm) to identify the diameter classes where the predictions are better. The models frequently found in the literature to predict biomass are of two types: the power model and the polynomial model [45]. In this study, the power model was used because it has long been noted that a growing plant maintains the proportion of weight between different parts [46,47] and because the polynomial model frequently exhibits abnormal behavior outside their range of validity. The mathematical model commonly used to predict the phytomass was adopted: $B = aD^b$ Where where a and b are the scaling or adjustment coefficients, D the DBH and B the aboveground biomass of a tree [44,48,49,50]. In this study, three allometric models [40] were evaluated to predict the aboveground biomass of *M.oleifera*:

$$B = aDb \qquad (1)$$

$$B = a\,(D^2H)^b \qquad (2)$$

$$B = aD^bH^c \qquad (3)$$

In order to eliminate the influence of the heteroscedasticity of the data, the transformation in logarithmic form is regularly used to change the nonlinear model into a linear model [51]. Therefore, (1), (2) and (3) have been converted to (4), (5) and (6) respectively as follows:

$$Ln(B) = a + b*ln\,(D) \qquad (4)$$

$$Ln(B) = a + b*ln\,(D^2H) \qquad (5)$$

$$Ln(B) = a + b*ln(D) + c*ln\,(H) \qquad (6)$$

For each of these models, the following indicators, making it possible to judge the good quality of the adjustment of the model, were used to select the best model:

- The adjusted R^2: This coefficient, between 0 and 1, gives an idea of the proportion of the explained variability of the aerial biomass by the model. The closer it is to 1, the better the model.

$$R^2 = \frac{1-SCR}{SCT}$$

Where SCT: Sum of Total Squares and SCR: Sum of Residual Squares.

- the residual standard error (RSE): square root of the residual variance around the regression function. The lower a model has a CSR, the better it is:

$$RSE = \text{Standard deviation }(\varepsilon i) \text{ where } \varepsilon i = ln\,(AGB\ obs) - ln\,(AGB\ pred)$$

Where i: Residual error; AGB obs: Measured above-ground biomass; Pred AGB: Predicted aboveground biomass.

- Akaike's Information Criterion (AIC): measurement of the goodness of fit of a regression model proposed by [52]. The best model minimizes the value of the AIC obtained by the following formula:

$$AIC = -2\,ln\,(L) + 2p \text{ with p the number of model parameters and L the maximized likelihood.}$$

The logarithmic transformation of the data generally leads to a bias in the estimate of the phytomass [28,53]. A correction is necessary and consists of multiplying the estimated phytomass by a correction factor (CF) which is calculated as follows: CF= exp {RSE²/2}; the CF is a number that is always greater than 1. The lower these criteria, in particular RSE and AIC, and the higher the adjusted R^2, the better the model will be [28].

All these statistical analyses were performed with Microsoft office Excel 2016, and the allometric equations developed in R Studio software.

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3. RESULTS
3.1. Relationship between diameter and height

The correlation established between the diameter and the height of the individuals in the two zones is significant (Fig. 2) with a coefficient of determination of 0.93 and 0.90 respectively for the High guinean savannahs (HGS) and the Sudano-Sahelian zone (SS). In the field of forestry, height-diameter relationships make it possible to best estimate the height of a tree knowing its diameter. Thus the allometric relationship of all the individuals measured fits better with the following equations:

(a) HGS: H= 0.316D + 2.250, R^2 = 0.90, n= 7 and P < 0.001;

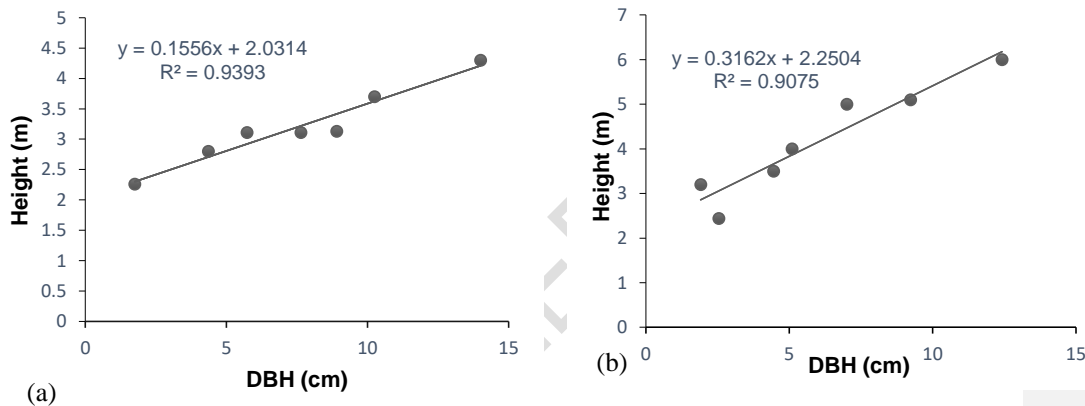(b) SS: H= 0.155D + 2.031, R^2=0.93, n=7 and P < 0.001.

Figure 2: Relationship between diameter and height

The diameter-height relationship is a good indicator of the ecological conditions for the growth of a species [54]. The equations obtained present coefficients of determination of the order of 93.93% and 90.75%. They make it possible to predict the height of a tree from the diameter. This distribution model shows that it is in the middle diameter classes: [5; 9[cm that it is appropriate to predict the total height of the individuals studied. The biases observed are lower for the lower diameter class (class I) than those of the upper diameter class (class III) on the distribution of the point cloud.

3.2. Development of allometric equations specific to *Moringa oleifera*

The various data from the allometric equations obtained by testing the three mathematical models for each zone (HGS and SS) zones, as well as a model grouping the data from the two zones (Global), are grouped in Tables 1, 2, 3, 4, 5 and 6 according to the different compartments. The variables a, b and c are the model adjustment coefficients, N

the number of samples, R²aj the adjusted coefficient of determination, CF the correction factor, RSE the residual standard error and AIC the Akaike information criterion.

3.2.1. Leaves

The constants regression of all the equations retained except those of the SS zone are statistically significant *(P < .05).* They range from *P = .31* to *P = .49* (SS), *P = .004* to *P = .01* (HGS) and *P = .01* to *P =.03* (Global). The presented prediction models explain about -6.5 to 15.5%, 79.8 to 82.5% and 32.2 to 36.5% of the variation in the biomass of SS zone leaves, HGSs and the northern zone (Global) respectively. Linear models with DBH as the sole predictor predicted leaf biomass of *M. oleifera* the least. The incorporation of height as a second variable in addition to DBH was necessary for a better estimation of leaf biomass (Table 1). Adding height in these models has improved the quality of the fit. This improvement is observed with the leaf models of the HGSs and of all of the two zones (AIC = 20.102; RSE = 0.784; Adj.R² = 0.825 and AIC = 53.116; RSE = 1.406; Adj.R² = 0.365).

Table 1: Allometric models of leaves

Zones	Allometrics models	a	b	c	R^2adjusted	RSE	N	CF	AIC	P
SS	$\ln(B)=a+b\ln(D)$	-2.799 (2.17)	0.815 (1.11)		0.083	1.868	7	5.724	32.259	0.49
	$\ln(B)=a+b\ln(D^2H)$	-3.151 (2.44)	0.384 (0.48)		-0.065	1.852	7	5.556	32.141	0.46
	$\ln(B)=a+b\ln(D)+c\ln(H)$	-13.061 (6.88)	-3.801 (3.13)	16.417 (10.56)	0.155	1.65	7	3.901	30.955	0.31
HGS	$\ln(B)=a+b\ln(D)$	-5.564 (0.88)	2.544 (0.51)		0.798	0.841	7	1.424	21.087	0.004
	$\ln(B)=a+b\ln(D^2H)$	-6.343 (0.95)	1.059 (0.19)		0.825	0.784	7	1.359	20.102	0.002
	$\ln(B)=a+b\ln(D)+c\ln(H)$	-7.610 (2.1)	1.289 (1.27)	2.243 (2.74)	0.804	0.828	7	1.408	21.319	0.01
Global	$\ln(B)=a+b\ln(D)$	-4.194 (1.26)	1.631 (0.60)		0.323	1.452	14	2.869	54.020	0.01
	$\ln(B)=a+b\ln(D^2H)$	-4.853 (1.25)	0.736 (0.25)		0.365	1.406	14	2.686	53.116	0.01
	$\ln(B)=a+b\ln(D)+c\ln(H)$	-6.069 (1.83)	0.841 (0.85)	2.562 (2.00)	0.356	1.416	14	2.725	54.084	0.03

Biomass (B), diameter at breast height (D), height (H), Coefficient of regression model (a, b and c), specimen number (N), coefficient of determination adjusted (R²adj), correction factor (CF), residual standard error (RSE) and Akaike information criteria (AIC).

3.2.2. Branches

The constants regression of all the equations retained are statistically significant *(P < .05)* except those of SS zone. They range from *P = .06* to *P = .16* (SS), *P = .003* to *P = .02* (HGS), *P < .001* (Global). The presented prediction models explain about 39-43.9%, 77.6-80.8% and 59.1-62.5% of the variation in branch biomass in the SS, HSG and Northern (Global) zones respectively. Linear models with DBH as the sole predictor were used to predict the biomass of the branches of the Global (AIC = 48.941; RSE = 1.211; Adj.R² = 0.623). For the SS zone and the HGSs, the incorporation of the height as a second variable in addition to the DBH in the form ln(B)=a+bln(D^2H) was necessary for a better estimation of the biomass of their branches (Table 2).

Table 2: Allometric branches models

Zones	Allometrics models	a	b	c	R^2adjusted	RSE	N	CF	AIC	P
SS	ln(B)=a+bln(D)	-1.685 (1.08)	1.282 (0.55)		0.420	0.93	7	1.541	22.498	0.06
	ln(B)=a+bln(D^2H)	-2.075 (1.20)	0.570 (0.23)		0.439	0.915	7	1.519	22.270	0.06
	ln(B)=a+bln(D)+cln(H)	-4.996 (3.98)	-0.206 (1.81)	5.296 (6.11)	0.390	0.954	7	1.576	23.294	0.16
HGS	ln(B)=a+bln(D)	-5.906 (1.16)	3.438 (0.66)		0.808	1.104	7	1.839	24.890	0.003
	ln(B)=a+bln(D^2H)	-6.909 (1.30)	1.420 (0.27)		0.819	1.071	7	1.774	24.469	0.003
	ln(B)=a+bln(D)+cln(H)	-7.356 (3.02)	2.550 (1.83)	2.084 (3.95)	0.776	1.193	7	2.037	26.420	0.02
Global	ln(B)=a+bln(D)	-3.996 (0.93)	2.406 (0.50)		0.623	1.211	14	2.081	48.941	0.000
	ln(B)=a+bln(D^2H)	-4.715 (1.08)	1.033 (0.21)		0.622	1.213	14	2.086	48.985	0.000
	ln(B)=a+bln(D)+cln(H)	-4.337 (1.63)	2.263 (0.76)	0.465 (1.78)	0.591	1.261	14	2/214	50.855	0.002

Biomass (B), diameter at breast height (D), height (H), Coefficient of regression model (a, b and c), specimen number (N), coefficient of determination adjusted (R²adj), correction factor (CF), residual standard error (RSE) and Akaike information criteria (AIC).

3.2.3. Trunks

For the trunk biomass estimation models, the constants regression of all the equations retained are statistically significant *(P < .05)*. They range from *P = .004* to *P = .01* (SS), *P < .001* to *P = .001* (HGS), *P < .001* (Global). The presented prediction models explain about 77.6-84%, 90.9-95.2% and 74.2-78.9% of the variation in the biomass of SS zone tree trunks, HGSs and northern zone (Global) respectively. For all these areas, the incorporation of the height as a second variable in addition to the DBH giving the form ln(B)=a+bln(D)+cln(H), was necessary for a better estimation of the biomass of their trunks (Table 3).

Table 3: Allometric trunk models

Zones	Allometrics models	a	b	c	R^2adjusted	RSE	N	CF	AIC	P
SS	ln(B)=a+bln(D)	-1.211 (0.52)	1.244 (0.26)		0.776	0.447	7	1.105	12.246	0.005
	ln(B)=a+bln(D^2H)	-1.582 (0.55)	0.55 (0.11)		0.799	0.423	7	1.093	11.471	0.004
	ln(B)=a+bln(D)+cln(H)	-3.832 (1.57)	0.065 (0.71)	4.192 (2.42)	0.840	0.378	7	1.074	10.333	0.011
HGS	ln(B)=a+bln(D)	-3.942 (0.44)	2.471 (0.25)		0.94	0.417	7	1.090	11.289	0.000
	ln(B)=a+bln(D^2H)	-4.574 (0.62)	1.002 (0.12)		0.909	0.511	7	1.139	14.135	0.000
	ln(B)=a+bln(D)+cln(H)	-2.641 (0.94)	3.270 (0.57)	-1.871 (1.23)	0.952	0.372	7	1.071	10.102	0.001
Global	ln(B)=a+bln(D)	-2.769 (0.50)	1.929 (0.27)		0.788	0.656	14	1.240	31.782	0.000
	ln(B)=a+bln(D^2H)	-3.244 (0.64)	0.807 (0.13)		0.742	0.723	14	1.298	34.526	0.000
	ln(B)=a+bln(D)+cln(H)	-2.068 (0.84)	2.224 (0.39)	-0.958 (0.92)	0.789	0.654	14	1.238	31.486	0.000

Biomass (B), diameter at breast height (D), height (H), Coefficient of regression model (a, b and c), specimen number (N), coefficient of determination adjusted (R²adj), correction factor (CF), residual standard error (RSE) and Akaike information criteria (AIC).

3.2.4. Above-ground biomass

The constants regression of the equations retained are statistically significant *(P < .05)*. They range from *P = .02* to *P = .04* (SS), *P < .001* (HGS and Global).The presented prediction models explain about 60.3-66.5%, 97.5-97.9% and 74-76% of the variation in the total biomass of the SS zone, the HGSs and the northern zone (Global) respectively. DBH as a single variable was found to be the best predictor of total biomass in HGSs and for the overall equation (Table 4). In this model, the values of RSE and AIC are the lowest (0.291

and 6.271; 0.77 and 36.512) as well as the strongest adjusted R^2 (0.979 and 0.760) compared to the two other models. As for the SS zone, the linear regression of this model expresses higher values of RSE and AIC (0.627 and 16.979) as well as a lower adjusted R^2 (0.603). This model is therefore the least suitable for predicting the total biomass of *M.oleifera* in the SS zone.

Table 4: Allometric models of above-ground biomass

Zones	Allometrics models	a	b	c	R^2adjusted	RSE	N	CF	AIC	P
SS	ln(B)=a+bln(D)	-0.453 (0.73)	1.189 (0.37)		0.603	0.627	7	1.217	16.979	0.02
	ln(B)=a+bln(D^2H)	-0.816 (0.80)	0.529 (0.15)		0.628	0.607	7	1.202	16.522	0.02
	ln(B)=a+bln(D)+cln(H)	-3.653 (2.40)	-0.250 (1.09)	5.119 (3.69)	0.665	0.576	7	1.180	16.230	0.04
HGS	ln(B)=a+bln(D)	-3.916 (0.30)	2.982 (0.17)		0.979	0.291	7	1.043	6.271	0.000
	ln(B)=a+bln(D^2H)	-4.750 (0.37)	1.224 (0.07)		0.977	0.304	7	1.047	6.876	0.000
	ln(B)=a+bln(D)+cln(H)	-4.223 (0.80)	2.794 (0.44)	0.441 (1.05)	0.975	0.319	7	1.052	7.973	0.000
Global	ln(B)=a+bln(D)	-2.340 (0.60)	2.117 (0.32)		0.760	0.777	14	1.352	36.512	0.000
	ln(B)=a+bln(D^2H)	-2.963 (0.70)	0.907 (0.14)		0.756	0.785	14	1.360	36.796	0.000
	ln(B)=a+bln(D)+cln(H)	-2.554 (1.04)	2.027 (0.48)	2.027 (1.14)	0.740	0.809	14	1.387	38.429	0.000

Biomass (B), diameter at breast height (D), height (H), Coefficient of regression model (a, b and c), specimen number (N), coefficient of determination adjusted (R²adj), correction factor (CF), residual standard error (RSE) and Akaike information criteria (AIC).

3.2.5. Belowground biomass

For the belowground biomass estimation models, the regression constants of all the equations retained are statistically significant *(P < .05)*. They range from *P < .001* to *P = .003.* The prediction models presented explain approximately 85.7 to 88% of the variation in belowground biomass. Belowground biomass using DBH as the sole variable performed better than that integrating height (adjusted R^2=0.880; RSE= 0.719; AIC=21.140) (Table 5).

Table 5: Allometric models of below-ground biomass

Allometric models	a	b	c	R^2ajusted	RSE	N	CF	AIC	P
ln(B)=a+bln(D)	-6.426 (0.47)	2.182 (0.30)		0.880	0.719	6	1.294	21.140	0.000
ln(B)=a+bln(D^2H)	-7.227 (0.58)	0.952 (0.13)		0.877	0.728	6	1.303	21.327	0.000
ln(B)=a+bln(D)+cln(H)	-6.709 (1.42)	2.090 (0.54)	0.329 (1.54)	0.857	0.784	6	1.359	23.068	0.003

Taking into account the criteria for assessing the precision and accuracy of the models developed, the best models of allometric equations according to compartments and zones, retained are summarized in table 6.

Table 6: Summary of the best allometric models

Compartments	Zones	Allometric models	a	b	c	R^2ajusted	RSE	N	CF	AIC	P
Leaves	SS	ln(B)=a+bln(D)+cln(H)	-13.061 (6.88)	-3.801 (3.13)	16.417 (10.56)	0.155	1.65	7	3.901	30.955	0.31
	HGS	ln(B)=a+bln(D^2H)	-6.343 (0.95)	1.059 (0.19)		0.825	0.784	7	1.359	20.102	0.002
	Global	ln(B)=a+bln(D^2H)	-4.853 (1.25)	0.736 (0.25)		0.365	1.406	14	2.686	53.116	0.013
Branches	SS	ln(B)=a+bln(D^2H)	-2.075 (1.20)	0.570 (0.23)		0.439	0.915	7	1.519	22.270	0.06
	HGS	ln(B)=a+bln(D^2H)	-6.909 (1.30)	1.420 (0.27)		0.819	1.071	7	1.774	24.469	0.003
	Global	ln(B)=a+bln(D)	-3.996 (0.93)	2.406 (0.50)		0.623	1.211	14	2.081	48.941	0.000

		Model	a	b	c	R²adj	CF	N	RSE	AIC	p
Trunks	**SS**	$\ln(B)=a+b\ln(D)+c\ln(H)$	-3.832 (1.57)	0.065 (0.71)	4.192 (2.42)	0.840	0.378	7	1.074	10.333	0.01
	HGS	$\ln(B)=a+b\ln(D)+c\ln(H)$	-2.641 (0.94)	3.270 (0.57)	1.871 (1.23)	0.952	0.372	7	1.071	10.102	0.001
	Global	$\ln(B)=a+b\ln(D)+c\ln(H)$	-2.068 (0.84)	2.224 (0.39)	-0.958 (0.92)	0.789	0.654	14	1.238	31.486	0.000
Aboveground biomass	**SS**	$\ln(B)=a+b\ln(D^{2}H)$	-3.633 (2.40)			0.628	0.607	7	0.529 (0.15)	16.522	0.02
	HGS	$\ln(B)=a+b\ln(D)$	-3.916 (0.30)	2.982 (0.17)		0.979	0.291	7	1.043	6.271	0.000
	Global	$\ln(B)=a+b\ln(D)$	-2.340 (0.60)	2.117 (0.32)		0.760	0.777	14	1.352	36.512	0.000
Belowground biomass	**Global**	$\ln(B)=a+b\ln(D)$	-6.426 (0.47)	2.182 (0.30)		0.880	0.719		1.294	21.140	0.000

Biomass (B), diameter at breast height (D), height (H), Coefficient of regression model (a, b and c), specimen number (N), coefficient of determination adjusted (R²adj), correction factor (CF), residual standard error (RSE) and Akaike information criteria (AIC).

4. Discussion

The significant and positive diameter-height relationship corroborates those reported by Mamadou [55] on 574 individuals of 8 species from the Ngaoundere savannas (R^2=0.5063) and by Halilou [56] on 96 individuals belonging to 16 species from the Ngaoundere savannas. (R^2=0.4956). The diameter-height relationship is also a good indicator of the ecological growth conditions of a species [54]. The choice of the mathematical model to adjust the parameters must be carefully considered in the estimation of the biomass of woody plants [57]. Leaf biomass, branch biomass, trunk biomass, total aboveground biomass (AGB) and belowground biomass (BGB) of individuals were calculated using the power model. This mathematical model has been widely used in the literature for predicting the standing biomass of woody species in Europe [48] and in Africa [45,57,58,59]. The allometric models developed vary from one compartment to another and even from one area to another. This variation would be linked to the variation in biomass observed between the different parts of the species Ganame et al. [57]. The sample size was small at 14 individuals. Indeed, the sample size in the development of allometric models is variable in the literature and takes into account the availability of resources (individuals) and the time allocated to the study Tchindebe et al. [60]. Some predictive allometric equations of biomass have been constructed from different numbers of individuals depending

Comment [k21]: Since author are using Site-specific allometric equations for the biomass prediction, what are the input variables and output variables? I would suggest, the author put them in the one sentence so that the reader may easily captured the variables that may influence the prediction result.
If necessary, put in the table.

Also, in this discussion section, the author could elaborate how the relationship between the input and output variable.

on the ecosystem: 26 trees in the forest zone of Benin by Guendehou et al. [61], 20 trees in the wooded savannah of the Sudanian zone of Senegal by Mbow et al. 2014 [62], 38 trees in the Sahelian zone in Senegal by Thiam et al. [63], 20 trees in the Sudano-Sahelian savannas of Cameroon by Tchindébé et al. [40]. However, this number of individuals is equal to that used by Manzo et al. [64] in *Faidherbia albida* agrosystems in Aguié, Niger.

Allometric models developed with diameter (D) as the only explanatory variable were the most effective in predicting branch biomass, aboveground biomass of individuals from High guinea savannas, global as well as belowground biomass. Numerous studies have shown that the DBH is the most commonly used explanatory variable for predicting the biomass of different compartments of woody species [24,45,65]. Indeed, DBH can be easily measured in the field with more precision than other dendrometric parameters. In addition, this variable is still available in inventory data Ganame et al [57]. However, linear models with DBH as the sole predictor predict leaf biomass the least in this study. The leaves are the most consumed component of *M.oleifera* [6,66,67]. This heavy use explains its abusive exploitation, making the individuals less and less healthy. Haoua et al. [68] showed that anthropogenic activities are major causes of the decrease in biomass of the most exploited parts of a woody. Ducta et al. [69] report the influence of sample quality on the models. In this case, it significantly influenced the establishment and choice of the leaf model. The incorporation of height as a second variable in addition to DBH was therefore necessary to improve the prediction of leaf biomass. The $\ln(B)=a+b\ln(D^2H)$ and $\ln(B)=a+b\ln(D)+c\ln(H)$ models better predict the biomass of other compartments and zones. Including height as a secondary variable contributes in some cases to the improvement of the model fit. Studies have reported that using DBH as a sole predictor of biomass underestimates [70] or overestimates tree biomass [71,72]. Other studies have recommended adding a second and/or third variable to the DBH to improve the accuracy of biomass estimation [73,74]. In addition, some authors like Picard et al. [41], Ngomanda et al. [75] and Sawadogo et al. [76] have found that the inclusion of tree height as an integrated or secondary independent variable can improve model performance with the advantage of increasing the applicability of the equations at larger scales. Although obtaining tree height in forest inventories is not an easy task [77], incorporating the height parameter is known to significantly improve tree biomass [78,79]. Biomass prediction models vary across different tree compartments. The results of this study are similar to those obtained by Djomo et al. [26], , Ganame et al. [57], Sawadogo et al. [76], Dimobe et al. [80] and Traore et al. [81] who all showed variation in the allometric equations depending on the parts of the tree. These models (except those of the trunk) for the same species, also vary according to the climatic zones.

5. Conclusion

This study established mono-specific allometric equations to predict the biomass of leaves, branches, trunks, roots, above-ground and below-ground biomass of *Moringa oleifera* in the Sudano-Sahelian zone as well as the High guinean savannahs of Cameroon. The three models opposite were tested: $\ln(B) = a + b*\ln(D)$, $\ln(B) = a + b*\ln(D^2H)$ and $\ln(B) = a + b*\ln(D) + c*\ln(H)$. Tree biomass allocation varies between compartments and sites of M. oleifera. Tree height did not influence the model estimating overall branch biomass, biomass, branch biomass of high guinean savannahs as well as overall above-ground and below-ground biomass. On the other hand, its incorporation as a second explanatory variable improved the prediction performance of the biomass of the other compartments in their respective zones. Thus, the best models for the prediction of aboveground biomass of *M. oleifera* are -3.653-0.250lnD+5.119lnH (Sudano-Sahelian), -3.916 + 2.982lnD (High guinean savannahs), -2.340 + 2.117lnD (Global) and finally for the roots -6.426 + 2.182lnD. The results of this study provide a reliable and rapid contribution to the assessment of the biomass and carbon stock of *M. oleifera* in agroforestry systems under the ecological conditions of Cameroon.

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