Scientific Research Publishing

Open Journal of Forestry, 2024, 14, 346-368
https://www.scirp.org/journal/ojf
ISSN Online: 2163-0437
ISSN Print: 2163-0429

Supervised Learning Method: Critical Analysis and Updating of Cubing Rate Formulas for Determining Bark Masses of *Prunus africana* (Hook. f.) Kalkman (Rosaceae) in Cameroon

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How to cite this paper: Bile, A. N., Mpouam, A., Fouadjio, B., Guedeu, L., Muhesi, K., Tassiamba, S., Kouam, P., Wete, E., Ela, M., Yimga, M., Ambara, J., Fono, L. A., & Betti, J. L. (2024). Supervised Learning Method: Critical Analysis and Updating of Cubing Rate Formulas for Determining Bark Masses of *Prunus africana* (Hook. f.) Kalkman (Rosaceae) in Cameroon. *Open Journal of Forestry, 14,* 346-368.
https://doi.org/10.4236/ojf.2024.143020

Received: March 4, 2024
Accepted: July 27, 2024
Published: July 30, 2024

Abstract

The stem barks of *Prunus africana* are used in the treatment of the benign prostate. Cameroon is one of the important exporters of the barks. Despite the important measures adopted in Cameroon for sustaining its harvesting, some many chalenges still remain. The objective of this work is to refine the forest management parameters in relation to *P. africana* in the regions of Adamaoua and the South-West by developing a volume rate which makes it possible to estimate the production for a new stem. The work took place in two phases: in the South-West in 2010 and in Adamaoua in 2011. Data collection used the semi-direct method, while the cubing equation was deduced by the multiple linear regression method. Two models for volume estimation and three models for mass prediction were developed. The predictive parameters retained are diameter, height of the bole and thickness of the bark. Results show that the average mass of the dry bark for a given *P. africana* tree species is 27.55 ± 14.44 kg and this varies according to the site. The strong adjusted coefficient of determination (adjusted R^2) observed illustrates the reliability of the proposed models. These models provide a reliable tool that can be adopted as a standard in Cameroon for *P. africana*.

Keywords

Prunus africana, Prostate, Quota, Mass, Model, Sustainable Management

1. Introduction

The forests of Central Africa, cover nearly 236 million hectares (Ngbolua et al., 2022) and provide many goods and services to a large number of stakeholders (Ligot et al., 2018). However, they are regressing at a rate of 0.23% area per year (FAO, 2010; Ngbolua et al., 2022). This regression could be more or less significant in mountain forests, which are less diverse in terms of species compared to sub-mountane forests. Characteristic trees of the mountain forests include *Schefflera abyssinica*, *Canthium dunlapii*, *Nuxia congesta*, *Clausena anisata*, *Syzygium staudii*, *and Prunus africana* (Betti & Ambara, 2011). *P. africana* is a species whose bark is used locally or exported for medicinal purposes in the treatment of various diseases such as prostate, malaria, urogenital infections, etc. (Muhesi et al., 2023). Barks are largely found in the international trade for their use in the treatment of the benign prostate. *P. africana* is listed in appendix 2 of CITES and classified as a special product of particular interest in Cameroon. The majority of *P. africana* populations in Cameroon are in the Northwest, Southwest and Adamaoua regions (Momo et al., 2016). The rate of debarking and the quantities harvested are significant enough to guarantee an uncertain future for future generations and, above all, for the species (Tadjuidje, 2011). For example, in the Tchabal Mbabo forest massif, Ndedy Bile et al. (2022) found a stem mortality rate of 3.63%, with 1.12% linked to previous logging. Stand management in its natural area requires quantification of the resource with a view to planning and conciliating harvesting and biodiversity conservation (Rabiou et al., 2015). Cameroon, a member of the International Tropical Timber Organization (ITTO) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), has benefited from support from the joint ITTO-CITES program for the sustainable management of *Pericopsis elata* (Afrormosia) and *P. africana* (Pygeum), two CITES listing tree species (Ekodeck et al., 2023). These interventions have enabled the country to appropriate mechanisms for the management of CITES species and the production of Non-Detriment Findings (NDF). Such measures include the creation of *Prunus* Allocation Units (PAU), the settlement of the Minimum Exploitability Diameter (DME) at 30 cm (ANAFOR, 2014), the adoption of the 2/4 opposed harvesting technique, the consideration of a half-rotation of 7 years (Mpouam et al., 2022; Ndedy Bile et al., 2022). Despite this, the quota calculation technique is still not very clear, with concerns regarding the sampling technique, the productivity of an exploitable tree, bias correction, whether or not to use the average productivity of a stem as suggested by different authors (Ondigui, 2001; Betti & Ambara, 2011, 2013). Those concerns have led the

Scientific Review Group (SRG) of the European Commission to make some reservations (Letter ARES, 2023 5208020-27/07/2023) about the final validation of the 2023 quota of dried barks (Ekodeck et al., 2023) proposed by Cameroon (Betti et al., 2023). In fact, the quota should be defined on the basis of harvesting inventories. These inventories are conducted at the sampling rate of 100% of annual cutting plot and on exploitable trees. Exploitable trees are those which have reached 30 cm of diameter at breast hight. It is imperative to have tools that enable us to know the standing timber value likely to provide the total volume (Kahindo, 2009; Kaluka, 2015). To compensate for this, cubage equations/rates have been developed by different authors (Burkhart & Avery, 1994; Ondigui, 2001; Betti & Ambara, 2011, 2013; Ingram 2014). Whatever be the type of inventory, it is imperative to be able to estimate the mass of *P. africana* bark to be harvested. The problem is that these equations give the woody potential as for timber logging. Also, the existing equations only provide the quota in terms of the volume (m^3) of bark, not in mass (kilogram) as it is the case for *P. africana*. The cubage tariff must be established on the basis of reliable observations of volumes and possible inputs and parameters.

According to Rondeux (1998), there are two main types of cubage tariff: 1) "stand" tariffs and 2) "tree" tariffs. The latter allow estimates to be made for individual trees, based on one or more of their dendrometric characteristics and/or the stand to which they belong. This shows that there are relationships between the parameters (the one to be predicted and its predictors). Statistical regression methods judge the quality of fits using parameters such as the coefficient of determination (R^2), or parameters based on the value of residuals such as the residual standard deviation (RSD) (Dagnelie, 1975). The relationship can be demonstrated by linear or non-linear regression (single or multiple) (Ngbolua et al., 2022). Multiple linear regression allows a quantitative variable "y" to be explained and/or predicted by "p" quantitative variables that minimize the least squares criterion (Cornillon et al., 2018). As growth parameters vary according to site and altitude (Mpouam et al., 2022), it would be interesting to have an equation (cubing rate) specific to each zone (*P. africana* site), bearing in mind that the parameters of this equation must be easily obtained during a data collection operation (inventory or other) to minimize the workload, collection time and consequently the costs associated with this activity. Thus, the bark production (mass in kg or tons) of a *P. africana* stem could be estimated by its dendrometric parameters, i.e. its diameter at breast height (at 1.30 m or butt diameter), the height of the bole (from 1.30 m to the point of insertion of the first large branch) and the thickness of its bark (unexploited side). The basic hypothesis is that "the productivity of *P. africana* stem would not depend solely on the diameter". This work contributes to refining the management parameters in relation to *P. africana* in the Adamaoua and South-West regions of Cameroon. Specifically, it aims to: 1) determine the average production of a stem, 2) explore the dendrometric parameters which influence the productivity of a stem, and 3) develop a cubing rate that enables production to be estimated for a new stem.

2. Material and Method

2.1. Study Area

2.1.1. Species Description

Prunus africana is a mountain tree found between 800 and 3000 m altitude. It is a canopy species, 30 to 40 m high (Momo et al., 2016) and 40 to 120 cm in diameter at maturity (Njamnshi & Ekati, 2008). The bole is straight, often fluted, trimmed at the base with simple serrations or four buttresses with a concave or convex profile, 8 to 10 cm thick, sometimes branched into a "V" towards the ground, spreading 1 m from the tree and rising to 1 m in height (Vivien & Faure, 1985). It has small, simple inflorescences in auxiliary racemes 2 to 8 cm long. Each raceme contains 15 to 24 flowers (Hall et al., 2000).

2.1.2. Massif Description

Tchabal Mbabo is located around 90 km from the town of Banyo. It culminates at an altitude of 2240 meters (MINFOF, 2018). The vegetation of Tchabal Mbabo is varied and rich. There are several plant formations (strata): forest galleries, grassy savannah, dry forests, wooded savannahs (Letouzey, 1985). Average maximum temperatures are around 30˚C, generally in March, with minimums between 15˚C (December to January) and 18˚C (July). The wind is dry and humid in the rainy season and hot and dry in the dry season (Akoa et al., 2011). Tchabal Ngandaba is located between the North and Adamaoua-Cameroon regions, precisely in the Faro (North side) and Faro et Deo (Adamaoua side) departments. It lies to the south of the Meré river, around 60 km from Tignère, and reaches an altitude of 1960 metres. Depressions containing forest galleries can be found on the slopes of the mountains and between them. The average annual temperature is around 23˚C. Average maximum temperatures are around 30˚C, generally in March, and minimum temperatures between 15˚C (December - January) and 18˚C (July) (Ekodeck et al., 2023). Mount Cameroon is an active volcanic mountain 45 km long and 30 km wide, located between 3˚57' - 4˚27'N and 8˚58' - 9˚24'E in the southwest region of Cameroon (Betti et al., 2019). Maximum temperatures are reached in January and February, reaching an average of 30˚C (Momo et al., 2016), at altitude the average temperature is 22˚C and decreases by 0.6˚C every 100 m of elevation until reaching 4˚C at the summit (Yankam, 2013). This is the only place in Africa where the forest extends uninterrupted from sea level to the tree line at 2500 m altitude (Momo et al., 2016). Plant formations then depend on altitude and the intensity of anthropogenic activity, which becomes less pronounced as one progress towards higher altitudes (Mezafack et al., 2022). This vegetation is characterized by *Agauria sp.*, *Gnidia glauca*, *Crassocephalum mannii*, *Maesa lanceolata*, *Philippia mannii*, *Nauxia congesta*, *Ficus elastica*, *Hypericum sp.*, *Syzygium staudtii* (Wete et al., 2020).

2.2. Methodology

2.2.1. Data Collection

The data collection was carried out as part of the project "Non-Detriment Findings for *P. africana* (Hook. f.) Kalkman in Cameroon". It was carried out in two phases: firstly in the South-West region, specifically at Mont Cameroun in December 2010, and secondly in May 2011 in the Adamaoua region, more specifically at Tchabal Mbabo and Tchabal Ngandaba (**Figure 1**) mountains.

2.2.2. Stem Selection Criteria

To obtain a representative sample of the natural population of *P. africana*, in order to better assess the productivity of a tree, stems were selected according to several more or less interrelated criteria: 1) geographical position, here the trees were selected randomly and above all according to their accessibility (the terrain being rugged); 2) bole shape, here only straight stems were considered; 3) diameter at breast height (Dbh), here only those with a Dbh ≥ 30 cm; 4) health status, here only living stems; and 5) the stem had not yet been exploited (bark harvesting). For each of the stems selected, information on diameter (D), bole height (H), thickness of the unharvested side (E) and geographical position (GPS) were recorded on a scorecard to estimate the stem volume (V) and then deduce the bark mass (P) produced by the stem.

The diameter and height of the bole are measured using the "Bitterlich Relascope" or "SPIEGEL RELASKOP". For a good estimate, the best position to see the bole (from the Dph to the first large branch) was chosen. The horizontal and slope distances between our position and the tree were measured. This was followed by measurements of logging height (chest height) and useful height (bole height). We measured the diameter and percentage of slope at operating height (DBH) and the diameter and percentage of slope at the first major branch level. After these measurements, we determined the intermediate levels or slope percentage measurements ($P1$, $P2$, $P3$) using the equidistance formula which is:

$$Eq = \frac{(Pu - Pa)}{4}$$

with $P1 = Pa + Eq$, $P2 = P1 + Eq$, $P3 = P2 + Eq$ et $Pu = P3 + Eq.$

The thickness of unmined bark was obtained using the "Pressler Tarrière". Unit volume (over or under bark) was calculated using the Bitterlich Relascope wide-band formula (National Office for Forest Development, 1992), expressed as:

$$V = \frac{\pi dh^2}{8.106} \times ((P1 - Pa) \times (D1^2 + Da^2) + (P2 - P1) \times (D2^2 + D1^2) + (P3 - P2) \times (D3^2 + D2^2) + (Pu - P3) \times (Du^2 + D3^2))$$

where, V is the unit volume (on or under the bark);

$dh = ds \times \cos\alpha$ = corrected horizontal distance;

ds is the distance along the slope; Pa, Pu, $P1$, $P2$, $P3$ are the percentage of slope at the logging level (or useful level), at the first level of the large branch, at point 1, 2 and 3 respectively; Da, Du, $D1$, $D2$ and $D3$: diameter in Relascope units (RU) obtained at the logging level, at the level of the first large branch, at point 1, 2 and 3 respectively.

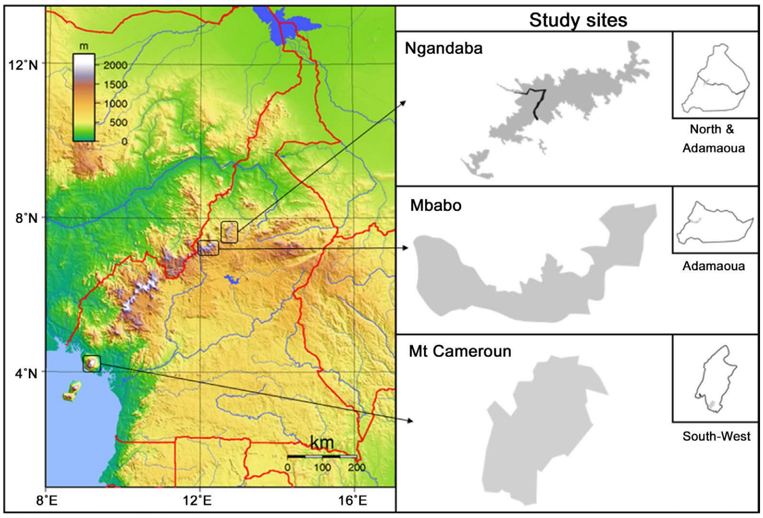

Figure 1. Study sites.

We also used the Smalian formula (Massenet, 2006; Mille & Louppe, 2016) to estimate the volume:

$$V = \frac{\pi}{8}\left(Da^2 + Du^2\right)h$$

where, Da is the diameter at the logging level of the tree = DBH; Du is the diameter at the first large branch level; h is the height of the trunk (distance between the logging level and the first large branch). Bark volume was deduced from the following equation:

$$Vb = V - Vo,$$

where: Vb is the bark volume of the stem; V is the volume of the tree on the bark = with bark; Vo is the volume of the tree under the bark = without bark. Assuming that Do = D–2e with e = bark thickness, Do = diameter under bark and D = diameter over bark, bark volume was determined by the equation (Vb), and mass by multiplying by density:

$$Vb = \frac{h}{2} \times \left(e \times \left(Da + Du\right) - 2e^2\right)$$

2.2.3. Data Analysis

The average values for diameter, height, bark thickness and mass of bark produced were calculated and then compared. This comparison was carried out using the one-factor ANOVA (aov) combined with the Tukey Krammer multiple comparison test (TukeyHSD). These two tests were used to see whether the diameter, height, bark thickness, volume and mass of bark produced for a stem varies according to several groups (in our case regions/sites). The hypotheses are:

$H0$: Equality between the items to be compared.

$H1$: A difference between the items to be compared.

At the 5% threshold, if the p-value is less than 0.05, then the $H0$ hypothesis of equality between the items is rejected.

Econometric modeling was performed using linear regression with the "lm" function on R. Its aim is to find a relationship between a continuous quantitative dependent variable (***Y***, representing in our case the bark mass of a stem) and one (simple regression) or several (multiple regression) explanatory variables (***X***, representing here diameter, bole height and bark thickness). A multivariate analysis was carried out to test the impact of the parameters, with the aim of creating a basic prediction model on a new *P. africana* stem taken at random. This involved developing, validating and evaluating the model's performance.

A) Model development: according to Chesneau (2022) and James et al., (2023), this involved testing the significance or otherwise of the predictor variables (basic "lm" model containing all variables or parameters) via the "lm" function, then selecting the significant variables from the basic model previously developed by the Akaïke information criterion (AIC) and the Bayesian information criterion (BIC), which are based on maximum likelihood and penalize the number of model parameters (using the step AIC function (direction = backward) in the Mass library). The equation of a multiple linear regression model is:

$$Y_i = \beta_0 + \beta_1 x_{1,i} + \cdots + \beta_p x_{p,i} + \epsilon_i$$

where Y is the "variable to be explained" and $X_1, \cdots, X_p$ are the "explanatory variables", $\beta_0, \cdots, \beta_p$ are unknown real coefficients and ϵ is a quantitative variable of mean value zero, independent of $X_1, \cdots, X_p$, which represents a sum of random and multifactorial errors. The multiple linear model is written in matrix form as follows (Chesneau, 2022):

$$Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix}, X = \begin{pmatrix} 1 & x_{1,1} & \cdots & x_{p,1} \\ 1 & x_{1,2} & \cdots & x_{p,2} \\ \vdots & \vdots & \cdots & \vdots \\ 1 & x_{1,n} & \cdots & x_{p,n} \end{pmatrix}, \beta = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{pmatrix}, \epsilon = \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{pmatrix}$$

The standard assumptions on the model are: X is of full column rank (so $(X^t X)^{-1}$ exists), ϵ and $X_1, \cdots, X_p$ are independent and et $\epsilon \sim N_n\left(0_n, \sigma^2 I_n\right)$ where $\sigma > 0$ is an unknown parameter.

B) Model validation: this is an important step, which generally involves checking the hypothesis of residual linearity (shapiro-wilk test: shapiro.test), residual independence or autocorrelation (Durbin-Watson test: dwtest), treatment of influential points, leverage points (performance library) and residual homogeneity (Breusch-Pagan test: bptest) (Rakotomalala, 2015).

C) Model performance: this is assessed by resampling techniques using K-fold cross-validation (k = 10, n = 3). Here the dataset is separated into k subsets, a subset (tree) is removed, the model is trained and tested on the reserved subset, repeating the procedure as many times as there are k training subsets. A good model is determined by a number of indicators (Cornillon et al., 2018; Chesneau, 2022):

- ✓ **the R^2 and the *adjusted* R^2**

The R^2 or coefficient of determination is a real number always between 0 and 1. It measures the quality of the model; the closer R^2 is to 1, the better the model

$$\hat{R}^2 = 1 - \frac{\left\|\hat{Y} - Y\right\|^2}{\left\|\hat{Y}1_n - Y\right\|^2} \text{ where } \hat{Y} = X\hat{\beta} \text{ and } \bar{Y} = (1/n)\sum_{i=1}^{n} Y_i$$

As the R^2 is highly dependent on p (number of variables), it cannot be used to compare the quality of 2 models that differ in the number of explanatory variables. This is why we prefer its adjusted version (*adjusted* R^2), presented below.

$$\hat{\hat{R}}^2 = 1 - \frac{\left\|\hat{Y} - Y\right\|^2 \big/ \left(n - (p+1)\right)}{\left\|\hat{Y}1_n - Y\right\|^2 \big/ (n-1)} = 1 - \frac{n-1}{n-(p+1)}\left(1 - \hat{R}^2\right)$$

- ✓ **AIC and BIC criteria**

$$AIC = 2k - 2\ln(L)$$

$$BIC = -2\ln(L) + k\ln(N)$$

With k the number of parameters, L the estimated likelihood function and N the number of observations in the sample.

- ✓ The **Mean Absolute Error (MAE)**, the arithmetic mean of the absolute values of the deviations

$$\text{MAE} = \frac{\sum_{i=1}^{n}\left|y_i - x_i\right|}{n}$$

- ✓ The standard deviation of residuals via the **Root Mean Squared Error (RMSE)**, which is the square root (RSE) of the arithmetic mean of the squared deviations between model predictions and observations. And deduce the error rate of each model.

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n}\frac{\left(\hat{y}_i - y_i\right)^2}{n}}$$

Boxplots with p-values indicating the level of significance were obtained using the package ggpubr (Kassambara, 2020). Tables and charts are produced with Excel 2013 and R version 4.2.1 libraries. The correlation matrix between the different parameters was obtained using the GGally and corrr package (Schloerke et al., 2021). Models and predictions (effects) are obtained with package ggeffect. All statistical analyses of the data were performed using R 4.2.1 software (R Core Team, 2022) under the RStudio-2022.07.1-554 script editor.

3. Results and Discussions

3.1. Results

3.1.1. Critical Analysis of the Current Cubing Rate

The current formula takes into account only one parameter for estimating the productivity of a given *P. africana* stem. This approach, which provides volume and deduces mass using diameter alone, seems to have some limitations. Lets consider three Prunus stems (A, B and C) of different diameters (with Diameter_A < Diameter_B < Diameter_C), the productivity (Prod) will always be greater for the stem with the largest diameter (Prod_A < Prod_B < Prod_C). This is not always the case in reality. If we include a second parameter for the same stems, namely the bole height, the highest productivity will not necessarily be for the stem which has the largest diameter. This productivity could even vary if we include a third parameter, such as the bark thickness (D). Figure 2 and Table 1 illustrate and give a brief summary of this critical analysis with a view to proposing a new equation.

3.1.2. Regional Volume Estimates

1) Sample description and correlation

Table 2 shows the characteristics of the stems according to the two study regions (Adamaoua and South-West). Apart from thickness, which varies according to region (p-value = 4.4^{e-14}), the stems appear to be similar in terms of diameter and height. Despite this, there is a significant difference between the mean volume values (p-value = 3.8^{e-07}).

The relationships between the parameters are shown in Figure 3. Diameter and bole height are significantly correlated with the stem volume.

2) Development of volume models

Figure 4 shows the models developed for each region. We note that all β coefficients are significant (Adamaoua and Sud-West). There is no multicollinearity, as the variance inflation factor (VIF) is less than 5 for all variables respectively in each model.

3) Model validation and performance

The residual analysis is satisfactory. The volumes predicted by the models are shown in Figure 5. They increase with the growth of the parameters, so for a 100 cm diameter stem the volume could be around 0.22 m^3 in Adamaoua and 0.14 m^3 in the South-West. This volume must then be multiplied by the corresponding density (or volume mass) for each region to obtain the bark mass in kilogram.

The performance of the various models is shown in Table 3. The equations (which take into account diameter, bole height and thickness) are all significant, and the adjusted R^2 is greater than 0.9 for all models.

3.1.3. Mass Estimates for *P. africana* Production Sites

1) Sample description by site

Distribution

The sample comprises 43 stems, 105 stems and 45 stems respectively from Mbabo, Mont Cameroun and Ngandaba, for a total of 193 stems. All diameter classes are represented, with a predominance of 30 - 50 cm stems. Figure 6 illustrates the distribution of stems by site.

Average diameter

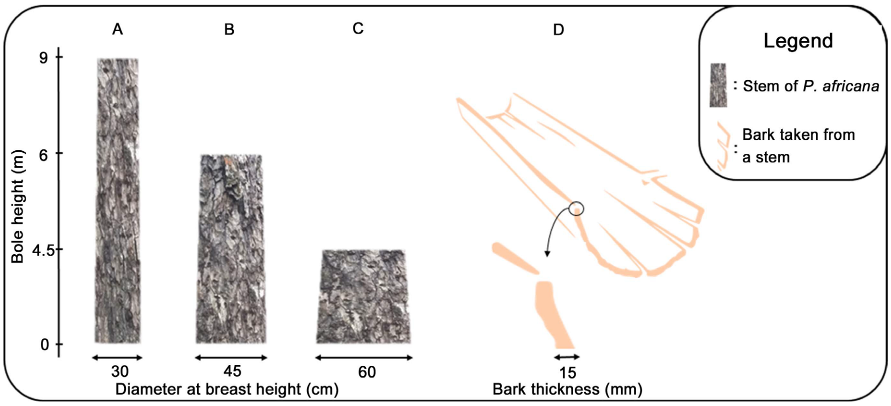

Figure 2. Predictor parameters.

Table 1. Critical analysis of models.

Parameters	Equation	
	Actual	News
Number of parameters	1	3
Predicted biomass	Volume	Volume and Mass
Supplementary operation	Yes	No
Reproducibility	Difficult	Affordable
Advantage	We can estimate just with the diameter	Takes into account more dendrometric parameters of the stem
Disadvantage	Does not take into account other stem parameters that could influence productivity	Parameter values must be available at the time of application

Table 2. Dendrometry and stem volume.

Parameters	Adamaoua, N = 88	South-West, N = 105	*p*-value[1]
Diameter (Cm)	57.84 (19.09)	60.86 (21.41)	0.4
Height (m)	6.86 (2.08)	7.02 (2.12)	0.57
Thickness (mm)	12.18 (4.8)	8.05 (1.9)	4.4^{e-14}
Volume (m^3)	0.13 (0.07)	0.09 (0.04)	3.8^{e-07}

Mean (standard deviation); [1]Anova.

The average diameter was 59.49 ± 20.39 cm, and varied according to the site (Anova: $7.92^{e-05***}$), being greater at Mbabo (67.04 ± 20.98 cm) than at Mont Cameroun (60.86 ± 21.41 cm) and Ngandaba (49.05 ± 11.79 cm) as shown in Figure 7.

Figure 3. Correlation between sampled parameters by region.

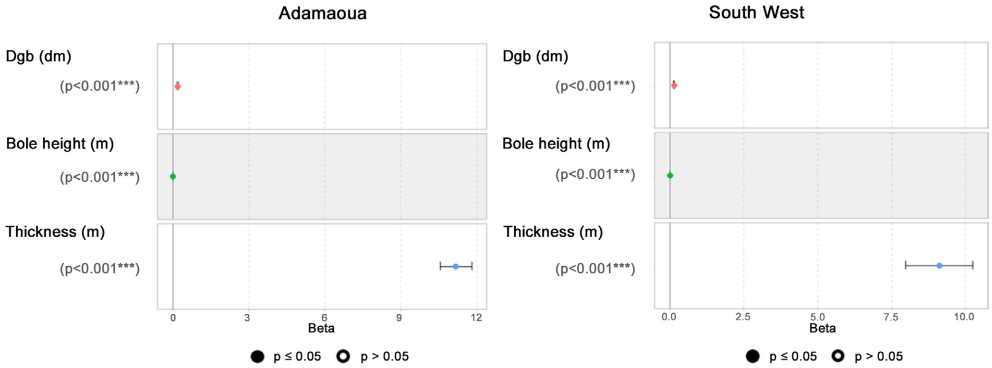

Figure 4. Multiple regression model by region.

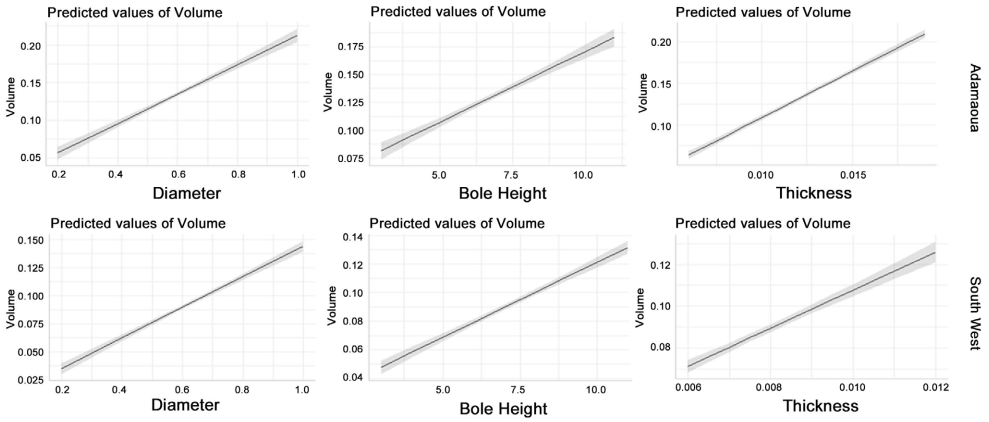

Figure 5. Mass predicted by models for each region.

Table 3. Model performance by region.

Parameters	Adamaoua	South-West
Equation	Volume = −0.195418+ 0.0175839*(D) + 0.0133692*(H) + 10.89701*(E)	Volume = −0.138904+ 0.1360422*(D) + 0.0104642*(H) + 9.1102488*(E)
***p*-value**	<2.2e−16	<2.2e−16
Number of variables	3	3
ajusted R^2	0.96	0.94
AIC	−517	−676
BIC	−505	−663
MAE	0.01	0.007
RMSE	0.012	0.009
Error rate	9.3%	10.2%

D: Diameter at breast height (dm), H: Height of bole (m), E: Bark thickness (m).

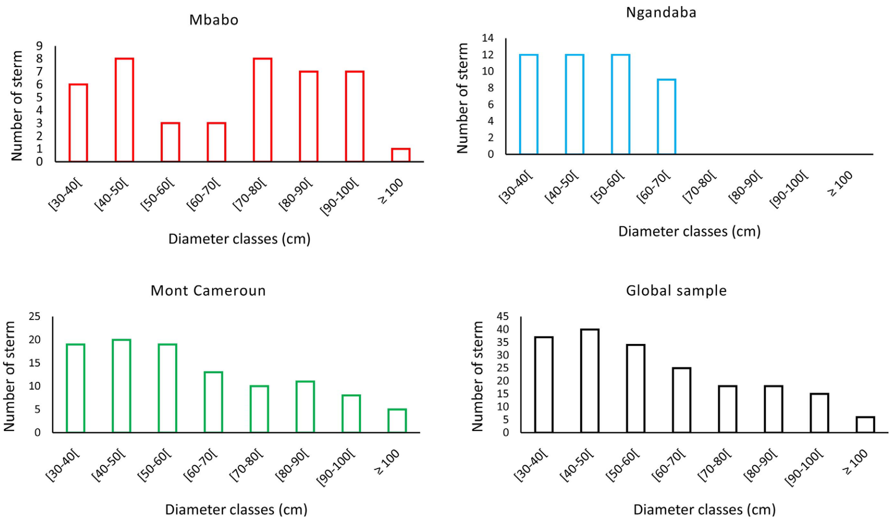

Figure 6. Distribution of sampled stems by site.

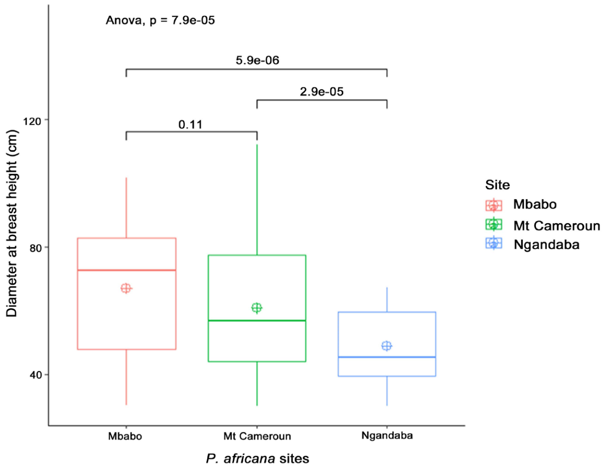

Figure 7. Stem diameter.

Average bole height

Figure 8 shows average bole heights by site. The average bole height is 6.95 ± 2.1 m. It is 7.27 ± 2.5 m at Mbabo, 7.02 ± 2.12 m at Mont Cameroun and 6.46 ± 1.5 m at Ngandaba. There was no significant difference between the three sites (Anova: 0.17).

Average bark thickness

The mean thicknesses are illustrated in Figure 9. The average bark thickness was 9.93 ± 4.06 mm. This varies significantly among different sites (Anova: < 2.2^{e-16}***). They are 8.41 ± 1.83 mm at Mbabo, 8.04 ± 1.9 mm at Mont Cameroun and 15.77 ± 3.81 mm at Ngandaba.

Average productivity of a given exploitable Prunus tree (bark mass)

The average productivity for a given exploitable (DBH ≥ 30 cm) Prunus tree using the 2/4 opposed harvesting technique is 27.55 ± 14.44 kg of the dried bark. This productivity varies significantly according to the site (Figure 10), being higher at Ngandaba (36.96 ± 17.81 kg) than at Mbabo (29.2 ± 15.16 kg) and Mont Cameroun (22.84 ± 9.88 kg).

2) Relationship between bark mass produced and parameters

Variation of productivity as a function of parameters

Figure 11 illustrates the dry bark mass in kilograms produced by the 2/4-opposite method per site, highlighting their variation as a function of diameter, bole height and bark thickness. The bark thickness increases with diameter growth. We can also see the impact of bole height, which would also seem to contribute to the increase in the productivity (the majority of the largest circles are for the largest masses per site). The effect of the thickness seems to vary from site to site.

Evaluation of correlations between bark mass produced and parameters

Figure 12 illustrates the spatial correlation network between bark mass and parameters (diameter, bole height and thickness). At Mbabo and Mont Cameroun, there are strong correlations (tending towards blue) between mass and diameter on the one hand, and mass and height on the other hand. At Ngandaba, there are strong correlations between mass and diameter, as well as between mass and the bark thickness.

3) Modeling

Development of mass models

Figure 13 shows the models developed for each site. We note that all β coefficients are significant (A, B and C). There is no multicollinearity, as the variance inflation factor (VIF) is less than 5 for all variables respectively in each model.

Model validation and performance

Model validation involves analysis of the residuals. The masses predicted by the model are illustrated in Figure 14. Without taking other parameters into account, a 30 cm-diameter stem could produce around 15 kg of bark in Mbabo and Mont Cameroun, and just over 20 kg in Ngandaba.

The performance of the various models is presented in Table 4. The equations (which take into account diameter, barrel height and thickness) are all significant,

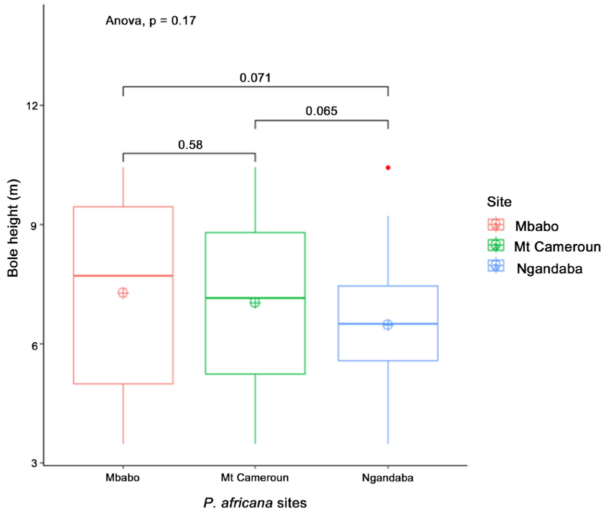

Figure 8. Stem bole height.

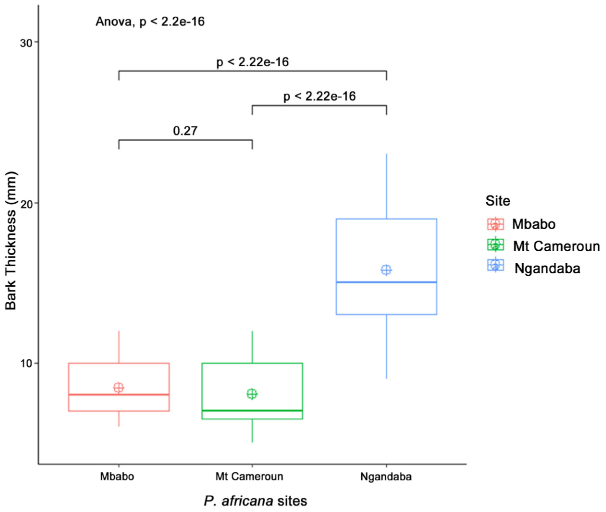

Figure 9. Stem bark thickness.

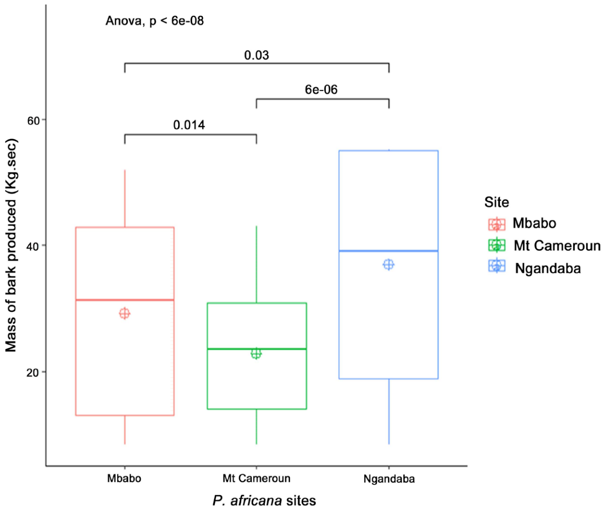

Figure 10. Bark mass at 2/4 opposites.

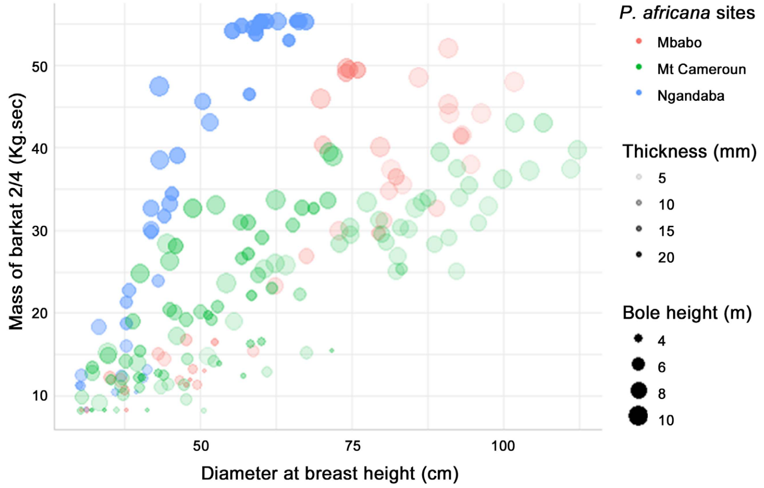

Figure 11. Variation in mass as a function of stem parameters.

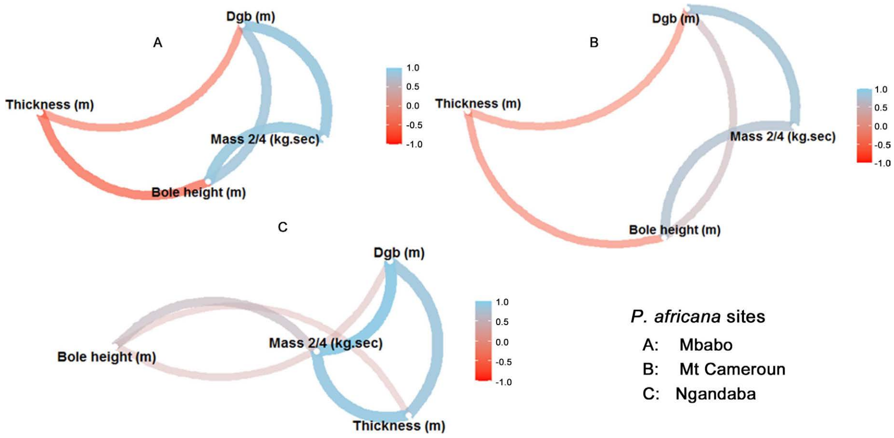

Figure 12. Spatial correlation network between parameters and stem bark mass.

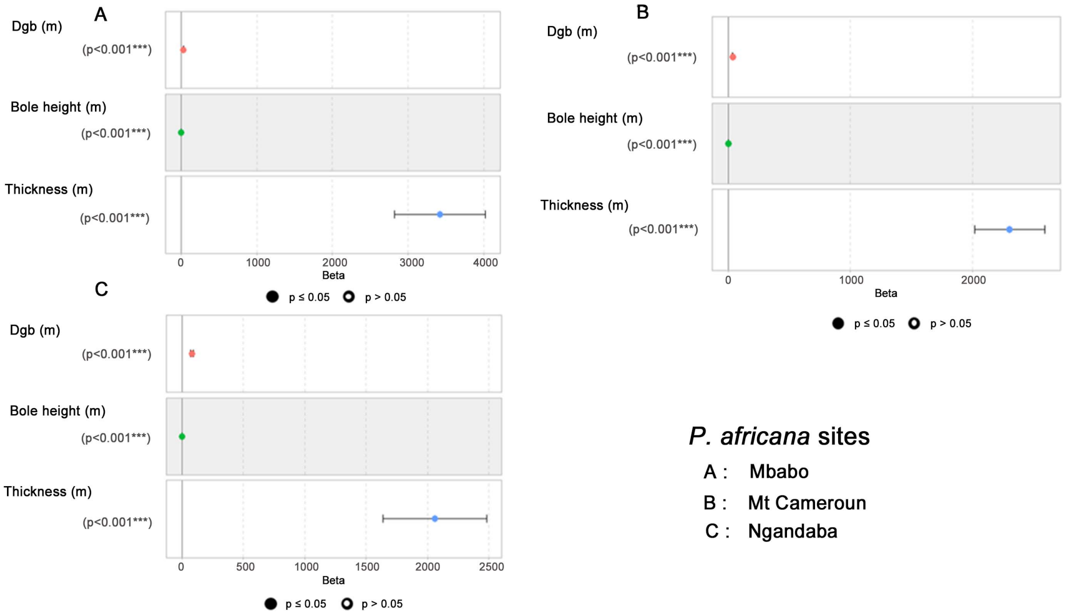

Figure 13. Multiple regression model bysite.

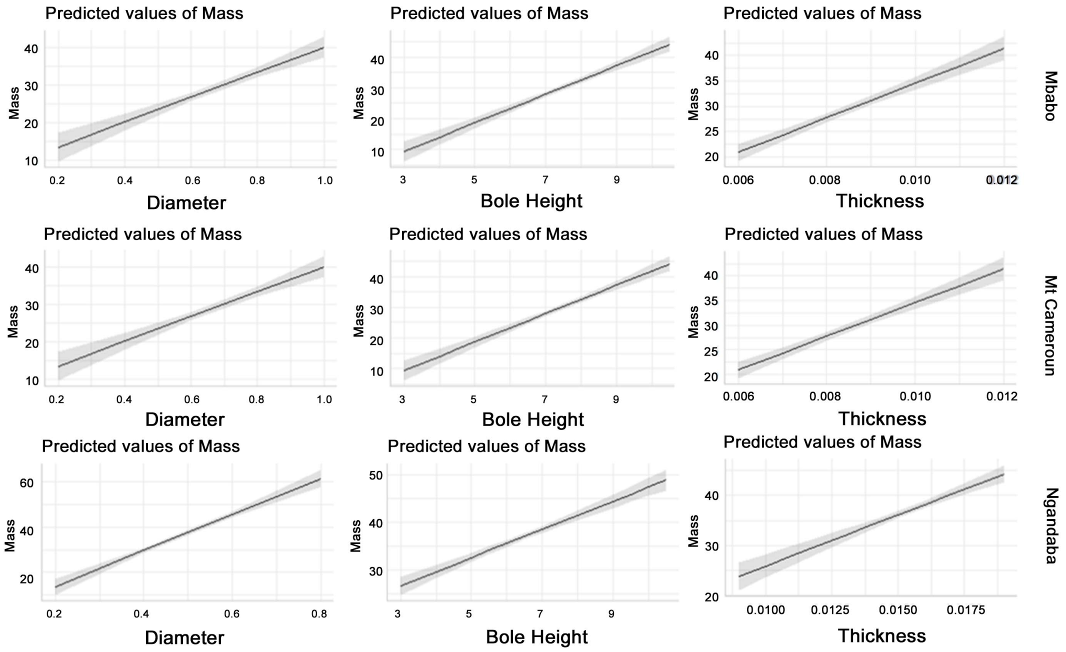

Figure 14. Mass predicted by models for each site.

Table 4. Model performance by site.

Parameters	Mbabo	Mt Cameroun	Ngandaba
Equation	−55.5124 + 33.1542*(D) + 4.6356*(H) + 3422.1792*(E)	−35.1721 + 34.4553*(D) + 2.6498*(H) + 2307.1031*(E)	−53.2862 + 79.9095*(D) + 2.9679*(H) + 2061.1876*(E)
p-value	<2.2e−16	<2.2e−16	<2.2e−16
Number of variables	3	3	3
ajusted R^2	0.97	0.94	0.98
AIC	215.66	486.47	215.34
BIC	224.46	499.74	207.28
MAE	2.166	1.183	1.744
RMSE	2.64	2.34	2.14
Error rate	9.06%	10.24%	5.8%

D: Diameter at breast height (m), H: Height of bole (m), E: Bark thickness (m).

and the adjusted R^2 is greater than 0.9 for all models. AIC, BIC, MAE and RMSE are also presented, the lower they are, the better the model.

3.2. Discussions

3.2.1. Critical Analysis of Previous Estimations (Equations)

Ligot et al. (2018) show that in Central Africa, volume estimation is essentially based on the use of single-entry, species-specific cubing rates that predict harvestable volume from tree diameter. This is also the case for the current *P. afri-*

cana formula, which tends to make predictions in the same way as timber logging. Unfortunately, these tariffs often provide estimates that are fraught with error: underestimation or overestimation of standing tree volume (Zobi et al., 2010). In addition, for *P. africana*, it is the bark that is harvested, so it would be interesting to include other parameters. As stem volume and dry bark mass (kg. dry) increase with growth in diameter, bole height and bark thickness, there is a non-negligible correlation. Bauer et al. (2019) show that bark thickness at 1 m 30 provides greater accuracy in calculating bark volume.

3.2.2. Sample Description, Bark Mass Produced and Correlations with Parameters

The trees sampled have diameters greater than or equal to 30 cm, considered as the Minimum exploitable Diameter (MED) of *Prunus africana* in Cameroon. In total, we have 193 trees. For a tariff that is formulated for a limited area where growing conditions are relatively homogeneous, it is advised to have a sample ranging from 30 to 100 trees (Loetsh, 1961; Ekodeck et al., 2023). There are no significant differences between the diameters and heights of the two regions (Adamawa and South West). However, in terms of production site, the largest diameters are found in Mbabo and Mont Cameroun respectively. This may be explained by their relief, with higher altitudes above 2,000 m (Ndedy Bile et al., 2022; Momo et al., 2016), which provides optimal conditions for the species' growth. Mpouam et al. (2022) clearly demonstrate that stem diameter increases with altitude. This diameter could also be impacted by the annual increase in diameter and the climate (seasonally variable) specific to each zone. In the same way, Fétéké et al. (2016) show that tree growth is continuous but seasonally variable. Average bole height is 6.95 ± 2.1 m, close to the 7 m found in 2022 by Ndedy Bile et al. at Tchabal Mbabo and the 6.2 m found by Ekodeck et al. (2023), showing that the sample used reflects the natural population of *Prunus africana*. In contrast to the other sites, the low heights found at Ngandaba could be caused on the one hand by the fact that temperatures there are higher, with the phenological rhythms of the trees being influenced above all by the intensity of solar radiation and the extent of the dry season (Reich, 1995; Richardson et al., 2013; Fétéké et al., 2016) and by the fact that, due to warming and anthropogenic activities, the clusters are not large and the canopy is fairly open, stem density being low, this limits inter-specific and intra-specific competitions that could stimulate the tree to grow taller to better capture light. Bark thicknesses differ both from region to region and from site to site. Lekefack (2016) obtained 12.03 ± 2.64 mm at Mont Cameroun, which is higher than the 8.04 ± 1.9 mm found at the same site, with the growth rate of unharvested bark decreasing with diameter growth over the same period (Ndedy Bile et al., 2022). The greatest thicknesses are found at Ngandaba, which could be explained by the fact that the trees are not tall enough, and as the canopy is fairly open, these trees are exposed to more heat, tending to spread their crowns and stimulate bark growth to adapt to environmental conditions. The increase in bark thickness is therefore the result of adaptation to environmental conditions (Mpouam et al., 2022). Bark volumes vary from region to region, and are highest in Adamaoua. This could be explained by the slightly higher dendrometric characteristics. This is also the case for productivity (dry bark mass), which varies from site to site, being higher at Ngandaba than at Mbabo and Mont Cameroun. This difference in productivity could be due to the difference in thickness. On a large tree, thickness tends to decrease with height, and Gérardin et al. (2020) show that the thickest bark is found towards the base of the trunk and the thinnest bark is found at the top of the tree, except at Ngandaba where the trees are not very tall with a large spreading crown this decrease in thickness seems very slight, the proportion of bark increases with the crown, small-diameter trees have a higher average percentage of bark than those of large trees (Hassegawa & Achim, 2015).

3.2.3. Modeling: Model Development, Validation and Performance Evaluation

Different equations are developed for each site, Muhesi and Sahani (2017) in their research on *Grevillea robusta* and *Cedrella odorata* advocate that the cubing rate should vary according to ecological zones. The β coefficients of the parameters diameter, bole height and bark thickness are all significant (p-value < 0.05) and positive; had they been negative, the parameter would have had to be excluded at the risk of returning a negative mass (Kahindo, 2006). This demonstrates once again that they are important in modeling the volume and mass of bark produced by a stem. The performance of the different models can be seen from the equations, all of which are significant, with a higher adjusted R^2 for the Ngandaba model. According to Kaluka (2015), an R^2 value of 0.8 indicates good regression. The equation or model with the highest coefficient of determination (R^2) should be chosen (Ngbolua et al., 2022); overall for our models, they are all close to 1, which shows that these models explain well the variation in volume on the one hand and bark mass produced on the other hand as a function of the different parameters. The BIC (Bayesian Information Criterion) penalizes the number of parameters more heavily than the AIC (Akaike Information Criterion) (Schwarz, 1978; Ibrahima et al., 2002), but their values in the models are not significantly different, although the lower they are, the more perfect the model (Dorisca et al., 2011). Seka and Bégin (2020) used the same approach when developing cubage rates for estimating gross harvestable volumes of *Cylicodiscus gabunensis* Harms in Southern Cameroon. Error rates ranging from 5 to 10.5% once again testify to the quality of the models, with low residual deviations, for a (new) stem dry mass will be predicted with an accuracy of ±2.64 kg at Mbabo, ±2.34 kg at Mont Cameroun and ±2.14 kg at Ngandaba.

4. Conclusion

At the end of this study which verified the hypothesis that, apart from diameter, other paramaters could contribute to a better estimate of the productivity of stem. The aim of which was to determine productivity and develop a cubing rate for estimating the production of bark from a *P. africana* stem, we found that average productivity was 27.55 ± 14.44 kg.sec, varying from site to site, with the highest productivity at Ngandaba (36.96 ± 17.81 kg.sec). This prompted us to develop region- and site-specific equations. Two models for volume estimation and three models for mass prediction were developed, with diameter, bole height and bark thickness as predictor parameters. All β coefficients are significant and positive. The adjusted coefficient of determination (adjusted R^2) is close to 1 for each model, with error rates varying between 5 and 10.5%, once again testifying to the quality of the models. These models provide an additional reliable tool for the management of *P. africana* and could be used for quota determination in their specific areas. This study therefore contributes to the sustainable management and conservation of this species, which could also play a significant role in carbon sequestration in the figth against climate change.

Aknowledgements

The present work was carried out within the framework of the "Project for an action plan and update of the Non-Detriment Finding for the sustainable management of Prunus africana (Rosaceae), a tree species listed in Appendix II of CITES in Cameroon" of the CITES Threatened Tree Species Program (CTSP) coordinated by the CITES General Secretariat and funded by the Commission of the European Union. The authors would like to thank the Cameroon National Herbarium (CNH), local authorities and the companies AFRIMED and PHARMAFRIC for their collaboration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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