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Research Article

Site-Species Allometry Equation for *Theobroma cacao* L. Biomass Estimation in Agroforestry Systems of Cameroon

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The accuracy of biomass estimates through mathematical expressions remains essential for the sustainability of the REDD$^+$ process. The objective of this research was to develop allometric models by site species to evaluate the biomass of *Theobroma cacao* in agroforestry systems in the Central Region of Cameroon. Biomass data were obtained by the destructive method on a sample of 50 trees (5 cm $\leq D \leq$ 27 cm). Allometric models were developed using aboveground (AGB), belowground (BGB), and total biomass (TB) as dependent variables and tree dendrometric parameters as independent variables. Nine linear models were adjusted based on the Akaike information criterion (AIC), residual standard error (RSE), coefficient of determination (R^2), and various statistical tests including the normality test, heterogeneity, and autocorrelation for the analysis of residuals. The different results show that only the diameter appears to be a good predictor of biomass with an R^2 greater than 0.94, 0.85, and 0.95, respectively, for aboveground biomass (M1: $\ln B = -1.613 + 1.83 \times \ln (D)$), belowground biomass (M1: $\ln B = -2.611 + 1.65 \times \ln (D)$), and total biomass (M1: $\ln B = -1.297 + 1.79 \times \ln (D)$). Incorporating crown diameter and height into the models slightly improved the quality of adjusted. Comparison of the models in this study with pantropical equations previously used to estimate *Theobroma cacao* biomass shows that the models in this study provide a better estimate. The allometric equations developed in this work to estimate the AGB, BGB, and TB of *Theobroma cacao* can be used under the same environmental conditions to accurately predict the biomass accumulated in agroforestry systems by this species and thus allow the implementation of activities aimed at reducing emissions from deforestation and degradation (REDD$^+$) for the benefit of local communities through the carbon market.

1. Introduction

Theobroma cacao is a crop produced in several countries around the world [1]. Today, global demand for cocoa continues to increase and forecasts for 2035 are around 5 million tonnes of beans, while all producing countries only supply 4 million tonnes [2].

According to the National Cocoa and Coffee Office of Cameroon, cocoa represents 2% of the national gross domestic product (GDP), 6% of primary GDP, 30% of GDP in the subsector of agricultural products intended for processing, and 40% of primary sector exports [3].

For two decades, Cameroon has benefited from the recovery in world prices and the commitment of the State to revive its cocoa production [4] with a maximum production of 290000 tonnes of cocoa per year [5]. Cameroon has produces 193–295 tonnes of cocoa beans during the 2021-2022 campaign [6]. It is today positioned as the 5th largest cocoa-producing country in the world after Ivory Coast, Ghana, Indonesia, and Nigeria and the fourth producing country in Africa [2]. It is by far the first in Central Africa ahead of the Democratic Republic of Congo and the Congo, which are the two Central African nations succeeding it in terms of production [7].

In Cameroon, cocoa cultivation is booming; out of the 10 regions in the country, seven of them are cocoa producers [8]. According to the results of the 2021-2022 cocoa campaign produced by the National Cocoa and Coffee Office [9], the Central, South-West, Littoral, and South regions represent the largest cocoa production areas with surface estimates which vary between 375000 ha and 600000 ha. The Central Cameroon region alone covers 50.36% of national production, provides 60–70% of exports, and constitutes an important source of income for the rural world, with around 400000 producers and nearly 2 million people who directly depend on it [10].

In these different production regions, cocoa is mainly cultivated in monoculture, but there are agroforestry systems in which it is cultivated in association with woody species and which guarantee the sustainability of these systems [11].

Agroforestry systems in general and particularly those based on cocoa preserve a certain level of biodiversity which can reach a level close to that of a secondary forest [12].

Agroforestry systems based on cocoa trees, therefore, appear to be a credible alternative for achieving the millennium objectives in terms of conservation of local species and the fight against poverty in the world and thus contribute to the fight against global warming [13].

Agroforestry systems based on cocoa trees also play a crucial role in the recycling of nutrients and consequently in soil fertility [14]. In addition to their ability to produce biofuels, they provide farmers with different products that they consume or sell to increase their income and contribute to reducing greenhouse gas (GHG) concentrations in the atmosphere, thus regulating the carbon cycle [8].

According to the IPCC report [15], 30% of agricultural land converted to agroforestry and particularly those based on cocoa by 2040 would generate a net sequestration potential of 586 million tonnes of carbon per year. Oelbermann et al. [16] also indicated that the potential for carbon storage through the conversion of agricultural plots into agroforestry plots is very high on a global scale. Gockowski and Sonwa [17] and Temgoua et al. [8] found that cocoa-based agroforestry systems store more than 105 tC ha^{-1} in their aboveground biomass, among which that of *Theobroma cacao* is also important, thus contributing to the reduction of carbon dioxide (CO2) in the atmosphere.

With the advent of the $REDD^+$ mechanism, agroforestry systems could benefit from several advantages through payment for ecosystem services such as carbon credits. Indeed, the $REDD^+$ mechanism calls for a quantification of biomass through the development of allometric equations; a significant number of studies have been carried out in order to establish mixed allometric equations for the estimation of biomass in Cameroon, particularly in the humid tropical zone [18, 19]. Due to the lack of local allometric models to estimate the biomass of *Theobroma cacao*, some Central African countries, particularly Cameroon, rely on pantropical models such as those developed by Chave et al. [18] and Chave et al. [20] to estimate the AGB and BGB of *Theobroma cacao*. However, Molto et al. [21] reported three categories of errors in biomass estimation, including the choice of the allometric equation for estimating species biomass. The main reason for adjusting allometric models for this species is that the available equations are not suitable for estimating the biomass of *Theobroma cacao*; moreover, the models adjusted in Asia [22] cannot be adapted to the different biophysical conditions of the study area. The use of Chave models [18, 20] and other mixed models adjusted to forests allowed us to considerably evaluate the biomass of this species. However, adjusting the allometric models of *Theobroma cacao* would improve the precision of the estimates. The objective of this study was to develop site-specific allometric equations to estimate aboveground (AGB), belowground (BGB), and total biomass (TB) of *Theobroma cacao* in agroforestry systems in the Central Cameroon region.

2. Materials and Methods

2.1. Study Area. This study was carried out in the Central Region of Cameroon, in the department of Mbam and Inoubou, more specifically in the locality of Makénéné. The study area is located between 4°28′–5°00′ N and 10°28′–11°00′ E [23]. The climate of the area is the equatorial type with two rainy seasons interspersed with two dry seasons, with an average annual temperature of 25°C and average annual rainfall is 1440 mm [23]. The relief is made up of two sets of highlands and lowlands. The highlands with altitudes ranging from 600 to 900 m are located in the central and eastern parts of the area and cover three quarters of the territory. Having a yellow ferralitic red soil type, the clayey texture of these soils gives them a good water retention capacity and also a sufficient permeability due to the presence of pseudosand. These soils are suitable for growing coffee and cocoa but require long-term amendments. The vegetation is represented by secondary forests dominated by large trees [24, 25]. There are also areas dominated by wooded savannahs [26].

2.2. Data Collection. Biomass data for the adjustments were collected by destructive sampling of 50 trees of *Theobroma cacao* over a range of diameters from 5 to 27 cm. In the opinion of cocoa farmers, systematic sampling was carried out on cocoa trees and made it possible to select the different architectural types as defined by Jagoret et al. [3] from an age range of 0 to 70 years. Before each tree was felled, dendrometric parameters were measured. The circumference was measured at 30 cm above the ground level and the diameter was obtained from the following formula:

$$D = \frac{C}{3.141593}, \quad (1)$$

where C is the circumference in cm at 30 cm from the ground and D is the diameter in cm.

The total height of each cocoa tree was measured once the tree was felled. As for the crown diameter of the cocoa trees, the average of the crown diameters according to the orientations (North-South, East-West, North-East/South-West, and North-West/South-East) was used to calculate the average crown diameter of each cocoa tree sampled [27]. The cocoa trees were then cut 5 cm above the ground using a chainsaw and divided into compartments (leaves, branches, stems, pods, and trunks). The pods and leaves were bagged directly while the stems, branches, and trunks were cut into small pieces, bagged, and weighed using a scale brand electronic balance (precision = 1 g). To determine belowground biomass, the underground portion was dug until the main root and all lateral roots extending from the crown were visible. Once dug, the main components of the root portion were treated as indicated by [28] as follows: the root crown was cleaned to remove soil and weighed to obtain the fresh weight. Broken roots at the crown were followed and collected while the taproot was followed and collected to a minimum diameter. On each cocoa tree sampled, all lateral roots were selected and followed to a minimum diameter of 1 cm. A sample from each compartment was taken and dried in an oven in the laboratory of the Faculty of Agricultural Sciences of the University of Dschang at a temperature of 70°C for the leaves and 105°C for the roots, branches, trunk, and the pods and then we monitored the evolution of the weight at 6 hour intervals until a constant weight was reached. The dry mass of the sample obtained was used to calculate the total dry mass of each compartment of the tree according to the following formula:

$$\text{Dry mass of compartment} = \left(\frac{\text{Fresh mass of compartment} \times \text{dry mass of sample}}{\text{fresh mass of sample}}\right)[19]. \quad (2)$$

The total dry mass of the cocoa tree was obtained by adding the various compartments that make it up.

2.3. Data Analysis

2.3.1. Adjustment of the Allometric Equations. To adjust the allometric models, variables such as the diameter (D), total height (H), and crown diameter (C) were used [29]. The response variable was aboveground biomass (AGB), belowground biomass (BGB), and total biomass (TB). Nine models were tested in this study to select the best based on the comparison criteria; these models have been commonly used for establishing allometric equations [18, 29, 30].

(1) $\ln B = a + b \times \ln D + \varepsilon$,

(2) $\ln B = a + b \times \ln\,(D \times C) + \varepsilon$,

(3) $\ln B = a + b \times \ln\,(D \times H) + \varepsilon$,

(4) $\ln B = a + b \times \ln\,(D^2 \times H) + \varepsilon$,

(5) $\ln B = a + b \times \ln\,(D^2 \times C) + \varepsilon$,

(6) $\ln B = a + b \times \ln\,(D) + C \times \ln\,(C) + \varepsilon$,

(7) $\ln B = a + b \times \ln\,(D) + c \times \ln\,(H) + \varepsilon$,

(8) $\ln B = a + b \times \ln\,(D^2 \times C) + c \times \ln\,(H) + \varepsilon$,

(9) $\ln B = a + b \times \ln\,(D) + c \times \ln\,(C) + d \times \ln\,(H) + \varepsilon$.

2.3.2. Selection of the Best Model. The logarithmic transformation of the variables introduces a bias into the estimate. The correction factor (CF) with $CF = (RSE)^2)/2$ was used to correct the biases generated by this transformation [29].

The best models were selected based on parameters such as the Akaike information criterion (AIC) which allows a tradeoff between bias and variance for a model [31]. The residual standard error (RSE) (%) and the relative root mean square error (RRMSE) (%) make it possible to assess the precision of the model, especially since the lower they are, the more predictive the model is [32]. As for the deviation or residual error (E) (%), it allows us to express the error linked to the prediction of a model.

Residual error (E) (%), relative root mean square error (RRMSE) (%), and Akaike information criterion (AIC) were, respectively, calculated using the following formulas:

$$\text{Residual error}\,(\%) = 100 \times \frac{1}{n}\sum_{i=1}^{n}\frac{(\text{Mpi} - \text{Mi})}{\text{Mi}}$$
$$\text{RRMSE} = \sqrt{\frac{1}{n}}\left(\frac{\text{Mpi} - \text{Mi}}{\text{Mi}}\right)^2, \quad (3)$$

where Mpi is the tree dry weight predicted by the regression model, Mi is the observed dry weight, and n is the total number of trees [30].

$$\text{AIC} = 2K - 2\ln(L), \quad (4)$$

where k is the number of parameters in the regression model and L is the probability of the adjusted regression model [27].

The best models are those with a coefficient of determination is approximately equal to one, lower standard residual error, and lower AIC [31–33].

2.3.3. Model Validity Testing. The adjustment of the models is completed by verifying that the mentioned hypotheses on the residuals are well verified and statistical tests required to complete by validation of the adjustment of the models are done [27]. Thus, the following tests were performed:

(i) Normality test (Shapiro–Wilk test) to verify the normality of the residuals;

(ii) Heteroscedasticity test (studentized Breusch–Pagan) to verify the heterogeneity of the residuals;

(iii) Autocorrelation test (Durbin Watson test) to check the independence of the residuals.

2.3.4. Ratio of Belowground Biomass (BGB) to Aboveground Biomass (AGB). The ratio (R) between belowground biomass and aboveground biomass was calculated using the following formula: R = (BGB/AGB) [34].

2.3.5. Comparison of the Models with the Equations Commonly Used to Calculate the Biomass of Theobroma cacao. Dendrometric parameters collected from destroyed cocoa trees were used in the pantropical allometric equations developed by Chave et al. [18], Chave et al. [20], and in the allometric equation developed by Somarriba et al. [22] to calculate the aboveground biomass of this species. Belowground and total biomass were obtained from the guidelines established by the IPCC [35]. The different biomasses obtained from these models were compared to the actual biomass obtained and to the biomass predicted by the models developed as part of this work. The relative root mean square error (RRME) and the residual error (E) were used to assess the models. The following aboveground (AGB), belowground (BGB), and total (TB) biomass estimation equations were used:

(1) Aboveground Biomass (AGB). The models in this study were compared with models commonly used to estimate the aboveground biomass of *Theobroma cacao*. They are listed below:

(i) Chave et al. [18] model: $AGB = 0.0673 \times (\rho\ D^2\ H)^{0.976}$

(ii) Chave et al. [20] model: $AGB = 0.0509 \times \rho\ D^2\ H$

(iii) Somarriba et al. [22] model: $\text{Log (AGB)} = (-1.684 + 2.158 \times \text{Log}\ (d_{30}) + 0.892 \times \text{Log (alt)})$

With B: aboveground biomass (kg); d_{30}: trunk diameter at 30 cm; alt: total height (m); D: diameter at 30 cm; and ρ: wood density.

(2) Belowground Biomass (BGB). The belowground biomass estimated by each model was obtained by multiplying the aboveground biomass by $R = 0.24$ [35]. The following formulas were used:

(i) BGB = Chave et al. [18] × 0.24

(ii) BGB = Chave et al. [20] × 0.24

(iii) BGB = Somarriba et al. [22] × 0.24

(3) Total Biomass (TB). Total biomass was obtained by adding aboveground biomass (AGB) to belowground biomass (BGB) [35]. The following formulas were used:

(i) TB = Chave et al. [18] × (1 + 0.24)

(ii) TB = Chave et al. [20] × (1 + 0.24)

(iii) TB = Somarriba et al. [22] × (1 + 0.24).

2.3.6. Data Processing. The aboveground biomass, belowground biomass, and total biomass data were processed using the Excel spreadsheet and the 64 bit R software version 4.2.3 served as a basis for the various statistical tests.

3. Results

3.1. Total Allometric Equations. The allometric models were developed from a dataset of 50 trees of *Theobroma cacao* species with a diameter ranging from 5 to 27 cm. The graphic explorations of the scatterplots preceded the choice of the potential function for the adjustment and provide information on the nature of the relationships between the dendrometric variables and the dry biomass of *Theobroma cacao*. Figure 1 shows the linearized relationships by logarithmic function between total dry biomass and diameter (a), total dry biomass and crown diameter (b), and finally, total dry biomass and height (c).

After exploring the different relationships (Figure 1), the results of the adjusts are reported in Table 1.

Table 1 shows the different adjusted models, the nine preselected models for aboveground, belowground, and total dry biomass. According to Table 1, diameter (D) taken as an independent variable appears to be a good predictor of biomass with an adjusted R^2 equals to 0.942, 0.855, and 0.952, respectively, for aboveground biomass ($\ln\ B = -1.613 + 1.83 \times \ln\ (D)$), belowground ($\ln\ B = -2.611 + 1.65 \times \ln\ (D)$), and total dry biomass ($\ln\ B = -1.297 + 1.79 \times \ln\ (D)$). Adding the crown diameter (C) slightly improves the quality of the adjusts with an adjusted R^2 greater than 0.945, respectively, for aboveground ($\ln\ B = -1.594 + 1.63 \times \ln\ (D) + 0.3 \times \ln\ (C)$) and total biomass and ($\ln B = -1.278 + 1.57 \times \ln (D) + 0.37 \times \ln (C)$) and 0.864 for belowground biomass ($\ln B = -2.574 + 1.33 \times \ln\ (D) + 0.55 \times \ln\ (C)$). When we simultaneously integrate the three variables ($\ln\ (B) = a + b \times \ln\ (D) + c \times \ln(C) + d \times \ln\ (H) + \varepsilon$), the quality of adjustment is not improved.

3.2. Statistical Test for Model Validity. Table 2 shows the results of the different statistical tests for the best performing models. From this table, it is observed that the residuals show a normal distribution with the group of points in the Q-Q plot forming a straight line. However, the validation of the models was not just limited to the analysis of the distribution of the residuals. From Table 2, the p values of the Shapiro test are higher than the probability of 0.05, the Durbin–Waston test statistic is between 1.5 and 2.5, and the Breusch–Pagan test statistic is higher than 0.05; except for model M2 for estimating aboveground biomass, M3 and M4 for estimating belowground biomass, and M2 and M5 for estimating total biomass of *Theobroma cacao*, the Breusch–Pagan test is lower than 0.05, affecting its validation.

3.3. Selection of Allometric Equations. According to the results in Table 1, models M6: $B = \text{Exp}\ (-1.594 + 1.63 \times \ln\ (D) + 0.36 \times \ln\ (C))$; M5: $B = \text{Exp}\ (-2.564 + 0.64 \times \ln\ (D^2 \times C))$, and M6: $B = \text{Exp}\ (-1.278 + 1.57 \times \ln\ (D) + 0.37 \times \ln\ (C))$, respectively, for aboveground, belowground, and total biomass of *Theobroma cacao* have standard residual errors equal to 0.180, 0.267, and 0.157 and lower AIC than those of the other models (Table 1); these models are more efficient. However, with the exception of model M2 for estimating

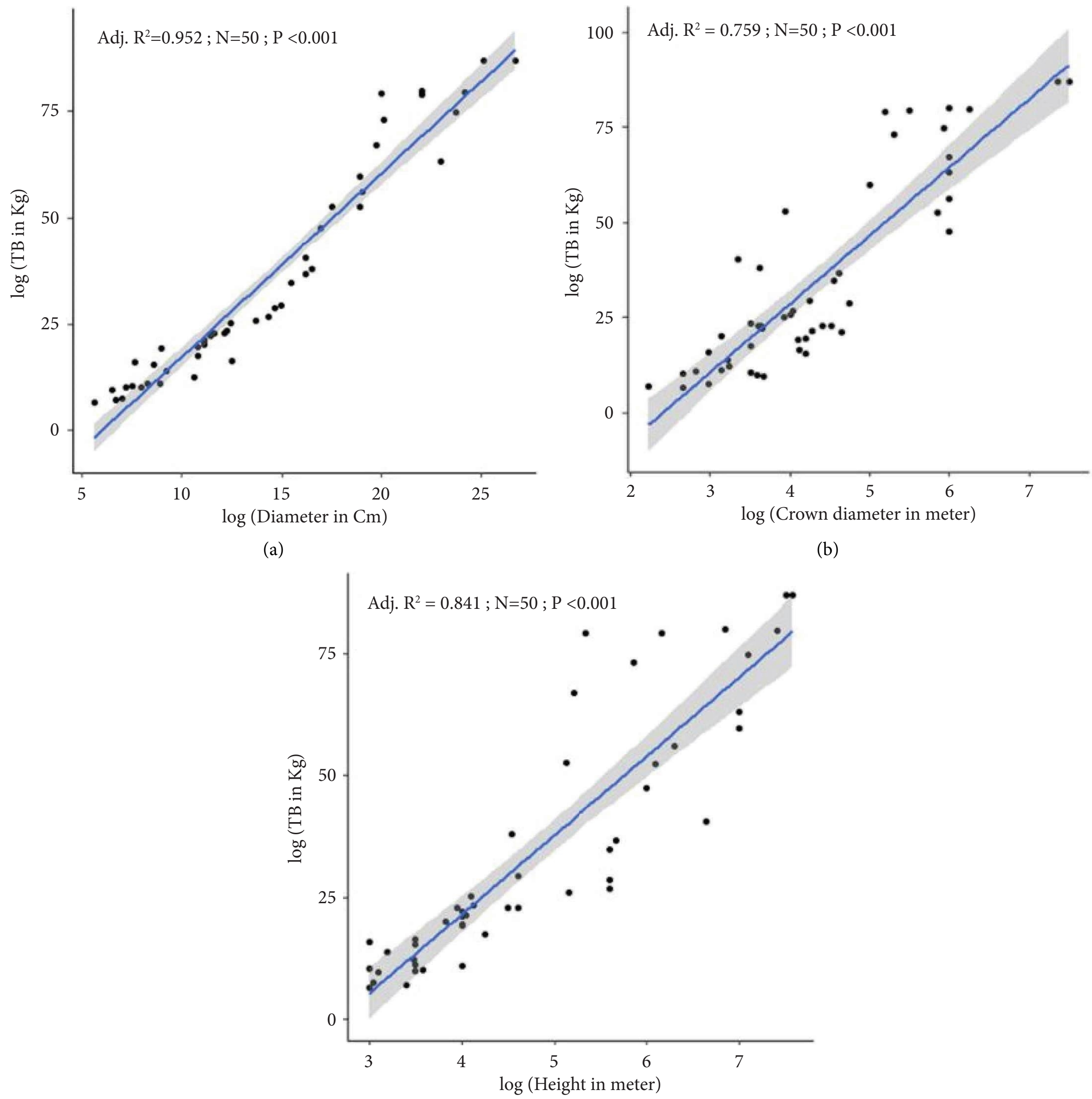

Figure 1: Linear regressions between total biomass and diameter (a), crown diameter (b), and height of *Theobroma cacao* (c).

aboveground biomass, M3 and M4 for estimating belowground biomass, and M2 and M5 for estimating total biomass of *Theobroma cacao*, all the other models listed in Table 1 are valid and can be used to estimate aboveground, belowground, and total biomass of *Theobroma cacao*. Since measuring the total height and crown diameter in the field is more difficult than measuring diameter, we recommend the model M1: $B = \mathrm{Exp}\ (-1.613 + 1.83 \times \ln\ (D))$ for the aboveground biomass, M1: $B = \mathrm{Exp}\ (-2.611 + 1.65 \times \ln\ (D))$ for the belowground biomass, and M1: $B = \mathrm{Exp}\ (-1.297 + 1.79 \times \ln\ (D))$ for the total biomass of *Theobroma cacao*.

3.4. Ratio of Belowground Biomass to Aboveground Biomass. The ratio of belowground biomass to aboveground biomass is 0.22.

3.5. Comparison of the Models of This Study with the Equations Commonly Used to Calculate the Biomass of Theobroma cacao. Table 3 shows the different values of the relative root mean square error and average error of the models in this work and those commonly used to estimate *Theobroma cacao* biomass. Table 3 shows that in terms of aboveground (AGB) biomass, the models developed by Chave et al. [18] and Chave et al. [20] underestimate biomass by −3.34% and −15.273%, respectively. The model by Somarriba et al. [22] underestimates biomass by −81.88%. However, to minimize bias, the models M1, M3, M4, M5, M6, M7, M8, and M9 adjusted in this work can be used to estimate the aboveground biomass of *Theobroma cacao*. If a few models are given priority, model M6: $B = \mathrm{Exp}\ (-1.594 + 1.63 \times \ln\ (D) + 0.36 \times \ln\ (C))$ overestimates biomass by 3.21%. Model

Table 1: Models parameters and performance criteria for biomass estimation of *Theobroma cacao*.

Models	Model expression	N	D	a	b	c	d	RSE	RRMSE	Residual error (%)	AIC	FC	R^2
Aboveground biomass (AGB)													
M1	$\ln B = a + b \times \ln(D) + \varepsilon$	50	5–27	-1.63^{***}	1.83^{***}			0.186	0.198	3.47	−22.46	0.017	0.942
M2	$\ln B = a + b \times \ln(D \times C) + \varepsilon$	50	5–27	-1.42^{***}	1.12^{***}			0.211	0.219	4.43	−9.72	0.022	0.925
M3	$\ln B = a + b \times \ln(D \times H) + \varepsilon$	50	5–27	-1.41^{***}	1.1^{***}			0.209	0.212	4.31	−10.83	0.021	0.927
M4	$\ln B = a + b \times \ln(D^2 \times \mathrm{H}) + \varepsilon$	50	5–27	-1.52^{***}	0.69^{***}			0.193	0.197	4.31	−18.65	0.019	0.937
M5	$\ln B = a + b \times \ln(D^2 \times C) + \varepsilon$	50	5–27	-1.55^{***}	0.70^{***}			0.185	0.196	3.44	−22.69	0.017	0.942
M6	$\ln B = a + b \times \ln(D) + c \times \ln(C) + \varepsilon$	50	5–27	-1.61^{***}	1.63^{***}	0.3^{ns}		0.180	0.190	3.21	−24.50	0.016	0.945
M7	$\ln B = a + b \times \ln(D) + c \times \ln(H) + \varepsilon$	50	5–27	-1.61^{***}	1.74^{***}	0.153		0.187	0.194	3.48	−20.81	0.017	0.941
M8	$\ln B = a + b \times \ln(D^2 \times \mathrm{C}) + c \times \ln(H) + \varepsilon$	50	5–27	-1.53^{***}	0.65^{***}	0.21		0.186	0.191	3.41	−21.43	0.017	0.942
M9	$\ln B = a + b \times \ln(D) + c \times \ln(H) + d \times \ln(C) + \varepsilon$	50	5–27	-1.60^{***}	1.56^{***}	0.10^{ns}	0.35	0.182	0.187	3.25	−22.67	0.017	0.944
Belowground biomass (BGB)													
M1	$\ln B = a + b \times \ln(D) + \varepsilon$	50	5–27	-2.65^{***}	1.65^{***}			0.278	0.316	7.92	17.78	0.039	0.855
M2	$\ln B = a + b \times \ln(D \times C) + \varepsilon$	50	5–27	-2.49^{***}	1.03^{***}			0.275	0.306	7.70	16.87	0.038	0.857
M3	$\ln B = a + b \times \ln(D \times H) + \varepsilon$	50	5–27	-2.42^{***}	0.98^{***}			0.301	0.372	9.56	25.79	0.045	0.829
M4	$\ln B = a + b \times \ln(D^2 \times H) + \varepsilon$	50	5–27	-2.52^{***}	0.62^{***}			0.288	0.345	8.68	21.55	0.041	0.843
M5	$\ln B = a + b \times \ln(D^2 \times C) + \varepsilon$	50	5–27	-2.60^{***}	0.64^{***}			0.267	0.293	7.20	13.67	0.036	0.866
M6	$\ln B = a + b \times \ln(D) + c \times \ln(C) + \varepsilon$	50	5–27	-2.61^{***}	1.33^{***}	0.55^{*}		0.269	0.294	7.27	15.55	0.036	0.864
M7	$\ln B = a + b \times \ln(D) + c \times \ln(H) + \varepsilon$	50	5–27	-2.67^{***}	1.76^{***}	−0.160		0.280	0.312	7.94	19.61	0.039	0.852
M8	$\ln B = a + b \times \ln(D^2 \times C) + c \times \ln(H) + \varepsilon$	50	5–27	-2.62^{***}	0.68^{***}	−0.190		0.269	0.290	7.21	15.37	0.036	0.864
M9	$\ln B = a + b \times \ln(D) + c \times \ln(\mathrm{H}) + d \times \ln(C) + \varepsilon$	50	5–27	-2.64^{***}	1.48^{***}	0.245	0.57	0.271	0.289	7.26	17.12	0.037	0.862
Total biomass (TB)													
M1	$\ln B = a + b \times \ln(D) + \varepsilon$	50	5–27	-1.31^{***}	1.79^{***}			0.164	0.169	2.68	−34.83	0.013	0.952
M2	$\ln B = a + b \times \ln(D \times C) + \varepsilon$	50	5–27	-1.10^{***}	1.10^{***}			0.188	0.189	3.48	−21.41	0.017	0.937
M3	$\ln B = a + b \times \ln(D \times H) + \varepsilon$	50	5–27	-2.42^{***}	0.98^{***}			0.301	0.805	−80.38	25.79	0.045	0.829
M4	$\ln B = a + b \times \ln(D^2 \times H) + \varepsilon$	50	5–27	-1.2^{***}	0.67^{***}			0.172	0.171	2.92	−29.89	0.015	0.947
M5	$\ln B = a + b \times \ln(D^2 \times C) + \varepsilon$	50	5–27	-1.23^{***}	0.68^{***}			0.161	0.164	2.57	−36.62	0.013	0.954
M6	$\ln B = a + b \times \ln(D) + c \times \ln(C) + \varepsilon$	50	5–27	-1.29^{***}	1.57^{***}	0.37^{*}		0.157	0.159	2.41	−38.68	0.012	0.956
M7	$\ln B = a + b \times \ln(D) + c \times \ln(H) + \varepsilon$	50	5–27	-1.29^{***}	1.71^{***}	0.135		0.165	0.167	2.68	−33.18	0.014	0.951
M8	$\ln B = a + b \times \ln(D^2 \times C) + c \times \ln(H) + \varepsilon$	50	5–27	-1.22^{***}	0.64^{***}	0.183		0.162	0.160	2.55	−35.32	0.013	0.953
M9	$\ln B = a + b \times \ln(D) + c \times \ln(H) + d \times \ln(C) + \varepsilon$	50	5–27	-1.28^{***}	1.52^{***}	0.08^{ns}	0.37^{*}	0.158	0.157	2.42	−36.82	0.012	0.956

B: total biomass; *D*: diameter; *H*: height of tree; *C*: crown diameter; *N*: the number of trees; *a*, *b*, *c*, and *d*: the coefficients of the variables; RRMSE: relative root mean square error; RSE: residual standard error; Adj R^2: coefficient of determination; AIC: Akaike information criterion; and CF: correcting factor. *Note*. The results are significant at a 95% confidence interval. $^{**}p < 0.01$; $^{*}p < 0.05$; and ns: nonsignificant, $p > 0.05$. p value of all models: $2.2e\_16$. $^{***}p < 0.001$.

Table 2: Statistical tests for model validity.

Models	Model expression	Shapiro–Wilk	p value	Breusch–Pagan	p value	Durbin–Watson	p value
Aboveground biomass (AGB)							
M1	$\ln B = -1.613 + 1.83 \times \ln(D)$	0.968	0.194	2.564	0.109	2.348	0.875
M2	$\ln B = -1.398 + 1.12 \times \ln(D \times C)$	0.978	0.463	0.022	0.881	2.031	0.488
M3	$\ln B = -1.389 + 1.1 \times \ln(D \times H)$	0.986	0.809	2.12	0.145	1.830	0.226
M4	$\ln B = -1.501 + 0.69 \times \ln(D^2 \times H)$	0.988	0.874	2.920	0.087	1.860	0.259
M5	$\ln B = -1.533 + 0.70 \times \ln(D^2 \times C)$	0.979	0.512	0.197	0.657	2.143	0.653
M6	$\ln B = -1.594 + 1.63 \times \ln(D) + 0.36 \times \ln(C)$	0.972	0.277	0.995	0.608	2.311	0.832
M7	$\ln B = -1.593 + 1.74 \times \ln(D) + 0.153 \times \ln(H)$	0.977	0.423	6.946	0.031	1.908	0.313
M8	$\ln B = -1.513 + 0.65 \times \ln(D^2 \times C) + c \times \ln(H)$	0.983	0.697	3.864	0.145	1.945	0.367
M9	$\ln B = -1.583 + 1.56 \times \ln(D) + 0.10 \times \ln(H) + 0.35 \times \ln(C)$	0.977	0.424	6.066	0.109	2.267	0.788
Belowground biomass (BGB)							
M1	$\ln B = -2.611 + 1.65 \times \ln(D)$	0.989	0.934	0.771	0.380	1.892	0.312
M2	$\ln B = -2.452 + 1.03 \times \ln(D \times C)$	0.979	0.513	2.795	0.09	2.067	0.541
M3	$\ln B = -2.375 + 0.98 \times \ln(D \times H)$	0.956	0.09	0.02	0.881	1.411	0.011
M4	$\ln B = -2.479 + 0.62 \times \ln(D^2 \times H)$	0.986	0.192	0.042	0.838	1.475	0.0201
M5	$\ln B = -2.564 + 0.64 \times \ln(D^2 \times C)$	0.980	0.559	2.318	0.128	1.728	0.136
M6	$\ln B = -2.574 + 1.33 \times \ln(D) + 0.55 \times \ln(C)$	0.981	0.582	2.445	0.294	1.759	0.153
M7	$\ln B = -2.631 + 1.76 \times \ln(D) – 0.160 \times \ln(H)$	0.994	0.995	4.077	0.130	1.908	0.313
M8	$\ln B = -2.584 + 0.68 \times \ln(D^2 \times C) – 0.190 \times \ln(H)$	0.979	0.495	4.887	0.087	1.684	0.105
M9	$\ln B = -2.603 + 1.48 \times \ln(D) + 0.245 \times \ln(\mathrm{H}) + 0.57 \times \ln(C)$	0.986	0.576	5.09	0.165	1.912	0.324
Total biomass (TB)							
M1	$\ln B = -1.297 + 1.79 \times \ln(D)$	0.976	0.401	1.328	0.249	2.308	0.842
M2	$\ln B = -1.083 + 1.10 \times \ln(D \times C)$	0.979	0.539	0.00066	0.974	1.999	0.444
M3	$\ln B = -2.375 + 0.98 \times \ln(D \times H)$	0.972	0.276	0.263	0.608	1.473	0.02
M4	$\ln B = -1.185 + 0.67 \times \ln(D^2 \times H)$	0.973	0.312	0.724	0.395	1.491	0.023
M5	$\ln B = -1.217 + 0.68 \times \ln(D^2 \times C)$	0.984	0.729	0.039	0.843	2.022	0.484
M6	$\ln B = -1.278 + 1.57 \times \ln(D) + 0.37 \times \ln(C)$	0.974	0.323	0.455	0.796	2.229	0.747
M7	$\ln B = -1.276 + 1.71 \times \ln(D) + 0.135 \times \ln(H)$	0.981	0.576	6.763	0.0340	1.59	0.05
M8	$\ln B = -1.207 + 0.64 \times \ln(D^2 \times C) + 0.183 \times \ln(H)$	0.982	0.654	5.4	0.067	1.768	0.152
M9	$\ln B = -1.268 + 1.52 \times \ln(D) + 0.08 \times \ln(C) + 0.37 \times \ln(H)$	0.975	0.379	7.164	0.067	2.199	0.711

Table 3: Comparison of the models in this study with models commonly used to calculate the biomass of *Theobroma cacao*.

Authors	Model	RRMSE	Residual error (%)	Biomass (kg)
Aboveground biomass (AGB)				
Chave et al. [18]	$\text{AGB (kg)} = 0.0673 \times (\rho\ D^2\ H)^{0.976}$	0.339	−3.34	1618.65
Chave et al. [20]	$\text{AGB (kg)} = 0.0509 \times \rho\ D^2 H$	0.350	−15.273	1440.26
Somarriba et al. [22]	$\text{Log AGB (kg)} = (-1.684 + 2.158 \times \log\ (d_{30}) + 0.892 \times \log\ (\text{alt}))$	0.82	−81.88	207.74
Model 1	$\ln\ B = -1.613 + 1.83 \times \ln\ (D)$	0.198	3.47	1421.56
Model 6	$\ln\ B = -1.598 + 1.628 \times \ln\ (D) + 0.36 \times \ln\ (C)$	0.190	3.21	1426.075
Observed biomass	—	—	—	1419.874
Belowground biomass (BGB)				
IPCC [35]	BGB = Chave et al. [18] × 0.24	0.514	6.991	388.48
IPCC [35]	BGB = Chave et al. [20] × 0.24	0.468	−6.076	345.66
IPCC [35]	BGB = Somarriba et al. [22] × 0.24	0.81	−80.79	49.86
Model 1	$\ln\ B = -2.611 + 1.655 \times \ln\ (D)$	0.316	7.92	315.47
Model 5	$\ln\ B = -2.564 + 0.64 \times \ln\ (D^2 \times C)$	0.294	7.20	316.84
Observed biomass	—	—	—	316.693
Total biomass (TB)				
IPCC [35]	TGB = Chave et al. [18] × (1 + 0.24)	0.348	−2.877	2007.128
IPCC [35]	TGB = Chave et al. [20] × (1 + 0.24)	0.356	−14.834	1785.92
IPCC [35]	TGB = Somarriba et al. [22] × (1 + 0.24)	0.822	−80.67	257.60
Model 1	$\ln\ B = -1.297 + 1.79 \times \ln\ (D)$	0.169	2.68	1732.12
Model 6	$\ln\ B = -1.278 + 1.57 \times \ln\ (D) + 0.37 \times \ln\ (C)$	0.158	2.41	1738.01
Observed biomass	—	—	—	1736.567

M1: $B = \text{Exp}\ (-1.613 + 1.83 \times \ln\ (D))$ overestimates biomass by 3.47% and also appears to be a good predictor of *Theobroma cacao* biomass. The M1 model for estimating aboveground biomass, represented by the red curve (Figure 2), is almost identical to the observed biomass curve (green), resulting in a lower bias value (3.47%).

The model developed by the IPCC [35] overestimates belowground biomass by 6.991% when the model of Chave et al. [18] is used and underestimates the belowground biomass by −6.076% when the model of Chave et al. [20] is used. When the Somarriba [22] model is used, biomass is underestimated by −80.79%. Models M1: $B = \text{Exp}\ (-2.611 + 1.65 \times \ln\ (D))$ and M5: $B = \text{Exp}\ (-2.564 + 0.64 \times \ln\ (D^2 \times \text{C}))$ overestimate biomass by 7.92% and 7.20%, respectively. The models M1, M2, M5, M6, M7, M8, and M9 adjusted in this work can be used to estimate the belowground biomass of *Theobroma cacao* (Table 3). However, if one of the nine models should be selected, we recommend model M1: $B = \text{Exp}\ (-2.611 + 1.65 \times \ln\ (D))$. For belowground biomass, model 1 (red curve in Figure 3) is almost identical to the green curve (observed biomass), hence the low value of the bias with model M1 (7.92%) (Table 3) compared with the actual observed value.

Models M1 and M6 overestimate total biomass by 2.68% and 2.41%, respectively. When the Chave et al. [18] and Chave et al. [20] models are used, the IPCC model underestimates biomass by −2.877% and −14.834%, respectively. When the Somarriba et al. [22] model is used, the IPCC model underestimates biomass by −80.67% (Table 3). Based on inventory data (crown diameter and diameter), we recommend models M1: $B = \text{Exp}\ (-1.297 + 1.79 \times \ln\ (D))$ and M6: $B = \text{Exp}\ (1.278 + 1.57 \times \ln\ (D) + 0.37 \times \ln\ (C))$, which overestimate biomass by 2.68% and 2.41%, respectively. The M1 model for total biomass represented by the red curve in Figure 4 is almost merged with the green curve (observed biomass), hence the low value of the deviation between the observed value and the biomass value predicted by the M1 model. Chave et al. [18] and Chave et al. [20] predict with a large overestimation, while Somarriba et al. [22] underestimates the biomass with a very large deviation; their models are not suitable for predicting the total biomass of *Theobroma cacao*. The M1 model is recommended.

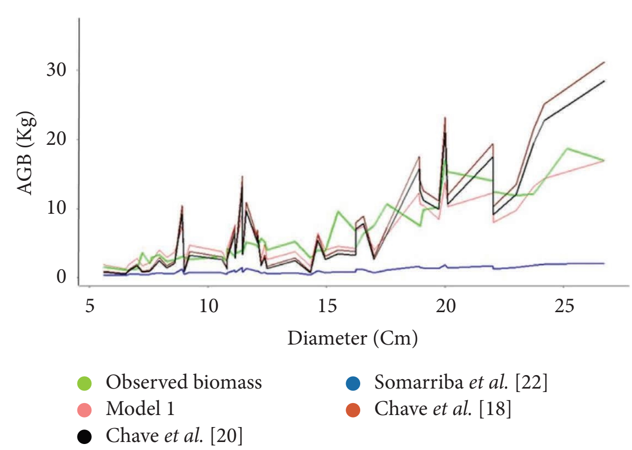

Figure 2: Comparison of our models with previously equation use to estimate aboveground biomass of *Theobroma cacao*.

4. Discussion

In this study, we showed the plasticity of the relationship between aboveground, belowground, and total biomass and inventory data (diameter, crown diameter, and height). With the high species diversity in the tropics, it is difficult to adjust the equations for each species [27]. With this in mind, this study made it possible to develop single-specific equations for the estimation of the aboveground, belowground, and total biomass of *Theobroma cacao* in a diameter range

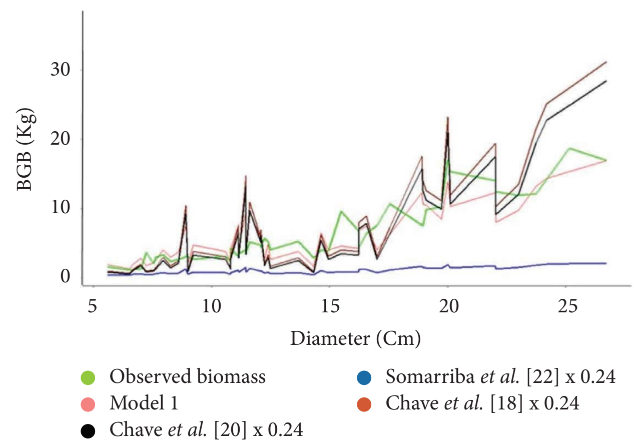

Figure 3: Comparison of our models with previously equation use to estimate belowground biomass of *Theobroma cacao*.

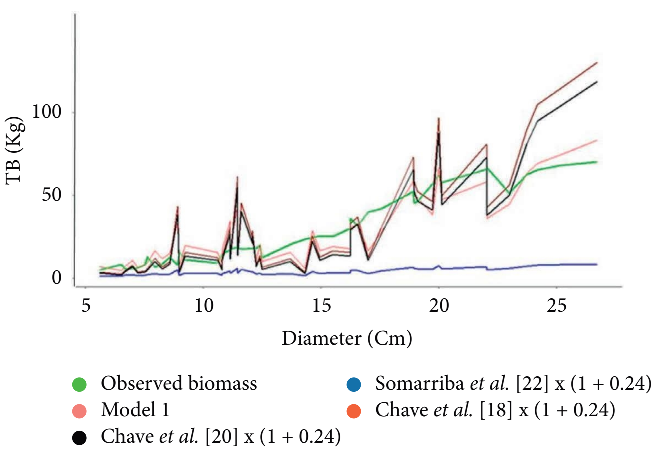

Figure 4: Comparison of our models with previously equation use to estimate total biomass of *Theobroma cacao*.

between 5 and 27 cm. This result is similar to those of Victor Awé et al. [36] (5.76 and 24.80 cm) for the allometric equation of *Boscia senegalensis* developed in Cameroon. The allometric models developed vary from one compartment to another. The choice of method and mathematical model for parameter adjustment must be considered judiciously in estimating woody plant biomass [37]. Aboveground, belowground, and total biomass of *Theobroma cacao* were adjusted using the linear form of the power model. This mathematical model has been widely used in the literature to predict the standing biomass of African woody species [36]. Indeed, power models generally remain extrapolable with good reliability because they are based on an allometric model invariant at all scales, which explains their wide use in biomass-forecasting equations in favor of logarithmic or polynomial models [38]. The logarithmic transformation of the variables carried out in this study remains necessary to reduce the differences that may exist in a real environment and to satisfy the conditions of normality and homoscedasticity of the residuals [27]. The sample size used to develop the allometric models of *Theobroma cacao* was 50 trees. Indeed, the size of the sample in the development of allometric equations varies in the literature and takes into account the financial and material resources and the time allocated to the study [39]. Some allometric biomass equations were constructed from a limited number of individuals, i.e., 17 trees [39], 20 trees [33], 38 trees [40], 15 and 43 trees [41], 40 trees ([36]), and 40 and 50 trees [42]. Biomass estimation models vary according to the different compartments of *Theobroma cacao*. The results of this study are similar to those obtained by [36] who showed a variation in allometric equations depending on the parts of the tree.

Among the variables explaining the biomass of *Theobroma cacao*, the diameter appears to be a good predictor with an R^2 greater than 94%. The R^2 coefficients of determination were slightly above 0.95 for the aboveground biomass equations, 085 for the belowground biomass equations, and an average of 0.95 for the total biomass equations. Numerous studies have also shown that taking into account the diameter as the only input variable makes it possible to reduce errors and increase the precision of biomass [19, 29, 30].

Adding crown diameter and height to the models did very little to improve the quality of adjustment This weak link between the diameter of the crown and the biomass on the one hand and the height and the biomass on the other hand could be explained by the fact that cocoa trees are called upon to compete for light in the undergrowth of agrosystems. Forests, moreover, vegetative multiplication by budding leading to the complex from type I to type V as defined by Jagoret et al. [3], associated with random pruning would bias the allometry (ABG-CD/H). The residual standard errors (RSEs) for aboveground, belowground, and total biomass range from 0.185 to 0.211, 0.267 to 0.311, and 0.162 to 0.301, respectively; similarly, the relative root means square error (RRMSE) varies from 0.180 to 0.192, 0.272 to 0.281, and 0.161 to 4.42, respectively, for aboveground, belowground, and total biomass. These low errors demonstrate the normality of the residuals, their independence, and heterogeneity, suggesting a close link between biomass and the explanatory variables [27]. The estimation model (M5b) for the total biomass presents a coefficient of determination (adjusted R^2) greater than 0.94, and the value of the AIC and the RSE low but has not been validated by the various tests in occurrence the Breusch–Pagan test or the value of the statistic is less than 0.05. A model can have a high coefficient of determination and the residual standard error (RSE) and the Akaike information criterion (AIC) low and be rejected by the assessment of certain validation criteria, and in particular, the different statistical tests [32, 33, 43]. The ratio of belowground biomass to aboveground biomass (BGB/AGB) gives a ratio of 0.22 which is close to the ratio of 0.24 proposed by the IPCC [35]. The order of magnitude of the biases of the models developed as part of this research remains less than 5%. This result remains similar to that of Feukeng et al. [27] which for monospecific equations of the species *Trema orientalis* and *Distemonanthus benthamianus* finds biases at respective values of 0.1% and 4.04%.

The bias values of the pantropical models developed by Chave et al. [18] and Chave et al. [20] used on our data to estimate the aboveground biomass of *Theobroma cacao* and those of the belowground and total biomasses estimated using the IPCC [35] method range from −3.34% to −81.84% for aboveground biomass, from −80.79 to 6.91 for belowground biomass, and from −2.877 to −80.67 for total biomass. The models developed by Chave et al. [18] and Chave et al. [20] considerably overestimated the aboveground biomass of *Theobroma cacao*. When the IPCC [35] method is used to estimate the belowground and total biomass of *Theobroma cacao*, this biomass is also overestimated. This overestimation could be explained by the fact that these pantropical mixed equations for estimating aboveground biomass developed by Chave et al. [18] and Chave et al. [20] and those for belowground and total biomass developed by the IPCC [35] which predict biomass less than the monospecific models developed in this work were adjusted not only for *Theobroma cacao* but also for several other species [27]. The model of Somarriba et al. [22] applied to our data, underestimated the aboveground biomass of *Theobroma cacao*. This underestimation could be due to the fact that the Somarriba et al. [22]'s model was developed to estimate the aboveground biomass of Asian cocoa trees having a climate very different from that of the Central Cameroon region which served as the study area. The biotic and abiotic factors of these different zones would also better explain this difference [44].

5. Conclusion

This research aimed to develop allometric equations to estimate the biomass of *Theobroma cacao*, and it made it possible to adjust nine models to estimate the aboveground, belowground, and total biomass of *Theobroma cacao*. The M2 models for estimating aboveground biomass, M3 and M4 for estimating belowground biomass, and M2 and M5 for estimating total biomass have not been validated by the various statistical tests and cannot be used to estimate the biomass of this species. Since measuring height is sometimes difficult, we recommend models taking only diameter (D) as an explanatory variable to estimate biomass. Adapting models to architectural types could better increase the precision of biomass estimates for this species. The models obtained in this work could be used in areas similar to the study sites to assess the biomass and carbon sequestration capacity of *Theobroma cacao*. This study is a contribution to filling the data gap on the mitigation of the effects linked to climate change and also appears to be of informative value to serve as a basis for the effective implementation of the REDD+ mechanism in Cameroon through the payment of carbon credits.in

Data Availability

The data used to support this finding are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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