Allometric models to estimate the aboveground biomass of tropical highlands savannahs trees.

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*Original article**Plant biology***Allometric models to estimate the aboveground biomass of tropical highlands savannahs trees****WOUOKOUE TAFFO Junior Baudoin, FONKOU Théophile, NGUETSOP Victor François***

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*Corresponding author E-mail address: vfngquetsop@yahoo.fr**ABSTRACT**

The development of tree allometric equations is crucial to accurate savannah carbon assessment. In Africa, the absence of multi-species allometric equations for savannah ecosystems has led to broad use of pan moist tropical equations developed for forest to estimate tree biomass. The aim of this study was to develop accurate multi-species allometric regressions for estimation of the aboveground biomass of trees in the Western Highlands savannahs of Cameroon. Data of aboveground woody biomass were obtained from destructive sampling of 103 trees belonging to 7 species across a range of diameter (5–38 cm). The dry aboveground biomass varied from 6.19 kg for the smallest tree to 669.45 kg for the largest tree. Proportional relationships between aboveground biomass and diameter breast height (DBH) are constructed derived from eight regression models (linear, growth, compound, exponential, quadratic, cubic, power and logarithmic). The best models were selected using coefficients of determination (R^2) and relative error. The best local multi-species models using only diameter as input variable were quadratic and cubic regressions with respectively R^2 of 0.914 and 0.917. The quadratic model overestimates the biomass with a bias of 0.04 % while the cubic model underestimates it with a 0.012 % bias. In this study, the two multi-species allometric equations developed for savannahs can be used to produce accurate estimates of biomass and carbon stocks from diameter measurement in forest inventory data.

Key words: Aboveground biomass, Allometric equations, DBH, Highlands, savannahs.

RÉSUMÉ

Le développement des équations allométriques des arbres est crucial pour une évaluation précise du carbone de la savane. En Afrique, l'absence des équations allométriques multi-espèces pour les écosystèmes de la savane a conduit à une large utilisation des équations pour estimer la biomasse des arbres des forêts tropicales humides. L'objectif de cette étude était de développer des régressions allométriques multi-espèces précises pour estimer la biomasse aérienne des arbres dans les savanes des Hautes Terres de l'Ouest Cameroun. Les données de la biomasse aérienne des ligneux ont été obtenues à partir des échantillons destructifs de 103 arbres appartenant à 7 espèces dans une gamme de diamètre (5–38 cm). La biomasse aérienne variait de 6,19 kg pour le plus petit arbre à 669,45 kg pour le plus grand arbre. Les relations proportionnelles entre la biomasse aérienne et le diamètre à hauteur de poitrine (DHP) ont été construites à partir de huit modèles de régression (linéaire, croissance, composé, exponentiel, quadratique, cubique, puissance et logarithmique). Les meilleurs modèles ont été sélectionnés en utilisant les coefficients de détermination (R^2) et l'erreur relative. Les meilleurs modèles locaux multi-espèces utilisant uniquement le diamètre comme variable d'entrée étaient des régressions quadratiques et cubiques avec respectivement un R^2 de 0,914 et 0,917. Le modèle quadratique surestime la biomasse avec un biais de 0,04 % alors que le modèle cubique la sous-estime avec un biais de 0,012 %. Dans cette étude, les deux équations allométriques multi-espèces développées pour les savanes peuvent être utilisées pour produire des estimations précises des stocks de biomasse et de carbone à partir de la mesure du diamètre des données d'inventaire forestier.

Mots clés : Biomasse aérienne, DHP, équations allométriques, savanes, Hautes Terres.

INTRODUCTION

Forest ecosystems exert a large influence on the global carbon cycle through the flux and storage of carbon in plant biomass and quantification of these carbon fluxes and stocks depends to a great degree on allometric models used to estimate aboveground tree biomass [1]. Total aboveground biomass is frequently estimated using allometric models, which express the tree biomass as a

function of easily measurable variables such as diameter at breast height, total height and/or wood density [2]. Although many techniques exist for estimating forest biomass at different spatial scales, they all ultimately rely on ground and destructive measurements of individual tree biomass [7]. One of the major sources of uncertainty in estimating the amount of biomass is the lack of reliable regression equations which can

convert accurately the parameters measured directly in the field into biomass. General and site specific allometric equations have been developed from biomass of mixed tropical species [1]; [8]; [9]; [14]; [4]; [11]; [13]; [10]. However, few allometric equations for biomass estimation have been developed specifically for African tropical savannahs. For biomass estimations in African savannahs, general allometric equations derived from data collected outside Africa are often used [1]; [9]. This pantropical model developed by [1] are largely consider as the best current approximation for the sites for which the local equations are not available. [1] showed that the predictive power of their total models differs between the sites; for some areas, the relative error could be less, whereas for others, it could be high. For this reason, the evaluation of the accuracy of these models with new data and in various geographical places is necessary. At the local scale, the simplest models are based only on the diameter at breast height of tree (DBH) which is the best common predictor of biomass in the allometric models because it is strongly correlated with biomass. In addition, DBH can be easily measured in the field and is always available in forest inventories data ([6]; [12]; [15]). When these models exist, they are the most practical options for the aboveground biomass (AGB) evaluation ([3]; [11]). Although the need is great, few allometric equations are available for the savannah formations. They are due to the highly variability of the trees height [4], anthropic disturbances (agriculture, overgrazing and firewood gathering) and changes of land use at the origin of greenhouse gas emissions. These reasons impose the development of methods in order to quantify, in a reliable way, stocks and carbon flow of savannahs. The aim of this study was to develop allometric models for estimating total aboveground biomass from diameter at breast height for woody savannah species.

MATERIALS AND METHODS

Study area

The study was carried out in mounts Bambouto and mount Mbapit located in the Western Highlands of Cameroon between latitude 4°54' - 6°36' North and longitude 9°18' - 11°24' East (Figure 1). The Western Highlands of Cameroon cover a surface area of 31 192 km². The climate is of tropical soudanian type with two main seasons, the rainy season that last from Mid-March to Mid-

November and the dry season from November to March. Nevertheless, this general pattern can be modified according to the altitude of the site. Altitude varies from 1100 to 2400 m above sea level entailing mean annual rainfall variation from 1500 to 2600 mm in highest altitudes and 3 to 4-months (November/December–March) dry season. The annual average temperature is around 20 °C. The predominant soils are the andosols, ferralitic soils and ferruginous soils. The vegetation is dominated by *Pennisetum purpureum* and *Imperata cylindrica* and ligneous cover is strongly influenced by the anthropogenic activities (agricultural and pasture) ([23];[24]).

Figure 1. Localization of study site in the West region of Cameroon

Destructive sampling and biomass data

A total of 103 samples trees with DBH ≥ 5 cm belonging to species *Terminalia glaucescens* Planch. ex Benth (17 individuals), *Vitellaria paradoxa* C.F.Gaertn (20 individuals), *Ficus vallis-choudae* Delile (16 individuals), *Entada africana* Guill. & Perr. (17 individuals), *Cussonia arborea* Hochst.ex A. Rich (17 individuals), *Adenocarpus mannii* (Hook. f.) Hook.F (13 individuals) and *Erica mannii* (Hook.F) Beentje (3 individuals) were harvested for biomass estimation and allometric equation parameterization of the study area. The samples were collected from June to October 2015. Tree species selection was based on their distribution in the different diameter classes and their abundance. We excluded trees with DBH < 5 cm because such trees hold a small fraction of AGB in woodlands and would otherwise dominate the signal in regression models. The common practice for measuring DBH (diameter at

breast height) is to measure trunk diameter at 130 cm aboveground. Each tree was felled at ground level and separated into bole, branches and leaves. For trees with multiple stems, the bole biomass of one single stem was considered as the sum of weights of each stem of this tree. Each section was weighed in the field using a steelyard of 100 kg capacity. A sample of 2-cm thick disk was cut from the base of each stem section and oven-dried at 105°C until constant weight. Moisture content of the sample was subsequently evaluated. The dry mass was measured with an electronic balance (precision=1 g) in the laboratory and was used to estimate the moisture content. The biomass of each bole section was calculated by multiplying the wet mass of each component by the dry/wet ratio of each sample. The total biomass of a tree was calculated by summing the dry mass of the stems, branches and leaves.

Data analysis and modelling

Allometric model construction was based on regressing a dependent variable (AGB), against independent variable (DBH). We fitted the following model relating AGB to the compound variable using SPSS 20 software: Linear: $Y = a + bX$; Logarithmic: $Y = a + \ln(X)$; Quadratic: $Y = a + bX + cX^2$; Cubic: $Y = a + bX + cX^2 + dX^3$; Compound: $Y = abX$; Power: $Y = aX^b$; Growth: $Y = \exp(a + bX)$; Exponential: $Y = a e(bX)$ and Polynomial: $Y = a + bX + cX^2 + dX^3 + \dots + ax_n + p$ with X being the DBH and Y being aboveground biomass. Before establishing the allometric equation, scatter plots were used to see whether the relationship between independent and dependent variables was linear (Figure 2).

Evaluation of the quality of allometric selected models

To select the best statistical model, we used the coefficient of determination (R^2). Besides goodness of fit measures, we evaluate a posteriori the performance of the regression model by measuring the deviation of the predicted versus measured total AGB of study site and was expressed as a relative error as outlined by [1]. Error = 100 (AGB predict – AGB measured)/AGB measured. The comparison of the means was done by statistical tests of ANOVA and permit to check the distribution around the slope of the regression.

RESULTS

Chemical analysis

Models of allometric equations developed

Diameter at breast height varies from 5.3 cm to 37.04 cm. Total dry aboveground biomass for study site was 6585.01 kg and varied between 6.19 kg for the smallest tree and 669.45 kg for the largest tree. The correlation test between the biomass and DBH is done through the analysis of the distribution of the scatter dots of these two parameters. Figure 2 shows the distribution of dry biomass as function of diameter and shows that the increase in the diameter of trees did not take the same pattern as that of the corresponding biomass. The variation of biomass increases slowly as function of diameter classes until a certain diameter of trunk (≈ 21 cm), then increases very quickly afterwards, although the number of samples in this section is relatively low. The variation of these two parameters shows that we do not have a linear relation between the DBH and biomass. This figure shows thus that the greatest risks of bias are located at the level of trees with large diameter (> 21 cm). We can observe on the cloud of dots a greater dispersion of biomass values of large trees that express a certain irregularity in the relation between the later and DBH. This shows that we can obtain a good prediction of biomass for trees with small diameters (< 21 cm) which are dominant in the savannah ecosystems.

Figure 2. Cloud of dot of the total dry biomass (kg) as function of the diameter at breast height (cm) for 103 trees.

Multi-specific allometric equations developed

Eight multi-species allometric models related to highlands savannahs were tested with only diameter at breast height (Table 1). The models

showed very different coefficients of determination (R^2), explaining the differences of models in adjusting of raw data. Thus, to better approximate the biomass from the DBH, the regressions with highest adjusted R^2 (> 0.9) were retained. Models

with highest R^2 led to very weak residues. The table 1 shows the results of the adjustment of several allometric models, the quadratic and cubic models respectively have the greatest value of R^2 (0.914 and 0.917 respectively).

Table 1. Models description based on diameter at breast height for the estimation of total aboveground biomass of highlands savannahs

Model	Regression formula (y=)	Error (%)	R^2	Adj R^2	SEE
Linear	$13.944 \times \text{DBH} - 128.292$	0.002	0.679	0.676	56.504
Exponential	$4.124 e^{(0.156 \times \text{DBH})}$	2.16	0.808	0.806	0.448
Growth	$\exp(1.417 + 0.156 \times \text{DBH})$	2.18	0.808	0.806	0.448
Compound	$4.124 \times 1.169^{\text{DBH}}$	2.515	0.808	0.806	0.448
Power	$0.131 \times \text{DBH}^{2.205}$	-17.06	0.784	0.782	0.476
Cubic	$37.501 - 5.284 \text{ DBH} + 0.234 \text{ DBH}^2 + 0.011 \text{ DBH}^3$	-0.012	0.917	0.914	29.09
Quadratic	$93.403 - 16.652 \text{ DBH} + 0.893 \text{ DBH}^2$	0.04	0.914	0.912	29.439
Logarithmic	$-360.289 + 166.994 \ln(\text{DBH})$	-0.048	0.473	0.468	72.363

Y – aboveground biomass, DBH – diameter at breast height, SEE – standard error of estimate, Adj R^2 – adjusted value of the coefficient of determination

These adjusted models explain more than 90% of variability in the biomass. These coefficients of determination indicate a strong relation between the biomass and DBH.

Using only diameter in the allometric equation predicted total aboveground biomass of the savannah with more accuracy and better goodness of fit of data (Figure 3 and 4).

Figure 3. Relationship between aboveground biomass (AGB) and tree diameter (D). Each dot corresponds to an individually weighed tree. Black line corresponds to the curve of predictions of biomass by cubic regression models.

Figure 4. Relationship between aboveground biomass (AGB) and tree diameter (D). Each dot corresponds to an individually weighed tree. Black line corresponds to the curve of predictions of biomass by quadratic regression models.

Accuracy of biomass estimation

A very strong allometric relationship between aboveground biomass and diameter at breast height for the compiled trees was obtained. Such relationship implied that the variability of aboveground biomass could be highly explained by the variability of diameter at breast height at a global scale since the datasets originate from Highlands savannas and for species belonging to different genera and families. To test the

consistency of fits, we compared the values directly measured in the field through destructive methods for all trees (103) with estimations of our models. The result confirms simple model (cubic and quadratic) to be of the best estimating aboveground biomass from DBH in the study site. These two models have indeed shown low relative errors and high coefficients of determination; respectively 0.012 % and adjusted $R^2 > 0.914$ for cubic and 0.04 % bias, adjusted $R^2 > 0.912$ for quadratic regression. The analysis of average errors (Table 1) shows that the quadratic and cubic equations are the best estimator. For allometric equations, the errors in the estimates of aboveground biomass from tree diameter were well distributed across the whole range of diameter. The pattern of the graph (Figure 5) is typical of a variance increases with increasing of trees diameter. The calculated value of F is greater than the critical value of F, the main hypothesis is rejected and the risk of error is known. The results of the ANOVA statistical tests show that the best models are quadratic and cubic with low F values, reflecting the small differences between the values predicted by these models and the observed data in the field.

Figure 5. Relationships between the relative error in the estimation of aboveground biomass and tree diameter at breast height. Each dot corresponds to the error made on an individually weighed tree.

Comparison between quadratic and cubic regressions

We observed that for the smallest diameters (5-9 cm) the best models tend to overestimate trees aboveground biomass. For the average diameters (9-33 cm) the models underestimate the trees

aboveground biomass slightly and for the high diameters greater than 33 cm, they overestimate the trees aboveground biomass (Figure 6).

Figure 6. Difference in the best regression models in diameter classes. Each dot corresponds to an individually weighed tree. Red and green lines correspond to quadratic and cubic allometric models respectively.

- 1 quadratic and cubic models overestimate trees biomass for diameters less than 9 cm
- 2 quadratic and cubic models underestimate trees biomass for diameters in between 9 - 33 cm
- 3 quadratic and cubic models overestimate trees biomass for diameters greater than 33 cm

DISCUSSION

Concerning the relative contribution of the trees size, it was noted that the small diameter trees can give a significant cover rate, but their impact on the total biomass is less significant than the large trees. However, the presence of young trees implies an active dynamic of sequestration and high potential of growth whereas the old trees reached their limit of growth thus have a low capacity of carbon sequestration. The consequence of low productivity of the savanna ecosystems is the relatively weak sequestration of carbon compared to the tropical forest ecosystems, however they require a careful estimation of carbon for the potential advantages of clean development mechanism projects. Several equations have been published relating tree biomass to diameter or diameter coupled with height. Almost all of these relationships, whether intended for application to particular species, mixed-composition forests, specific sites,

biogeographical regions, or climate-related biomes, are based on allometric equations [22]. The study of [21] with 132 trees in Central Amazon showed that simple model with only diameter as input is a good estimator which estimates biomass of mixed-species only with an average error of 19.8 %. Using only diameter as input variable, the mixed-species regression model (cubic, and quadratic) provided a satisfactory estimation of biomass with an average error of only 0.012 and 0.04 % respectively. The test of mixed-species allometric equations shows that variation in aboveground biomass was explained at more than 90 % just only by diameter for best models. These results indicate that DBH is a strong indicator of aboveground biomass, which implies that the variability of trees biomass in the savannah ecosystems is largely explained by the variability of DBH. The apparently small differences in the equations for small trees could add up to a large amount of carbon when looking at a landscape; this is an example of bias problem. In this study, the mixed-species allometric equations using diameter at breast height predicted total aboveground biomass of the stand with more accuracy and better goodness of data fit. Similar to our findings, [4] indicated in the allometric equations related to the tree species of sudanian and sudano-guinean savannahs of Senegal that, the variation in biomass was explained by diameter at breast height. Diameter at breast height is the common and best predictor for biomass in allometric models because it is strongly correlated with biomass; in addition, DBH can be easily measured in the field and is always available in forest inventories data ([5]; [20]). These results agree with previous reports ([3]; [6]; [9]) that diameter alone is a good predictor of biomass especially in terms of the multiple trade-offs between accuracy, cost and practicability of measurements. The value of model constants varies with species, stand age, site quality, climatic conditions and stocking of stands constraints in the aboveground biomass variation. In the presence of complex environmental gradients, allometric equations can provide additional information to improve the knowledge of biomass distribution ([1]; [18]). [19] reported that, the variation in environmental factors such as topography and edaphic characteristics (e.g. soil nutrient availability) may complicate attempts to generalize aboveground biomass on a regional or landscape scale.

On the mathematical logic plan, the quadratic model is a very simple function compared with the cubic model, but the later express better the logic of tree growth. Indeed, the trunk of a tree increases in volume and follows a cubic logic. This logic is related to a growth of cylinder surface of the bole but also a vertical growth explaining cubic logic. Both models are the most adapted due to the fact that they present less bias for the large diameters and predict well the small diameters. It has, however, been shown that allometric models that focus on large trees tend overestimate biomass for small trees ([16]; [17]).

CONCLUSION

The present study showed that the multi-species regression equations developed for the Western Highlands savannahs provide good estimates of total aboveground biomass of when using only diameter as input variable. They can be used to improve estimations of total aboveground biomass from diameter measurements in vegetation inventory data. These findings are especially timely given the urgent need to quantify biomass and carbon stocks in the tropics. The best allometric equations to quantify the aboveground biomass of the savannah from the diameter at breast height are the cubic and quadratic regressions. These models explained more than 90 % of the variability of the total aboveground biomass. Regression models should not be used beyond their range of validity. The models proposed here are valid in the range 5-38 cm for diameter and the resulting AGB estimated from the equation is then in kilograms. These will improve the quality of tropical biomass estimates and bring consensus regarding the contribution of the savannah to the global carbon cycle.

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