

# Aboveground biomass allometric equations and carbon content of the shea butter tree (*Vitellaria paradoxa* C.F. Gaertn., Sapotaceae) components in Sudanian savannas (West Africa)

Kangbéni Dimobe  · Dethardt Goetze · Amadé Ouédraogo · Sylvanus Mensah · Koffi Akpagana · Stefan Porembski · Adjima Thiombiano

Received: 15 February 2017 / Accepted: 14 February 2018  
© Springer Science+Business Media B.V., part of Springer Nature 2018

**Abstract** *Vitellaria paradoxa* is one of the most economically important trees in West Africa. Although being a key component of most sub-Saharan agroforestry systems, little information and argument exist regarding its biomass and carbon potential. Here, we developed biomass equations for *V. paradoxa* tree components in Sudanian savannas. A destructive sampling approach was applied, which was based on measuring stem, branch and foliage biomass of thirty individual trees selected from a wide spectrum of diameter at breast height (dbh) and tree height (h).

Basal diameter ( $d_{20}$ ), dbh, h and crown diameter ( $c_d$ ) were measured and used as predictors in biomass equations. Carbon content was estimated using the ash method. Variance explained in biomass allometric equations ranged from 81 to 98%, and was lower for foliage than for branch and stem biomass models, suggesting that leaf allometries are less responsive to tree size than branch and stem allometries. Stem biomass was best predicted by  $d_{20}$ , branch biomass by dbh, and leaf biomass by crown diameter. For aboveground biomass, adding height to dbh as compound variable ( $dbh^2 \times h$ ) did not make any significant change, as compared with model based on dbh alone. However, adding crown diameter to dbh and height reduced the error by 15% and improved model fits. Carbon contents in *V. paradoxa* foliage, branch and stem were 55.29, 55.37 and 55.82%, respectively, and higher than reference value suggested by the IPCC. Established allometric equations can be used to accurately predict aboveground biomass of the species in the Sudanian savannas of West Africa.

---

K. Dimobe (✉) · A. Ouédraogo · A. Thiombiano  
UFR-SVT, Laboratory of Plant Biology and Ecology,  
University Ouaga1 Pr Joseph Ki-Zerbo,  
03 B.P. 7021, Ouagadougou 03, Burkina Faso  
e-mail: kangbenidimobe@gmail.com;  
kangbeni.dimobe@uni-rostock.de

K. Dimobe · D. Goetze · S. Porembski  
Department of Botany, Institute of Biological Sciences,  
University of Rostock, 18051 Rostock, Germany

K. Dimobe · K. Akpagana  
Laboratory of Botany and Plant Ecology, Department of  
Botany, University of Lomé, P.O. Box 1515, Lomé, Togo

S. Mensah  
Laboratory of Biomathematics and Forest Estimations,  
University of Abomey-Calavi,  
03 B.P. 2819 Abomey-Calavi, Benin

S. Mensah  
Department of Forest and Wood Science, Stellenbosch  
University, Matieland, South Africa

**Keywords** Allometry · Biomass uncertainty · Crown diameter · Destructive sampling · Estimation error · Semi-arid area

## Introduction

Recent increases in atmospheric greenhouse gas concentrations are presumed to alter global climate (IPCC 2007). As global strategy to contribute to mitigate the adverse effects of increased greenhouse gas emissions, decisions on landscape management should aim to increase their potential for carbon sequestration (Paustian et al. 1998; Smith et al. 2008; Thomson et al. 2010; Sharma et al. 2016). Biomass and carbon accounting in natural and semi-natural vegetation types has rapidly become the focus over the last decades (Brown 2002; Chave et al. 2005; Chauhan et al. 2010, 2012), as being paramount step towards the implementation of the emerging carbon credit market mechanism such as reducing emission from deforestation and forest degradation (REDD+).

Aboveground plant biomass (AGB) is defined as the amount of organic matter in living and dead plant material above the soil surface (Litton and Boone Kauffman 2008), and serves as indicator for carbon stock above the ground. The most accurate method of tree biomass measurement is destructive sampling (Basuki et al. 2009), whereby individual trees are selected, cut down, packed, dried till constant mass (Brown 1997). Biomass allometric models are an essential tool to estimate individual tree biomass, which further can be up-scaled to stand level, thus contributing to accurate accounting of stock and flux of biomass and carbon in terrestrial ecosystems (Brown 1997; Chave et al. 2005; IPCC 2007). Numerous AGB models were published over the last two decades (Brown et al. 1989; Brown 1997; Chambers et al. 2001; Baker et al. 2004; Chave et al. 2004, 2005; Návar 2009), and were based on predictors such as dbh, height, wood density, crown diameter and basal diameter. Some models were also developed from combination of two or three parameters (e.g. dbh, height and wood density) in order to improve their predictive abilities (Chave et al. 2005, 2014; Fayolle et al. 2013; Ngomanda et al. 2014; Ploton et al. 2016), although the additional use of height for improvement of regression fits can be species-sensitive (Xiang et al. 2016; Mensah et al. 2017). However, accurate estimates of biomass in many tropical regions of Africa are lacking, due to difficulties in obtaining field data for establishing appropriate models for predicting biomass of individual trees in species-rich ecosystems (Chave et al. 2005). In addition, limited number of

studies targeted dryland environments and species. Though recent studies (Chave et al. 2005; Shirima et al. 2011; Kuyah et al. 2012) reported allometric models that are specific to African ecosystems, very few of them referred to Sudanian savanna ecosystems of West Africa. Furthermore, recent reports showed that the application of existing pantropical biomass equations at fine scale does not always guarantee an optimal precision of biomass estimation due to site- and species-specific characteristics (Fayolle et al. 2013; Ngomanda et al. 2014; Djomo et al. 2016). Therefore, pantropical equations or species-specific equations from other sites should not be used without validation with local field data.

Accurate estimations of tree biomass at fine scale can be obtained through allometric regressions, which were first developed using dbh as the sole explanatory variable (Gower et al. 1999). Tree height can also be incorporated as the second variable to improve the precision of biomass estimates (Ketterings et al. 2001; Cai et al. 2013). Incorporation of wood density or crown diameter can further reduce the estimation error, especially for multi-species biomass estimation (Ploton et al. 2016; Mensah et al. 2016a).

*Vitellaria paradoxa* C.F. Gaertn., is a mesopharenophyte that belongs to the family of Sapotaceae. The species has a mean height of 7.5 m, but can reach 12 m with a mean stem diameter of 50 cm (Arbonnier 2002). Also referred to as the shea butter tree, *V. paradoxa* was reported three decades ago by Poulsen (1981) as the second most important oil crop in Africa. While the fruits are directly consumed for their vitamins and energy contents, the seeds are sold raw as kernels or processed to make the shea butter, which can be used either for cooking, skincare, medicine, or for many other benefits supporting local development (Lovett 2004). Furthermore, almost all other organs are used; for example, the leaves serve as fodder for livestock, and constitute a good alkaline in the paint industry (Lovett and Haq 2000). As essential components of natural/semi-natural savannas and agroforestry systems, *V. paradoxa* contributes to local households' income and is important as cash crop for exportation. It has also become the most economically and culturally important tree species in the Sudano-Sahelian regions where oil palms do not grow (Boffa 2015). *Vitellaria paradoxa* is an agro-managed crop, which grows in the wild and parklands across the sub-Saharan African savannas

(Lamien et al. 2004; Bayala et al. 2009). Shea butter tree provides other regulation services such as wind breaks and erosion control in agroforestry systems, serves as habitat for other organisms (Jasaw et al. 2015), and contributes to local climate regulation through carbon sequestration.

The present study is mainly guided by the lack of allometric models for estimation of biomass of *V. paradoxa* tree components in the Sudano-Sahelian regions, despite its well-known socio-economic and ecologic importance. The few available studies were carried out in Nigeria (Jibrin and Abdulkadir 2015). Secondly, as site- and species specific allometric models differ with species, tree status, climate and soil (Zianis and Mencuccini 2004), they are generally preferred over generic allometric models (Montagu et al. 2005). Hence, the aim of this study was to use a destructive approach to develop specific models that predict height and biomass of *V. paradoxa* tree components. Specific objectives were to (1) develop dbh–height equations for *V. paradoxa*; both linear and non-linear equations were tested; we assumed that growth in tree height would be a multiplicative process through exponential scaling with diameter growth; (2) establish allometric equations for estimation of *V. paradoxa* tree biomass components (stem, branch, leaf), using basal diameter  $d_{20}$  (diameter at 20 cm above the ground), dbh and crown diameter ( $c_d$ ); we assumed that  $d_{20}$  or dbh would be better predictors for stem biomass, while crown diameter would better predict the leaf biomass; (3) establish allometric equation for aboveground biomass (foliage plus woody structure) of *V. paradoxa*; we hypothesized that dbh would be better predictor of AGB than dendrometric parameters such as  $d_{20}$  and crown diameter; and that combining height and crown diameter to dbh would improve the regression fits of the established equation; (4) determine the carbon content in leaf, branch and stem components of *V. paradoxa* trees; because foliage, branch and stem have different physiological activities (Mensah et al. 2016b), we assumed that carbon content would vary with species tree components.

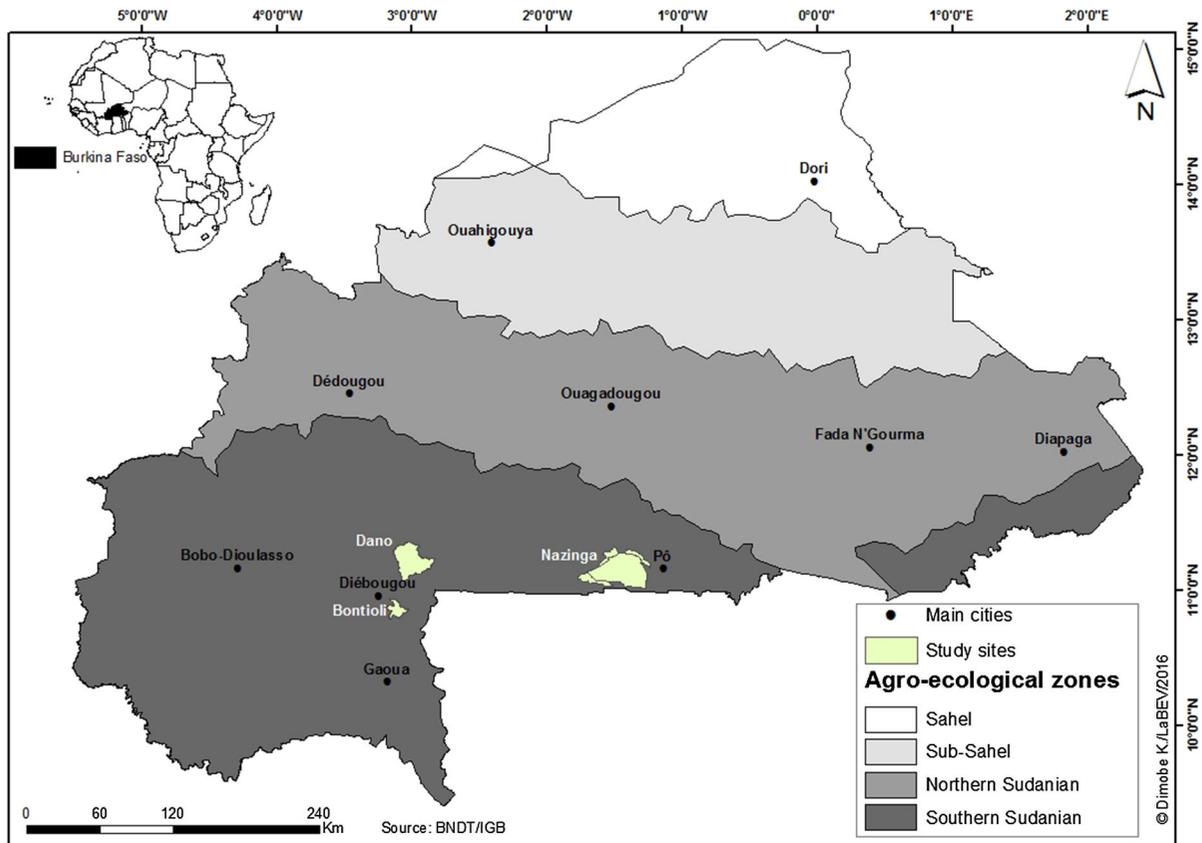
## Materials and methods

### Study area

The study was carried out in different savannas types (shrub savanna, tree savanna and woodland) within the Dano basin (between latitudes 11°04'27"N and 11°21'50"N and longitudes 2°50'15" and 3°08'37"W), the Total Wildlife Reserve of Bontioli (latitudes 10°70' and 10°95'N and longitudes 3°02' and 3°20'W) and the Nazinga Game Ranch (latitudes 11°01' and 11°18'N and longitudes 1°18' and 1°43'W). These sites are located in the southern Sudanian agro-ecological zone of Burkina Faso in flat area with an average altitude of 300 m a.s.l. They are situated within the Sudanian regional centre of endemism (White 1986; Fontès and Guinko 1995) (Fig. 1). Dominant vegetation types are tree and shrub savannas with a grass layer dominated by annual grasses such as *Andropogon pseudapricus* Stapf. and *Loudetia togoensis* (Pilger) C.E. Hubbard and perennial grasses such as *Andropogon gayanus* Kunth. and *Andropogon asciodis* C.B.Cl. Most dominant families are Fabaceae-Mimosaceae and Combretaceae. Dominant woody species are *Detarium microcarpum* Guill. & Perr., *Combretum nigricans* Lepr. ex Guill. & Perr., *Acacia macrostachya* Reichenb. ex Benth., *Entada africana* Guill. & Perr., *Lannea acida* A. Rich., *Anogeissus leiocarpa* (DC.) Guill. & Perr. and *Vitellaria paradoxa* C.F. Gaertn. The climate is tropical with a unimodal rainy season, lasting for about 6 months from May to October. The temperature ranges from 16 to 32 °C in December–January and 26 to 40 °C in March–April. The most frequently encountered soils are Lixisols (Driessen et al. 2001).

### Forest inventory, destructive tree sampling and laboratory procedures

Data were collected through two phase sampling. For the first phase (April to May 2014), forest inventories were carried out using 280 plots of 1000 m<sup>2</sup> (50 m × 20 m) to measure dendrometric data such as stem dbh (diameter at breast height), total height, crown diameter and basal diameter on all individual trees of *V. paradoxa*. For the second phase (April to May 2015), a destructive sampling of *V. paradoxa* trees was conducted for quantification of tree biomass stock potential. Based on previous studies (Mbow



**Fig. 1** Location of Burkina Faso in Africa and of the study sites in Burkina Faso

et al. 2013; Bayen et al. 2015), the establishment of allometric models relies on dedicated field campaigns where by economically feasible and statistically acceptable number of trees of different size classes must be selected, felled and then measured in detail. *Vitellaria paradoxa* individuals were thus divided into classes based on stem diameter and total height. Sample individuals were selected from inventory plots based on their abundance in a particular stem diameter class, so that individuals from more abundantly represented stem diameter classes could be more frequently sampled. A destructive sampling of 30 individual trees (10 individuals in each study site) of *V. paradoxa* was conducted. The individuals were grouped into four stem diameter classes: 5–15 (17 individuals), 15–25 (6 individuals), 25–35 (4 individuals) and  $\geq 35$  cm (3 individuals) (Table 1).

Prior to the destructive sampling, total tree height was measured using a height-measuring pole (for stems  $\leq 6$  m) or a clinometer (for stems  $> 6$  m); dbh

**Table 1** Statistical summary of sample tree characteristics and biomass data

	Mean	SE	Min	Max
<b>Items</b>				
<b>Sample tree characteristics</b>				
Basal diameter ( $d_{20}$ , cm)	20.55	1.80	9.30	41.80
Trunk diameter (dbh, cm)	16.92	1.64	7.50	36.60
Crown diameter ( $c_d$ , m)	4.76	0.36	1.66	9.36
Tree height (h, m)	7.11	0.34	4.30	11.10
<b>Sample tree biomass data</b>				
Stem (kg)	32.03	5.86	5.04	116.14
Branch (kg)	114.28	28.83	6.67	564.67
Foliage (kg)	7.56	1.33	0.65	36.07
Aboveground (kg)	153.86	35.72	13.88	716.89

was measured using a tape graduated in cm, and crown diameter was determined using a distance meter tape (average of two perpendicular readings). These

parameters were recorded for all the thirty individual trees of *V. paradoxa*. To avoid bias and to account for structural variety, the crown diameter was measured twice, along the east–west direction and the north–south one (Meyer et al. 2014). For trees forking below 1.3 m, the diameter of all ramifications was measured and later the quadratic mean diameter (root-mean-squared) was calculated using the formula below:

$$D = \sqrt{\sum_{i=1}^n dbh_i^2} \quad (1)$$

where  $D$  is the quadratic mean diameter, and  $dbh_i$  is the diameter of different measured stems.

The thirty sample trees were felled with a hand-saw. Once felled, the tree total height and stem lengths were measured. Branches were cut off from the stem and all foliar material was collected and packed in labeled bags. The fresh weights of the three components of each individual tree (i.e. stem, branches and leaves) were recorded in the field using a standard 100 kg hanging scale balance, which was regularly recalibrated to minimize bias. Small samples from leaves, stem and branches were extracted and weighed for determination of the dry to green weight ratio (DG-ratio) using an electronic balance (range 0–5 kg, precision 0.5 g). The samples of branches and stem were taken as a pie shape or cylinder (discs of 5 cm thickness). The fresh weight of each disc was recorded in the field at the time when they were cut off from the stem and taken to the laboratory for drying. All collected aboveground samples were oven dried to a constant weight at 105 °C (samples of branches and stems) or 75 °C (samples of leaves). Sample dry weight was recorded immediately after drying. All mean DG-ratios for each tree component were computed. The dry weight of each component was obtained by multiplying the mean DG-ratio by the green weight of the respective tree component. Total aboveground dry weight was computed as the sum of all component weights (kg).

#### Estimation of carbon content and stock

The organic carbon content in selected individuals of *V. paradoxa* was estimated by ash method as described elsewhere (Allen et al. 1986; Jana et al. 2009). The leaves, branches and stems of each individual were separated in order to estimate the amount of carbon

content. Composite samples were formed from the dry matter samples of the stems, branches and leaves in order to determine their total carbon content. These samples were crushed in a cutting mill. Five 2-g samples of each component were then collected and submitted for analysis to the Laboratory of Plants and Soils at the University Ouaga1 Pr Joseph Ki-Zerbo (Burkina Faso). Each 2-g sample was placed in a lidless porcelain crucible and placed for 2 h inside a muffle furnace set at 550 °C, until calcination was completed. The samples were then removed and cooled in a desiccator to be weighed later. After cooling, the crucible with ash was weighed and the percentage of organic carbon was calculated according to the formula given by Allen et al. (1986).

$$\%Ash = (W_3 - W_1)/(W_2 - W_1) \times 100 \quad (2)$$

$$\%Carbon = (100\% - \%Ash) \times 0.58 \quad (3)$$

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

The carbon stock in leaves, branches and stems of each individual tree was calculated separately, and summed up to determine the total organic carbon stock for each individual tree.

## Data analysis

### Estimation of tree height

We examined the relationship between tree dbh and height using linear, logarithmic, exponential and power models. Scatter plots were set to identify the theoretical distribution that fitted well with the data (Supplementary Information). As a result, the power law model (Eq. 4) outperformed the linear, logarithmic and exponential models; and therefore was used to develop the tree dbh–height allometry.

$$h = \alpha \times (dbh)^\beta \times \varepsilon \quad (4)$$

In Eq. (4),  $h$  is height in meter,  $dbh$  the diameter at breast height in cm,  $\alpha$  and  $\beta$  the parameters, and  $\varepsilon$  is the random error. Natural logarithm was applied to  $h$  and  $dbh$  in Eq. (4) to obtain the following linearized form (Eq. 5), where  $\varepsilon'$  is the additive error.

$$\text{Ln}(h) = \text{Ln}(\alpha) + \beta \text{Ln}(\text{dbh}) + \varepsilon' \quad (5)$$

### Developing biomass allometric equations

Similar to dbh–h allometry, we used scatter plots to identify the theoretical distribution that fitted best with tree biomass. For the basal diameter  $d_{20}$  (diameter at 20 cm above the ground), the diameter at breast height (dbh) and the crown diameter ( $c_d$ ), the power law model was revealed to be the most plausible theoretical equation that could be used to fit the biomass data (Supplementary Information). We therefore built for each of the tree biomass components (leaf, branch and stem), an allometric equation using the following linearized form of the power law model.

$$\text{Ln}(Y) = \text{Ln}(\alpha) + \beta \text{Ln}(X) + \varepsilon' \quad (6)$$

where Y denotes the leaf biomass (LB), branch biomass (BB) or stem biomass (SB); X stands for  $d_{20}$ , dbh or  $c_d$ ;  $\text{Ln}(\alpha)$  and  $\beta$  are regression coefficients, and  $\varepsilon'$  denotes the residual variance.

We used the same equation (Eq. 6) to estimate the parameters for the aboveground biomass (leaf plus branch plus stem) allometric models. Predictors for the models were  $d_{20}$ , dbh or  $c_d$ . The best fitted model was selected using adjusted determination coefficient ( $R^2$ ), residual standard error (RSE), root mean squared error (RMSE), and Akaike information criterion (AIC) (Burnham and Anderson 2002; Zeng et al. 2011; Vahedi et al. 2014). AIC is a likelihood-based measure of model fit that accounts for the number of parameters estimated in a model (i.e. models with large numbers of parameters are penalized more heavily than those with smaller numbers of parameters), such that the model with the lowest AIC has the best fit, given the number of parameters included. AIC takes into account the number of parameters in the models and penalize them accordingly (Burnham and Anderson 2002; Chave et al. 2005).

Based on the selected aboveground biomass model, we further developed two allometric Eqs. (7) and (8) using total height as additional independent variable. We tested whether additional use of total height or/and crown diameter as predictor (Ploton et al. 2016) would improve the precision of the estimates. Because separate use of potentially correlated independent variables in regression equations could give rise to collinearity (Sileshi 2014), we only considered the

allometric equation that combined dbh (or  $d_{20}$ ) with two additional variables (tree height and crown diameter) as single predictor variable:

$$\text{Ln}(\text{AGB}) = \text{Ln}(\alpha) + \beta \text{Ln}(\text{dbh}^2 \times h) + \varepsilon_1 \quad (7)$$

$$\text{Ln}(\text{AGB}) = \text{Ln}(\alpha) + \beta \text{Ln}(c_d \times \text{dbh}^2 \times h) + \varepsilon_1 \quad (8)$$

The use of natural logarithmic transformations in Eqs. (5), (6), (7) and (8) helped to normalize the response variable, and thus to meet the prerequisites of linear regression for simple estimation of the parameters. Since logarithmic transformation equations induced systematic bias in the estimation of the response (in the original values), a correction factor (CF) was computed to adjust the bias using the following equation (Baskerville 1972).

$$\text{CF} = \exp(\text{RSE}^2/2) \quad (9)$$

where RSE is the residual standard error of the regression.

Total carbon stock of a tree has been evaluated by the sum of all the carbon contents of leaves, branches and stem of the tree. The percentage of carbon in fresh biomass and in each component of the tree, as well as in the whole tree were calculated based on carbon content percentage in the dry biomass of leaves, branches and stem. All statistical analyses were performed using the statistical software R 3.2.2 (R Development Core Team 2016).

## Results and discussion

### *Vitellaria paradoxa* tree height–diameter and biomass component equations

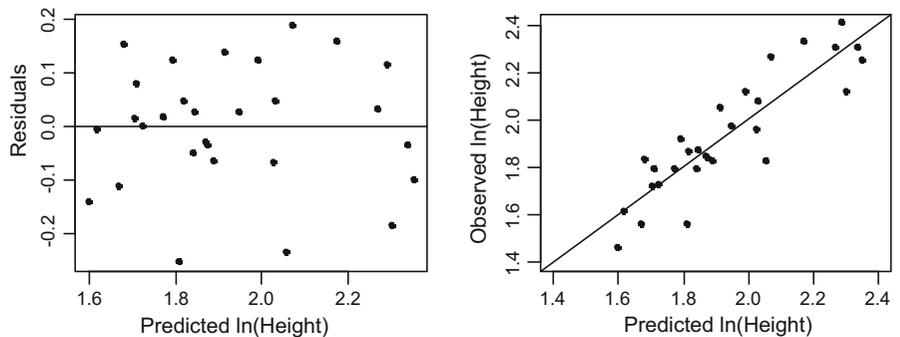
*Vitellaria paradoxa* tree height and dbh fitted well with the power law model (Supplementary Information). Thus our first hypothesis is accepted. The indicators for goodness of fit and correction factors obtained from the linearised form of the power law model (Eq. 5), are summarized in Table 2. The dbh–h model coefficients were significant ( $P < 0.001$ ), with 78.45% of variance explained. In addition, the plots of the observed versus predicted values of height showed a 1:1 linear trend (Fig. 2). Allometric dbh–h models (linear and non-linear) are often used to describe the relationship between tree diameter and height (Fang

**Table 2** Fitted allometric equations (based on independent variables:  $d_{20}$  in cm; dbh in cm and  $c_d$  in m) for estimation of height and biomass of tree components

Model	Predictor	Parameter	Est.	SE	P value	R <sup>2</sup> (%)	RSE	RMSE	AIC	CF	
Height	Equation 5	Intercept	$\ln(\alpha)$	0.64	0.12	< 0.001	78.45	0.117	0.113	- 38.12	1.007
		dbh	$\beta$	0.47	0.05	< 0.001					
Stem biomass	Equation 6	Intercept	$\ln(\alpha)$	- 2.87	0.21	< 0.001	96.63	0.167	0.161	- 17.57	1.014
		$d_{20}$	$\beta$	2.03	0.07	< 0.001					
		Intercept	$\ln(\alpha)$	- 2.01	0.24	< 0.001	94.39	0.216	0.208	- 2.79	1.023
		dbh	$\beta$	1.87	0.09	< 0.001					
Branch biomass	Equation 6	Intercept	$\ln(\alpha)$	- 4.59	0.33	< 0.001	95.93	0.264	0.255	9.06	1.036
		$d_{20}$	$\beta$	2.91	0.11	< 0.001					
		Intercept	$\ln(\alpha)$	- 3.49	0.23	< 0.001	97.36	0.213	0.205	- 3.46	1.023
		dbh	$\beta$	2.73	0.08	< 0.001					
		Intercept	$\ln(\alpha)$	- 0.52	0.39	0.187	83.39	0.534	0.516	49.88	1.153
		$c_d$	$\beta$	2.99	0.25	< 0.001					
		Intercept	$\ln(\alpha)$	- 3.53	0.47	< 0.001	81.96	0.367	0.355	28.15	1.069
		$d_{20}$	$\beta$	1.78	0.16	< 0.001					
Leaf biomass	Equation 6	Intercept	$\ln(\alpha)$	- 2.79	0.41	< 0.001	80.90	0.378	0.365	29.81	1.074
		dbh	$\beta$	1.65	0.15	< 0.001					
		Intercept	$\ln(\alpha)$	- 1.26	0.25	< 0.001	83.68	0.349	0.337	25.25	1.063
		$c_d$	$\beta$	1.97	0.16	< 0.001					

SE standard error, R<sup>2</sup> adjusted R square, RSE residual standard error, RMSE root mean squared error, AIC akaike information criterion, CF correction factors

**Fig. 2** Residuals versus predicted values and observed versus predicted values of total height. Predicted values are obtained from Eq. 5 (Table 2)



and Bailey 1998; Chave et al. 2005); and linearized power law model (log–log) described as the most parsimonious (Nogueira et al. 2008; Feldpausch et al. 2010; Mensah et al. 2017). The good fit of the log–log model to the dbh–height data is consistent with previous reports (Chave et al. 2005; Feldpausch et al. 2010; Mensah et al. 2016a, 2017), confirming the suitability of log–log model for species-specific dbh–h relationships. The value of the dbh–h explained variance suggests some variation in height for

relatively similar values of dbh, and that both dbh and height would be important for tree biomass estimation.

Leaf biomass, branch biomass and stem biomass were estimated from basal diameter, diameter at breast height and crown diameter, again using the power law model (Xiang et al. 2016). The results of the fitted allometric equations showed for all the biomass components higher explained variance (80.9–97.4%). The explained variance was however,

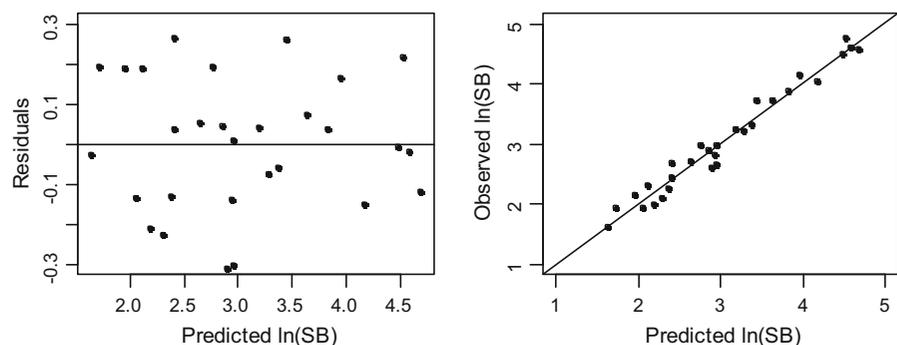
lower for leaf biomass models than for branch and stem biomass models, as also reported in previous studies (Morote et al. 2012; Mensah et al. 2017). These results suggest that foliage allometries are less responsive to tree size than branch and stem allometries. This is probably because leaves are more sensitive to light exposure than branches and stem (Antin et al. 2013). For stem biomass models, Eq. (6) including basal diameter as single predictor, i.e.  $SB = 1.014 \times \exp(-2.87 + 2.03 \ln(d_{20}))$  provided higher  $R^2$  (96.63%), lower RSE 0.167, lower RMSE 0.161 and lower AIC  $-17.57$  and was the best fitting (Table 2). For branch biomass, the best statistical fits (higher  $R^2$ , lower RSE, lower RMSE, lower AIC and lower CF) were obtained with the Eq. (6) based on dbh as predictor. As for the leaf biomass, the results showed that model with crown diameter had the highest  $R^2$ , the lowest RSE, the lowest RMSE, the lowest AIC and the lowest CF (Table 2), and was therefore considered as the best fit. These results confirm our second hypothesis and indicate that the predictors are specific to biomass components, with basal diameter, dbh and crown diameter alone appearing as good predictor for stem biomass, branch biomass and leaf biomass respectively. The predictive abilities and accuracy of these models are demonstrated by the homoscedastic trend and good coincidence to the  $y = x$  linear equation shown in the diagnostic plots of residuals (and observed values) versus predicted values of stem biomass (Fig. 3), branch biomass (Fig. 4) and leaf biomass (Fig. 5).

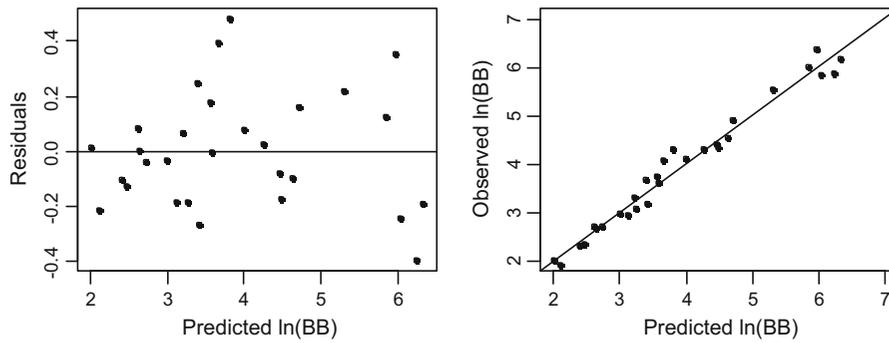
#### *Vitellaria paradoxa* aboveground biomass equations

There is an increasing and urgent need for reliable estimates of biomass and carbon stocks in tropical

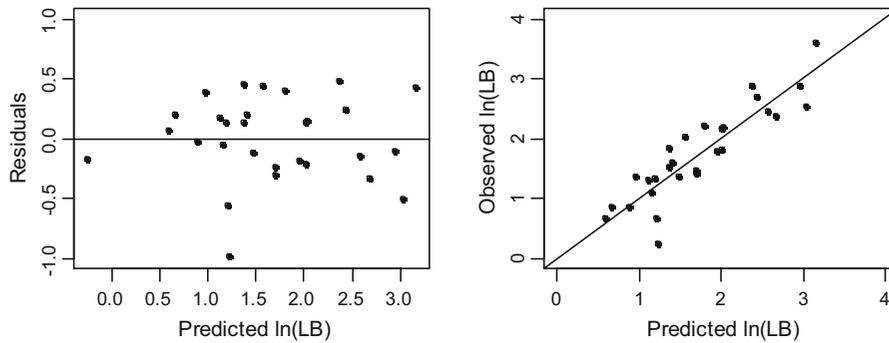
forests and savannas, in particular in West Africa where the information is lacking (UNFCCC 2006). The Kyoto protocol requires transparent reporting of vegetation and tree biomass changes, which implies the use of a precise procedure of quantifying tree biomass and its uncertainty. Five allometric tree biomass models were fitted for their relative performance in predicting aboveground biomass. The coefficients of regression, indicators for goodness of fit and correction factors for these allometric tree biomass equations are shown in Table 3. Adjusted coefficients of determination varied from 83 to 98%. Among models with single predictor (Eq. 6), the one with crown diameter showed the poorest fits (Table 3). Diameter at breast height was a better predictor of aboveground biomass than basal diameter, confirming our third hypothesis. Compared with model based on dbh alone, addition of height to dbh as compound variable ( $dbh^2 \times h$ ) did not significantly improve the statistical fits ( $R^2$ : 97.86 and 97.84%; RSE: 0.170 and 0.171; RMSE: 0.164 and 0.165; AIC:  $-16.47$  and  $-16.17$ ; Table 3). However, as hypothesized, adding crown diameter to dbh and height as compound predictor ( $c_d \times dbh^2 \times h$ ) reduced the RSE by 15% and made further significant change:  $R^2$ : 98.47%; RSE: 0.144; RMSE: 0.139; AIC:  $-26.23$ . Based on the selected model, the plots of residuals (and observed values) versus predicted values of AGB (Fig. 6), suggested homogeneity of residuals and  $y = x$  linear trend. These results indicate that the selected model (with  $c_d$  and  $dbh^2 \times h$  as predictors) appeared to be the most suitable, and can be used to predict AGB of *V. paradoxa* in the studied environment. Previous studies showed that dbh is the most commonly used independent variable (Henry et al. 2011; Mbow et al. 2013; Vahedi et al. 2014) since it is the easiest tree parameter to measure. However,

**Fig. 3** Residuals versus predicted values and observed versus predicted values of stem biomass (SB). Predicted values are obtained from Eq. 6 using  $d_{20}$  as best predictor (Table 2)





**Fig. 4** Residuals versus predicted values and observed versus predicted values of branch biomass (BB). Predicted values are obtained from Eq. 6 using dbh as best predictor (Table 2)



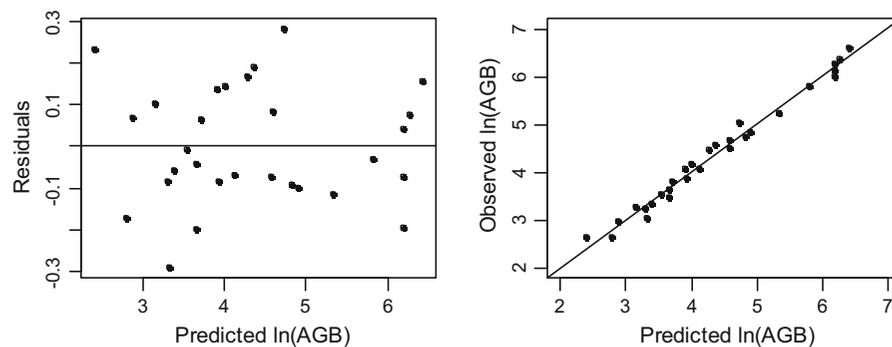
**Fig. 5** Residuals versus predicted values and observed versus predicted values of leaf biomass (LB). Predicted values are obtained from Eq. 6 using  $c_d$  as best predictor (Table 2)

**Table 3** Aboveground biomass (in Kg) allometric equations (based on independent variables:  $d_{20}$  in cm; dbh in cm and  $c_d$  in m) with coefficient estimates and statistic fits

Model	Predictor	Parameter	Est.	SE	<i>P</i> value	$R^2$ (%)	RSE	RMSE	AIC	CF	
AGB	Equation 6	Intercept	$\ln(\alpha)$	- 3.22	0.25	< 0.001	97.04	0.199	0.193	- 7.14	1.020
		$d_{20}$	$\beta$	2.59	0.09	< 0.001					
	Equation 7	Intercept	$\ln(\alpha)$	- 2.22	0.17	< 0.001	97.86	0.170	0.164	- 16.47	1.015
		dbh	$\beta$	2.43	0.07	< 0.001					
		Intercept	$\ln(\alpha)$	0.44	0.34	0.216	83.16	0.477	0.460	43.32	1.121
		$c_d$	$\beta$	2.65	0.22	< 0.001					
Equation 8	Intercept	$\ln(\alpha)$	- 2.81	0.20	< 0.001	97.84	0.171	0.165	- 16.17	1.015	
	$dbh^2 \times h$	$\beta$	0.98	0.03	< 0.001						
Equation 8	Intercept	$\ln(\alpha)$	- 2.24	0.16	< 0.001	98.47	0.144	0.139	- 26.23	1.010	
	$c_d \times dbh^2 \times h$	$\beta$	0.75	0.02	< 0.001						

according to Alvarez et al. (2012), models based upon dbh only may underestimate AGB especially in mature trees and may show uncertainty. The additional use of height and crown diameter in this study is

expected to account for variation in biomass of trees having the same diameter. The inclusion of tree height as a predictor in allometric models was studied by many authors (Chave et al. 2005; Ngomanda et al.



**Fig. 6** Residuals versus predicted values and observed versus predicted values of AGB. Predicted values are obtained from Eq. 8 using  $c_d \times dbh^2 \times h$  as best predictor

2014; Picard et al. 2015; Preece et al. 2015; Mensah et al. 2017). Mensah et al. (2017) and Ngomanda et al. (2014) reported improved biomass equations due to inclusion of tree height. In addition, the use of highly correlated variables such as dbh and height as a compound variable ( $dbh^2 \times h$ ) helps avoiding collinearity issues while accounting for within species variation of height for a given value of dbh (Mensah et al. 2017). Yet, some authors found that tree height might be undesirable variable due to the difficulties in accurate measurements (Peichl and Arain 2006). This would be mostly the case in complex and closed-canopy forest environments, in contrast to savannas and woodlands where tree height and crown diameter can be determined with more relative precision.

#### Averaged carbon content, biomass and carbon stock of *V. paradoxa* tree components

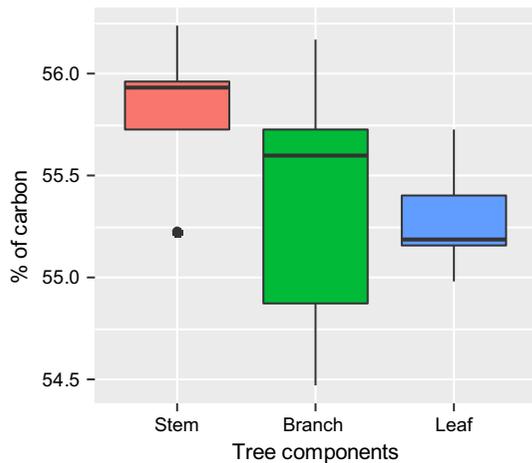
The percentage of carbon in leaves, branches and stem of *V. paradoxa* was 55.29, 55.37 and 55.82%, respectively (Table 4), and did not vary significantly between tree components ( $P$  value = 0.218), although

it decreased slightly from the stem to the leaves (Fig. 7). Thus, our fourth hypothesis was not confirmed. Altogether, the average carbon content of *V. paradoxa* in the aboveground compartment was 55.49%. Carbon content of 0.5 was recognized as an acceptable average to be used as conversion factor (Hoen and Solberg 1994; Redondo-Brenes 2007; Sarmiento et al. 2005). The obtained values of carbon content suggest that leaf biomass, branch biomass, stem biomass and AGB would be underestimated when applying the recommended value. Fonseca et al. (2012) made similar observation in Costa Rica, detecting underestimations of AGB between 4 and 6%. Our findings are also consistent with the one by Elias and Potvin (2003) who reported that the use of carbon fractions in the range of 0.45 and 0.50 might account for 10% negative difference when applied to the same site and the same set of data. Our results further showed that the average carbon content varied slightly among tree components. Ganeshaiyah et al. (2003) found that carbon content of tree components was dependent on the ash content which in turn, depends on the amount of structural components. In

**Table 4** Averaged carbon content, biomass and carbon stock in *V. paradoxa* tree components. Averaged values are based on the sampled individuals

Tree components	Mean carbon content (%) (from 5 samples)	Biomass (kg)	Carbon stock (kg)
Leaves	55.29 (0.26)	219.16	121.17
Branches	55.37 (0.61)	3314.00	1834.96
Stem	55.82 (0.34)	928.74	518.42
AGB	55.49 (0.49)	4461.95	2475.94

Data in parentheses represent standard deviation



**Fig. 7** Carbon content in *V. paradoxa* tree components

this study, the carbon content was found to be slightly higher in stems of *V. paradoxa*, followed by branches and leaves. Accordingly, Kraenzel et al. (2003) reported that woody tissues of trunk, roots, branches and twigs were higher carbon content pools than soft tissues of leaves, flowers and fine roots. The results are also in conformity with findings by Chauhan et al. (2009), Wani and Qaisar (2014), Fonseca et al. (2012) and Bayen et al. (2015). Specifically, Bayen et al. (2015) determined the average carbon content to be 48% in leaves and 54% in the wood of *Jatropha curcas* in Burkina Faso. Wani and Qaisar (2014) recorded an average carbon content of 46.39% in the stem wood of *Cedrus deodara* against 46.05 and 42.81% in its branches and leaves, respectively; 43.21% in the stem wood of *Fraxinus floribunda* against 42.42 and 36.70% in its branches and leaves, respectively; and 43.66% in the stem wood of *Ulmus wallichiana* against 43.03 and 36.41% in its branches and leaves, respectively. Fonseca et al. (2012) recorded an average carbon content of 48.11, 46.46 and 42.95% respectively for the stem wood, branches and leaves of *Vochysia guatemalensis* in Costa Rica. The estimated biomass and carbon stock varied with tree components (Table 4), branch biomass being the major component of AGB. The carbon stock followed the same trend as observed for the biomass, and was higher in the branches than in the leaves and stem (Table 4).

## Conclusion

The choice of an appropriate allometric model is critical for reducing uncertainties in tree biomass and carbon stock estimates. This study is among the first to develop allometric relationships for estimating AGB for socio-economically important species like *V. paradoxa* in West Africa sudanian savannahs. The power law model applied showed strong dbh-height allometry, which supports the need for incorporating tree height in *V. paradoxa* biomass allometric equations. Stem biomass and branch biomass were better predicted by stem characteristics (dbh and basal diameter) while crown diameter was the best predictor for foliage biomass. Tree crown has been largely ignored in both allometric theory and practical attempts to improve biomass estimates for regions where little or no directly measured biomass data exist. This study suggests that both tree height and crown diameter should be incorporated in biomass equations, and provides a detailed contribution for accurate estimation of aboveground biomass of *V. paradoxa* in savanna ecosystems. Estimating tree component biomass is useful for carbon stock and fire dynamic studies, as stem, branches and foliage have different physiological activities and fuel characteristics. The established models can be used to accurately predict the biomass of *V. paradoxa* tree components in dry areas or similar environments. However, the use of these allometric models to other sites would require knowledge of tree size structures, and a thorough review of their applicability to the studied plant community.

**Acknowledgements** The authors express their gratitude to the German Federal Ministry of Education and Research (BMBF) through the program WASCAL (West African Science Service Center on Climate Change and Adapted Land Use, [www.wascal.org](http://www.wascal.org)) for funding this research. The authors are very grateful to the Ministry of Environment of Burkina Faso for the permission to cut trees in the study sites, and to work in protected areas. Our thanks are extended to the field assistants and local people who helped in data collection. Finally, we would like to thank the anonymous reviewers for their helpful comments that greatly improved this article.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

- Allen SE, Grimshaw HM, Rowland AP (1986) Chemical analysis. In: Moore PD, Chapman SB (eds) Methods of plant ecology. Blackwell, Oxford, pp 285–344
- Alvarez E, Duque A, Saldarriaga J, de las Salas G, del Valle I, Lema A, Moreno F, Orrego S, Rodríguez L (2012) Tree above-ground biomass allometries for carbon stocks estimation in the natural forests of Colombia. *For Ecol Manag* 267:297–308
- Antin C, Péliissier R, Vincent G, Couteron P (2013) Crown allometries are less responsive than stem allometry to tree size and habitat variations in an Indian monsoon forest. *Trees* 27:1485–1495
- Arbonnier M (2002) Arbres, arbustes et lianes des zones sèches d’Afrique de l’Ouest. Versailles
- Baker TR, Phillips OL, Malhi Y, Almeida S, Arroyo L, Di Fiore A, Erwin T, Killeen TJ, Laurance SG, Laurance WF (2004) Variation in wood density determines spatial patterns in Amazonian forest biomass. *Glob Change Biol* 10:545–562
- Baskerville G (1972) Use of logarithmic regression in the estimation of plant biomass. *Can J For Res* 2:49–53
- Basuki TM, Van Laake PE, Skidmore AK, Hussin YA (2009) Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *For Ecol Manage* 257:1684–1694
- Bayala J, Ouédraogo S, Ong C (2009) Early growth performance and water use of planted West African provenances of *Vitellaria paradoxa* C.F. Gaertn (karité) in Gonsé, Burkina Faso. *Agrofor Syst* 75:117–127
- Bayen P, Bognounou F, Lykke AM, Ouédraogo M, Thiombiano A (2015) The use of biomass production and allometric models to estimate carbon sequestration of *Jatropha curcas* L. plantations in western Burkina Faso. *Environ Dev Sustain*. <https://doi.org/10.1007/s10668-015-9631-4>
- Boffa J-M (2015) Opportunities and challenges in the improvement of the shea (*Vitellaria paradoxa*) resource and its management Occasional Paper 24. World Agroforestry Centre, Nairobi
- Brown S (1997) Estimating biomass and biomass change of tropical forests: a primer. Food & Agriculture Organization, Rome
- Brown S (2002) Measuring carbon in forests: current status and future challenges. *Environ Pollut* 116:363–372
- Brown S, Gillespie AJR, Lugo AE (1989) Biomass estimation methods for tropical forests with applications to forest inventory data. *For Sci* 35:881–902
- Burnham KP, Anderson DR (2002) Model selection and multimodel inference: a practical information-theoretic approach. Springer Science & Business Media, New York
- Cai S, Kang X, Zhang L (2013) Allometric models for above-ground biomass of ten tree species in northeast China. *Ann For Res* 56:105–122
- Chambers JQ, dos Santos J, Ribeiro RJ, Higuchi N (2001) Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. *For Ecol Manag* 152:73–84
- Chauhan SK, Gupta N, Ritu Yadav S, Chauhan R (2009) Biomass and carbon allocation in different parts of agroforestry tree species. *Indian For* 135(7):981–993
- Chauhan SK, Sharma SC, Beri V, Ritu Yadav S, Gupta N (2010) Yield and carbon sequestration potential of wheat (*Triticum aestivum*) and poplar (*Populus deltoides*) based agri-silvicultural system. *Indian J Agric Sci* 80(2):129–135
- Chauhan SK, Sharma R, Sharma SC, Gupta N, Ritu (2012) Evaluation of poplar (*Populus deltoides* Bartr. Ex Marsh.) boundary plantation based agri-silvicultural system for wheat-paddy yield and carbon storage. *Int J Agric For* 2(5):239–246
- Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R (2004) Error propagation and scaling for tropical forest biomass estimates. *Philos Trans R Soc B Biol Sci* 359:409–420
- Chave J, Andale C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T (2005) Tree allometry and improved estimation of carbon stock and balance in tropical forests. *Oecologia* 145:87–99
- Chave J, Rejou Mecham M, Burquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martinez-Yrizar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Péliissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G (2014) Improved allometric models to estimate the above ground biomass of tropical trees. *Global Change Biol* 20:3177–3190
- Djomo AN, Picard N, Fayolle A, Henry M, Ngomanda A, Ploton P, McLellan J, Saborowski J, Adamou I, Lejeune P (2016) Tree allometry for estimation of carbon stocks in African tropical forests. *Forestry* 89:446–455
- Driessen P, Deckers J, Spaargaren O, Nachtergaele F (2001) In: Lecture notes on the major soils of the world. Food and Agriculture Organization (FAO), Rome
- Elias M, Potvin C (2003) Assessing inter-and intra-specific variation in trunk carbon concentration for 32 neotropical tree species. *Can J For Res* 33(6):1039–1045
- Fang Z, Bailey RL (1998) Height–diameter models for tropical forests on Hainan Island in southern China. *For Ecol Manag* 110:315–327
- Fayolle A, Doucet JL, Gillet JF, Bourland N, Lejeune P (2013) Tree allometry in Central Africa: testing the validity of pantropical multi-species allometric equations for estimating biomass and carbon stocks. *For Ecol Manage* 305:29–37
- Feldpausch TR, Banin L, Phillips OL, Baker TR, Lewis SL, Quesada CA, Affum-Baffoe K, Arets EMM, Berry NJ, Bird M, Brondizio ES, de Camargo P, Chave J, Djagbletey G, Domingues TF, Drescher M, Fearnside PM, Franca MB, Fyllas NM, Lopez-Gonzalez G, Hladik A, Higuchi N, Hunter MO, Iida Y, Salim KA, Kassim AR, Keller M, Kemp J, King DA, Lovett JC, Marimon BS, Marimon-Junior BH, Lenza E, Marshall AR, Metcalfe DJ, Mitchard ETA, Moran EF, Nelson BW, Nilus R, Nogueira EM, Palace M, Patino S, Peh KSH, Raventos MT, Reitsma JM, Saiz G, Schrod F, Sonke B, Taedoumg HE, Tan S, White L, Woll H, Lloyd J (2010) Height–diameter allometry of tropical forest trees. *Biogeosci Discuss* 7:7727–7793
- Fonseca W, Alice FE, Rey-Benayas JM (2012) Carbon accumulation in aboveground and belowground biomass and

- soil of different age native forest plantations in the humid tropical lowlands of Costa Rica. *New For* 43(2):197–211
- Fontès J, Guinko S (1995) Carte de la végétation et de l'occupation du sol du Burkina Faso. Notice explicative. Ministère de la Coopération Française. Projet Campus (88 313 101), Toulouse
- Ganeshaiah K, Barve N, Nath N, Chandrashekara K, Swamy M, Shaanker R (2003) Carbon allocation in different components of some tree species of India: a new approach for carbon estimation. *Curr Sci* 85(11):1528
- Gower ST, Kucharik CJ, Norman JM (1999) Direct and indirect estimation of leaf area index, f APAR, and net primary production of terrestrial ecosystems. *Remote Sens Environ* 70:29–51
- Henry M, Picard N, Trotta C, Manlay RJ, Valentini R, Bernoux M, Saint-André L (2011) Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. *Silva Fenn* 45(3B):477–569
- Hoehne HF, Solberg B (1994) Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. *For Sci* 40(3):429–451
- IPCC (2007) Climate change: mitigation. Contribution of Working Group III to the Fourth Assessment Report
- Jana BK, Biswas S, Majumder M, Roy PK, Mazumdar A (2009) Comparative assessment of carbon sequestration rate and biomass carbon potential of young *Shorea robusta* and *Albizia lebbek*. *Int J Hydro-Clim Eng Assoc Water Environ-Model* 1:1–15
- Jasaw GS, Saito O, Takeuchi K (2015) Shea (*Vitellaria paradoxa*) butter production and resource use by urban and rural processors in Northern Ghana. *Sustainability* 7:3592–3614
- Jibrin A, Abdulkadir A (2015) Allometric models for biomass estimation in Savanna Woodland Area, Niger State, Nigeria. *Int J Environ Chem Ecol Geol Geophys Eng* 9:270–278
- Ketterings QM, Coe R, van Noordwijk M, Palm CA (2001) Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *For Ecol Manag* 146:199–209
- Kraenzel M, Castillo A, Moore T, Potvin C (2003) Carbon storage of harvest-age teak (*Tectona grandis*) plantations, Panama. *For Ecol Manag* 173(1):213–225
- Kuyah S, Dietz J, Muthuri C, Jamnadass R, Mwangi P, Coe R, Neufeldt H (2012) Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *Agric Ecosyst Environ* 158:225–234
- Lamien N, Ouédraogo SJ, Diallo OB, Guinko S (2004) Productivité fruitière du karité (*Vitellaria paradoxa* Gaertn. CF, Sapotaceae) dans les parcs agroforestiers traditionnels au Burkina Faso. *Fruits* 59:423–429
- Litton CM, Boone Kauffman J (2008) Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Biotropica* 40:313–320
- Lovett P (2004) The shea butter value chain: production, transformation and marketing in West Africa. Technical Report No. 2, USAID West Africa Trade Hub
- Lovett PN, Haq N (2000) Evidence for anthropic selection of the sheanut tree (*Vitellaria paradoxa*). *Agrofor Syst* 48:273–288
- Mbow C, Verstraete MM, Sambou B, Diaw AT, Neufeldt H (2013) Allometric models for aboveground biomass in dry savanna trees of the Sudan and Sudan-Guinean ecosystems of Southern Senegal. *J For Res* 19:340–347
- Mensah S, Veldtman R, du Toit B, Glèlè Kakai R, Seifert T (2016a) Aboveground biomass and carbon in a South African mistbelt forest and the relationships with tree species diversity and forest structures. *Forests* 7:79
- Mensah S, Glèlè Kakai R, Seifert T (2016b) Patterns of biomass allocation between foliage and woody structure: the effects of tree size and specific functional traits. *Ann For Res* 59(1):49–60
- Mensah S, Veldtman R, Seifert T (2017) Allometric models for height and aboveground biomass of dominant tree species in South African Mistbelt forests. *South For J For Sci* 79(1):19–30
- Meyer T, D'Odorico P, Okin GS, Shugart HH, Caylor KK, O'Donnell FC, Bhattachan A, Dintwe K (2014) An analysis of structure: biomass structure relationships for characteristic species of the western Kalahari, Botswana. *Afr J Ecol* 52:20–29
- Montagu KD, Düttmer K, Barton CVM, Cowie AL (2005) Developing general allometric relationships for regional estimates of carbon sequestration—an example using *Eucalyptus pilularis* from seven contrasting sites. *For Ecol Manag* 204:115–129
- Morote FAG, Serrano FRL, Andrés M, Rubio E, Jimenez JLG, de las Heras J (2012) Allometries, biomass stocks and biomass allocation in the thermophilic Spanish juniper woodlands of Southern Spain. *For Ecol Manag* 270:85–93
- Návar J (2009) Biomass component equations for Latin American species and groups of species. *Ann For Sci* 66:1–21
- Ngomanda A, Engone Obiang N, Lebamba J, Moundounga Mavourolou Q, Gomat H, Mankou GS, Loumeto J, Midoko Iponga D, Kossi Ditsouga F, Zinga Koumba R, Botsika Bobé KH, Mikala Okouyi C, Nyangadouma R, Lépengué N, Mbatchesi B, Picard N (2014) Site specific versus pantropical allometric equations: which option to estimate the biomass of a moist central African forest? *For Ecol Manag* 312:1–9
- Nogueira EM, Fearnside PM, Nelson BW, Barbosa RI, Keizer EWH (2008) Estimates of forest biomass in the Brazilian Amazon: new allometric equations and adjustments to biomass from wood-volume inventories. *For Ecol Manag* 256:1853–1867
- Paustian K, Cole CV, Sauerbeck D, Sampson N (1998) CO<sub>2</sub> mitigation by agriculture: an overview. *Clim Change* 40:135–162
- Peichl M, Arain MA (2006) Above-and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. *Agric For Meteorol* 140:51–63
- Picard N, Rutishauser E, Ploton P, Ngomanda A, Henry M (2015) Should tree biomass allometry be restricted to power models? *For Ecol Manag* 353:156–163
- Ploton P, Barbier N, Momo ST, Réjou-Méchain M, Boyemba Bosela F, Chuyong GB, Dauby G, Droissart V, Fayolle A, Goodman RC (2016) Closing a gap in tropical forest biomass estimation: taking crown mass variation into account in pantropical allometries. *Biogeosciences* 13:1571–1585
- Poulsen G (1981) Important forest products in Africa other than wood—a preliminary study (Project Report RAF/78/025)
- Preece ND, Lawes MJ, Rossman AK, Curran TJ, Van Oosterzee P (2015) Modelling the growth of young rainforest trees for

- biomass estimates and carbon sequestration accounting. *For Ecol Manage* 351:57–66
- R Core Team (2016) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <https://www.R-project.org/>
- Redondo-Brenes A (2007) Growth, carbon sequestration, and management of native tree plantations in humid regions of Costa Rica. *New For* 34(3):253–268
- Sarmiento G, Pinillos M, Garay I (2005) Biomass variability in tropical American lowland rainforests. *Ecotropicos* 18(1):1–20
- Sharma R, Chauhan SK, Tripathi AM (2016) Carbon sequestration potential in agroforestry system in India: an analysis for carbon project. *Agrofor Syst* 90(4):631–644
- Shirima DD, Munishi PKT, Lewis SL, Burgess ND, Marshall AR, Balmford A, Swetnam RD, Zahabu EM (2011) Carbon storage, structure and composition of miombo woodlands in Tanzania's Eastern Arc Mountains. *Afr J Ecol* 49:332–342
- Sileshi GW (2014) A critical review of forest biomass estimation models, common mistakes and corrective measures. *For Ecol Manag* 329:237–254
- Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C (2008) Greenhouse gas mitigation in agriculture. *Philos Trans R Soc B Biol Sci* 363:789–813
- Thomson AM, Calvin KV, Chini LP, Hurt G, Edmonds JA, Bond-Lamberty B, Frohking S, Wise MA, Janetos AC (2010) Climate mitigation and the future of tropical landscapes. *Proc Natl Acad Sci USA* 107:19633–19638
- UNFCCC (2006) Report of the conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol. 103
- Vahedi AA, Mataji A, Babayi-Kafaki S, Eshaghi-Rad J, Hodjati SM, Djomo A (2014) Allometric equations for predicting aboveground biomass of beech-hornbeam stands in the Hyrcanian forests of Iran. *J For Sci* 60:236–247
- Wani NR, Qaisar KN (2014) Carbon percent in different components of tree species and soil organic carbon pool under these tree species in Kashmir Valley. *Current World Environment* 9
- White F (1986) *La végétation de l'Afrique-Recherches sur les ressources naturelles*. Orstom-Unesco, Paris
- Xiang W, Zhou J, Ouyang S, Zhang S, Lei P, Li J, Deng X, Fang X, Forrester DI (2016) Species-specific and general allometric equations for estimating tree biomass components of subtropical forests in southern China. *Eur J For Res* 135:963–979
- Zeng WS, Zhang HR, Tang SZ (2011) Using the dummy variable model approach to construct compatible single-tree biomass equations at different scales—a case study for Masson pine (*Pinus massoniana*) in southern China. *Can J For Res* 41:1547–1554
- Zianis D, Mencuccini M (2004) On simplifying allometric analyses of forest biomass. *For Ecol Manag* 187:311–332