ESJ Natural/Life/Medical Sciences

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

Gouwidida Elice Kabore
Laboratory of Plant Biology and Ecology,
University Joseph KI-ZERBO / University Center of Ziniaré
Philippe Bayen
Laboratory of Plant Biology and Ecology, University of Dédougou
Sidzabda Djibril Dayamba
African Forest Forum, Nairobi, Kenya & Centre National de la Recherche Scientifique et Technologique (CNRST) / Institut de l'Environnement et de Recherches Agricoles (INERA), Ouagadougou, Burkina Faso
Adjima Thiombiano
University Joseph KI-ZERBO, Laboratory of Plant Biology and Ecology,
Ouagadougou, Burkina Faso

Doi:10.19044/esj.2023.v19n12p166

Submitted: 01 November 2022
Accepted: 24 April 2023
Published: 30 April 2023

Cite As:
Kabore G.E., Bayen P., Dayamba S.D. & Thiombiano A. (2023). *Distribution and Carbon Sequestration Potential of Cola laurifolia Mast.: A Dominant Native Riparian Species along Permanent Rivers in Sub-Saharan Africa.* European Scientific Journal, ESJ, 19 (12), 166. https://doi.org/10.19044/esj.2023.v19n12p166

Abstract

The continuously increasing interest in carbon market call for adequate approaches to assess and monitor the growth and carbon of tree species. Species-specific models for estimating aboveground biomass (AGB) are the accurate means of quantifying species' carbon pools. This study aimed at developing allometric equation for Cola laurifolia Mast., a dominant and multi-purpose riparian species along the Mouhoun River in Burkina Faso. The study first used a destructive sampling approach on thirty trees individuals of different diameter classes after collecting their dendrometric data. Explanatory parameters used to build the models were tree diameter at breast height (Dbh), basal diameter at 20 cm (D20), height (H), and mean crown diameter (MCd). Model development involved looking at different forms of models and different compartments of the tree (leaves, branches, stems and total above ground biomass). Subsequently, field inventory data were collected in protected and communal areas along three zones of the Mouhoun river (upstream, midstream and downstream) to assess and compare the carbon stock in the different areas and also characterize their population (assessment of regeneration status of the species). The results showed that the log-log linear model was the best-fitted form for the three tree compartments (i.e., leaf, branch, stem) and the total AGB, and incorporated Dbh and H as predictors. The total AGB model was more accurate with the highest goodness of fit (high R2) low residual standard error (RSE) ($R^2=0.92$; RSE=0.28) as compared to the three component models. Nevertheless, all the allometric equations established for the prediction of leaves, stem, branches and total aboveground biomass were statically significant ($p \leq 0.0001$). The study also showed that the population structure of the species reflects a low regeneration potential along the studied river zones (i.e., upstream, intermediate and downstream zones), calling for initiatives to address the issue. The carbon stock was found to be 56.40 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 study also compared the outputs from existing generalized allometric models to our newly developed specific-equation and found that they overestimate or underestimate the carbon stock of C. laurifolia. The results confirm the value of species-specific model which therefore calls for more effort to develop such models for all dominant species for greater accuracy in AGB estimations at scale.

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, current and future anthropogenic emissions of greenhouse gas (GHG) and natural climate variability (IPCC 2014).

Though many sectors (transport, industry, etc.) contribute to GHG emissions, forest degradation is also responsible of a major part. In an analysis of emissions from forest degradation in 74 developing countries in tropical and subtropical areas, a value as high as 2.1 billion tons of carbon dioxide was found, from which 53% were derived from timber harvesting, 30% from wood fuel harvesting and 17% from forest fires (Pearson et al. 2017). Therefore, wood harvested by local population represent an important pool of carbon (Ifo et al. 2017). On the other hand, previews 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.

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 support carbon trading (Makungwa et al. 2013), assess sustainable production, and evaluate the impacts of various silvicultural practices (Santa Regina, 2000: Mankessi et al. 2022). Many carbon stock evaluations focused in protected areas and tropical forests (K. Ouédraogo et al. 2020), with some considering 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 and Butt 2017).

Availability of adequate approaches / methodologies for accurate estimation of carbon stocks still constrain the monitoring, evaluation and reporting in carbon trading. It is believed that 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, several 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 these efforts, very few species have got species-specific equations and authors usually resort to use generalized biomass equations as suggested by Chave et al. (2014). It remains, however, evident that species-specific equations are recommended instead of generalized equations for accurate assessments of biomass and carbon stock (Daba and Soromessa 2019). Species-specific allometric equations are therefore preferred because trees may differ in their architecture as well as the density of their wood (Ketterings et al. 2001). This calls for continued efforts to develop allometric equations for individual species to help progressively reduce current gaps in knowledges. The need to develop species-specific allometric equations is particularly relevant to species with high socio-economic values, high carbon stock 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 (Sambaré et al. 2010). The fruits of the species are 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 et al. 2018) indicating that these species should be given special attention to foster their sustainability.

Specific allometric models have been developed for some savanna tree species with high socio-economic values in Burkina Faso, including, *Vitellaria paradoxa* (Dimobe, Mensah, et al. 2018), *Diospyros mespiliformis* (K. Ouédraogo et al. 2020), *Pterocarpus erinaceus* (Ganamé et al. 2020), *Balanites aegyptiaca* (S. Ouédraogo et al. 2020), and for some species of *Vachellia* 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 current work aims at generating specific allometric models for estimating the biomass and carbon stock of *C. laurifolia* and by so doing provide means (tools) to stakeholders for documenting evidence of its potential carbon market potential in different areas.

The specific objectives were to (i) characterise the population of *C. laurifolia* along the Mouhoun river in Burkina Faso and (ii) develop a species-specific allometric equation to predict the biomass of *C. laurifolia*.

We hypothesised that:

(i) Dbh and H are the best predictors of the biomass of the different components of *C. laurifolia*.

(ii) *C. laurifolia* population structure along the Mouhoun river is instable

Methodology

Study area

The Mouhoun river is located in the southern, western and southwestern parts of Burkina Faso, between longitudes 2°41'-2°46'W and latitudes 9°29'-9°47'N. The study site represents upstream, midstream and downstream zones (Figure 1) of the river. The downstream was selected because of the high density of *C. laurifolia* occurring for the carbon stock assessment compared to the upstream and midstream. The study site lies in the north and south Sudanian phytogeographical zones, which is dominated by steppe, savannas and dry forests (Fontès and Guinko 1995). The area is characterised by rainy season from May to October with an average annual rainfall of 1000 mm and relatively low seasonal temperature ranges (20-25 °C) (Meteorological Service of Burkina Faso). The main soil types encountered in the study area are leached ferruginous and eutrophic brown soils. The prominent species 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.

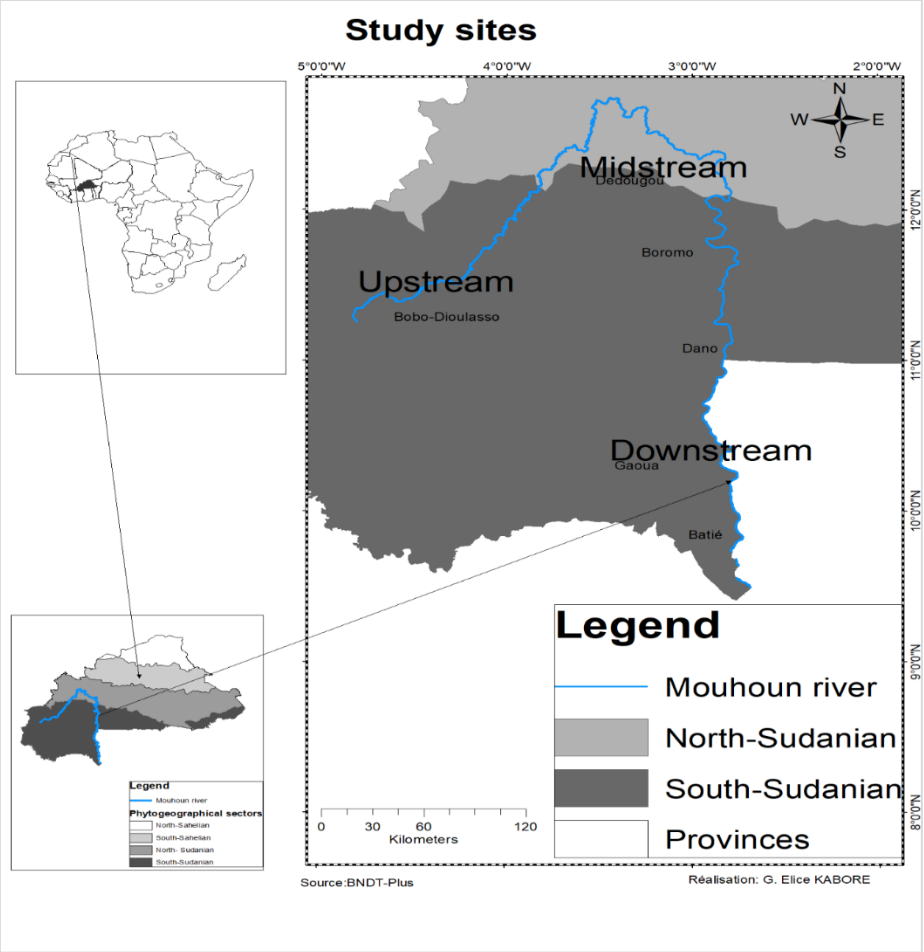


Figure 1. Location of the study area in Burkina Faso, West Africa

Species description

Cola laurifolia also known as “Kola feuille de Laurier” in French and “Tamtiyè” in Birifor, a local language, is a multi-purpose tree. It reaches 8-25 m height, 80 cm diameter and belongs to the Malvaceae family (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 zones of the river: upstream, midstream and downstream. A first phase forest inventory was carried out using 360 rectangular plots of 500 m² size (10 m x 50 m). A total of 134, 117 and 109 plots were established respectively in upstream, downstream and midstream of the Mouhoun river (Figure 1). The plots were spread throughout a protected area (PA – the protected forest of Koulbi) and communal areas (CA). Within each plot, the following dentrometric parameters were recorded on each individual tree of *C. laurifolia*: diameter at 20 cm and Diameter at Breast Height (Dbh) using a tailor tape, length of the stem (SL) and total tree height (H) using a graduated pole, and the Mean Crown Diameter (MCd) using a metric tape. In total, 1986 individual trees of *C. laurifolia* were measured in the 360 plots before selecting thirty individuals in five Dbh classes of 5-10; 10-15; 15-20; 20-25 and 25-30 cm, for destructive sampling. The destructive sampling was conducted only in the communal area as such practice is forbidden in protected area.

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

1- For each selected individual tree, the diameter at 20 cm and the Diameter at Breast Height (Dbh), the length of the stem (SL), the total tree height (H), and the Mean Crown Diameter (MCd) 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 was weighed to determine the fresh biomass weight of components 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 components 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. 2012).

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:

$$TDB = (DB_s/FB_s) \text{ x } TFB \tag{1}$$

where DB_S = Dry Biomass per sample, FB_S = Fresh Biomass per sample and TFB = Total Fresh Biomass.

Data processing and analysis

In a first step, the Dbh size class distribution of *C. laurifolia* and its population densities in the three different zones along the river (i.e. upstream, midstream, and downstream) and the two land use (i.e. protected area-PA vs. communal area-CA) was examined. To determine if there were significant differences in mean Dbh between the different river zones and land use, a two ways analysis of variance was conducted.

The second step was an assessment of the 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 (Chavan and Rasal 2011; Bayen et al. 2015). 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):

$$Ash\ (\%) = (W3 - W1)/(W2 - W1) \times 100 \tag{2}$$

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

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

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 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 et al. 2016).

Seemingly, the relationship between biomass and predicator variables was first explored to identify outliers using 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; K. Ouédraogo et al. 2020). This method suggested the power law model as appropriate for *C. 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 $\beta 0$ and $\beta 1$ 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, leaf and aboveground biomass. Equations (5) with only Dbh, as predictor variable; equation (6) with Dbh and H as predictor variables; equation (7) with Dbh fitted with H as predictor variables; and equation (8), Dbh is fitted with height and crown diameter as additional predictor variables. The three equations of components biomass (*Yi)* were fitted as follows:

$$ln\,(Yi) \;=\; ln\,(\alpha) \;+\; \beta ln\,(Dbh)$$

(5)

$$ln\,(Yi) = \; ln\,(\alpha) + \; \beta ln\,(Dbh) + \gamma \ln\,(\mathrm{H})$$

(6)

$$ln\,(Yi) = ln\,(\alpha) + \beta\; ln\,(Dbh^2\; x\; H)$$

(7)

$$ln\,(Yi) \;=\; ln\,(\alpha) \;+\; \beta ln\,(Dbh^2 \times\; H) \;+\; \gamma ln\,(MCd)$$

(8)

Seemingly Unrelated Regressions (SUR) were used to fit the 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 et al., 2018; Ganamé et al., 2020). The advantage of using SUR method is that it allows for fitting simultaneously the biomass equations, thus accounts for correlations between regressions residuals (Dimobe et al. 2018). In the additive system, tree component equation and total aboveground biomass equation are built separately from equation (5) to(8) as follow:

For Equation (5)

$$\ln(Yl) = \ln(\alpha_l\,) + \; \beta_l \ln(Dbh)$$

5.1

$$\ln(Yb) = \ln(\alpha_b\,) + \; \beta_b \ln(Dbh)$$

5.2

$$\ln(Ys) = \ln(\alpha_s\,) + \; \beta_s \ln(Dbh)$$

5.3

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

Where *Yl*, *Yb*, *Ys* and *AGBt* are the leaf, branch, stem 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)

$$\ln(Yl) = \ln(\alpha_l\,) + \; \beta_l \ln(Dbh) + \gamma \ln\,(H)$$

6.1

$$\ln(Yb) = \ln(\alpha_b\,) + \; \beta_b\, ln(Dbh) + \gamma ln\,(H)$$

6.2

$$\ln(Ys) = \ln(\alpha_s\,) + \; \beta_s\, ln(Dbh) + \gamma ln\,(H)$$

6.3

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

For Equation (7)

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

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

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

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

For Equation (8)

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

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

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

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

The log-transformation 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 R², 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. (2016). 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 [R²], low residual standard error [RSE]).

The model validation in regard to the assumptions of normality and homoscedasticity, (Makungwa et al. 2013) was done using the Shapiro–Wilk test and Breush–Pagan test, respectively (Ouédraogo et al. 2020). 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 are 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 9.

$$\%\ Relative\ error = \frac{(predited\ biomass - observed\ biomass)}{observed\ biomass} \times 100 \tag{9}$$

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 protected areas (PA), the upstream zone had the highest density (140±276 ind. ha^{-1}), while in the Communal areas (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 mean diameter and diameter range show a generally small individuals of *C. laurifolia* population (Table 1). These populations have poor regeneration potential, with the first size class (i.e., 5-10 cm Dbh) having low numbers of individuals (Figure 2). In the CA, *C. laurifolia* has low numbers of individuals in both the upstream and the midstream zones (68±138 and 60±131, respectively) but higher numbers of individuals in the downstream (Table 1).

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

Land use	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
	midstream	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
	midstream	18,93±9,94	5.09-52.52	60±131	254
	Downstream	26.05	5.73-92.31	164±159	221

Legend: Ind =individual; Ha =hectar ;Values in the table are: means ± standard deviations

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 use 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-use 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 midstream (Table 3).

Table 2. Comparison of diameter and density along river zones and land use

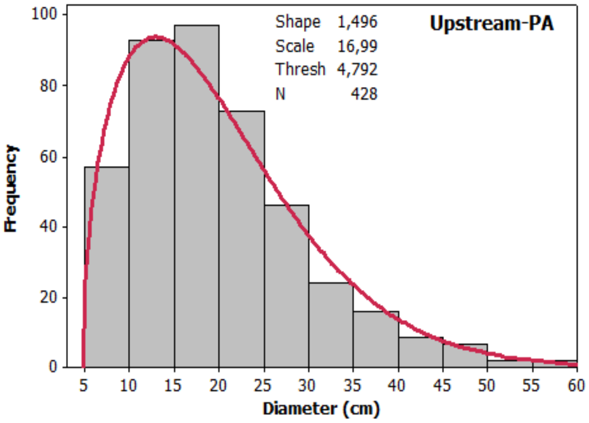
	Diameter (cm)			**Density (ind./ha)**		
	F	*P*-values	Df	F	*P-value*	Df
Land use	1.0437	0.30769	1	2.7005	0.10124	1
River zones	33.7196	4.273e-14***	2	16.2164	1.865e-07 ***	2
Land-use*River zones	3.2846	0.03864*	2	3.9434	0.02027 *	2

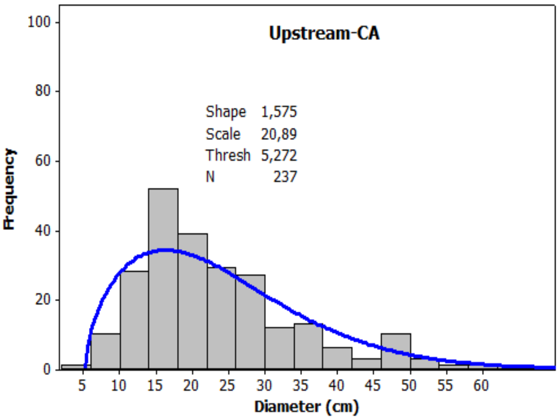
Legend: * is low significant; ***: High significant, Df: Degrees of freedom, F: ratio (Means Square Between) / (Means Square Error); P: Probability

Table 3. Comparison of mean diameters and mean densities in protected and communal areas

Land use	**Protected Area**			**Communal Area**		
River zones	Upstream	midstream	Downstream	Upstream	midstream	Downstream
Mean Diameters	9.067831 ^{a}	9.244273 ^{a}	19.65108 ^{b}	8.725934 ^{a}	7.476588 ^{a}	26.35759 ^{b}
LSD*	3.519					
Mean densities	138 ^{a}	117 ^{a}	129 ^{a}	68 ^{a}	59 ^{a}	164 ^{b}
LSD*	45					

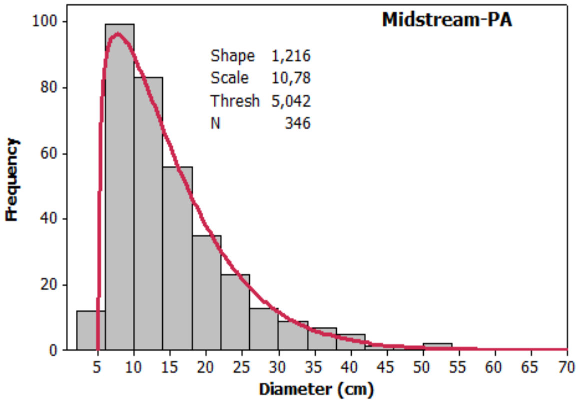
Legend: LSD* is Least significant difference, PA: Protected area, CA: Communal area



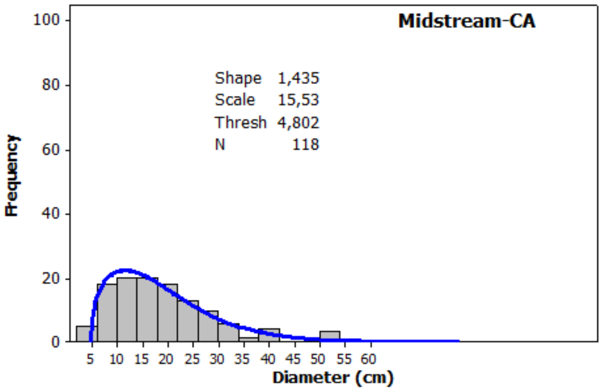

Upstream-CA
Shape 1,575
Scale 20,89
Thresh 5,272
N 237
Frequency
0
20
40
60
80
100
Diameter (cm)
5
10
15
20
25
30
35
40
45
50
55
60

d

a


Midstream-PA
Shape 1,216
Scale 10,78
Thresh 5,042
N 346
Frequency
0
20
40
60
80
100
Diameter (cm)
5
10
15
20
25
30
35
40
45
50
55
60
65
70

b


Midstream-CA
Shape 1,435
Scale 15,53
Thresh 4,802
N 118
Frequency
0
20
40
60
80
100
Diameter (cm)
5
10
15
20
25
30
35
40
45
50
55
60

e

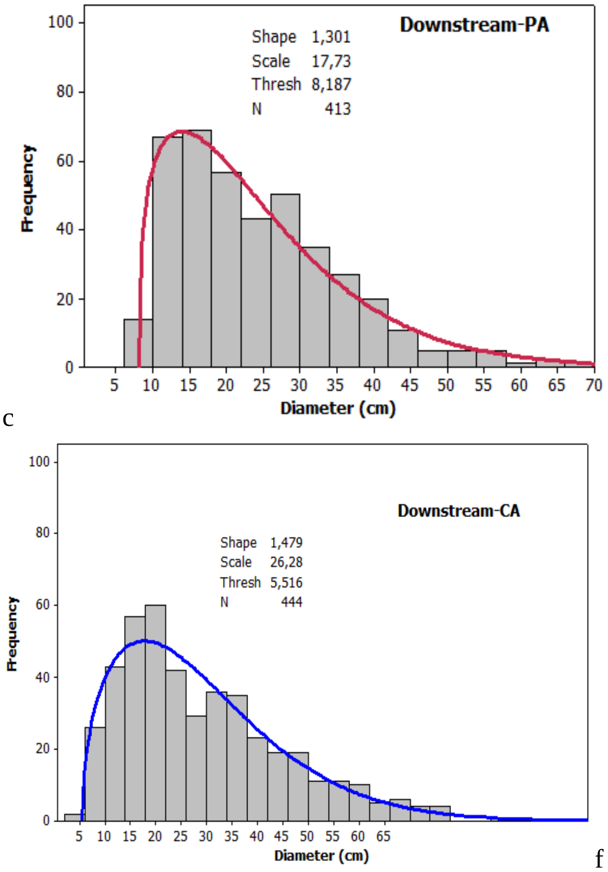


Figure 2. Size class distribution of the population of *C. laurifolia* in Protected Area (a, b, c) *vs* Communal Area (d, e, f)
Legend: N is number of trees

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

Among the three tree components, the branches provided the highest proportion ($P<0.0001$, $X^2=37.84$) (Figure 3) of the total biomass (i.e., 69.68 %), followed by the stem and leaves. At the study site, the average biomass per tree is approximately 104.28 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 of *C. laurifolia* trees is approximately 56.40 kg (Table 5). Per ha, carbon stock within leaves is low (0.61 t/ha) compared with that found in the wood (stem and branches) 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 are highest in the downstream zone in the CA (17.1 t/ha and 9.249 t/ha, respectively) followed by the upstream zone in the PA (14.6 t/ha and 7.89 t/ha, respectively) (Table 6).

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

	AGB	Stem	Branch	Leaf
Biomass proportion (%)	100	23.28	69.6800	7.02
Total biomass (kg)	3128.62	728.64	2180.12	158.37
Mean Biomass per tree (kg)	104.28±106.97.	24.29±19.11	72.67±87.86	7.33±6.44
Mean Biomass per ha (Mg)	17,10±18,06	3,98±3,13	11,92±14,41	1,20±1,06
Biomass range	1.75-59.08	0.63-11.20	0.71-58.90	0.17-4.37

Legend: AGB is Aboveground Biomass; Mg is Megagram or ton

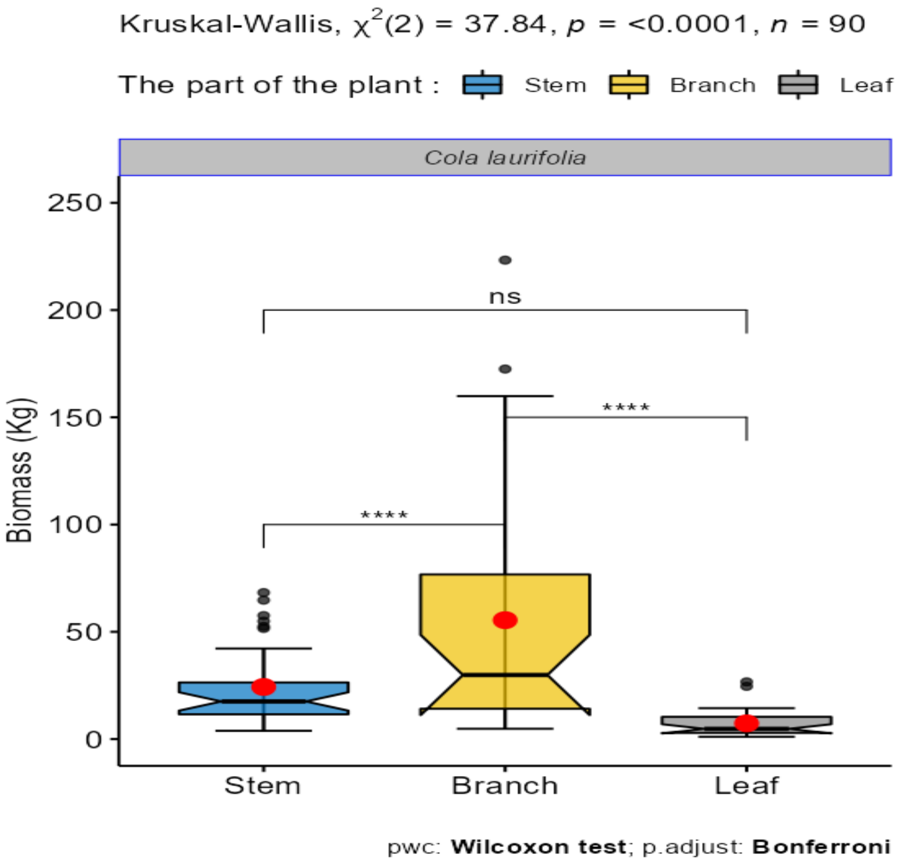


Figure 3. Biomass allocation and non-parametric test between component biomass of *C. laurifolia* Mast. Legend: ns: non-significant

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

Tree component	AGB	Stem	Branch	Leaf
Carbon rate (%)	54.09±2.42	55.41±0.27	56.02±0.28	50.85±0.75
Total Carbon stock (kg)	1654.35	394.12	1174.67	85.66
Carbon stock (kg / tree)	56.04±59.58	13.13±10.34	39.15±25.70	2.85±3.48
Carbon stock (Mg / ha)	9.249±2.96	2.205±0.51	6.676±2.36	0.61±0.17

Legend: AGB is Aboveground Biomass, Mg is Megagram or ton

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

Land use	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

Legend: Mg is Megagram or ton

The aboveground biomass of all three components increased with tree Dbh (D130) and tree height (H). The better fitted parameter is Dbh (figure 4).

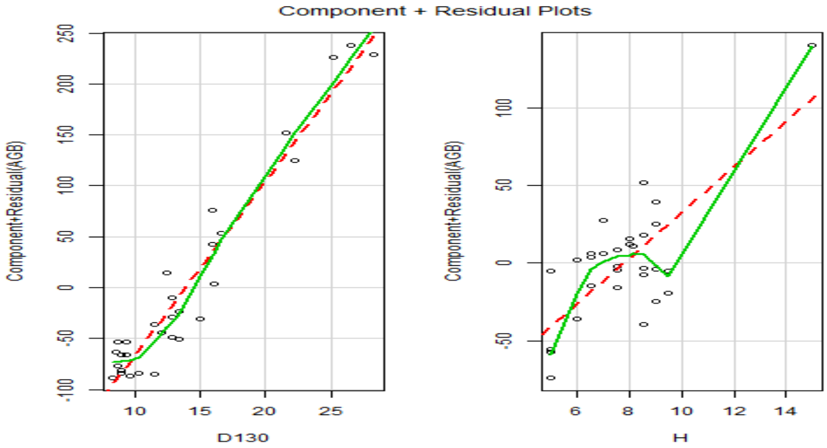


Figure 4. *Cola laurifolia* biomass and residual variation with in tree components across tree size

Legend: H is Height, D130 is Diameter at 1.30 meters or Diameter at Breast Height, green line is Real data shape, red line is least squares fit

The total Aboveground Biomass (AGB), Stem Biomass (SB), Branch Biomass (BB), and Leaf Biomass (LB) models are based on the Dbh, H, D20, Stem Length (SL) and Mean Crown Diameter (MCd) and the significant parameters are Dbh, H and MCd with the log-log linear form. (Table 7). The total aboveground biomass equation shows the highest coefficient of determination (R^2=0.92) using Dbh+H as predictors parameters (Table 7). The log 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 Residual Standard Error (RSE), low Akaike Information Criterion (AIC) and high coefficient of determination with the model using DBH+H as predictors (Table 7).

However, the total aboveground 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).

With 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) the biomass of *C. laurifolia* is overestimated with a high relative error (40.60%) (Table 9). The same tendency is found with allometric models developed by Mbow et al. (2009) for savanna vegetation with relative errors of 3.86%, 7.49% and 7.59% for the quadratic, cubic and polynomial equations, respectively with less gap compared to dry forest of South America model. The pantropical model developed by Chave et al. (2014) underestimated the biomass of *C. laurifolia* with a large bias (-16.65%) (Table 9).

Table 7. Fitted allometric equations developed for estimation of *C. laurifolia* of stem, branches and leaves biomass 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**	**R²**	**RSE**	**AIC**	**CF**	**VIF**
5.1	Dbh	1.8431	1.8589	-	75.18	0.40	33.86	1,0408	-
5.2	Dbh+H	-2.712	1.788	0.121	**77.55**	0.385	32.85	1,0379	0.99
5.3	Dbh².H	-2.7728	1.7224	-	52.14	9	53.56	1,0786	1.04
5.4	Dbh².H	-4.4419	1.2980	0.554	55	0.55	53.71	1,0786	-
Stem	+MCd			9		0.55			0.99
biomass									2.10

6.1	Dbh	-4.2304	3.0718	-	87.34	0.436	39.31	1,0488	-
6.2	Dbh+H	-5.5274	2.9666	0.775	**89.59**	4	35.45	1,0414	0.99
6.3	Dbh².H	-5.6299	2.8047	7	58.81	0.403	74.69	1,1689	1.04
6.4	Dbh².H	-8.0164	2.1979	-	61	0.79	74.82	1,1598	-
Branch	+MCd			0.554		0.77			0.99
biomass				9					2.10
7.1	Dbh	-3.7223	2.0988	-	74.43	0.459	42.34	1,0541	-
7.2	Dbh+H	-4.8760	2.0053	0.690	**77.68**	0.44	40.27	1,0496	0.99
7.3	Dbh².H	-4.9420	1.9963	0	54.39	0.61	59.7	1,0975	1.04
7.4	Dbh².H	-6.9355	1.4894	-	57.57	0.60	59.53	1,0942	-
Leaf	+Mcd			0.662					0.99
biomass				8					2.10
8.1	Dbh	-2.4681	2.5976	-	89.53	0.33	22.81	1,0276	-
8.2	Dbh+H	-3.7670	2.4923	0.776	**92.76**	0.28	13.73	1,0198	0.99
8.3	Dbh².H	-3.8507	2.4322	9	63.4	0.62	60.34	1,1009	1.04
8.4	Dbh².H	-6.1178	1.8557	-	67	0.60	59.58	1,0942	-
Abovegro	+Mcd			0.753					0.99
und				8					2.10
biomass									

Dbh is diameter breast height; D20 is basal diameter at 20 cm above the ground, MCd is Mean crown diameter; H is total tree height, AI is: Akaike Information Criterion; VIF is Variance Inflation Factor; Cf is correction factor.

Table 8. Comparison of different tree components biomass and total aboveground biomass for log-log model using Dbh and H as predictors.

	Stem biomass (kg)	**Branch biomass(kg)**	**Leaf biomass (kg)**	**AGB (kg)**
Observed	728.64	2171.49	158.37	3058.5
Prédicted	732.16	2202.66	155.96	3090.78
Résidual	4.48	31.17	-2.4	32.28
% error	0.48	1.43	-1.53	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	$Y=42.69-12.800(dbh)+1.242(dbh)^2$	3128.62	4243.51	35.63
Mbow et al. (2009)	Savannas pmm>900	Cubic	$Y=-58.18+13.61DBH-0.517(DBH)^2+0.0225(DBH)^3$	3128.62	3244.20	3.69
		Quadratic	$Y=49.84-10.34(DBH)+(0.89(DBH)^2$	3128.62	3134.62	0.19

		Polynomial	$Y=0.0225(DBH)^3-(0.5167(DBH)^2+13.613(DBH)-58.18$	3128.62	3247.44	3.80
Chave et al. (2014)	Pantropical		$AGB=0.0673*(\rho D^2H)^{0.976}$	3128.62	2515.50	-19.59

DBH, dbh and D are diameter breast height

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* notified 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. This result are in accordance with those reported by many authors (Ganamé et al. 2020; S. Ouédraogo et al. 2020;

K. Ouédraogo et al. 2020) who found the highest biomass in branches. 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. Moreover, the carbon content of *C. laurifolia* documented in the current study 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 reported 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 a study conducted 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. Our result is consistent with those found for *Diospyros mespiliformis* (Ouédraogo et al. 2020) and *Pterocarpus erinaceus* (Ganamé et al. 2020) where log-log model have the best fitted equations. 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 considered quite reasonable should be less than 1.3 %. However, Bondé et al. (2017) found an error of -2.76 % with an equation which was significant.

Models developed in this study using Dbh and H as predictors, showed more accuracy (when comparing their predicted values to field observed values) compared to some existing generalized models in the literature (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. But it also confirms the idea that whenever an adequately developed species-specific model is available, it should be preferred to generalized equations. It should however be stressed that the output of all models remains an estimation and care should be taken when considering the accuracy of biomass and carbon data obtained via non-destructive methods.

Conclusion

This study used destructive sampling method to develop a reliable allometric models for estimating the aboveground biomass (AGB) and carbon stock of *C. laurifolia*, a common riparian species in Sub-Saharan Africa. The models were then used to estimate biomass and carbon stock of the species based on field inventory data collected in protected and communal areas along three zones of the Mouhoun river (upstream, midstream and downstream) in Burkina Faso. AGB was highest in downstream river zones within communal areas. The mean Dbh similarly followed this pattern. The diameter size class distribution of *C. laurifolia* showed an unstable population with poor regeneration potential along the three zones. The best-fit allometric model for biomass estimation was found to be the log-linear form. The linear model corrected by generalized form is more accurate because it provides little bias. This study found that the model that used both parameters Dbh and height as predictors was the best fit for total aboveground, stem, branches and leaf biomass and carbon stock prediction. This confirms the first hypothesis of the study. The carbon content of *C. laurifolia* is higher than 50% generally used in the literature for species. The use of existing generalized 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 large diameter of *C. laurifolia* and others important riparian species of the Mouhoun River and other ecosystems. Our study also found that *C. laurifolia* along the Mouhoun river shows poor regeneration, confirming our second hypothesis and calling for initiatives to promote the regeneration of the species.

Acknowledgements

We acknowledge the logistic and financial support of the Biodiversity and Climate Research center (Bik-F). We also thank Dr John Meadows for proofreading and editing input. Our thanks are also addressed to all the people who contributed to the realization of this work.

References:

1. Arbonnier, M. (2019). Arbres, arbustes et lianes des zones sèches d'Afrique de l'Ouest (Quae). https://www.quae.com/produit/1554/9782759225484/arbres-arbustes-et-lianes-d-afrique-de-l-ouest
2. Basuki, T. M., Laake, P. E. Van, Skidmore, A. K., & Hussin, Y. A. (2009). Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. Forest Ecology and Management, 257, 1684–1694. https://doi.org/10.1016/j.foreco.2009.01.027
3. Bayen, P. (2016). Restauration des sols dégradés par afforestation et évaluation des potentialités de séquestration du carbone de six espèces ligneuses en zones sahélienne et soudano-sahélienne du Burkina Faso. Université Ouaga I PR Joseph KI-ZERBO.
4. Bayen, P., Bognounou, F., Lykke, A. M., Ouédraogo, M., & Thiombiano, D. (2015). The use of biomass production and allometric models to estimate carbon sequestration of Jatropha curcas L. plantations in western Burkina Faso. Environment, Development and Sustainability, 7(1). https://doi.org/10.1007/s10668-015-9631-4
5. Bayen, P., Noulèkoun, F., Bognounou, F., Lykke, A. M., Djomo, A., Lamers, J. P. A., & Thiombiano, A. (2020). Models for estimating aboveground biomass of four dryland woody species in Burkina Faso, West Africa. Journal of Arid Environments, 180(2019). https://doi.org/10.1016/j.jaridenv.2020.104205
6. Bebber, D. P., & Butt, N. (2017). Tropical protected areas reduced deforestation carbon emissions by one third from 2000-2012. Scientific Reports, 7(1), 1–7. https://doi.org/10.1038/s41598-017-14467-w
7. Bondé, L., Ganamé, M., Ouédraogo, O., Nacoulma, B. M., Thiombiano, A., & Boussim, J. I. (2017). Allometric models to estimate foliage biomass of Tamarindus indica in Burkina Faso. Southern Forests: A Journal of Forest Science, 1–8. https://doi.org/10.2989/20702620.2017.1292451
8. Brown, S., Schroeder, P., & Birdsey, R. (1997). Aboveground biomass distribution of US eastern hardwood forests and the use of large trees as an indicator of forest development. *Forest Ecology and Management*, *96*, 37–47.
9. Castilho, C. V. De, Magnusson, W. E., Aaujo, R. N. O. de, Luizao, R. C. C., Luizao, F. J., Lima, A. P., & Higuchi, N. (2006). Variation in aboveground tree live biomass in a central Amazonian Forest: Effects of soil and topography. *Forest Ecology and Management*, *234*, 85–96. https://doi.org/10.1016/j.foreco.2006.06.024

10. Chavan, B. L., & Rasal, G. B. (2011). Potentiality of Carbon Sequestration in six year ages young plant from University campus of Aurangabad. *Global Journal of Researches in Engineering*, *11*(7). https://doi.org/ISSN 2249-4596
11. Chave, A. J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., Chave, J., Andalo, C., Brown, S., … Riéra, B. (2005). Tree Allometry and Improved Estimation of Carbon Stocks and Balance in Tropical Forests Tree allometry and improved estimation and balance in tropical forests of carbon stocks. *Ecology*, *145*(1), 87–99. https://doi.org/10.1007/s00442-005-0100-x
12. Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., Duque, A., Eid, T., Fearnside, P. M., Goodman, R. C., Henry, M., Martínez-Yrízar, A., Mugasha, W. A., Muller-Landau, H. C., Mencuccini, M., Nelson, B. W., Ngomanda, A., Nogueira, E. M., Ortiz-Malavassi, E., … Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10), 3177–3190. https://doi.org/10.1111/gcb.12629
13. Daba, D. E., & Soromessa, T. (2019). The accuracy of species-specific allometric equations for estimating aboveground biomass in tropical moist montane forests: Case study of Albizia grandibracteata and Trichilia dregeana. *Carbon Balance and Management*, *14*(1), 1–13. https://doi.org/10.1186/s13021-019-0134-8
14. Dayamba, S. D., Djoudi, H., Zida, M., Sawadogo, L., & Verchot, L. (2016). Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa. *"Agriculture, Ecosystems and Environment,"* *216*, 61–72. https://doi.org/10.1016/j.agee.2015.09.023
15. Delitti, W. B. C., Meguro, M., & Pausas, J. G. (2006). Biomass and mineralmass estimates in a "cerrado" ecosystem. *Brazilian Journal of Botany*, *29*(4), 531–540. https://doi.org/10.1590/S0100-84042006000400003
16. Dimobe, K., Goetze, D., Ouédraogo, A., Mensah, S., Akpagana, K., Porembski, S., & Thiombiano, A. (2018). Aboveground biomass allometric equations and carbon content of the shea butter tree (Vitellaria paradoxa C.F. Gaertn., Sapotaceae) components in Sudanian savannas (West Africa). *Agroforestry Systems*, *93*(3), 1119–1132. https://doi.org/10.1007/s10457-018-0213-y
17. Dimobe, K., Mensah, S., Goetze, D., Ouédraogo, A., Kuyah, S., Porembski, S., & Thiombiano, A. (2018). Aboveground biomass

partitioning and additive models for Combretum glutinosum and Terminalia laxiflora in West Africa. *Biomass and Bioenergy*, *115*(November 2017), 151–159. https://doi.org/10.1016/j.biombioe.2018.04.022

18. Djomo, A. N., Ibrahima, A., Saborowski, J., & Gravenhorst, G. (2010). Allometric equations for biomass estimations in Cameroon and pan moist tropical equations including biomass data from Africa. *Forest Ecology and Management*, *260*(10), 1873–1885. https://doi.org/10.1016/j.foreco.2010.08.034
19. Ejikeme, C. M., Ezeonu, C. S., & Eboatu, A. N. (2014). Determination of Physical and Phytochemical Constituents of Some Tropical Timbers Indigenous To Niger Delta Area of Nigeria. *European Scientific Journal*, *10*(18), 1857–7881.
20. Fayolle, A., Doucet, J., Gillet, J., Bourland, N., & Lejeune, P. (2013). Forest Ecology and Management Tree allometry in Central Africa : Testing the validity of pantropical multi-species allometric equations for estimating biomass and carbon stocks. *Forest Ecology and Management*, *305*, 29–37. https://doi.org/10.1016/j.foreco.2013.05.036
21. Fontès, J., & Guinko, S. (1995). *Carte de la végétation et de l'occupation du sol du Burkina Faso. Notice explicative. Toulouse, Institut de la Carte Internationale de la Végétation ;* (P. C. (88313101) Ministère de la Coopération Française (ed.); 1995th ed., Issue Ouagadougou, Institut du Développement Rural-Faculté des Sciences et Techniques).
22. Ganamé, M., Bayen, P., Dimobe, K., Ouédraogo, I., & Thiombiano, A. (2020). Aboveground biomass allocation, additive biomass and carbon sequestration models for Pterocarpus erinaceus Poir. in Burkina Faso. *Heliyon*, *6*(4). https://doi.org/10.1016/j.heliyon.2020.e03805
23. Glèlè Kakaï, R., Salako, V. K., Padonou, E. A., & Lykke, A. M. (2016). Méthodes statistiques multivariées utilisées en écologie. Annales des sciences Agronomiques, 20, 139-157.
24. Gnoumou, A., Bognounou, F., Hahn, K., & Adjima Thiombiano. (2011). Woody plant diversity and stand structure in the Comoe-Leraba Reserve, Southwestern Burkina Faso (West Africa). *Journal of Biological Sciences*, *11*(2), 111–123.
25. Gofc-Gold. (2008). Reducing greenhouse gas emissions from deforestation and degradation in developing countries: a sourcebook of methods and procedures for monitoring, measuring and reporting. In *GOFC-GOLD Report version COP13-2*. https://doi.org/10.1017/CBO9781107415324.004
26. Henry, M., Besnard, A., Asante, W. A., Eshun, J., Adu-bredu, S.,

Valentini, R., Bernoux, M., & Saint-andré, L. (2010). Wood density , phytomass variations within and among trees , and allometric equations in a tropical rainforest of Africa. *Forest Ecology and Management*, *260*(8), 1375–1388. https://doi.org/10.1016/j.foreco.2010.07.040

27. Hunter, M. O., Keller, M., Victoria, D., & Morton, D. C. (2013). Tree height and tropical forest biomass estimation. *Biogeosciences*, *10*(12), 8385–8399. https://doi.org/10.5194/bg-10-8385-2013
28. Idu, M., Erhabor, J. O., & Ovuakporie-uvo, O. (2014). Ethnomedicinal Plants Used By the Idoma People- Benue State , Nigeria. *American Journal of Ethnomedicine*, *1*(1), 72–88.
29. Ifo, S. A., Mbemba, M., Koubouana, F., & Binsangou, S. (2017). Stock de carbone dans les gros débris ligneux végétaux : cas des forêts tropicales pluvieuses de la Likouala, République du Congo. *European Scientific Journal, ESJ*, *13*(12), 384. https://doi.org/10.19044/esj.2017.v13n12p384
30. IPCC. (2014). *Mitigation of Climate Change Summary for Policymakers and Technical Summary Mitigation of Climate Change*.
31. Ketterings, Q. M., Coe, R., Noordwijk, M. Van, Ambagau, Y., & Palm, C. A. (2001). Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and Management*, *146*, 199–209.
32. Kraus, T. E. C., Dahlgren, R. A., & Zasoski, R. J. (2003). Tannins in nutrient dynamics of forest ecosystems - A review. *Plant and Soil*, *256*(1), 41–66. https://doi.org/10.1023/A:1026206511084
33. Makungwa, S. D., Chittock, A., Skole, D. L., Kanyama-Phiri, G. Y., & Woodhouse, I. H. (2013). Allometry for biomass estimation in Jatropha trees planted as boundary hedge in farmers' fields. *Forests*, *4*(2), 218–233. https://doi.org/10.3390/f4020218
34. Mankessi, F., Malonga, M. G. K., & Ifo, S. A. (2022). Dynamique du carbone organique du sol et de l'azote dans une chronoséquence de plantation de Acacia auriculiformis A. Cunn. ex Benth. (Fabaceae), à Bambou-Mingali (République du Congo). *European Scientific Journal ESJ*, *18*(8), 172–188. https://doi.org/10.19044/esj.2022.v18n8p172
35. Mbayngone, E., & Thiombiano, A. (2011). Dégradation des aires protégées par l'exploitation des ressources végétales: cas de la réserve partielle de faune de Pama, Burkina Faso (Afrique de l'Ouest). *Fruits*, *66*(3), 187–202. https://doi.org/10.1051/fruits/2011027
36. Mbow, C. (2009). *Potentiel et dynamique des stocks de carbone des savanes soudaniennes et soudanoguinéennes du Sénégal*. [Université Cheikh Anta Diop de Dakar (UCAD)]. https://doi.org/10.1177/0011392830310010006

37. Mbow, C., Verstraete, M. M., Sambou, B., Diaw, A. T., & Neufeldt, H. (2014). Allometric models for aboveground biomass in dry savanna trees of the Sudan and Sudan-Guinean ecosystems of Southern Senegal. *Journal of Forest Research*, *19*(3), 340–347. https://doi.org/10.1007/s10310-013-0414-1
38. Morse, J. L., Megonigal, J. P., & Walbridge, M. R. (2004). Sediment nutrient accumulation and nutrient availability in two tidal freshwater marshes along the Mattaponi River, Virginia, USA. *Biogeochemistry*, *69*(2), 175–206. https://doi.org/10.1023/B:BIOG.0000031077.28527.a2
39. Ngomanda, A., Engone Obiang, N. L., Lebamba, J., Moundounga Mavouroulou, Q., Gomat, H., Mankou, G. S., Loumeto, J., Midoko Iponga, D., Kossi Ditsouga, F., Zinga Koumba, R., Botsika Bobé, K. H., Mikala Okouyi, C., Nyangadouma, R., Lépengué, N., Mbatchi, B., & Picard, N. (2014). Site-specific versus pantropical allometric equations: Which option to estimate the biomass of a moist central African forest? *Forest Ecology and Management*. https://doi.org/10.1016/j.foreco.2013.10.029
40. Ouédraogo, K., Dimobe, K., & Thiombiano, A. (2020). Allometric models for estimating aboveground biomass and carbon stock for diospyros mespiliformis in West Africa. *Silva Fennica*, *54*(1). https://doi.org/10.14214/sf.10215
41. Ouédraogo, S., Ouédraogo, O., Dimobe, K., Thiombiano, A., & Boussim, I. J. (2020). Prediction of aboveground biomass and carbon stock of Balanites aegyptaca, a multipurpose species in Burkina Faso. *Heliyon*, *6*(8), 1–12. https://doi.org/10.1016/j.heliyon.2020.e04581
42. Pallo, F. J. P., Sawadogo, N., Sawadogo, L., Sedogo, M. P., & Assa, A. (2008). Statut de la matière organique des sols dans la zone sud-soudanienne au Burkina Faso. *Biotechnology, Agronomy and Society and Environment*, *12*(3), 29–38. http://www.pressesagro.be/base/index.php/base/article/view/365
43. Parresol, B. R. (1999). Assessing tree and stand biomass: A review with examples and critical comparisons. *Forest Science*, *45*(4), 573–593. https://doi.org/10.1093/forestscience/45.4.573
44. Pearson, T. R. H., Brown, S., Murray, L., & Sidman, G. (2017). Greenhouse gas emissions from tropical forest degradation: An underestimated source. *Carbon Balance and Management*, *12*(1). https://doi.org/10.1186/s13021-017-0072-2
45. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., & Wagner, F. (2003). *Good Practice Guidance for Land Use , Land-Use Change and Forestry Edited by*. Institute for Global Environmental Strategies,

Hayama, Kanagawa.

46. Picard, N., Saint-andré, L., & Henry, M. (2012). *Manuel de Construction d'équations Allométriques Pour l'estimation Du Volume et La Biomasse Des Arbres : De La Mesure de Terrain à La Prédiction*. Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Food and Agriculture Organization of the United Nations, Rome, Italy, 224.
47. Sambaré, O., Ouedraogo, O., Wittig, R., & Thiombiano, A. (2010). Diversité et écologie des groupements ligneux des formations ripicoles du Burkina Faso (Afrique de l'Ouest). *International Journal of Biological and Chemical Sciences*, *4*(5), 1782–1800. https://doi.org/10.4314/ijbcs.v4i5.65587
48. Santa Regina, I. (2000). Biomass estimation and nutrient pools in four Quercus pyrenaica in Sierra de Gata Mountains, Salamanca, Spain. *Forest Ecology and Management*, *132*(2–3), 127–141. https://doi.org/10.1016/S0378-1127(99)00219-4
49. Sprugel, D. G. (1983). Correcting for Bias in Log-Transformed Allometric Equations. *Wiley*, *64*(1), 209–210.
50. Teodoro, M., Oliveira, D., Damasceno-junior, G. A., Pott, A., Conceição, A., Filho, P., Rondon, Y., & Parolin, P. (2014). Regeneration of riparian forests of the Brazilian Pantanal under flood and fire influence. *FOREST ECOLOGY AND MANAGEMENT*, *331*, 256–263. https://doi.org/10.1016/j.foreco.2014.08.011
51. Thiombiano, A., Schmidt, M., Dressler, S., Ouédraogo, A., Hahn, K., & Zizka, G. (2012). Catalogue des plantes vasculaires du Burkina Faso. *Boissiera, Conservatoire et Jardin Botaniques de La Ville de Génève*, *65*, 1–391. http://goo.gl/1hizQw
52. Xie, L., Li, F., Zhang, L., Widagdo, F. R. A., & Dong, L. (2020). A bayesian approach to estimating seemingly unrelated regression for tree biomass model systems. *Forests*, *11*(12), 1–30. https://doi.org/10.3390/f11121302
53. Zhang, J., Ge, Y., Chang, J., Jiang, B., Jiang, H., Peng, C., Zhu, J., Yuan, W., Qi, L., & Yu, S. (2007). Carbon storage by ecological service forests in Zhejiang Province, subtropical China. *Forest Ecology and Management*, *245*(1–3), 64–75. https://doi.org/10.1016/j.foreco.2007.03.042
54. Zuur, A. F., Smith, E. N. M., & Springer, J. (2007). Analysing ecological data. In *Springer Science and Business Media* (vol 680).