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Distribution and Carbon Sequestration Potential of *Cola Laurifolia* Mast.: A Dominant Native Riparian Species Along Permanent Rivers in Sub-Saharan Africa

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Abstract

Species-specific models for estimating aboveground biomass (AGB) are the accurate means of quantifying species' carbon pools. *Cola laurifolia* Mast., a dominant and multi-purpose riparian species along the Mouhoun River in Burkina Faso have a regressive population. Few scientific studies exist concerning this riparian species population and carbon stock capacity. This study aims to allow this gap by formulating a species-specific allometric model for assessing with direct method for *Cola laurifolia* leave, branches, stem and whole AGB. Parameters used to perform models are tree diameter at breast height (DBH), basal diameter at 20 cm (D20), height (H), and mean crown diameter (CD) using data from 30 trees. Population structure shows a low regeneration potential at all of the studied river zones (i.e. upstream, intermediate and downstream zones). The carbon stock was found to be 54.14 kg C tree^{-1} and 9.24 Mg C. ha^{-1}. The density of *C. laurifolia* was higher in downstream zone, and consequently the carbon stock was higher in these areas. The log-log linear model is the best-fitted form incorporated DBH and H as predictors. This form is best fitted for the three tree components (i.e. leaves, branches, stem) and the AGB. The AGB model is more accurate with high coefficient of determination and low RSE (R^2=0.92; RSE=0.28) contrasted with leaves models. The global model has the best goodness of fit because of a low relative error (-0.213 %) compared to the use of three component models. The accuracy of our species-specific model confirms the need to develop such models for greater accuracy in AGB estimations.

Keywords: Allometry, aboveground biomass; Burkina Faso; species distribution; Mouhoun River

Introduction

Global warming, caused by an increase in atmospheric greenhouse gas concentrations, is a major concern for scientists, decision-makers and development agendas across the world. The planet's future climate will depend on the warming caused by past and future anthropogenic emissions of greenhouse gasses and natural climate variability (IPCC, 2014).

It is estimated that, 53% of these emissions are derived from timber harvesting, 30% from wood fuel harvesting and 17% from forest fires (Pearson et al., 2017). Therefore, woody debris harvested by local population represent an important pool of carbon (Ifo et al., 2017). Studies have demonstrated the carbon sequestration potential of different land uses in tropical areas (Dayamba et al., 2016; Mbow et al., 2014), showing that beyond the daily needs of local populations, these land uses could make great contributions to climate change mitigation (Hahn-hadjali & Thiombiano, 2000; Ouedraogo et al., 2005; Barbault & Chevassus-au-Louis, 2005; Mbayngone & Thiombiano, 2011; Traore et al., 2011).

Globally, initiatives such as the Clean Development Mechanism (CDM - initiated under the Kyoto Protocol) and Reducing Emissions from Deforestation and Degradation in Developing Countries ($REDD^+$ - initiated under the United Nations Framework Convention on Climate Change [UNFCCC]) are making financial resources available to enhance carbon sequestration and reduce emissions from land use change (Gofc-Gold, 2008). Therefore, information about biomass stocks in both the aboveground and belowground parts of trees is essential to begin carbon trading (Makungwa et al., 2013), assess sustainable production, and evaluate the impacts of various silvicultural practices (Santa Regina, 2000: Mankessi et al., 2022). The essential of carbon stock are evaluated in protected areas and tropical forests in growing plants (Ouédraogo et al., 2020), wood debris (Ifo et al., 2017), roots (Xie et al., 2020) and soils (Mankessi et al., 2022). Indeed, the management of protected areas that reduce deforestation also plays an important role in climate change mitigation and adaptation while delivering numerous ecosystem services and sustainable development benefits (Bebber & Butt, 2017).

The construction of allometric models will help to assess the dynamics (gains or losses) of biomass and carbon associated with changes in land use and management. More recently, equations have been developed for tropical forests of semi-arid areas of Africa (Mbow, 2009; Mbow et al., 2014), including green and semi-deciduous tropical forests in Ghana, Cameroon, the Democratic Republic of Congo and Gabon (Djomo et al., 2010; Henry et al., 2010; Fayolle et al., 2013;Ngomanda et al., 2014). Despite this, species-specific equations are recommended instead of generalized equations for accurate assessments of biomass and carbon stock (Daba & Soromessa, 2019). Species-specific allometric equations are therefore preferred because trees may differ in architecture as well as wood density (Ketterings et al., 2001). This calls for continued efforts to develop allometric equations for individual species to help progressively close current gaps in knowledges. The need to develop species-specific allometric equations is particularly relevant to species with high socio-economic values and high carbon capture and trading potential. Such values can raise landholders' interests in the improved management of these species.

Cola laurifolia Mast. is a riparian species with a great ecological and socio-economic importance (Idu et al., 2014). This species is commonly encountered in the first line of riverbank vegetation communities in Sub-Saharan Africa. The fruits of the species is consumed by local populations. Traditionally, the leaves are used as medicine, while the wood and branches are used as firewood, and to make bows (Idu et al., 2014). This species is important economically because of its high tannin content, which is useful in industry (Ejikeme et al., 2014). A recent study in Burkina Faso revealed that species in riparian forests including *C. laurifolia* store large amounts of carbon compared to other species (Dimobe, Goetze, et al., 2018) indicating that these species should be given special attention to foster their sustainability.

From the socio-economical savanna tree species occurring in Burkina Faso, there are specific allometric models developed for some of them, namely *Jatropha curas* (Bayen et al., 2015), *Vitellaria paradoxa* (Dimobe, Mensah, et al., 2018), *Diospyros mespiliformis* (Ouédraogo et al., 2020), *Pterocarpus erinaceus* (Ganamé et al., 2020), *Balanites aegyptiaca* (Ouédraogo et al., 2020), and for some species of Vachelia and Senegalia genus (Bayen et al., 2020). However, there are no specific models for estimating the biomass of *C. laurifolia* despite its socio-economic and ecological importance (Sambaré et al., 2010). The potential additional value of that species in the carbon market could help to stimulate its improved management. The current work will provide efficient biomass data and carbon assessment tools for *C. laurifolia* broad-scale carbon value quantifying.

This study has two specifics objectives namely to show the species state of population through diameter size classes distribution and to develop a species-specific allometric equation to predict the biomass of *C. laurifolia* along the Mouhoun river in Burkina Faso.

Methodology

Study area

The Mouhoun river is located in in the southern part of Burkina Faso at Batié, along the Mouhoun river between longitudes 2°41’-2°46’W and latitudes 9°29’-9°47’N. The study site represents a downstream position (see Figure 1) of the river and was selected because of the high density of *C. laurifolia* occurring there. The study site lies in the south Sudanian phytogeographical zone, which is dominated by steppe, savannas and dry forests (Fontès & Guinko, 1995). The annual rainy season occurs between May and October. The average annual rainfall at the study site for the period 1981-2011 was 1000 mm (Meteorological Service of Burkina Faso 2013). The area is marked by relatively low seasonal temperature ranges (20-25 °C) (Meteorological Service of Burkina Faso 2013). The main soil types encountered in the study area are leached ferruginous and eutrophic brown soils. The prominent species in the study area are *Isoberlinia doka* Craib & Stapf., *Vitellaria paradoxa* C.F. Gaertn., *Burkea africana* Hook., *Daniellia oliveri* (Rolfe) Hutch. & Dalz.and *Khaya senegalensis* (Desv.) A. Juss. in the savannas, and *Pterocarpus santalinoides* DC., *Cola laurifolia* Mast., *Parinari congensis* F. Didr., *Diospyros mespiliformis* Hochst. ex A. DC., *Syzygium guineense (Willd.)* DC., *Cassipourea congoensis* R. Br. ex DC. and *Diospyros elliotii (*Hiern) F.White in the riparian forests.

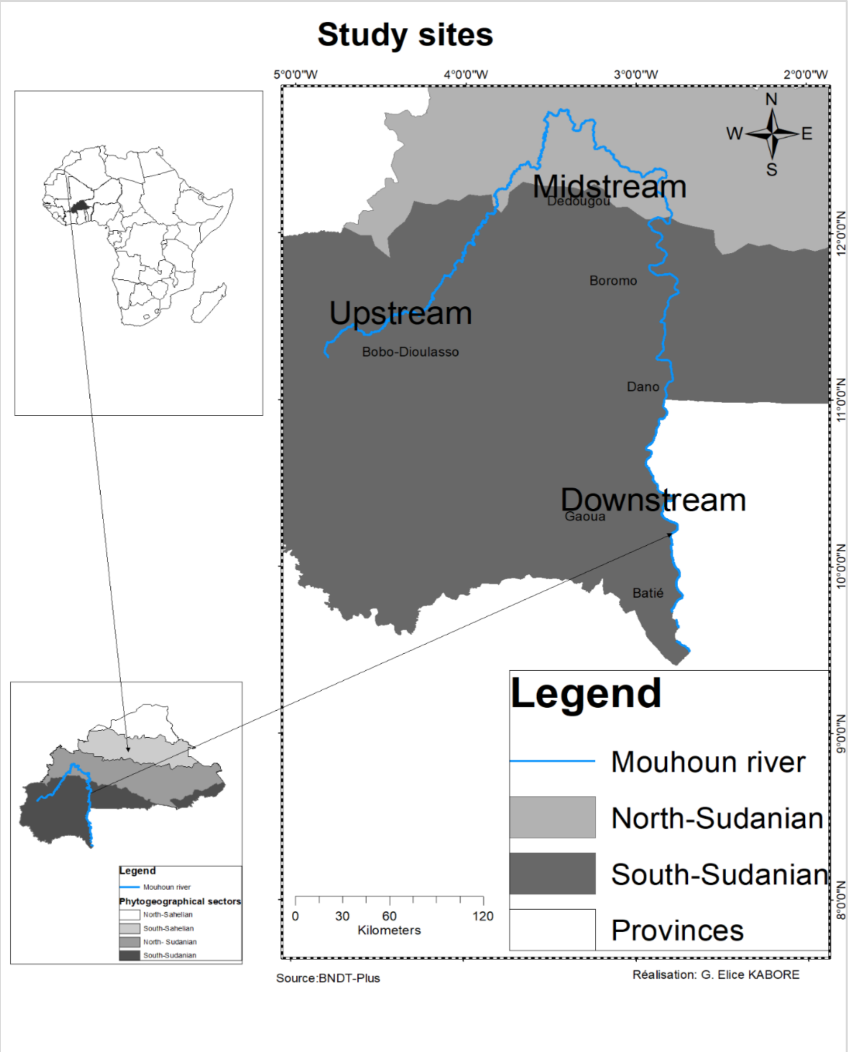


Figure 1. Location of the study area in Burkina Faso, West Africa

Study species

Cola laurifolia also known as "Kola feuille de Laurier" in French and "Tamtiyè" in Birifor is a multi-purpose tree. It reaches 8-25 m height, 80 cm diameter and belongs to the family Malvaceae (Arbonnier, 2019; Thiombiano et al., 2012). It is one of the main riparian species of permanent and semi-permanent rivers in Burkina Faso (Sambaré et al., 2010)One feature of the species' socio-economic importance is its high tannin content. Indeed, phytochemical analysis showed the high rate (i.e. 1180 mg/100 g) of tannins found in the bark of *C. laurifolia* (Ejikeme et al., 2014). This tannin can be extracted and used for domestic medicinal purposes (i.e. treatment of tonsillitis, pharyngitis, hemorrhoids and skin eruptions, diarrhoea and intestinal bleeding) and various commercial applications (i.e. domestic protective anti-predator substances, pesticides, plant growth regulator, …) (Ejikeme et al., 2014). In Nigeria, the Idoma people have long used *C. laurifolia* seeds (by maceration) to treat arthritis (Idu et al., 2014).

Forest inventory and biomass data

The study area was stratified into three major segments of the river: upstream, midstream and downstream. A first phase forest inventory was carried out using 360 plots which consisted of 500 m² (10 m x 50 m) rectangular plot. These plots were established based on a stratified radom sampling scheme. A total of 134, 117 and 109 plots were established in upstream, downstream and midstream of the Mouhoun river, respectively (Figure 1). The plots were spread throughout a protected area (PA – the protected forest of Koulbi) and communal areas (CA). Diameter at breast height (DBH) and at 20 cm from ground was measured with a diameter tape, within each plot for individual trees having more than 5 cm DBH. Overall, 1986 individual trees of *Cola laurifolia* were measured. Trees were stratified by size into five DBH classes of 5-10; 10-15; 15-20; 20-25 and 25-30 cm). 30 trees were harvested and the number of individuals of the 5 diameter classes is respectively 10, 11, 4, 3 and 2. The height is measured with a graduate pole and the crown diameter with the metric tape.

The destructive sampling was undertaken in the field in December 2012, following the 6-step measurement protocol for each selected individual:

1- For each selected individual tree, the diameter at 20 cm and the DBH, the length of the stem, the total tree height, and the mean crown diameter were measured.

2- The quadratic DBH was calculated for individuals forking before 20 cm above the ground

3- Each individual tree was then cut at the lowest point possible using a chain saw and the stem, branches and leaves were separated from felled trees. Each part is weighed to determine the fresh biomass weight of organs and entire tree.

4- One Subsample (discs) of the stem and branches per tree was collected and weighted in field using an electronic balance. For the leaves, 500 g were taken from each tree. Subsamples of the 3 organs were taken to the laboratory for drying to assess the dry biomass weight. they were oven dried at 105° C for the branches and stem, and 70° C for the leaves until the constant weight (Picard et al. 201).

5- To assess the dry biomass of each component, the fresh mass (kg) weighed in the field was corrected for the moisture content of the sample.

6- For each individual tree, the total dry biomass weight was obtained by summing up the dry biomass weights of the three components.

The total dry biomass (TDB) per tree component was obtained using equation 1:

$$TDB = (DB_s/FB_s) \times TFB \quad (1)$$

where DB_s = Dry Biomass per sample, FB_s = Fresh Biomass per sample and TFB = Total Fresh Biomass

Data analysis

the first step is the DBH size class distribution of *C. laurifolia* and its population densities establishment in the three different zones along the river (i.e. upstream, intermediate, and downstream) and the two land uses (i.e. protected area-PA vs. communal area-CA). To determine if there were significant differences in mean DBH between the different river zones and land uses, an analysis of variance was conducted.

The second step was an assessment of the biomass carbon content and carbon stock in each tree. The organic carbon stored in the samples of *C. laurifolia* components was estimated by the ash method (Bayen et al., 2015; Chavan & Rasal, 2011). Composite samples were formed from the dry matter samples of the stem, branches and leaves to determine their total carbon content. These samples were crushed in a cutting mill. Five 2 g samples of each tree component were then collected from trees from the five DBH size classes and submitted for analysis at the Laboratory of Plant and Soil of the University Joseph Ki-ZERBO. 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 following formulae given by Allen et al. (1986):

$$Ash\ (\%) = (W3 - W1)/(W2 - W1) \times 100 \quad (2)$$

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

$$Carbon = Biomass \times \%\ carbon \quad (4)$$

where 0.58 is the content of carbon in the organic matter, *W1* is the weight of crucibles, *W2* is the weight of the oven-dried grounded samples + crucibles, and *W3* is the weight of the ash + crucibles.

The total amount of organic carbon in each tree was assessed by summing up the quantity of organic carbon in the leaves and wood (stem and branches), which were calculated separately.

Allometric model data analysis

We performed equations of each part (stem, branch, leaf) and the whole tree to establish the relationships between their biomass and predictors variables (i.e. DBH, D20, mean crown diameter (MCd) and total height (H)). Biomass allocation pattern and the relationship between DBH and biomass fractions of each component was explored graphically (Dimobe, Mensah, et al., 2018). Bivariate and multivariate relationships between the components biomass and predictors variables were checked for each biomass component. The relationship between tree diameter and height was explored using scatter plots (Mensah at al. 2016).

Seemingly, the relationship between biomass and predicator variables was first explored to identify outliers but with cook's distance of residuals and the nature of correlation. Then, tree components biomass and predictors variables relationship was graphically explored with the pairwise scatter plot (Ganamé et al., 2020; Ouédraogo et al., 2020). This method suggested the power low model as appropriate for *Cola laurifolia*.

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

where Y is the biomass, X the predictors, ε the random error, and β0 and β1 the regression coefficients. This model was linearized, as follows:

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

where ln is the natural logarithm, Y the biomass, X the predictors, ε the random error, and β0 and β1 the regression coefficients

To minimize bias, the diameter-height relationship is advised whenever possible (Chave et al. 2014). Non-linear allometric equations (5), (6) (7) and (8) were generated for stem, branch, leaves and aboveground components. Equations (5) with only DBH, as predictor variable: equation (6), DBH and Tl as predictor variables and equation (7), equation (7) with DBH and H fitted as predictor variables; and equation (8), DBH is fitted with height and crown diameter as additional predictor variables. The three equations of component biomass (Yi) were fitted as follows:

$$ln\,(Yi) = ln\,(\alpha) + \beta ln\,(DBH) \quad (5)$$

$$ln\,(Yi) = ln\,(\alpha) + \beta ln\,(DBH) + \gamma \ln\,(\,SL) \quad (6)$$

$$ln\,(Yi) = ln\,(\alpha) + \beta\, ln\,(DBH^2\, x\, h) \quad (7)$$

$$ln\,(Yi) = ln\,(\alpha) + \beta ln\,(DBH^2 \times h) + \gamma ln\,(Cd) \quad (8)$$

Seemingly Unrelated Regressions (SUR) were used to fit the of allometric equations of each part biomass and total aboveground biomass to realize the additivity property between tree biomass components, achieved through constraint on equation parameters(Parresol, 1999; Dimobe, Goetze, et al., 2018; Ganamé et al., 2020). The advantage by using SUR method is that it allows for fitting simultaneously the biomass equations, thus accounts for correlations between regressions residuals (Dimobe, Mensah, et al., 2018). In the additive system, tree component equation and total aboveground biomass equation are built separately from equation (5)-(8) as follow:

For Equation (5)

$$\ln(Yl) = \ln(\alpha_l) + \beta_l \ln(DBH) \quad 5.1$$

$$\ln(Yb) = \ln(\alpha_b) + \beta_b \ln(DBH) \quad 5.2$$

$$\ln(Ys) = \ln(\alpha_s) + \beta_s \ln(DBH) \quad 5.3$$

$$AGBt = \boldsymbol{\alpha_l DBH^{\beta l} \times cf_l + \alpha_b DBH^{\beta} \times cf_b + \alpha_s DBH^{\beta s} \times cf_s}$$

Where *Yl*, *Yb*, *Ys* and *AGBt* are the stem, branch, leaf and total aboveground biomass, respectively; α and β are the regression coefficients and cf is the correction factor associated with these regressions.

For Equation (6)

$$\ln(Yl) = \ln(\alpha_l) + \beta_l \ln(DBH) + \gamma \ln(SL) \quad 6.1$$

$$\ln(Yb) = \ln(\alpha_b) + \beta_b\, ln(DBH) + \gamma ln(SL) \quad 6.2$$

$$\ln(Ys) = \ln(\alpha_s) + \beta_s\, ln(DBH) + \gamma ln(SL) \quad 6.3$$

$$AGBt = \boldsymbol{\alpha_l (DBH)^{\beta l} \times (SL)^{\gamma} \times cf_l + \alpha_b (DBH)^{\beta b} \times (SL)^{\gamma} \times cf_b + \alpha_s (DBH)^{\beta s} \times (SL)^{\gamma} \times cf_s}$$

For Equation (7)

$$\ln(Yl) = \ln(\alpha_l) + \beta_l \ln(DBH^2 \times H) \quad 7.1$$

$$\ln(Yb) = \ln(\alpha_b) + \beta_b \ln(DBH^2 \times H) \quad 7.2$$

$$\ln(Ys) = \ln(\alpha_s) + \beta_s \ln(DBH^2 \times H) \quad 7.3$$

$$\mathbf{AGB} = \boldsymbol{\alpha_l (DBH^2 \times H)^{\beta l} \times cf_l + \alpha_b (DBH^2 \times H)^{\beta b} \times cf_b + \alpha_s (DBH^2 \times H)^{\beta s} \times cf_s}$$

For Equation (8)

$$\ln(Yl) = \ln(\alpha_l) + \beta_l \ln(DBH^2 \times H) + \gamma \ln(MCd) \quad 8.1$$

$$\ln(Yb) = \ln(\alpha_b) + \beta_l \ln(DBH^2 \times H) + \gamma \ln(MCd) \quad 8.2$$

$$\ln(Ys) = \ln(\alpha_s) + \beta_l \ln(DBH^2 \times H) + \gamma \ln(MCd)$$
8.3

$$\mathbf{AGBt} = \alpha_l(DBH^2 \times H)^{\beta l} \times cf_l + MCd^{\gamma l} + \alpha_b(DBH^2 \times H)^{\beta b} \times cf_b + MCd^{\gamma b} + \alpha_s(DBH^2 \times H)^{\beta s} \times cf_s + MCd^{\gamma s}$$

The log-transform introduces a systematic bias that is generally corrected with a correction factor (CF) estimated from the standard error of the estimate (SEE) (Sprugel, 1983), the correction factor will be multiplied by the anti-log of the intercept of the equations to eliminate bias introduced by log transformation of the data.

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

The best species-specific equation selection and validation was based on the values of adjusted R^2, root mean squared error (RMSE), Akaike information criterion (AIC), percent relative standard errors (PRSE, %) and mean absolute deviation (MAD, %), as suggested by Chave et al. (2014) and Mensah et al. 20216. PRSE is defined as follows:

$$PRSE = 100 \times \frac{SE}{|\theta|}$$

The model selection and validation followed the step-down approach described by (Zuur et al., 2007) until the optimal model was found (we looked for lowest Akaike Information Criterion [AIC], highest adjusted [R^2], low residual standard error [RSE]).
The model validation in regard to the assumptions of normality, homoscedasticity, independence and linearity (Makungwa et al., 2013) was done using the Shapiro–Wilk test, Breush–Pagan test, Durbin–Watson test and Ramsey Reset test, respectively (Picard et al., 2012). The model goodness of fit was assessed using the RSE.
All the analyses were performed in R software (R development Core 2021) version 4.1.2.

Assessment of the accuracy of existing allometric equations for evaluating biomass and carbon stocks of C. laurifolia

The existing allometric equations we used were the quadratic equation developed by (Brown et al., 1997) for dry forest, the three equations developed by (Mbow et al., 2014) for savanna ecosystems and the pantropical equation developed by (Chave et al., 2014). We compared the predicted values of these models to the observed measures in our study using the relative error calculated from equation 7.

$$\%\ Relative\ error = \frac{(predited\ biomass - observed\ biomass)}{observed\ biomass} \times 100$$
(7)

Results

Structure and distribution of C. laurifolia along the Mouhoun River

Along the Mouhoun River, the density of *C. laurifolia* varies in the different river zones. In the PA, the upstream zone had the highest density (140±276 ind. ha^{-1}), while in the CA the downstream zone had the highest density (164±159 ind. ha^{-1}) (Table 1). The altitude decreases from the upstream to the downstream zone by at least 20 m.

The diameter size class distribution shows a generally young population of *C. laurifolia*. These populations have poor regeneration potential, with the first size class (i.e. 5-10 cm DBH) containing low numbers of individuals (Figure 2). In the CA, *C. laurifolia* has low numbers of individuals in both the upstream and intermediate zones (68±138 and 60±131, respectively) but higher numbers of individuals in the downstream (Table 1).

Table 1. Density of *C. laurifolia* at the different zones along the Mouhoun River

Land uses	River zones	DBH (cm)		Density (ind.ha^{-1})	Altitude (m)
		Mean	Range		
Protected areas	Upstream	20,10±10,46	5.09-71.30	140±276	279
	Intermediate	15,14±8,47	5.09-52.52	117±169	255
	Downstream	21.64	7.38-163.38	131±125	225
Communal areas	Upstream	20,24±11,09	5.14-124.14	68±138	275
	Intermediate	18,93±9,94	5.09-52.52	60±131	254
	Downstream	26.05	5.73-92.31	164±159	221

The mean DBH is significantly higher in the downstream compared to others river zones in the PA and CA (F=33.71; Df=2; P < 4.273e-14) (Table 2 and 3). The interaction between land uses and river zones is significant when considering the mean diameter (F=3.28; Df=2; P=0.039). The density of *C. laurifolia* varies significantly with the river zones in the CA (F=16.21; Df=2; P= 1.865e-07), and there is also a significant difference in density variation between the two land uses and the river zones (F=3.93; Df=2; P=0.02) (Tables 2 and 3). By using the Least Significant Difference (LSD) test, the density varies significantly with land use in upstream and intermediate (Table 3).

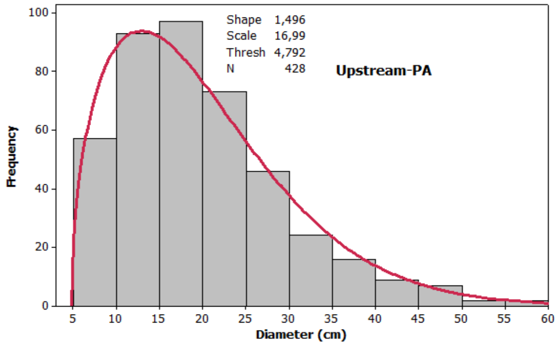
Table 2. ANOVA of river zones and land uses by diameter and density

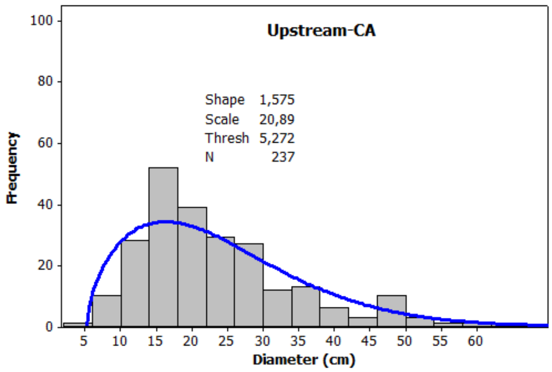
	Diameter (cm)			Density (ind./ha)		
	F	*P*-values	Df	F	*P-value*	Df
Land uses	1.0437	0.30769	1	2.7005	0.10124	1
River zones	33.7196	4.273e-14***	2	16.2164	1.865e-07 ***	2
Land-use*positions	3.2846	0.03864*	2	3.9434	0.02027 *	2

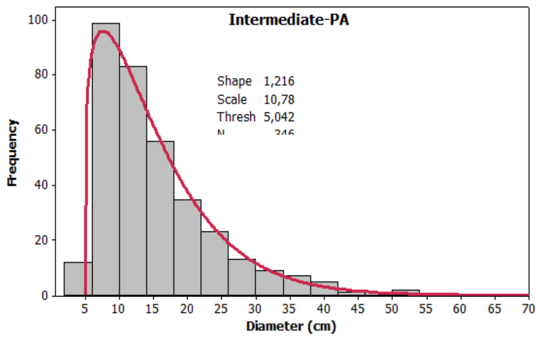
*: low significant; ***: High significant

Table 3. LSD from ANOVA of river zones and land uses by diameter and density

Land uses		**PA**			**CA**	
River zones	Upstream	Intermediate	Downstream	Upstream	Intermediate	Downstream
Mean Diameter	9.067831	9.244273	19.65108	8.725934	7.476588	26.35759
LSD			3.519			
Mean density	138	117	129	68	59	164
LSD			45			







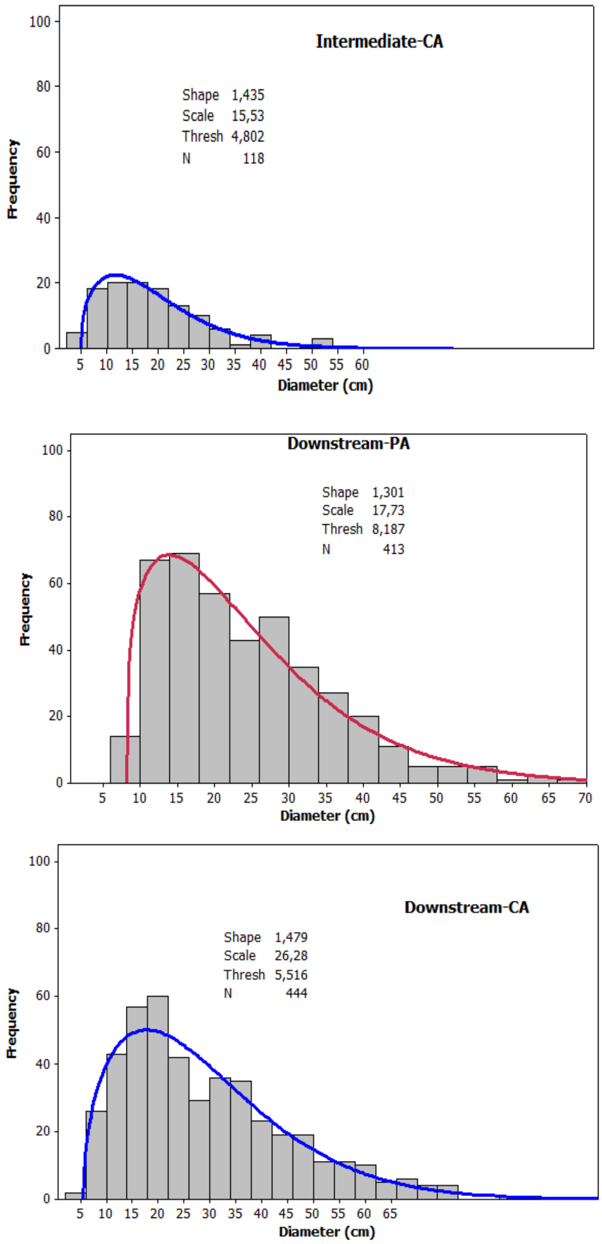


Figure 2. Size class distribution of the non-harvested trees of *C. laurifolia* in PA (a, b, c) *vs* CA (d, e, f) in Burkina Faso

Biomass, carbon stocks of C. laurifolia along the Mouhoun River and allometric equations

Among the three tree components, the branches provide the highest proportion of the total biomass (i.e. 71.68 %), followed by the stem and leaves (figure 3). At the study site, the average biomass per tree is approximately 101.95 kg and the biomass per ha is approximately 17 tons (Table 4). The mean carbon content of *C. laurifolia* is 54.09 %. However, carbon content varies according to the different tree components, being highest in branches (56.02±0.11) (Table 5). The carbon stock within individual *C. laurifolia* trees is approximately 55 kg (Table 5). The per ha carbon stock within leaves is low (0.61 t/ha) compared with that found in the wood of the tree (8.859 t/ha).

Along the river zones, the biomass and carbon stock of *C. laurifolia* varies with tree density. The biomass and carbon stock of the species is highest in the downstream zone in the CA (17.1 t/ha and 9.25 t/ha, respectively) followed by the upstream zone in the PA (14.6 t/ha and 7.89 t/ha, respectively) (Table 6).

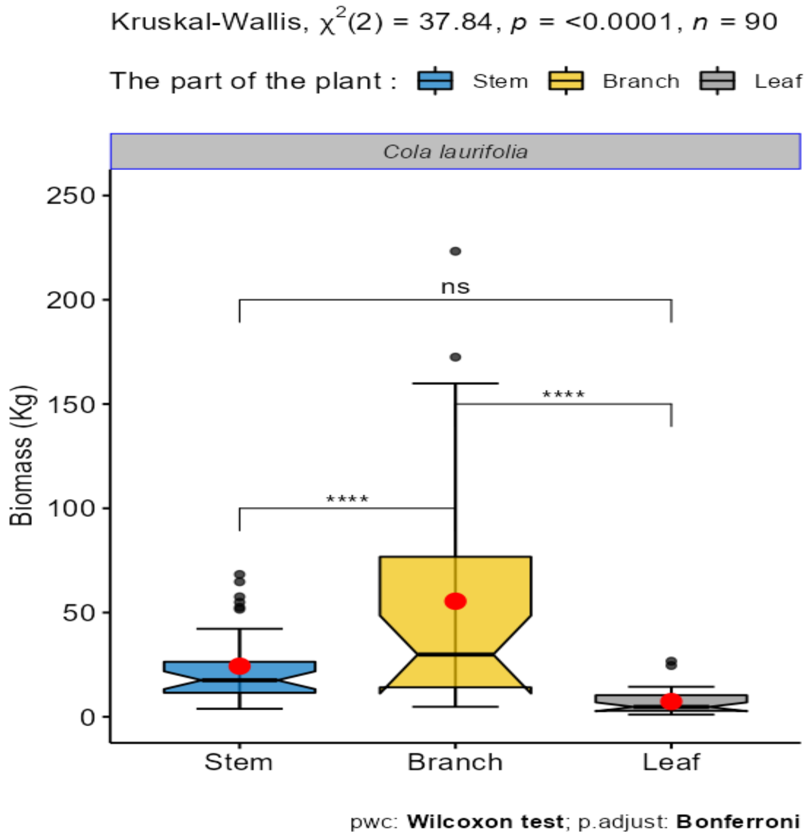


Figure 3. Biomass allocation and non-parametric test between organs of *Cola laurifolia*

Table 4. Proportions of dry biomass in different tree components of *C. laurifolia* in the downstream zone of the Mouhoun River

	AGB	Wood	Stem	Branches	Leaves
Biomass proportion (%)	100	94.83	23.82	71.00	5.17
Total biomass (kg)	3128.62	2900.69	728.64	2180.12	158.37
Mean Biomass per tree (kg)	104.29±110.15	96.96±104.18	24.29±19.11	72.67±87.86	7.33±6.44
Biomass range	10.67-360.23	9.63-411.67	3.85-68.28	4.28-359.15	1.06-26.67
Mean Biomass per ha (Mg)	17,10±18,06	15,90±17,09	3,98±3,13	11,92±14,41	1,20±1,06
Biomass range	1.75-59.08	1.58-67.51	0.63-11.20	0.71-58.90	0.17-4.37

Table 5. Total aboveground carbon and carbon per tree component of *C. laurifolia* in the study zone of the Mouhoun River

Tree component	AGB	Wood	Stem	Branches	Leaves
Carbon rate (%)	54.09±2.42	55.71±0.16	55.41±0.27	56.02±0.28	50.85±0.75
Carbon stock (kg)	1654.35	1568.78	394.12	1174.67	85.66
Carbon stock (kg/tree)	55.14±59.58	52.29±56.35	13.13±10.34	39.15±25.70	2.85±3.48
Carbon stock (Mg/ha)	9.249±2.96	8.859±2.8	2.205±0.51	6.676±2.36	0.61±0.17

Table 6. Biomass and carbon stock of *C. laurifolia* in the different zones along the Mouhoun River

Land uses	River zones	Density (ind.ha^{-1})	Biomass (Mg/ha)	Carbon stock (Mg/ha)
Protected areas	Upstream	140±276	14.600	7.896
	Intermediate	117±169	12.202	6.599
	Downstream	131±125	13.662	7.388
Communal areas	Upstream	68±138	7.091	3.835
	Intermediate	60±131	6.257	3.384
	Downstream	164±159	17.103	9.25

The aboveground biomass of all three components increased with tree DBH and tree height. The better fitted parameter is DBH (figure 4).

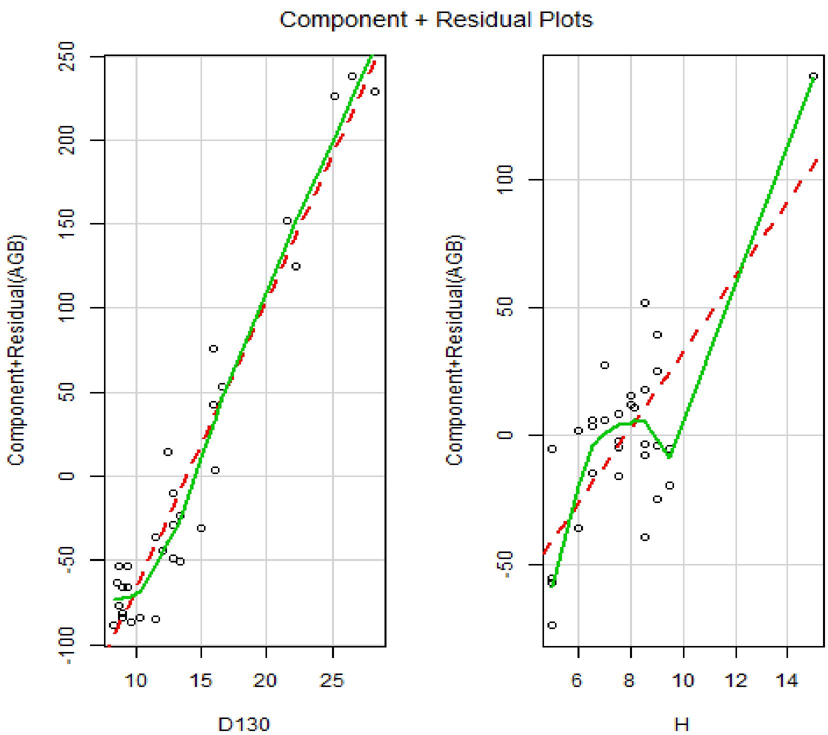


Figure 4. *Cola laurifolia* biomass and residual variation with in tree components across tree size

The AGB, BB, WB and LB models are based on the DBH, H, D20, SL and MCD and the significant parameters are DBH, H and MCd with the log-log linear form. (Table 7). The whole tree equation shows the highest coefficient of determination (R^2=0.92) with model incorporated DBH+H as predictors parameters (Table 7). The linear model was used in this study to develop the allometric equations for dry AGB and tree components estimation. The R^2 value varies from 0.52 to 0.92 with the log-log model (Table 7). Equations of stem, branch and leaf have low RSE, low AIC and high coefficient of determination with model used DBH+H as predictors (Table 7).

However, the whole tree biomass derived from summing the biomass estimates of the three components of the tree with the log-log model have a lower percentage of error (1.05%) compared to those from direct estimations of whole tree biomass (Error=3.19%) (Table 8).

The residuals between observed and predicted biomass show errors of -1.53% for leaf against 1.43% for branch biomass (Table 8)

The quadratic equation developed by Brown et al. (1997)for dry forests of South America (i.e. precipitation of more than 900 mm per year) overestimates the biomass with a high relative error (40.60%) (Table 10).

The allometric models developed by Mbow et al. (2009) for savanna vegetation also overestimate the biomass of *C. laurifolia*, with relative errors of 3.86%, 7.49% and 7.59% for the quadratic, cubic and polynomial equations, respectively. In contrast, the pantropical model developed by Chave et al. (2014) underestimated the biomass of *C. laurifolia* with a large bias (-16.65%).

Table 7. Allometric models developed for estimation of biomass of stem, branches and leaves of *Cola laurifolia* in Burkina Faso. ln(β0), β1 and γ represent the intercept and regression coefficients of the models, and their respective standard errors.

Equation N°	**Predictors**	**Models coefficients**			**Model goodness of fit**				
		Ln(α)	**β**	**γ**	**R^2**	**RSE**	**AIC**	**CF**	**VIF**
5.1	DBH	1.8431	1.8589	-	75.18	0.40	33.86	1,0	-
5.2	DBH+H	-2.712	1.788	0.12	**77.55**	0.38	32.85	408	0.99
5.3	DBH^2.H	-	1.7224	1	52.14	59	53.56	1,0	1.04
5.4	DBH^2.H	2.7728	1.2980	-	55	0.55	53.71	379	-
Stem	+Mcd	-		0.55		0.55		1,0	0.99
biomass		4.4419		49				786	2.10
								1,0	
								786	
6.1	DBH	-	3.0718	-	87.34	0.43	39.31	1,0	-
6.2	DBH+H	4.2304	2.9666	0.77	**89.59**	64	35.45	488	0.99
6.3	DBH^2.H	-	2.8047	57	58.81	0.40	74.69	1,0	1.04
6.4	DBH^2.H	5.5274	2.1979	-	61	3	74.82	414	-
Branch	+Mcd	-		0.55		0.79		1,1	0.99
biomass		5.6299		49		0.77		689	2.10
		-						1,1	
		8.0164						598	
7.1	DBH	-	2.0988	-	74.43	0.45	42.34	1,0	-
7.2	DBH+H	3.7223	2.0053	0.69	**77.68**	9	40.27	541	0.99
7.3	DBH^2.H	-	1.9963	00	54.39	0.44	59.7	1,0	1.04
7.4	DBH^2.H	4.8760	1.4894	-	57.57	0.61	59.53	496	-
Leaf	+Mcd	-		0.66		0.60		1,0	0.99
biomass		4.9420		28				975	2.10
		-						1,0	
		6.9355						942	
8.1	DBH	-	2.5976	-	89.53	0.33	22.81	1,0	-
8.2	DBH+H	2.4681	2.4923	0.77	**92.76**	0.28	13.73	276	0.99
8.3	DBH^2.H	-	2.4322	69	63.4	0.62	60.34	1,0	1.04
8.4	DBH^2.H	3.7670	1.8557	-	67	0.60	59.58	198	-
Abovegroun	+Mcd	-		0.75				1,1	0.99
d biomass		3.8507		38				009	2.10
		-						1,0	
		6.1178						942	

Table 8. Comparison of sums of different tree components and total aboveground biomass for log-log model incorporated Dbh and H

	Stem biomass (kg)	**Branches biomass(kg)**	**Leaves biomass (kg)**	**Wood biomass (kg)**	**AGB (kg)**
Observed	728.64	2171.49	158.37	2900.14	3058.5
Prédicted	732.16	2202.66	155.96	2994.87	3090.78
Résidual	4.48	31.17	-2.4	94.73	32.28
% error	0.48	1.43	-1.53	3.26	1.05

Table 9. Comparison of *C. laurifolia* aboveground biomass estimations with existing allometric models developed in similar climatic conditions

	Vegetations types	Models	Equations	Observed biomass	Precited biomass	% (error)
Brown et al. (1997)	Dry forest pmm>900	Quadratic	$Y=42.69-12.800(D) +1.242(D)^2$	3018.07	4243.51	40.603
Mbow et al. (2009)	Savannas pmm>900	Cubic	$Y=-58.18+13.61DBH-0.517(D)^2 +0.0225(D)^3$	3018.07	3244.20	7.492
		Quadratic	$Y=49.84-10.34(D) +(0.89(D)^2$	3018.07	3134.62	3.861
		Polynomial	$Y=0.0225(D)^3 - (0.5167(D)^2+13.613 (D)-58.18$	3018.07	3247.44	7.599
Chave et al. (2014)	Pantropical		$AGB=0.0673*(\rho D^2H)^{0.976}$	3018.07	2515.50	-16.6515

Discussion

Structure and distribution of C. laurifolia along the Mouhoun River

Along the Mouhoun River, the higher densities in the CA and mean DBH in the PA and CA of *C. laurifolia* in downstream zones can be explained by the better soil conditions in those areas (Pallo et al., 2008). Indeed, the nutrient accumulation in sediments is higher in downstream areas than in upstream areas (Morse et al., 2004). The population structure of *C. laurifolia* is unstable in all of the studied river zones. This is consistent with the findings of Glèlè et al. (2016), who found a Weibull shape parameter between 1 and 3.6, suggesting that *C. laurifolia* populations have low regeneration potential. Most of the species' individuals are concentrated in the lower diameter classes, indicating a generally young population (Gnoumou et al., 2011). The low regeneration can be explained by the importance of flooding along watercourses. Indeed, Teodoro et al. (2014) found along riparian zones that variation in flood duration and occurrence of fire interact in a synergistic manner to reduce stem numbers and modify species composition and distribution, while flood duration reduces species diversity. The low regeneration potential can also be explained by the phytochemical composition of *C. laurifolia*. Tannins, which is at high levels in *C. laurifolia* and particularly in the species' bark (Ejikeme et al., 2014), have ecological consequences include allelopathic responses, changes in soil quality and reduced ecosystem productivity (Kraus et al., 2003).

Biomass, carbon stocks of C. laurifolia along the Mouhoun River and allometric equations

The high density and mean DBH of *C. laurifolia* in downstream zones of the Mouhoun River (associated with better downstream soils) results in higher biomass and carbon stocks for the species in those areas. Similarly, a study undertaken in a central Amazonian forest reported variations in AGB with varying soil (textural) and topographical (altitude) conditions (Castilho et al., 2006). The most accurate method for the estimation of tree biomass is the felling of trees and weighing of the biomass within their component parts (Basuki et al., 2009). Carbon content in the branches of *C. laurifolia* is higher than that found in the leaves and the stem. It average carbon content is higher than the reference value used by the Intergovernmental Panel on Climate Change, which assumes the carbon content is equivalent to 50 % of the species' dry weight (Penman et al., 2003). Following this assumption to estimate carbon stocks in *C. laurifolia* can lead to an underestimation of the species' carbon sequestration potential. Thus, the carbon content of *C. laurifolia* is higher compared to that of savanna species (Mbow, 2009) but not overly different from that found in Acacia species (Bayen, 2016).

The AGB of *C. laurifolia* and the biomass of its components have log-log linear relationships with dendrometric parameters. The best-fit parameters with the dry biomass of *C. laurifolia* are the DBH, H, and MCd considering log-log model. This is consistent with the finding of Delitti et al. (2006), who found that linear equations best described the overall relationship between biomass, DBH and height. In the development of allometric models for predicting AGB, several studies have reported the high fit between a species' DBH and its AGB. However, the use of only DBH in allometric equations has resulted in poor estimates of AGB in Cameroon (Djomo et al., 2010). Besides, the use of DBH and height together for estimating biomass provides more reliable equations. However, tree height has often been ignored in carbon-accounting programs because measuring tree height accurately is difficult in closed-canopy forests (Hunter et al., 2013), such as the riparian forest in our study site.

Accurate estimates of carbon stocks depend to a great degree on the availability and adequacy of allometric equations to estimate tree biomass (Zhang et al., 2007). The species-specific log-log linear models developed in this study show a high coefficient of determination, and low relative errors and AIC. An accurate way to use a log-log model is by summing the biomass of the three tree components. This approach has a low relative error (1.05 %) compared to that for the whole tree AGB estimation (3.19 %). According to Mbow et al. (2013) this error, to be quite reasonable is less than 1.3 %. However, Bondé et al. (2017) found an error of -2.76 % but the equation was significant.

The performance of the incorporated DBH and H models developed in this study showed more accuracy compared to some existing generalized models (as presented in the results section). This may be the fact that existing models were not specifically developed for the forest type that was the focus of our study. This is in accordance with Chave et al. (2005), who have reported that models that do not include the forest type as a predictive variable typically overestimate the AGB. It should also be stressed that care should be taken when considering the accuracy of biomass and carbon data obtained via non-destructive methods.

Conclusion

This study used destructive sampling to develop a reliable allometric model for estimating the AGB and carbon stocks of *C. laurifolia*, a common riparian species in Sub-Saharan Africa. It AGB was found to be highest in downstream river zones within communal areas. The species' mean DBH similarly followed this pattern. The best-fit allometric model was found to be the log-linear form. The linear model corrected by generalized form is more accurate because provide little bias. This study suggests the use of model incorporated both parameters DBH and height for aboveground, stems, branches and leaf biomass and carbon stock prediction. The applicability of these developed equations should be restrictive to the diameter range used in this study 5-30 cm. They are accurate for *Cola laurifolia* species in riparian zones. The use of existing allometric models to estimate this riparian species' AGB will result in overestimates or underestimates, highlighting the importance of species-specific models for the greater accuracy they provide. Future studies should endeavor to develop species-specific allometric equations for other important riparian species of the Mouhoun River including *P. santalinoides*, *P. congensis* and *D. guineense*. An ecosystem-specific equation for riparian forest should also be developed.

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