



Species – Specific Allometric Equations for Predicting Biomass of *Faidherbia albida* (Del.) A. Chev. In the Sudano-sahelian Savannahs of Far-North, Cameroon

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Authors' contributions

This work was carried out in collaboration among all authors. Author AT designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors Tchobsala and MLMA managed the analyses of the study. Authors HA and IA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

To contribute to the accurate assessment of carbon of agroforest species of Sudano-sahelian ecosystems, a study based on the establishment of mono-specific allometric equations were investigated in the arboreous parks of the Far-North Cameroon. A total of 20 individual trees of *Faidherbia albida* was harvested in savannah and distributed across a range of diameter classes,

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from 10 to 60 cm. The diameter at breast height of these individuals and their height were measured. After tree cutting, biomass of compartments of leave, branches and stem 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^2_{adj}), the residual standard error (RSE) and the Akaike Information Criteria were used for choosing the best models. The main results reveal that there is a positive and significant relationship between the height of the trees and their diameter ($R^2 = 0.75$, $n = 17$ and $P < 0.05$). The best model for the biomass prediction of all compartments of *F. albida* is in the form $\ln(B) = a + b * \ln(D^2H)$, with $\ln(B) = -1.42 + 0.58 * \ln(D^2H)$ for leaf biomass, $\ln(B) = -5.83 + 1.11 * \ln(D^2H)$ for the branch, $\ln(B) = -4.01 + 0.94 * \ln(D^2H)$ for the stem, and finally $\ln(B) = -2.83 + 0.91 * \ln(D^2H)$ for the total biomass. Their adjusted coefficient of determination is 0.71, 0.90, 0.93 and 0.93 respectively. The branch biomass represents about 42.16% of the total aerial biomass and is the highest relative to the other compartments. These equations bring a contribution to a reliable and quick assessment of carbon stock of arboreous parks to *F. albida* in the framework of study on climate change mitigation in Sudano-sahelian zone in particular and in the World in general.

Keywords: Allometric equation; biomass; *Faidherbia albida*; arboreous park; Far-North; Cameroon.

1. INTRODUCTION

F. albida is a species from the Mimosaceae family, feature of agroforestry systems of sahelian zone. Multifunctional tree with atypical phenology [1], it carries leaves in dry season and lost them in rainy season. *F. albida* is a species appreciated by rural population for its soil fertility and its use as firewood by farmers. In addition to its ecological and economic functions, it includes some social and cultural values in the Northern part of Cameroon. Source of fodder, young leaves constitute an important balance to the feeding of cattle and some wild fauna [2,3]. It also provides products used in the traditional pharmacopoeia [4].

In Cameroon, more particularly in the Sudano-sahelian zone, that species is in a regressive dynamic due to the cuttings of firewood, to the lack of good management by the owners of those lots of cultivation [5] and to the fraudulent cuttings by transhumant shepherds. This issue leads to a dangerous decreasing or even irreversible if no measure is taken, of the population of that agroforestry species and thereby compromising its dynamic and its sustainable management in those savannahs. However, because of its non-negligent socio-economic and environmental roles, the management of that plant species requires a good steady of its growth and of its carbon stocking. During the last decade, considerable efforts of research were carried out in the estimation of tree and shrub biomass in forest ecosystems [6,7,8] and slightly in savannahs [9,10,11] and very few in the dry savannahs of the Far-North Cameroon [12,13].

For the estimation of ligneous biomass, allometric equations are largely used for avoiding the destruction of agroforest ligneous, combining different dendrometric measures of the tree and its aerial biomass. These allometric relationships are very important for the management of natural and artificial forestry resources [14,15,16,17] because they provide the best assessments of the forestry ligneous biomass, that is also an important aspect in the seeking of carbon emissions [17,18]. Consequently, the choice of an appropriate model for the development of allometric equations is important in agroforestry and environmental sciences [18].

The logarithmic model is the most frequent in literature [19] with a general equation in the form $B = aD^b$ (often presented in the logarithmic form) where B is the biomass, D the diameter at breast height of the tree, a, the regression coefficient and b, the constancy of regression. In addition, there are diverse independent variables in the allometric relations for estimating the biomass of forest ligneous. In most study, D (DBH' stem diameter at 1.3 m height above the ground) is used as sole independent variable in the development of equations [20,21]. However, incorporation of other variables like the height of the tree (H) often ensures a great accuracy of the allometric equations for some plant species [22,23,24]. Various allometric equations were developed in savannahs from different tropical plant species [25,26], but those equations vary according to ligneous species by reason of their architectural form. That is why the development of specific allometric equations is essential for the accuracy of the biomass and the carbon

stock. The objective of this study is to develop mono-specific allometric equations enabling to estimate with more accuracy the aerial biomass of *F. albida* in the Sudano-sahelian savannahs of the Far-North, Cameroon.

2. MATERIALS AND METHODS

2.1 Study Area

This study was carried out in the Far-North Cameroon, which extends on an area of 34 263 km², with more than 3 480 414 inhabitants. It is located between the 10° and 13° longitude North and between the 13°15' and 15°45' latitude East [27,28]. This region is intermediate between the Sudanese zone and the sahelian zone, which coincide with the Sudano-sahelian zone. The climate is the dry Sudano-sahelian type, characterized by two distinct seasons. The rainy season only last four to five months (between June and October) and the dry season varies between November and May. The pluviometric gradient of the study area varies between 500 and 1000 mm [29]. The annual average temperature is about 28°C, with very important thermal fluctuations rate between the extreme values (7.7° annual average).

The soil of the Far North region is of two types: ferruginous and ferralitic, resulting from the intense leaching affecting that region [30].

In general, the vegetation of the Sudano-sahelian zone of the Far North is marked by three clearly distinct vegetal formations: the thorny steppes in the peneplains, the vast grasslands that cover the areas temporarily flooded or "yaere", and the woody savannahs and the dry clear forests in the zones of relatively high altitude [31].

Populations of the study area are in majority agro-shepherds but agriculture is the most important activity with more than ten ethnic groups [32]. Breeding is a lifestyle of some ethnic groups such as Mororos and Peulh living out of urban center and some Arabe-Schao groups. Fishing is represented by the Kotoko people along Logone river and in the yaérés during water subsidence, and often also by Arab Schoa and Bornouan. Still in the zones of spreading of the flood from Logone, Mousgoum and Massa also practice fishing [33].

2.2 Sampling and Data Collection

After the authorization n° 263/ASAA/DRFOF/AD/SRF of the regional

Delegate of the Ministry of Forestry of Wildlife (MINFOF), twenty (20) individual trees of *F. albida* with various diameter at breast height (DBH), and total height (H) were sampled in the parklands and naturel way of the dry savannah of Far-North Cameroon. Sample trees were selected purposively, avoiding suppressed or sick trees or those with broken tops, hollows, or other damages. These sampled individuals were distributed at the rate of four (4) individuals in the five diameter classes (in cm) defined from 10 to 60 cm. The trees were felled as close to ground level as possible and after felling, each tree was separated into trunk, branches and leaves including small twigs, based on the method described by Picard et al. [34]. To validate the best model selected for predicting above ground biomass, four individual tree samples were selected, felled and treated as above mentioned. The fresh biomass of each compartment weighed using a scale. To obtain the dry weight, three samples of each compartment and each tree were collected. In the laboratory, samples of stems; and branches were oven-dried at a constant temperature of 105°C and leaves at 75°C to a constant weight after 72 hours. The water content (WC) in the various compartments (leaves, branches, stems) was determined after drying of the samples using the formula by WC (%) = ((FM-DM)/DM)*100, with WC is the water content of the sample, FM and DM are respectively the fresh and dry mass (Kg) of the samples. From the water content of the samples, the total dry mass (TDM) of each compartment has been calculated using the following formula: TDM = 100*TFM/(100+WC), where TFM and TDM are respectively the total fresh and dry mass (Kg). The total dry mass of each tree was estimated by adding the dry mass of the various compartments of the trees.

2.3 Data Analysis

Allometric equations have been established between the physical parameters of the tree such as diameter (D) and height (H), and tree biomass [35]. The simple allometric equation was generally written using the power curve in the following formula [36]:

$$Y=aX^b$$

Where Y is the dependent variable and X is the independent variable, and a, the coefficient and b the allometric constant. To take into account the heteroscedasticity of data [7,37], the formula is often linearized by using the logarithms [36], as follows (2):

$$\ln(Y) = \ln(a) + b\ln(X)$$

Where $\ln(a)$ and b are the intercept and slope of the regression line, respectively. The $\ln(a)$ and b are obtained by the method of least squares. In this study, the allometric relationships of the biomass and different dimensions such as D , D^2 , D^3 and D^2H , were also established using following equations (1 to 4):

$$\ln(B) = a + b*\ln(D) \quad (1)$$

$$\ln(B) = a + b*\ln(D^2H) \quad (2)$$

$$\ln(B) = a + b*\ln(D) + c*\ln(H) \quad (3)$$

$$\ln(B) = a + b*\ln(D) + c*\ln(D^2) + d*\ln(D^3) \quad (4)$$

Where B is the biomass (kg), D and H are respectively the tree diameter (cm) and total height (m), a , b and c are the coefficient of regression. The logarithmic transformation of data generally leads a bias in the biomass estimation [15,38], a correction is therefore necessary and consisted to multiply the estimated biomass by a correction factor which was calculated as follows:

$CF = \exp(RSE^2/2)$ [37,39]; CF is the number always high to 1. Some criteria were used to select the best predictive model when calculated. In addition to the coefficient of determination adjusted (R^2aj) and the value of the statistic signification (P), the residual standard error (RSE) and the Akaike information criteria (AIC) were calculated. RSE represents the standard deviation between the observed value and its prediction. The Akaike information criterion is a measure of the quality of the model used for the set of data considered. It allows to compare several models and to make the selection of the best model. $AIC = -2\ln(L) + 2p$, where p is the number of parameters in the model and L the maximum likelihood. These criteria make possible to judge the goodness of the model's fit; more the last criteria are low, best will be the model [40]. Statistical analyses were performed with Excell 2016 and Ri 386 3.1.2 software.

3. RESULTS

3.1 Diameter, Height and Biomass Distributions

Tree diameter and height of *F. albida* varied from 11.94 to 56.20 cm and from 6.20 to 17.15 m, with average of 34.93 cm and 11.47 m respectively (Table 1). Total biomass ranged from 36.89 to 1898.65 kg with average of 481.42 kg. For the

compartments, the leaf biomass ranged from 18.00 to 273.65 kg, that of the branches from 6.92 to 1004.48 kg and that of the stems from 11.52 to 488.82 kg, with the respective averages of 79.38 kg, 202.97 kg and 199.05 kg. The branches accumulated more biomass than the other compartments with a rate of 42.16% of the total biomass, followed by that of stems (41.35%).

3.2 Relationships between Tree Height and DBH

Seventeen trees were used to determine the relationships between tree height and diameter at the breast height (Fig. 1). The linear regression has shown a positive and significant ($P < 0.05$) correlation between the two physical tree parameters of *F. albida*, with a coefficient of determination of 0.7559. Tree height increased linearly and positively with diameter.

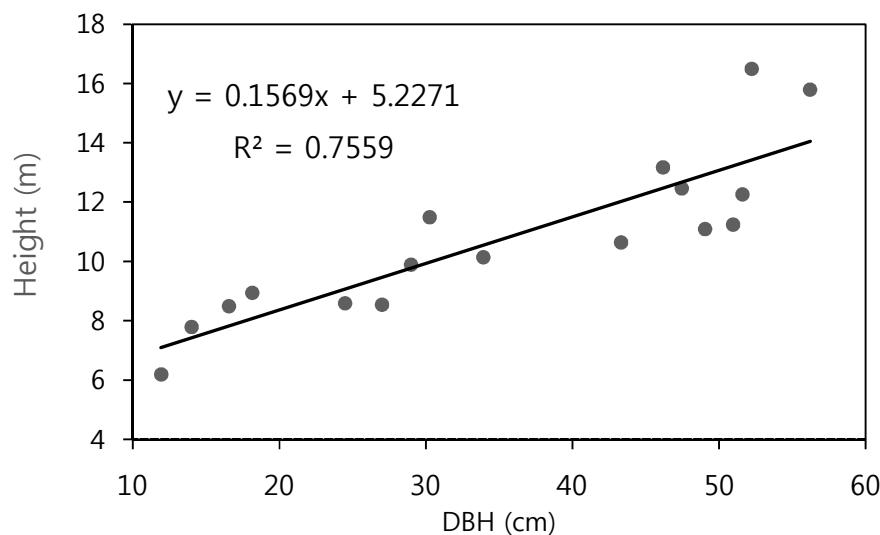
3.3 Development of Allometric Equations

Four models of allometric equation were developed for any compartment, with 20 individual trees. The allometric relationships of biomass of different compartments to diameter and height of *F. albida* were positive and significant ($P < 0.001$) with the high adjusted coefficient of determination ranged from 0.68 to 0.93 (Table 2). Regression coefficients (a , b and c) varied from -52.94 to -0.94, from 0.58 to 47.55 and from 0.45 to 15.27 respectively for a , b and c . These coefficients differed among compartments for the same model. The model taking into account only the diameter as the physical parameter of tree (Eq. 1) was significant ($p < 0.001$) for each of the four compartments of trees, with the coefficient of determination varying from 0.70 to 0.89. These high adjusted coefficients of determination showed that more than 70% of these relationships were explained by the single diameter.

By integrating the height of the tree in three models (Eq.2 to Eq4), no improvement was obtained in the precision with the model 4 [$\ln(B) = a + b*\ln(D) + c*\ln(D^2) + d*\ln(D^3)$] predicting the biomass of all compartments and total. Its adjusted coefficients of determination were lower and its residual standard error (RSE) was higher than those of model 1 (Eq. 1) taking into account only diameter. The standard error for all coefficients of regression (a , b , c and d) for all compartment biomass were higher than average value.

Table 1. Distribution of tree diameter and height and biomass of tree compartments and total

	Parameters		Biomass (Kg)			AGB
	DBH (cm)	H (m)	Stems	Branches	Leaves	
Minimum	11.94	6.20	11.52	6.92	18.00	36.89
Maximum	56.20	17.15	488.82	1004.84	273.65	1898.65
Average	34.93	11.47	199.05	202.97	79.38	481.42
Standard deviation	14.02	3.05	184.96	250.78	72.45	490.73

**Fig. 1. Relationships between tree height and DBH of *F. albida***

For the both other models (Eq.2 and Eq3), integrating the diameter squared multiplied by the height ($D^2 \cdot H$) or the height (H) in the fits of the forms $\ln(B) = a + b \cdot \ln(D^2 \cdot H)$ or $\ln(B) = a + b \cdot \ln(D) + c \cdot \ln(H)$ improved the model 1 (Eq.1). The adjusted coefficient of determination of these both models were higher (0.70 - 0.93) and their residual standard error (RSE) were lower (0.28 - 0.43) than the model taking into account only the diameter. However, despite the fact that the adjusted coefficients of determination of model 3 (Eq. 3) was similar to that of model 1 (Eq.1), its RSE was higher than that of model 1 and the standard error of its coefficient of regression (c) for leaf compartment was greater than the average value.

To select best model predicting the biomass of each compartment in addition to the coefficient of determination adjusted (R^2_{adj}), the residual standard error (RSE) and the Akaike value (AIC) which enable to evaluate the accuracy of the models have been taken into account. Thus, the allometric equation integrating square diameter multiplied by the height ($D^2 \cdot H$) was the best model for all tree compartments and was of the form $\ln(B) = a + b \cdot \ln(D^2 \cdot H)$. Its adjusted

coefficients of determination (R^2_{adj}) were higher, its RSE and AIC were lower than the values of all other models. These best equations were presented in the Table 3 and the Fig. 2. After selection of the best models, the hypothesis of the simple linear regression is conveniently respected. Exploration analysis revealed that the relationship between the biomass logarithm and the $D^2 \cdot H$ logarithm was linear, with a variance of $\ln(ABG)$ which is approximately constant. We can therefore adjust a simple linear regression for predicting $\ln(B)$ relative to $\ln(D^2 \cdot H)$ (Fig. 2).

3.4 Validation of the Best Allometric Model

The best allometric model established in this study was used to predict the above ground biomass. This model was of the form $\ln(ABG) = -2.83 + 0.91 \cdot \ln(D^2 \cdot H)$. The predicted biomass was compared to that measured on the field using linear regression (Fig. 3) and the correlation between the two biomasses was positive and highly significant ($p < 0.001$), with the coefficient of determination (R^2) of 0.96. The model overestimated the above ground biomass, but its total bias was low, about 26.13%.

Table 2. Parameters of fits between biomass (kg), DBH (cm) and height (m) of 20 individuals of *F. albida* in the sudano-sahelian savannahs of the Far-North Cameroon

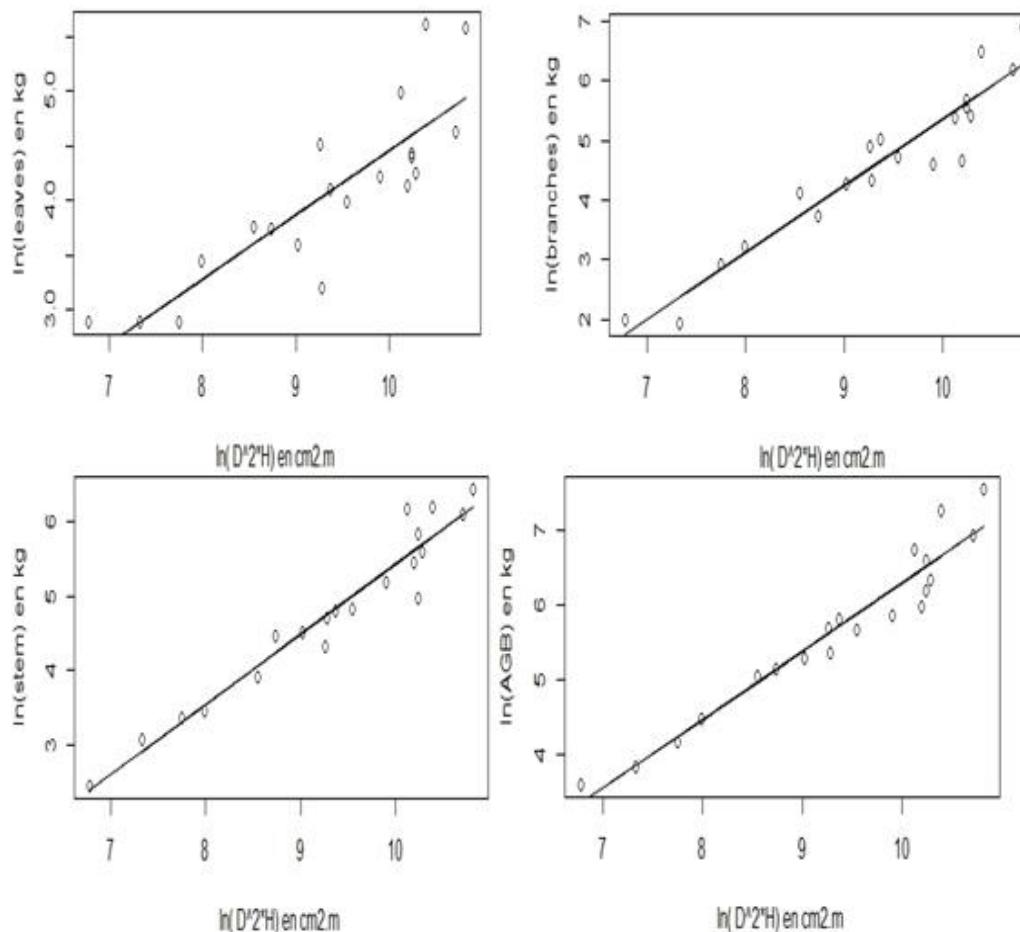
Allometric equations	a (se)	b (se)	c (se)	d (se)	R ² adj	AIC	RSE	CF
Leaf biomass								
1. ln(B) = a + bln(D)	-0.94(0.73)	1.44(0.21)	/	/	0.70	26.94	0.43	1.09
2. ln(B) = a + bln(D ² H)	-1.42 (0.78)	0.58(0.08)	/	/	0.71	26.28	0.42	1.09
3. ln(B) = a+ bln(D) + cln(H)	-1.34(0.89)	1.24(0.33)	0.45(0.57)		0.70	28.21	0.43	1.09
4. ln(B)=a+bln(D)+cln(D ²)+dln(D ³)	-6.78(48.91)	8.25(45.8)	-2.50(14.11)	0.29(1.43)	0.68	30.18	0.44	1.10
Branch biomass								
1. ln(B) = a + bln(D)	-4.83(0.80)	2.72(0.23)	/	/	0.88	3036	0.46	1.11
2. ln(B) = a + bln(D ² H)	-5.83(0.76)	1.11(0.08)	/	/	0.90	24.82	0.40	1.08
3. ln(B) = a+ bln(D) + cln(H)	-5.95(0.86)	2.14(0.32)	1.29(0.55)		0.90	26.70	0.41	1.08
4. ln(B)=a+bln(D)+cln(D ²)+dln(D ³)	-52.94(52.94)	47.55(49.57)	-13.72(15.27)	1.38(1.55)	0.87	33.34	0.48	1.12
Stem biomass								
1. ln(B) = a + bln(D)	-3.12 (0.63)	2.28(0.18)	/	/	0.89	20.63	0.36	1.06
2. ln(B) = a + bln(D ² H)	-4.01(0.54)	0.94(0.05)	/	/	0.93	11.11	0.28	1.03
3. ln(B) = a+ bln(D) + cln(H)	-4.26(0.59)	1.70(0.22)	1.31(0.38)		0.93	11.99	0.29	1.04
4. ln(B)=a+bln(D)+cln(D ²)+dln(D ³)	-15.58(42.46)	14.09(39.75)	-3.67(12.25)	0.37(1.24)	0.88	24.52	0.38	1.07
Above-ground biomass								
1. ln(B) = a + bln(D)	-2.01(0.59)	2.22(0.17)	/	/	0.89	18.31	0.34	1.05
2. ln(B) = a + bln(D ² H)	-2.83(0.53)	0.91(0.05)	/	/	0.93	10.50	0.28	1.03
3. ln(B) = a+ bln(D) + cln(H)	-2.97(0.59)	1.72(0.22)	1.11(0.38)		0.92	12.15	0.29	1.04
4. ln(B)=a+bln(D)+cln(D ²)+dln(D ³)	-19.72(39.6)	19.53(37.08)	-5.54(11.42)	0.58(1.15)	0.88	21.73	0.36	1.06

Tree diameter at breast height (D) and height (H). The coefficient of model equations (a, b, c and d) and standard errors in parenthesis (se). Adjusted coefficient of determination (R²adj.), Correction factor (CF), residual standard error (RSE), and Akaike information criteria (AIC)

Table 3. Selected best allometric models established between biomass (B), diameter (D) and height (H) for compartments and above ground biomasses

Compartments	Allometric equations	R ² adj.	AIC	RSE
Leaf biomass	$\ln(B) = -1.42 + 0.58 \ln(D^2H)$	0.71	26.28	0.42
Branch biomass	$\ln(B) = -5.83 + 1.11 \ln(D^2H)$	0.90	24.82	0.40
Stem biomass	$\ln(B) = -4.01 + 0.94 \ln(D^2H)$	0.93	11.11	0.28
Above ground biomass	$\ln(B) = -2.83 + 0.91 \ln(D^2H)$	0.93	10.50	0.28

B: biomass, D: diameter at breast height, H: tree height, AIC: Akaike information criteria; RSE: Residual Standard Error

**Fig. 2. Biomass (kg) - D²H (cm².m) relationships of *F. albida* for leaves, branches, stems and above ground biomass**

4. DISCUSSION

This study has enabled to establish allometric equations of predicting of the aerial biomass of *F. albida* in the diameter ranged from 10 to 60 cm. This species is proper to agrosystems of the Cameroon Sudano-sahelian zones because of its abundance relative to the others ligneous. At this species, the production of biomass varies

according to the compartment of these individuals and the study area. In fact, in our study, the branch biomass (202.97 kg) is the highest and represents 42.16% of the total biomass; the leaf biomass (79.38 kg) is the weakest and represents only 16.49% of the total biomass. Our results are similar to those of [41] and [42], who showed that the leafy production of *Acacia senegal* is weaker than the one of the

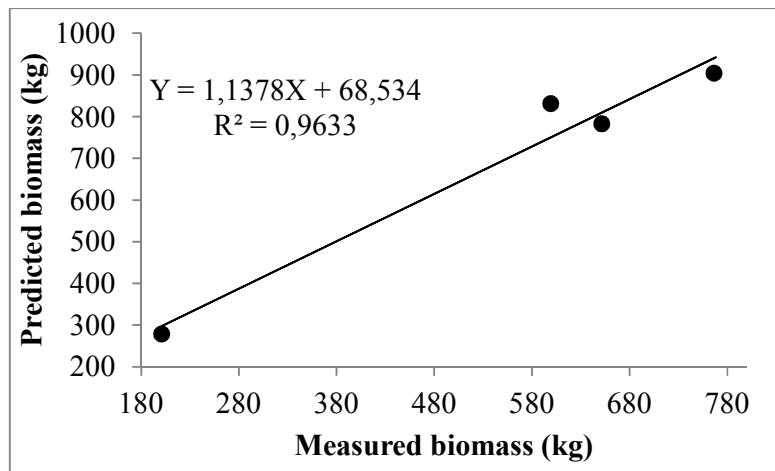


Fig. 3. Linear regression between measured and predicted biomasses

other compartments. In addition, for the branch biomass, our results are opposite to those of Hiernaux et al. [43] and of Thiam et al. [42], who discovered that the biomass of stems are higher than those of branches and leaves, according to their experiment realized on a sample of 44 individuals of *Acacia senegal* in Senegal. Differences in results can be attributed to internal features of population like their density, and to anthropogenic pressure as wood cuttings.

Determination of specific equations for that species is relevant for an accurate assessment of its production, the accurate estimation of the carbon stock and the sustainable management of its population. In fact, according to Bognounou, et al. [25], the specific allometric equations of prediction of the biomass is more precise than the global ones, multispecific of a woody population. According to Návar et al. [10], an equation for each species improves of about 12.5% the accuracy of the biomass assessment compare to a global equation of a community of ligneous. However, if there is no enough data to develop allometric equation for each species, we can establish mixed species allometric equation for estimating woody stands biomass [25]. For Cole and Ewel [44], the pooled species approach is a reasonable tool if the data base to which it's to be applied including a large number of species or takes important information for entire woody stands.

The number of sample and diameter range in the development of allometric models found in literature were variable and take into account the resources, site study and time allocated to the study [36]. In fact, Chave et al. [15] and Basuki et

al. [45] used more than 100 sample trees to establish allometric models. However Peltier et al. [46]; Larwanou et al. [47]; Ebuy et al. [48]; Tchindebe et al. [49] established their models with less than 20 sample trees. In our study, the sample trees (20 trees) used was low but acceptable according to fact that Laminou Manzo et al. [8] have developed the allometric models predicting the biomass of *F. albida*, with less than 15 sample trees.

The use of allometric equations presents a source of uncertainty in biomass estimation [50], which can be minimized through a process of selection and critical analysis of the parameters used [51]. Model accuracy and the inclusion of predictors are important considerations when selecting the best fit model [52]. In our study, we have included 20 individuals with diameter. And a model with DBH, and height (H) as identical predictors appeared as the best fits for all compartments compared to other models (Table 3). Their AIC and RSE values were lower and their coefficient of determination adjusted were higher. They have shown that the tree height influenced significantly the biomass as reported by Chave et al. [15], Sileshi [53]. These results were similar to those of Nelson et al. [54] and Chave et al. [40] who have shown that the best model for predicting tree biomass were the allometric models taking into account the D, and H as identical predictors. Contrary, these results differed from those of Bagnou & Kouyate [55] who have worked on savannah vegetation of Mali. As the total biomass, the best model of branch, and trunk biomass was the allometric equation which was not influenced by the height as found by Traore et al. [56]. Laminou Manzo [8]

has also found that the best allometric models predicting the biomass of *F. albida*, in Savannahs of Niger has taken account only DBH in the fits.

Selection of the best models of allometric equations is based on one or many criteria [7,57,58]. Indeed, Kuyah et al. [57] used only one Akaike criterion for estimating the tree biomass in Malia. On the contrary, Mbow et al. [58] formulated allometric equations whose choice was mainly based on the low value of the residual standard error (RSE). For each model they formulated, the RSE is less than 0.19. Fayolle et al. [53], selected instead models of rate of measurement combining the RSE to the AIC. The best model according to them is the one having the lower value of the AIC and of the RSE. In the framework of this study, all these criteria were taken into account for selecting the best model, and whatever the retained criterion, its values are better than those of the other models.

5. CONCLUSION

This study has enabled to establish the mono-allometric equations for the prediction of the biomass of leaves, branches, trunks and the total aerial biomass of *F. albida* in the Sudano-sahelian savannahs of the Far-North of Cameroon from data on 20 individual trees. It stands out that 42.16% of the total aerial biomass is concentrated in the branch compartment (202.97 kg) and the leaf biomass is the weakest (79.38 kg), with 16.50% of the total aerial biomass. The mathematical model in the forme $\ln(B) = a + b*\ln(D^2H)$ is the best for estimating the total aerial biomass of *F. albida*, with an overestimation of the biomass of about 26.13% in the study area. Results of this study bring a reliable and rapid contribution in the assessment of the biomass and carbon stock of *F. albida* in the agroforest parks and Sudano-sahelian zone of Cameroon.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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