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Research article

Aboveground biomass allocation, additive biomass and carbon sequestration models for *Pterocarpus erinaceus* Poir. in Burkina Faso

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A B S T R A C T

Efforts to develop allometric models for accurate estimation of biomass and carbon sequestration in Sub-Saharan African savanna ecosystems remain inconclusive. Most available allometric models are not site-specific, and hence do not account for the effects of regional climate variabilities on tree growth and capacity to sequester carbon. In contrast, site-specific biomass allometric models constitute a robust tool for forest and carbon emission management in the context of the reducing emissions from deforestation and degradation program (REDD+). Although site-specific models have been developed for several tropical tree species, such models do not exist for *Pterocarpus erinaceus* in Burkina Faso. In this study, we investigated biomass fraction patterns and used a system of additive allometric models for predicting aboveground biomass and carbon stocks of *P. erinaceus* components. Thirty *P. erinaceus* trees were destructively sampled to estimate the biomass of their stems, branches and leaves. The biomass fraction of each component was assessed and its relationship with tree diameter at breast height (dbh) examined. The best allometric equations of the tree components, selected from three non-linear models with dbh, height (ht) and crown diameter (C_d) as predictors, were combined to develop an additive allometric model, using the Seemingly Unrelated Regressions (SUR) method. The Ash method was then used to estimate the carbon content of the different components. Leaf and stem biomass fractions decreased when the dbh increased, whereas a reverse trend was observed for branch biomass. Dbh was the most correlated independent variable with all biomass components. $AGB = e^{-3.46}(dbh)^{1.62} + e^{-2.45}(dbh)^{2.31} + e^{-2.68}(dbh)$ was the most appropriate additive allometric equation for estimating the biomass of *P. erinaceus* trees. The carbon content of the leaves, branches and stems was 55.73%, 56.68% and 56.23%, respectively. The developed allometric equations can be used to accurately estimate the aboveground biomass of *P. erinaceus* in the savannas of Burkina Faso and other similar ecosystems in Sub-Saharan Africa.

1. Introduction

Following a dramatic increase in atmospheric carbon, average temperatures across the globe have increased leading high frequencies of droughts worldwide. Furthermore, various anthropogenic activities such as conversions of forests into arable lands and the expansion of high level of CO_2 have considerably reduced carbon uptake by trees and exacerbated atmospheric CO_2 concentrations (IPCC, 2007; Traoré et al., 2018). Development of efficient land use management plans that will enhance carbon sequestration and reduce CO_2 emissions are therefore urgently

needed. Developing such plans requires data on forest biomass and carbon stocks (Green et al., 2007). Consequently, scientists and government agencies are increasingly interested in collecting data on the potential for carbon sequestration by trees (nullI).

Tree biomass including stems, branches, leaves and roots constitute an important sink for atmospheric carbon (Sanquetta et al., 2015; Xue et al., 2016). Because atmospheric CO_2 is transformed into solid carbon within the leaves of trees through the process of photosynthesis, the abundance of aboveground biomass of a tree is an indication of the tree's capacity to efficiently store atmospheric carbon (Litton and Boone

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Kauffman, 2008; Dimobe et al., 2018a). Thus, several studies have focused on estimation of aboveground biomass of forests at the expense of belowground biomass (Bayen et al., 2015; Mensah et al., 2017; Djomo and Chimi, 2017; Dimobe et al., 2018a,b). Tree biomass can be estimated using both direct and indirect methods, and the most common and accurate method is the direct method known as destructive sampling (Fayolle et al., 2013; Jara et al., 2015).

The use of accurate allometric equations is required for an efficient estimation of tree biomass (Preece et al., 2012). Although the availability of destructive sampling data is necessary for developing suitable allometric equations (Djomo and Chimi, 2017), a lack of precise and robust equations hinders biomass estimation of Sub-Saharan African forests (Henry et al., 2011). The existing equations are limited to moist forests (Fayolle et al., 2013; Djomo and Chimi, 2017). According to Djomo and Chimi (2017), the lack of adequate allometric equations for estimating the biomass of African forest ecosystems has led to the misuse of the pan-tropical equation developed by Chave et al. (2014). Furthermore, the accuracy of biomass allometric equations is related to site conditions and species-specific characteristics (Ngomanda et al., 2014; Djomo et al., 2016). In recent years, there have been efforts to develop biomass allometric equations for African dryland species (Sawadogo et al., 2010; Massaoudou and Larwanou, 2018). Most of these studies developed separate allometric equations for tree components and total tree biomass. However, the inherent correlations among the biomass of the tree components have not been considered. Not considering the additive principle of the tree components has led to low-accuracy estimations of tree biomass of tree biomass (Bi et al., 2004). As a result, aboveground biomass predictions based on the total tree biomass model and the sum of the tree components model are not the same. Therefore, accounting for the additivity properties among tree components is necessary to improve statistical efficiency and ensure that the sum of tree biomass predictions based on the components biomass and the total biomass are the same (Paressol, 1999). Various model specifications such as the non-linear Seemingly Unrelated Regression (SUR) method have been widely used to achieve the additivity of tree biomass equations. The SUR method is commonly used because it creates a compatibility between the predictions of the biomass of tree components and total tree biomass, thereby improving the consistency of allometric equations' coefficients (Sanquetta et al., 2015).

In Burkina Faso, among the numerous studies conducted to develop biomass equations for tree species of high socio-economic value (Bognounou et al., 2013; Bayen et al., 2015; Dimobe et al., 2018a, 2018b), there is no species-specific equation for *Pterocarpus erinaceus*. This is despite *P. erinaceus* being a highly valued species throughout the Sudanian savanna and forest ecosystems. Earlier studies (Rabiou et al., 2015; Segla et al., 2015) reported the importance of the species for climate regulation due to its ability to efficiently uptake atmospheric carbon. Because of its high timber quality, *P. erinaceus* is overexploited in Burkina Faso (Traoré et al., 2011). Moreover, the species' branches are a major source of nitrogen for cattle in the dry season (Ouédraogo-Koné et al., 2008). Overexploitation of the species, especially for its timber, could lead to a population decline and associated loss of ecosystem services such as carbon sequestration. A sustainable management plan for *P. erinaceus* is therefore necessary for the long-term conservation of this economically- and environmentally-important tree species. In this context, assessing the carbon sequestration capacity of *P. erinaceus* will be a useful approach to motivate local communities and decision-makers to better conserve the species. This requires allometric equations that can be used to accurately assess the species' aboveground biomass (Alvarez et al., 2012).

In this study, we developed new allometric equations for predicting the biomass of *P. erinaceus* tree components and the species' total aboveground biomass (TAGB). Specifically, the study aims to:

(i) analyze the variation in biomass fractions of tree components of *P. erinaceus* according to diameter at breast height (dbh);

(ii) develop a system of additive allometric models for predicting the aboveground biomass of *P. erinaceus*; and

(iii) assess the carbon content in *P. erinaceus* tree components.

Many studies (Sanon et al., 2007; Bondé et al., 2017) have shown that the best explanatory variables for estimating tree biomass are closely linked to tree architecture (i.e. large tree, shrub and small tree). Because *P. erinaceus* is a large tree, we assumed that its dbh would be the most appropriate variable to predict the species' biomass. We hypothesized that:

(1) the biomass fraction increases with increasing dbh of *P. erinaceus*;

(2) dbh is the best predictor of the biomass of the different components of *P. erinaceus*; and

(3) the carbon content of each component of *P. erinaceus* is greater than 50%.

2. Materials and methods

2.1. Study area

The study was carried out in the Boulon-Koflandé Classified Forest (BKCF) in Burkina Faso. Located between latitudes 10°6' -10°9′ N and longitudes 4°12' - 4°36' W, with an area of 42 000 ha, BKCF is in the southern sudanian phytogeographical sector (Figure 1). The climate is characterized by a unimodal rainy regime with an annual rainfall ranging from 750 to 1300 mm. The mean annual rainfall for the last 30 years is 1033 mm and the mean monthly temperature is 28.9 °C. The main vegetation type is shrub and tree savannas. The herbaceous layer is dominated by *Andropogon gayanus*, *A. ascinodis*, *A. psceudapricus* and *Bracharia jubata*. The common woody species are mainly *P. erinaceus*, *Isoberlinia doka*, *Anogeissus leiocarpa*, *Burkea africana*, *Afzelia africana*, *Monotes kerstingii*, *Daniellia oliveri*, *Diospyros mespiliformis* and *Crossopteryx febrifuga*.

2.2. Species description

P. erinaceus Poir. is a multi-purpose tree that belongs to the Fabaceae-Faboideae family. The species is a deciduous tree with heights ranging from 8 to 15 m (Nacoulma et al., 2011). The bark surface is finely scaly and fissured. The leaves are alternate, pinnately compound with 3–7 pairs of alternate or subopposite leaflets, pubescent on the upper side, and ovate-elliptic. *P. erinaceus* is widely distributed in open dry forests of semi-arid and sub-humid zones of Africa where annual rainfalls range from 600 to 1200 mm (Rabiou et al., 2015; Segla et al., 2015). In Burkina Faso, the species is commonly found in Sudanian savannas (Thiombiano et al., 2010).

2.3. Biomass sampling

The data were collected during two sampling phases. Firstly, we conducted forest inventories from April–May 2017 to assess the abundance of *P. erinaceus* in the study area. Twenty-five (25) plots of 900 m² (30 m × 30 m) each were laid in different vegetation types based on the presence of *P. erinaceus*. Plots of this size have been widely used by several authors in West African savannas (Thiombiano et al., 2015; Ganamé et al., 2020). In each plot, *P. erinaceus* individuals were counted and dendrometric parameters such as dbh (cm) and total tree height (ht, cm) of each individual tree were measured. For multi-stemmed individuals, the dbh is derived from the quadratic mean of the dbh of all stems, using the following formula:

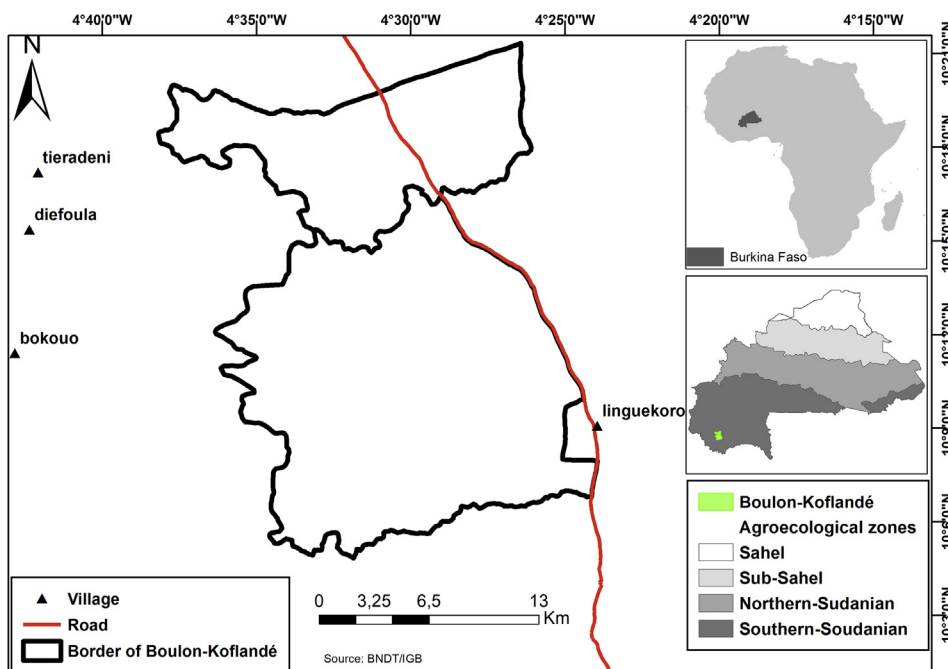$$d = \sqrt{\sum_{i=1}^{t} ds_i{}^2}$$

Figure 1. Location of the study area.

where ds_i is the diameter of the different stems and d is the quadratic mean diameter.

For ease of sampling, individual trees were grouped into five diameter classes: 5–15, 15–25, 25–35, 35–45, and ≥45 cm (Massaoudou and Larwanou, 2018). Secondly, a total of thirty (30) individual trees from the five diameter classes were selected according to their abundance in each diameter class (Table 1): 5–15 cm (5 individuals), 15–25 cm (9 individuals), 25–35 cm (6 individuals), 35–45 cm (5 individuals) and ≥45 cm (5 individuals). Tree harvesting was conducted from October to November 2017 to corresponded with the species' maximum leafing period. Because of its accuracy in estimating tree biomass, the destructive sampling method was used to quantify the aboveground biomass of the sampled individual *P. erinaceus* trees (Jara et al., 2015; Massaoudou and Larwanou, 2018). Prior to the harvesting, dbh, ht and crown diameter (C_d, m) were measured for the 30 individuals selected. The mean C_d of each tree was calculated by measuring the two perpendicular crown diameters (east-west and north-south).

To measure tree biomass, the 30 trees selected were cut down at the base using a chainsaw and each tree was divided into three components: branches, leaves and stem. We collected and packed all leaves into bags. To facilitate weighing, we cut the branches and stems into ridges. Each component's fresh biomass was recorded separately for each individual tree using a 100 kg scale balance. For each component, samples were also collected and immediately weighed to record the fresh weights. Branch and stem samples were dried at 105 °C in the laboratory, whereas leaf samples were dried at 75 °C. The samples were dried at these temperatures until constant weights were obtained. The dry mass to fresh mass ratio was evaluated for each tree component, dividing the dry weight by the corresponding fresh weight. Component dry biomass was calculated by multiplying the dry mass to fresh mass ratio by the component's

corresponding fresh biomass. The TAGB of each individual tree was estimated by summing dry biomass of the three components.

2.4. Carbon content assessment

The Ash method described by Bayen et al. (2015) and Dimobe et al. (2018a) was used in this study to evaluate the carbon content of the sampled individual *P. erinaceus* trees. Composite samples were formed for each component by grinding stem, branches and leaves sampled separately, after oven drying. Five 2 g dry powder samples of each component were incinerated in a crucible.

After the completion of calcination and cooling in a desiccator, carbon contents were assessed according to Allen et al. (1986):

$$A_{sh} \% = \frac{W_3 - W_1}{W_2 - W_1} * 100 \tag{1}$$

$$\text{Carbon \%} = (100 \% - A_{sh} \%) \times 0.58 \tag{2}$$

$$\text{Carbon} = \text{Biomass} \times \text{Carbon \%} \tag{3}$$

where W_1 is the crucible weight, W_2 is the weight of crucibles with samples, W_3 is the weight of crucibles and ash, and 0.58 is the content of carbon in dry organic matter (Allen et al., 1986).

The whole tree carbon stock was then determined by summing the previously calculated organic carbon contents of the three components.

2.5. Data analysis

One-way analysis of variance was used to compare wood specific density between the branch and stem components. To assess the leaf,

Table 1. Dendrometric characteristics of sampled trees.

DBH (cm)		Height (m)		Crown diameter (m)	
Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
9.55–79.58	31.05 ± 16.73	6.5–21	8.60 ± 2.70	4.5–16.25	12.05 ± 3.92

SD is a standard deviation.

branch and stem biomass fractions, we divided each component's biomass by the TAGB. To assess the patterns of biomass allocation, the relationship between dbh and biomass fractions of each component was examined (Dimobe et al. 2018b). The unilateral t-test was performed to compare the average carbon content of *P. erinaceus* to the reference value suggested by the IPCC.

Prior to the development of the allometric equations, we firstly checked for errors and screened for outlier data using Cook's distance of residuals. We continued by exploring graphically the relationship between each component's biomass and predictor variables using pairwise scatter plots. According to these plots, the power law model seems the most appropriate equation for fitting *P. erinaceus* biomass components:

$$Y = \beta_0 \; X^{\beta_1} * \; \varepsilon$$

where Y is the biomass, X the predictors, ε the random error, and β_0 and β_1 the regression coefficients. This model was linearized, as follows:

$$\ln(Y) = ln(\beta_0) + \beta_1(lnX) + \varepsilon$$

where ln is the natural logarithm, Y the biomass, X the predictors, ε the random error, and β_0 and β_1 the regression parameters.

Stem, branch and leaf biomass equations were established based on three non-linear models, as follows:

$$\ln (Y_i) = \ln(\alpha) + \beta \ln(dbh) \tag{1}$$

$$\ln (Y_i) = \ln(\alpha) + \beta \ln(dbh.C_d) \tag{2}$$

$$\ln (Y_i) = \ln(\alpha) + \beta \ln(dbh^2.ht) \tag{3}$$

where Yi is the biomass of the tree compartment, and α and β the regression coefficients.

Firstly, we used dbh as the lone explanatory variable (Eq. 1) and subsequently introduced C_d (Eq, 2) and tree height (Eq. 3).

Each biomass component and TAGB were simultaneously fitted using the SUR method to ensure the additivity property between tree biomass components, achieved through constraint on equation explanatory variables (Paressol, 1999; Zhao et al., 2015). The SUR method was used because it accounts for the inherent correlation between biomass components, and ensures the logical constraint among the sum of biomass predicted for the tree components and the estimation of total biomass in the same sampled tree (Bi et al., 2004; Zhao et al., 2015). The system of additive equations for tree components was built based on Eqs. (1), (2), and (3), as specified in the following formulas.

For Eq. (1):

$$\ln (Y_l) = \ln(\alpha_l) + \beta_l. \ln(dbh) \tag{1.1}$$

$$\ln (Y_b) = \ln(\alpha_b) + \beta_b. \ln(dbh) \tag{1.2}$$

$$\ln (Y_s) = \ln(\alpha_s) + \beta_s. \ln(dbh) \tag{1.3}$$

For Eq. (2):

$$\ln (Y_l) = \ln(\alpha_l) + \beta_l. \ln(dbh.C_d) \tag{2.1}$$

$$\ln (Y_b) = \ln(\alpha_b) + \beta_b. \ln(dbh.C_d) \tag{2.2}$$

$$\ln (Y_s) = \ln(\alpha_s) + \beta_s \ln(dbh.C_d) \tag{2.3}$$

For Eq. (3):

$$\ln (Y_l) = \ln(\alpha_l) + \beta_l. \ln (dbh^2.h) \tag{3.1}$$

$$\ln (Y_b) = \ln(\alpha_b) + \beta_b. \ln (dbh^2.h) \tag{3.2}$$

$$\ln (Y_s) = \ln(\alpha_s) + \beta_s \ln (dbh^2.h) \tag{3.3}$$

where Y_l, Y_b and Y_s are leaf, branch and stem biomass, respectively, and α and β are regression coefficients.

Additive correction factors (CF) were used to correct the errors systematically introduced by the logarithmic transformation because the introduced bias is a constant proportion of the estimation (Wiant and Harner, 1972). The CF were introduced using the following formula:

$$CF = exp\left(\frac{RSE^2}{2}\right)$$

where RSE is the regression residual standard errors.

To avoid the effect of multi-collinearity often associated with log-transformed equations with multiple predictors, the Variance Inflation Factor (VIF) was used. A value of VIF greater than 10 reflects collinearity among the predictors and unreliable coefficients (Massaoudou and Larwanou, 2018). The VIF was calculated as follows:

$$VIF = \frac{1}{1 - R^2}$$

where R^2 = Coefficient of determination.

Statistics of the goodness of fit such as the Adjusted R square (Adj.R^2), Root Mean Square Error (RMSE), and the Mean Absolute Deviation (MAD) were used to evaluate the fitted models' performance. The significance of the models and estimated parameters were also considered at 5%. The best performing models for each component were selected. Equations with the highest R^2, and the lowest RMSE and MAD values were the best models (Dong et al., 2018).

A paired t-test was used to test the difference between the fitted and observed values. The observed versus the predicted values linear trend was plotted. A relative errors trend was graphically explored to check the heteroscedasticity problem. The best allometric equations of the components were combined to obtain the optimal additive model to estimate the TAGB of the tree.

3. Results

3.1. Characteristics of the measured trees

A total of 91 individual *P. erinaceus* trees were recorded in the 25 plots. Tree density per plot ranged from 12 to 118 individuals. ha^{-1}, with a mean of 42.13 ± 9.13 trees. ha^{-1}. Tree dbh varied from 6.5 to 92.3 cm, with a mean of 26.74 ± 2.16 cm. The C_d and ht of individual trees ranged from 0.9 to 18.2 m and 2.5–18.5 m, respectively, with respective means of 6.60 ± 4.37 m and 9.33 ± 4.36 m.

3.2. Wood specific density

The wood specific density of *P. erinaceus* varied significantly between tree components (F = 7.62, p = 0.04). Branches had the highest wood specific density (0.91 ± 0.18 g.cm^{-3}), while the lowest value was recorded for stems ($0.80 \pm 0.$ 20 g.cm^{-3}). The mean wood specific density of the species was 0.86 ± 0.20 g.cm^{-3}.

3.3. Biomass distribution among the tree components

The relative proportions of the biomass of the *P. erinaceus* tree components to the total tree biomass is presented in Figure 2. The allocation of biomass was higher in the branches (55–70%) compared to that of the stem and leaves.

Leaf and stem biomass allocation decreased with increasing tree dbh, whereas branch biomass allocation increased with increasing tree dbh (Figure 3). The aboveground biomass of all three components increased proportionally with tree dbh (Figure 4). However, the biomass increase was more pronounced with tree dbh $\geq$45 cm, and was relatively low for leaves.
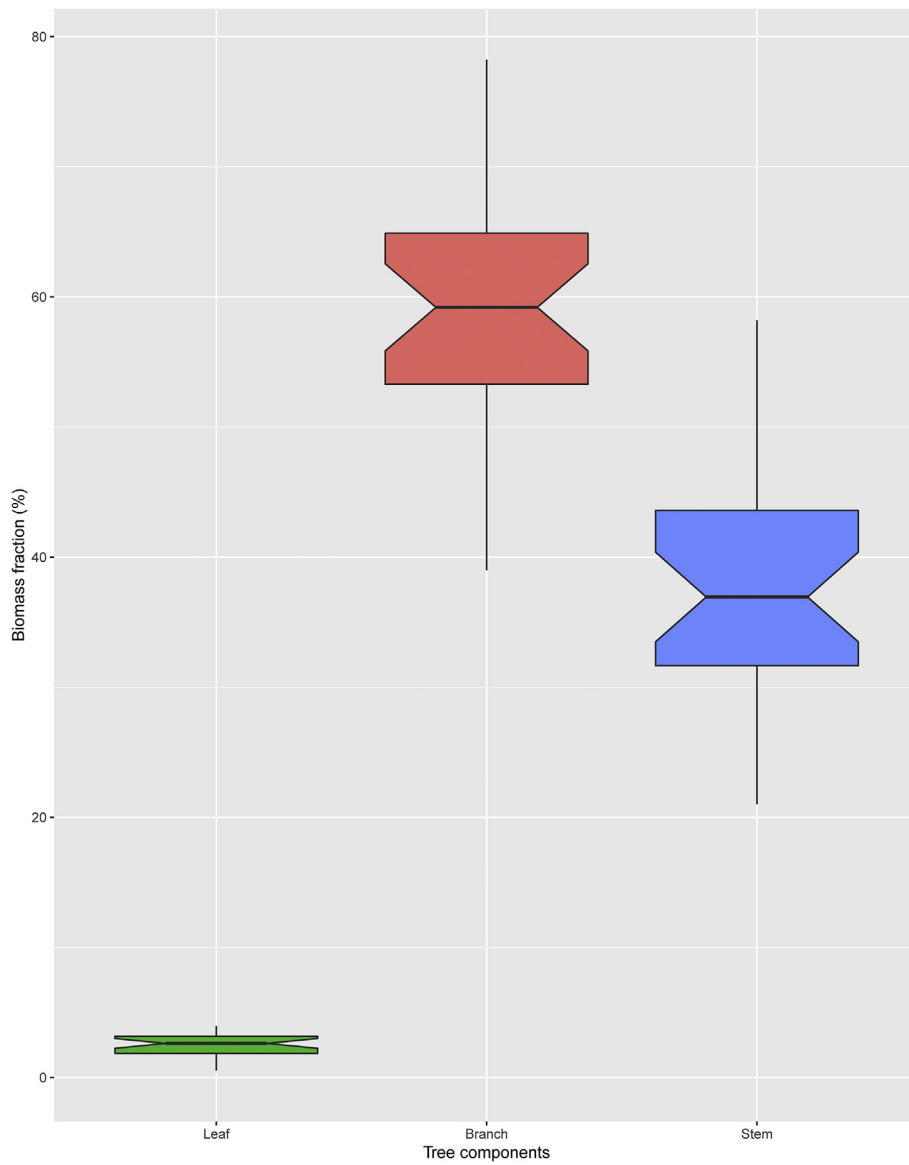
Figure 2. Biomass partitioning of aboveground components for *P. erinaceus*.
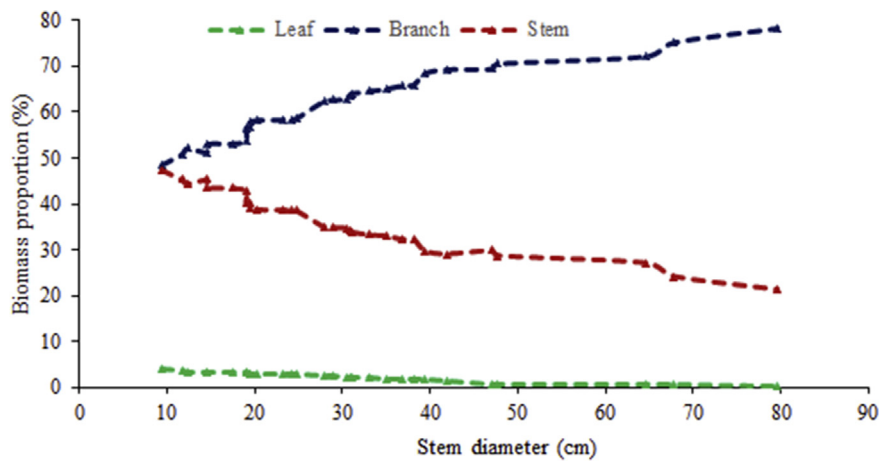

Figure 3. Variation of biomass allocation in the tree components according to diameter at breast height.
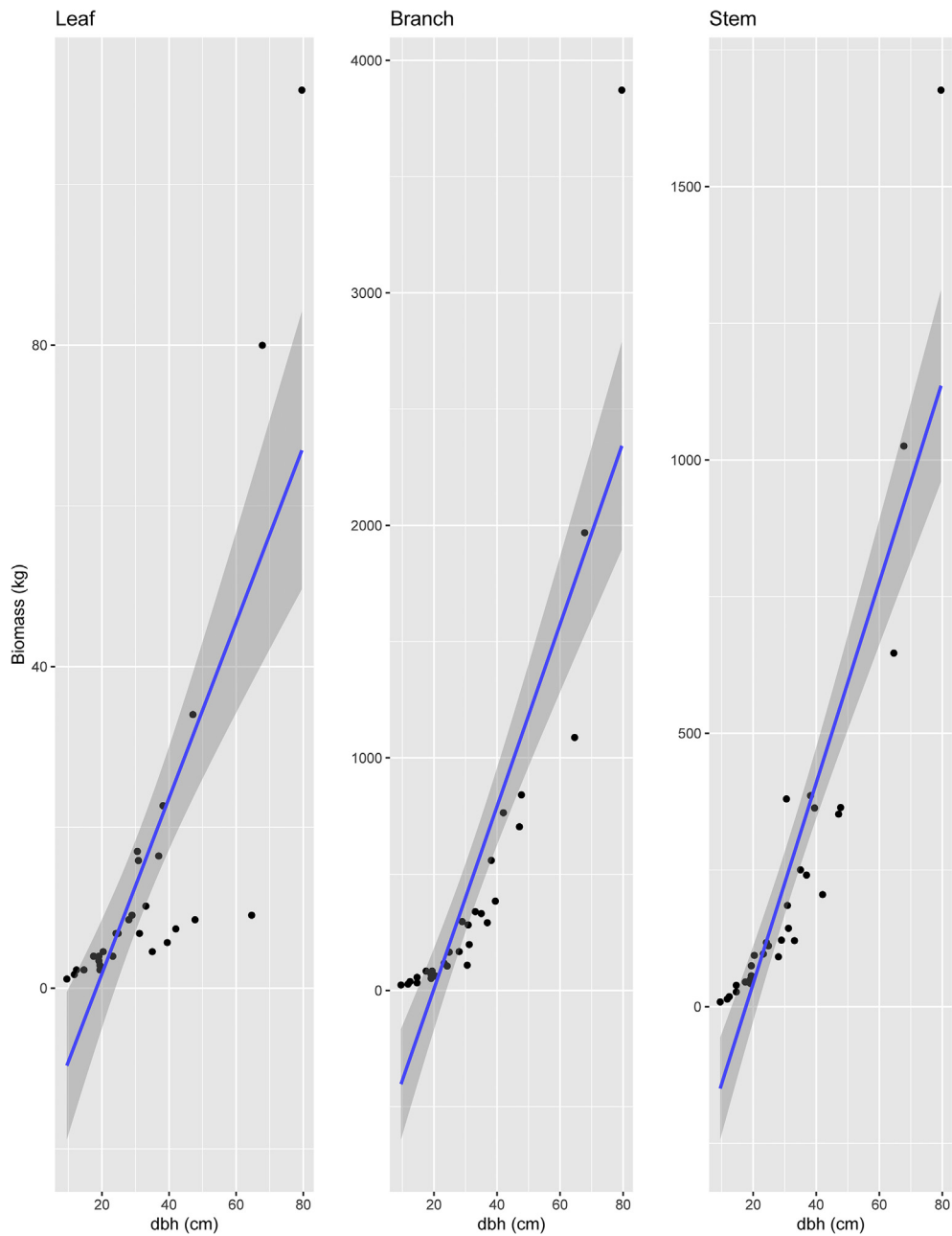
Figure 4. Biomass variation with in tree components across tree size. Legend: dbh is diameter at breast height.

Table 2. Fitted allometric equations for the three components and total AGB for *Pterocarpus erinaceus* tree.

Equation N°	Components	Predictors	Regression coefficients		Goodness of fit				
			$\ln(\alpha)$	β	R^2	RMSE	MAD	CF	VIF
1	Leaf	dbh	-3.46***	1.62***	0.73	0.49	0.36	1.03	
2	Leaf	dbh.C_d	-3.91***	1.07***	0.70	0.52	0.39	1.04	3.33
3	Leaf	dbh^2.ht	-3.57***	0.60***	0.65	0.56	0.44	1.05	2.86
4	Branch	dbh	-2.45***	2.32***	0.96	0.25	0.18	1.00	
5	Branch	dbh.C_d	-3.02***	1.52***	0.94	0.29	0.23	1.00	16.67
6	Branch	dbh^2.ht	-2.535***	0.85***	0.84	0.46	0.28	1.02	6.25
7	Stem	dbh	-2.69***	2.27***	0.93	0.30	0.23	1.00	
8	Stem	dbh.C_d	-3.02***	1.45***	0.89	0.38	0.28	1.01	9.09
9	Stem	dbh^2.ht	-3.01***	0.86***	0.90	0.37	0.24	1.01	10

3.4. Aboveground biomass allometric models

The established allometric equations explained 65–96% of the biomass variation, and the MAD and RMSE values varied from 0.18 to 0.44 and from 0.25 to 0.56, respectively (Table 2). The coefficients of the fitted models were greatly significant (P < 0.05). Leaf biomass equations (Eq. 1-Eq. 2 and Eq. 3) had the lowest explained variance. These models explained between 65 to 73% of the biomass variation. The goodness of fit showed that allometric models used to predict branch biomass had the highest adjusted R^2 (0.84–0.96), with the lowest RMSE (0.25–0.46) and MAD (0.18–0.28) values.

Table 3 presents the most suitable allometric equations for estimating the biomass of *P. erinaceus* components. Stem, branch and leaf biomass were optimally predicted when using dbh as the only predictor. Branch component showed a higher R^2 (0.96) and the lowest MAD and RMSE values (0.18 and 0.25, respectively) with this model. Similarly, we found less error for the leaf component, with values of 0.73, 0.49 and 0.36 for R^2, RMSE and MAD, respectively, using the same model. The dbh also explained 93% of stem biomass variation. The corresponding MAD and RMSE values were 0.23 and 0.30, respectively. The statistical fits of the three components did not significantly improve with the addition of C_d or ht as secondary predictors.

The paired t-test showed that the predicted and observed values were similar for leaf biomass (t = 0.967, p = 0.342), branch biomass (t = 0.978, p = 0.336) and stem biomass (t = -0.003, p = 0.998). The scatter plots of observed and predicted values of all components were close to the 1:1 linear trend (Figure 5). Significant heteroscedasticity was observed for each biomass component in the system of equation fitted (Figure 6), indicating the good performance of the models established in this study.

The most appropriate allometric equation for estimating the TAGB of *P. erinaceus*, obtained by combining the best performing models of each biomass component, was as follows:

$$TAGB = e^{-3,46}. (dbh)^{1,62} + e^{-2,45}. (dbh)^{2,31} + e^{-2,68}. (dbh)^{2,27}.$$ This equation explained near 95% of the biomass variation. No significant deviation was observed between observed and predicted biomass values (t = 0.836, p = 0.410). The scatter plot of predicted versus observed TAGB was also close to the y = x linear trend. The residuals plot showed that estimating the TAGB of *P. erinaceus* with this model produced small errors (Figure 6).

3.5. Aboveground biomass and carbon content of Pterocarpus erinaceus

The aboveground biomass varied significantly among the *P. erinaceus* tree components (F = 15.62, P = 0.005). Branches had the highest biomass value, while the lowest value was observed for the leaves (Table 4).

The carbon content of the branches and stems were 56.68% and 56.23%, respectively. These values were significantly different (F = 55.03, P < 0.001) to that found in the leaves (54.23%). Altogether, the unilateral t-test showed that the average carbon content of 55.74% for *P. erinaceus* tree components was greater than the value recommended by the IPCC. The density of *P. erinaceus* trees in the BKCF was 42.13 trees/ha, corresponding to 11,797.66 kg of carbon sequestered per hectare.

4. Discussion

4.1. Wood specific density

The wood specific density of *P. erinaceus* varied significantly between tree components. The higher wood density in the branches compared to the stems is likely related to anatomical traits associated with sap transport to different organs. Indeed, a tree's specific density increases with the decreasing width of growth rings which is due to the increased portion of thin-walled early wood in wide tree rings. According to Melo et al. (1990), *P. erinaceus* trees produce a heavy wood because the species' mean wood specific density is greater than 0.72 g.cm^{-3}. The mean wood densities reported by Henry et al. (2011) for trees in Africa were close to the recorded mean wood density (0. 82 g.cm^{-3}) in this study. Furthermore, this value was 10% higher than those (0.74 g.cm^{-3}) observed by Zanne et al. (2009). This observed discrepancy might be related to the Archimedes principle used by Zanne et al. (2009). In general, wood specific density in Sub-Saharan African tree species varies from 0.15 to 1.2 g.cm^{-3} (Henry et al., 2011).

4.2. Allometric equations

The dbh is the dendrometric parameter most correlated with all biomass components evaluated in this study. The allometric equations developed with dbh as an explanatory variable were the best performing models that provide a good prediction of *P. erinaceus* biomass. The precision of measuring the predictor variables is very important in the development of allometric equations (Picard et al., 2012). Indeed, dbh can be easily measured in the field and is readily available in forest inventory data. Moreover, the dbh measurement is more accurate than other explanatory variables. Some studies (Vahedi et al., 2014; Cao and Chen, 2015) found that dbh is the best predictor variable of woody species biomass. According to Henry et al. (2011), the most common predictor used to assess tree biomass in Sub-Saharan Africa was dbh. Some authors (Xue et al., 2016; Mensah et al., 2017; Dimobe et al., 2018a, 2018b) have suggested that the inclusion of tree height and/or crown diameter as additive variables to dbh can improve the prediction quality of allometric models. The fact that the combination of these variables with dbh did not improve the quality of the models developed in this study could be explained by the architecture of *P. erinaceus* trees.

The models with only dbh as an explanatory variable were developed based on the logarithmic form on the power model (ln-ln model). According to Vahedi et al. (2014) and Djomo et al. (2010), the ln-ln model is the optimal mathematical model for biomass studies because it can overcome the heteroscedasticity of the tree biomass model residuals. In fact, the first objective in developing an allometric equation is its applicability for non-destructive assessment of biomass. Therefore, using the logarithmic form on the power model produced a strong accuracy in biomass estimation for both the *P. erinaceus* tree components and the species' TAGB.

4.3. Pterocarpus erinaceus biomass and carbon allocation

The aboveground biomass partitioning pattern of the *P. erinaceus* tree components was affected by tree size. Decreasing stem and leaf biomass

Table 3. Selected biomass equations for *Pterocarpus erinaceus*.

Components	Biomass equation	R^2	MAD	RMSE	CF
Leaf	$\ln(LB) = -3.46 + 1.62\ln(dbh)$	0.73	0.36	0.49	1.03
Branch	$\ln(BB) = -2.45 + 2.31\ln(dbh)$	0.96	0.18	0.25	1.00
Stem	$\ln(SB) = -2.68 + 2.27\ln(dbh)$	0.93	0.23	0.30	1.00
TAGB	$AGB = e^{-3.46}(dbh)^{1.62}+e^{-2.45}(dbh)^{2.31}+e^{-2.68}(dbh)^{2.27}$	0.95	2.23	0.55	

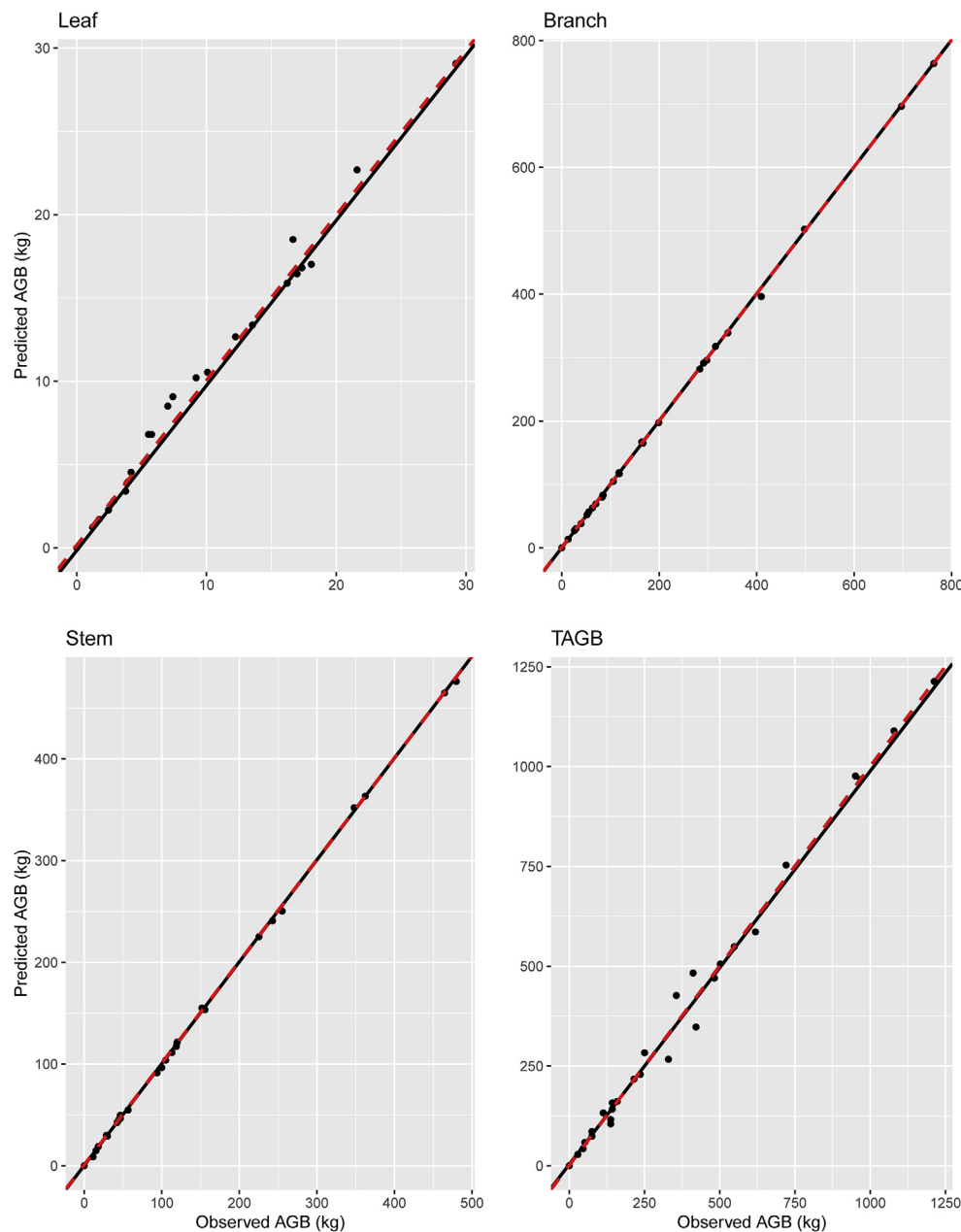LB = Leaf biomss; BB = branch biomass; SB = Stem biomass; AGB = Aboveground biomass.

Figure 5. Relationship between observed and predicted biomass for the leaf, branch, stem and total AGB. Legend: AGB is aboveground biomass and TAGB is total aboveground biomass.

fractions with increasing tree dbh might be due to a trend of decreasing foliage biomass production per unit of wood mass (Mensah et al., 2016). Many authors have indicated that a decrease in leaf biomass results from the declining production of foliage on older branches (Jagodzinski et al., 2014; Mensah et al., 2016). This may be related to the increased amount of heartwood of stems and branches with age (Morataya et al., 1999). Increasing branch biomass fractions with increasing dbh would be related to the prevalence of new branches on the old trees. These new branches behave like younger trees (Dimobe et al., 2018b). Our results also showed that biomass increasing with dbh was less pronounced in leaves than in stems and branches. This would be related to changes in the developmental stage and tree size. In fact, investments in support tissues of woody species increase with tree size (Poorter et al., 2012). The results are consistent with previous studies that indicated that trees allocate more biomass to woody structures at the expense of leaves as they grow (Luo et al., 2014; Mensah et al., 2016; He et al., 2018).

The average carbon content of *P. erinaceus* stems and branches (woody components) varied slightly and was substantially different from the average carbon content of the leaves. The proportion of organic carbon in different components of woody species depends on the ash content (Bayen et al., 2015). Differences in ash content between the woody components and leaves were observed as the leaves have the lowest amount of living tissue compared to the branches and stem. The mean carbon contents of the aboveground biomass components of *P. erinaceus* were different to the values suggested by the IPCC et al. (2006). Therefore, using the IPCC's suggested 50% conversion factor underestimates the carbon content of *P. erinaceus* leaves, branches and stems. Indeed, Thomas & Martin (2012) reported that taken together, the IPCC-suggested values did not closely match with wood carbon values found in the literature. Massaoudou and Larwanou (2018) observed a similar trend for *Faidherbia albida* and *Prosopis africana* in Niger, and Bayen et al. (2015) for *Jatropha curcas* and Dimobe et al. (2018a) for
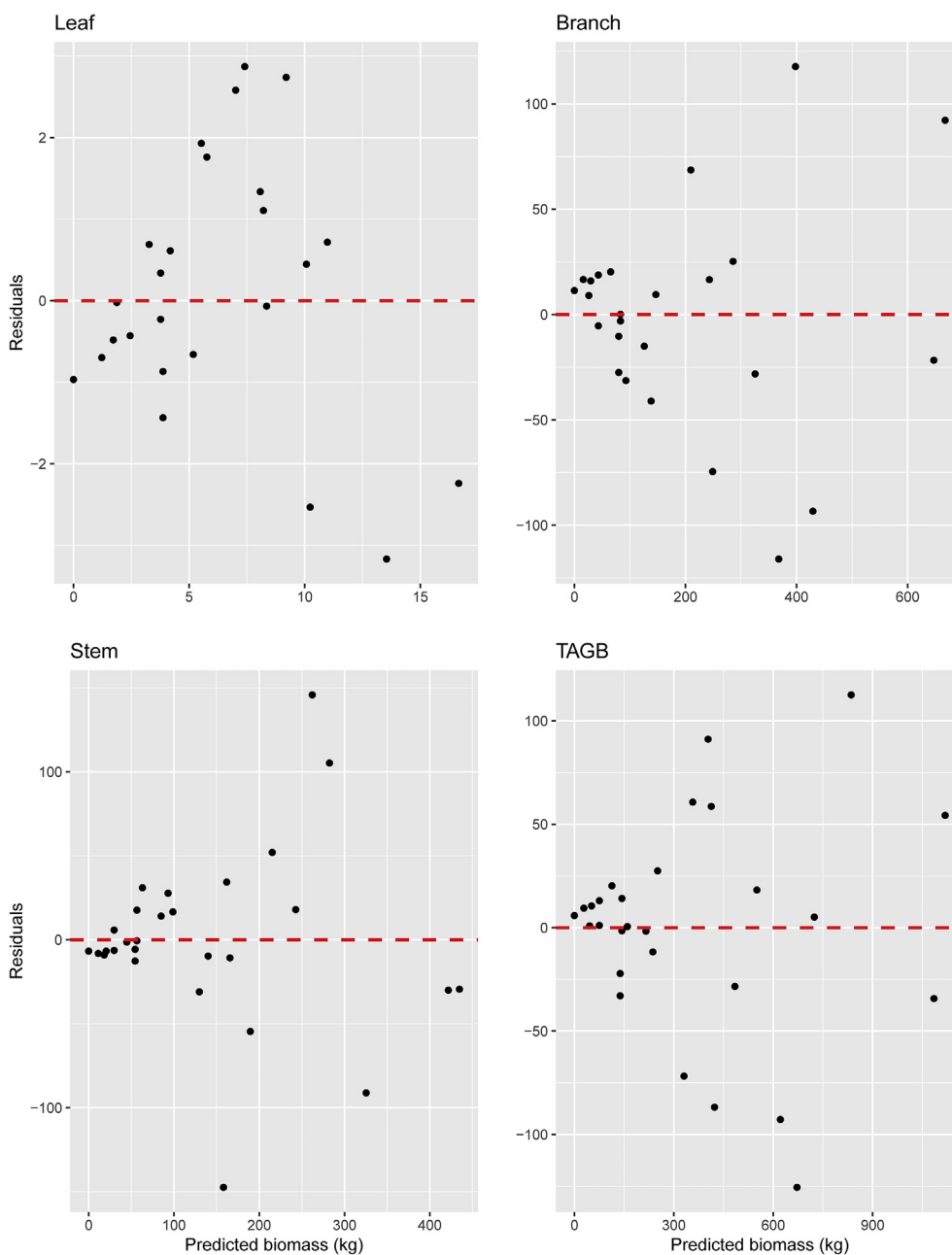
Figure 6. Residuals plots each biomass compartment and total AGB. Legend: Legend: AGB is aboveground biomass and TAGB is total aboveground biomass.

Table 4. Biomass, carbon content and carbon stocks of *Pterocarpus erinaceus* across the tree Components.

Tree components	Biomass ±SD (kg)	Carbon content ±SD (%)	Carbon stock ±SD (Kg)
Leaves	8.46 ± 6.96	54.23 ± 0.49	4.59 ± 3.41
Branch	298.39 ± 360.03	56.23 ± 0.41	167.98 ± 202.44
Stem	195.55 ± 230.38	56.68 ± 0.68	110.84 ± 130.57
AGB	502.39 ± 597.28	55.74 ± 1.18	280.03 ± 332.92

SD is a standard deviation.

Vitellaria paradoxa in Burkina Faso. With an average carbon content of about 16,399.10 kg ha^{-1}, *P. erinaceus* appears to have a high sequestration capacity.

The findings of this study address a growing need for the quantitative evaluation of the contribution of Sub-Saharan African savanna and sahelian ecosystems to climate change mitigation. The development of allometric models for the woody species of savanna ecosystems in Burkina Faso can contribute to the need for accurate biomass estimation and development of monitoring, reporting and verification frameworks for carbon assessment. The developed allometric models should contribute to improved knowledge of the existing biomass and carbon stock of Sub-Saharan African savanna ecosystems, and help monitor the evolution of

the constituent species in the context of REDD+. But species-specific allometric models are needed as a basis for the assessment of carbon stocks in dry savanna ecosystems and for the implementation of international programs such as REDD+ and CDM. This study therefore helps to fill the gap with regard to one important woody species of the Sub-Saharan African savanna ecosystem – *P. erinaceus*.

According to Paressol et al. (2001), Dong et al. (2015) and Zhao et al. (2015), the additive property is a necessary characteristic of a system of models to accurately estimate the biomass of tree components. The SUR method ensures this characteristic (Bi et al., 2004). In this study, the discussion was limited to the established allometric equations, and the method used for development of the models was not compared to other existing methods. An important factor in biomass model development is the biomass conversion and expansion factor which is a factor that converts stem volume to stem dry weight and thereafter expands stem biomass to the whole tree biomass. Including this factor as a predictor in allometric equation development could improve the robustness of predictions. The allometric equations described in this paper may not be appropriate for use in the prediction of aboveground biomass of a mixed-species forest, as the present study focused on just a single species – *P. erinaceus*. The number of individuals sampled to develop the allometric equations for this species was limited and could therefore introduce a bias in the prediction power of the models. In this case, the use of larger numbers of sample trees across the different dbh size classes could enhance the accuracy of the models. Finally, the applicability of the developed equations is limited to a range of dbh size classes and sites with similar biophysical conditions.

5. Conclusion

This study investigated biomass fraction patterns and the variability of biomass allometric equations and carbon stocks within different components of *P. erinaceus* trees. The results confirmed that dbh is the most correlated variable with all components of *P. erinaceus*. However, an appropriate model choice is required for reducing errors in tree biomass estimation. The power law model emerged as the best model that suits biomass estimation of *P. erinaceus* tree components and the species' total aboveground biomass. The results also showed that *P. erinaceus* trees allocate more biomass to woody structures at the expense of leaves as they growth. The aboveground biomass of the species increased proportionally with tree dbh. The findings revealed that the carbon content of *P. erinaceus* trees varied between different tree components, and that using the IPCC's suggested carbon default value of 50% underestimated the species' carbon content. The allometric models developed in this study can be used to accurately predict the biomass and carbon stocks of *P. erinaceus* trees in savanna ecosystems of Burkina Faso and other similar environments in Sub-Saharan Africa. The models can help to reduce the human and material costs of biomass and carbon estimation in these environments by employing a non-destructive method. *P. erinaceus* is found to have a high carbon sequestration potential and should therefore be better utilized for land restoration in the context of REDD + initiatives in Sub-Saharan Africa.

Declarations

Author contribution statement

M. Ganamé: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

P. Bayen, K. Dimobe and I. Ouédraogo: Conceived and designed the experiments; Wrote the paper.

A. Thiombiano: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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