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Revision of the Volume Function of Ayous (*Triplochyton scleroxylon*) for Sustainable Management of Forest Resources in Cameroon

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Abstract

During forest management in Cameroon, estimating the volume of standing timber is crucial before dividing the forest into annual cutting units and developing the industrialization plan of the logging company. Forest managers use volume functions from the software called TIAMA, but discrepancies between estimated and actual volumes have been noted. The study aims to evaluate the bias in actual estimation of standing volume of *Triplochyton scleroxylon* (Ayous), and to develop and test a new volume function for this species. Ayous was chosen due to its commercial value and its diameter range in the studied area. The study was conducted in the Forest Management Unit (FMU) 10035 located in the East region of Cameroon, using a sample of 177 Ayous trees. TIAMA's volume function applied to the sample showed a significant bias, with an average of 0.81 m^3 per stem. Consequently, a new volume function was developed to predict merchantable stem volume for Ayous in the area: $V = 38.0907 - 0.644838 \times D + 0.0037344 \times D^2$. This new volume function was tested against others, revealing that it provides less biased volume estimates. Moreover, volume estimates with it show no significant difference when compared to felled volume. Therefore, the adjusted volume functions are recommended for FMU-10035, to ensure more accurate timber volume estimations and improve forest management decisions.

Keywords

Forest Management, Volume Function, Standing Timber, *Triplochyton scleroxylon*, East Cameroon

1. Introduction

The updating of tree volume prediction models is a crucial step in promoting the sustainable management of forest resources in Cameroon, particularly for *Triplochyton scleroxylon*, locally named Ayous. Volume prediction models, which serve to estimate the volume of exploitable timber, are often poorly applied or underestimated, leading to significant losses in forest resources (Seka, 2019). According to Ligot et al. (2018), the accuracy of the volume functions for Ayous has an average margin of error between 1.5 m^3 and 3.5 m^3. It is suggested that the use of two-input models, integrating the total height of the tree with the diameter at breast height (DBH), could improve this accuracy. Forest management in Cameroon faces constant challenges, particularly in terms of governance and compliance with regulations. Current tree volume functions are not always used appropriately, resulting in estimation errors, especially due to unsuitable applications in certain geographical areas or heterogeneous diameter ranges (Fayolle et al., 2013; Agbahoungba & Gbo, 2016). This inconsistency highlights the need for a revision and standardization of tree volume functions to make them more effective and relevant.

Furthermore, the introduction of approaches combining various measurements in the calculation of tree volume aims to increase the accuracy of assessments in similar contexts (Sghaier & Youssef, 2022). By adopting more adaptive models that take into account the diversity of species and environmental characteristics, forest managers can better respond to variations in timber stock while enhancing sustainable logging practices. Adjustments to volume functions applied to local species such as Ayous could optimize the use of these critical resources and promote their protection, ensuring responsible and sustainable logging. The need for a reevaluation of volume functions is reinforced by the changing dynamics of tree populations, the increasing demand for timber, and the necessity to conserve biodiversity (Biwolé et al., 2019). Participatory management systems also emphasize the importance of involving local stakeholders in the decision-making process, which is essential for ensuring inclusive and sustainable forest resource management (Monthé et al., 2015; Goubi et al., 2019). Effective governance, considering the various forest users, could lead to positive outcomes in forest resource management and reduce illegal logging.

Currently, Central Africa is home to nearly 200 million hectares of forests, of which approximately 54 million hectares (27%) are classified as production forests, primarily in the form of logging concessions (Eba'a Atyi et al., 2022). More than 24% of this area is allocated to logging companies for timber exploitation (Lescuyer & Essoungou, 2013). In this region, the practice of selective logging is common, restricting pressure on forests to a limited number of species. To achieve sustainable management of these heavily exploited species, it is essential to have an accurate understanding of the exploitable volume. This is critically important for both forestry administration and managers at all key stages of forest planning and management. In Cameroon, when planning a logging concession, knowing the spatial distribution of the exploitable volume allows the subdivision of the concession into "equi-volume" five-year blocks, as well as the establishment of annual operational budgets and the planning of logging operations. This information is also crucial for developing the industrialization plan of logging companies and plays a decisive role in their economic profitability, which is one of the three pillars of sustainable management (Eba'a Atyi et al., 2022). In the context of forest inventories, standing timber volumes are assessed using allometric volume equations, known as volume functions. In Cameroon, these volume prediction models are established by species or groups of species and by geographical area, corresponding to the different phases of inventory. These functions are integrated into the software called TIAMA—forest inventory data processing applied to forest management modelling—, and Cameroonian logging companies are legally required to use them (Neba et al., 2014).

However, many companies have reported a mismatch between the volumes estimated during planning and the volumes obtained after logging, as measured by dendrometric methods. This observation has been confirmed by previous studies, such as that of Fayolle et al. (2013), which revealed considerable biases between timber volumes estimated by TIAMA volume functions and those measured after logging; the inventoried volumes are systematically underestimated compared to the volumes actually harvested (Neba et al., 2014). Following a consultation workshop between private sector operators and the forestry administration held in Douala from November 17 to 20, 2016, the Minister in charge of Forests (MINFOF) recommended a 15% increase in the estimated volumes of standing trees during logging inventories. However, this emergency measure, considered a temporary solution, has not sustainably mitigated the observed discrepancies. Indeed, some operators report that they only exploit a portion of the timber volume anticipated in their Operational Management Plan, either because this volume is not achieved with the number of authorized stems or due to a lower number of stems than planned in the management plan. This situation frequently leads to disagreements between the forestry administration and logging operators, who face penalties for exceeding quotas. This study therefore aims to evaluate the significance of the biases between the volumes of Ayous estimated by the TIAMA system and those obtained after logging. It also seeks to develop and test new volume functions for this species to ensure a more accurate assessment and improve the management of forest resources in Cameroon.

2. Materials and Methods

2.1. Study Area

The Forest Management Unit (FMU) 10035 of the forest concession 1102 was chosen due to the availability of its concessionaire to host the study. It is located in the East region of Cameroon, in the Haut Nyong Division, in the Ngoyla district, between 02˚52'55.64" and 02˚55'24.98" North latitude, and 13˚54'16.58" and 13˚40'06.37" East longitude (**Figure 1**). FMU-10035 is bounded: to the north by the Dja river and FMU-10036; to the south by FMU-10034; to the east by FMU-10032; to the west by FMU-09002. It is part of phase III of the national forest inventory and covered, under provisional convention, an initial area of 101,793 hectares. By decree N˚ 2014/2157/PM of July 21, 2014, this area was modified and reduced to 77,551 hectares.

The climate of the region is of the Guinean equatorial type, with four distinct seasons. The amount of rainfall reaches approximately 1500 mm per year. The relief of the study area is characterized, in the southeast, by a succession of hills with steep slopes. There are evergreen forests, semi-deciduous forests, and mixed forests. Between these three groups, other small ecosystems are scattered, such as dry savannas, wet savannas, "Limbali (*Gilbertiodendron dewewrei*)" forests, forests with wet meadows, forests with *Raphia regalis*, dry meadows, wet meadows, forests with *Raphia* spp., forests with *Mapania* sp., and forests with *Baphialepto botrys*. Two main types of soil are found in this locality: ferrallitic soils and hydromorphic soils. Nearly 51 plant species found in this area have significant commercial value.

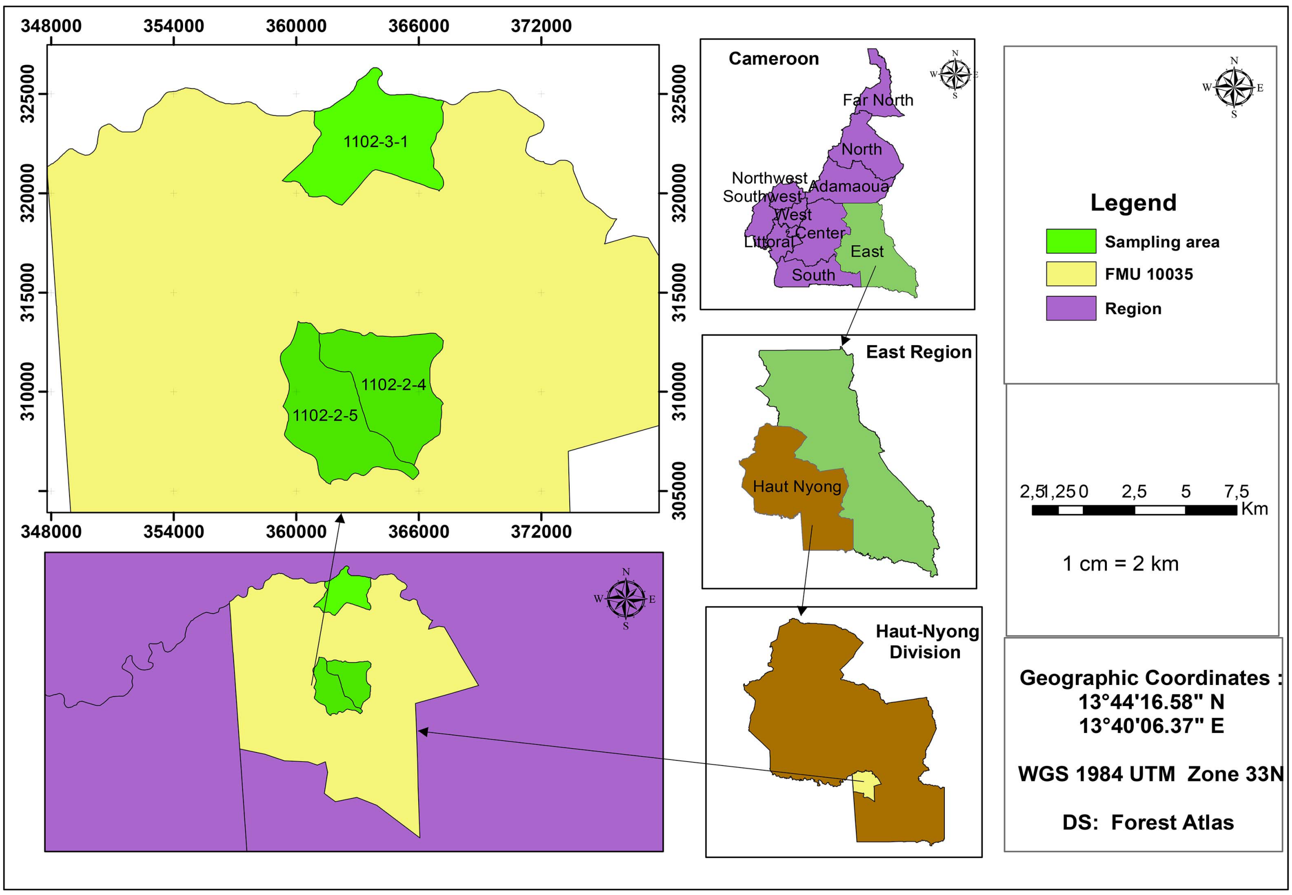

Figure 1. Geographical location of the study area.

2.2. Selected Species

Ayous (*Triplochyton scleroxylon*) was selected to establish the volume function due to its commercial interest, its presence and distribution across a wide range of diameters in the area, as well as the sustainable management issues it faces. With 229,794 m^3 of wood exported in 2021 (COMCAM, 2022) and 215,685 m^3 in 2022 (COMCAM, 2023), Ayous is ranked N˚ 1 among the most exported species, reflecting its strong commercial interest. Furthermore, following studies conducted by the Dynafac collective in 2022, discussions are already underway regarding its potential listing in Appendix II of CITES due to the sustainable management issues of the species.

2.3. Experimental Design and Data Analysis

As part of this study, 177 Ayous trees with a diameter greater than or equal to the minimum harvestable diameter (MHD) were randomly selected and measured. Before felling, the diameter at breast height (DBH) of the trees was measured using a diameter tape. After felling, the length of the trunk (L in m) was measured with a straight meter. The diameters of the large end and the small end were also measured with a metric tape to obtain their average (D_m). The merchantable stem volume of each tree was estimated using the TIAMA software. The volume of the trunk after felling (called DF10; V in m^3) of each log was calculated using the cylinder formula:

$$V = \frac{\pi}{4} \times D_m^2 \times L \tag{1}$$

With: $\frac{\pi}{4} = 0.7854$

Subsequently, 36 Ayous stems were removed from the dataset for two reasons. On one hand, the dataset did not contain enough individuals for the diameter classes to which they belonged, and on the other hand, after an initial regression, these data were considered outliers as they deviated significantly from the majority trend. However, the selected model and bias results did not significantly change when those stems are retained. The remaining sample retained for analysis consisted of 141 logs (**Table 1**). This approach follows the methodology employed by Kangas & Maltamo (2006), although it primarily concerns species with very large diameters.

Table 1. Distribution of sample size by diameter classes.

DBH Classes (cm)	85	95	105	115	125	135	145	Total
Sample size	18	41	40	17	18	4	3	141

A Student's t-test for two paired samples was used for comparisons between estimated (TIAMA) and felled (DF10) volumes since both values come from the same stems. This test was conducted on XLSTAT (null hypothesis H0: the difference between the means is equal to 0). The normality of paired differences was checked using the Shapiro-Wilk test.

To develop a new volume function, nonlinear and linear regressions were carried out between the DBH of each tree and the volumes of these same trees measured after felling. Only the single-entry volume functions were fitted to the data: they predict the merchantable stem volume from the DBH measured during the forest inventory. For our sample, various equation models were fitted to the data:

A quadratic model:

$$V_i = b \times D^2 \quad (2)$$

Three power models:

$$V_i = a + b \times D^c \quad (3)$$

$$V_i = a + b \times D + c \times D^2 \quad (4)$$

$$V_i = a \times D^b \quad (5)$$

An affine equation model:

$$V_i = a + b \times D \quad (6)$$

where V_i represents the volume to be estimated, D is the DBH (cm); a, b, and c are unitless coefficients to be estimated. The chosen model is the one that presents the lowest mean squared error (MSE) and the best Akaike information criterion (AIC).

A test sample of 21 trees was randomly taken from the database of the FMU-10035 manager. This sample served as a reference to compare the newly adjusted volume function with other volume functions (TIAMA and Dimako-Integrated Pilot Management (API)). All volume functions were applied to the test sample. The Student's t-test was used to determine and compare the significance level of the bias generated by each of the volume functions.

3. Results

3.1. Differences between Felled Volume and Volume Estimated by TIAMA

A paired t-test conducted on this sample revealed significant differences between the volumes estimated by the TIAMA software of the Cameroon Forest Administration and the volumes obtained after felling, with a p-value of 0.00041 (**Table 2**). Overall, it appears that the TIAMA volume functions significantly underestimate the exploitable volume, with an observed gap of 121.051 m^3, representing an underestimation rate of 7.33%.

Table 2. Significance of the bias provided by TIAMA volume function of Ayous.

Variables	Sample size	Minimum	Maximum	Mean	Standard deviation	Bias	P-value
Vol_DF10 (m^3)[a]	141	4.823	23.009	11.708	3.264	0.859	0.00041
Vol_TIAMA (m^3)[b]	141	6.754	20.946	10.850	3.227		

[a]. Volume measured after felling; [b]. Volume estimated with the TIAMA software.

3.2. Adjustment and Validation of Models

The adjustment of volume functions to an input linking the merchantable volume of the log to the DHP for the studied species provided parameters *a*, *b*, and *c*, as presented in **Table 3**.

Table 3. Coefficients and performance indicators of the volume functions with a single entry for Ayous, $V = f(\text{DBH})$.

Models	Coefficients			Performance indicators	
	a	*b*	*c*	MSE	AIC
$V_i = b \times D^2$	/	0.00111044	/	8.29381425	301.283342
$V_i = a + b \times D^c$	−31.402	9.95173	0.318776	7.07682308	280.879963
$V_i = a + b \times D + c \times D^2$	38.0907	−0.644838	0.0037344	5.96907701	256.877141
$V_i = a \times D^b$	0.0472492	1.1964	/	6.74944362	273.219551
$V_i = a + b \times D$	−2.09966206	0.1380808	/	6.80856674	272.44929

The best model, according to the fitting criteria, is presented by Model 3 ($V = a + b \times D^c$). A Student's t-test performed on the estimates based on this model revealed a P-value > 0.05, indicating that the differences between the estimated and the felled volumes are not statistically significant. Although the adjusted functions in this study provide more accurate volume estimates, they may not be recommended at this stage, as the test was conducted with the sample used to develop our rates, leading to a risk of self-validation bias. Therefore, the adjusted models were further validated by testing them on an independent dataset to ensure their applicability in varied contexts (Section 3.3).

3.3. Quality of Estimates

In this study, a total of 21 Ayous logs that were not part of the previous sample were used to compare the volume estimates from the TIAMA system, the volume function developed as part of API-Dimako, and the adjusted volume function from this research. The different volume functions were applied to the test sample, and the volumes obtained were compared to the felled volume (DF10) (**Table 4**).

Table 4. Volume estimates (m^3) for Ayous.

Estimations	TIAMA	API	Adjusted[a]	DF10[b]
Volume (m^3)	224.119	268.383	247.447	268.289
Variation	−16.46%	+0.04%	−7.77%	/

[a]. Volume estimated using the volume function developed in this study; [b]. Volume measured after felling.

By increasing the volume estimated by TIAMA by 15% as adopted by the Forestry Administration, the volumes will rise to 257.736 m^3. Unlike the previously observed data, the underestimation rate using the adjusted model is considerably reduced for this test sample, and the API volume function tends to provide more accurate estimates for the test sample (**Table 4**).

The Student's t-test conducted on the estimates reveals a significant difference between the TIAMA volume and the felled (DF10) volume (**Table 5**). The difference between the felled volume and the other estimates was not significant.

Table 5. Significance of the bias generated by each volume function.

Volume estimates	Sample size	Mean	Confidence interval	Bias	*P*-value
DF10	21	12.7756467355	/	/	/
Adjusted	21	11.783182857142	[−0.246; 2.231]	0.992	0.137
TIAMA	21	11.708418308816	[0.510; 3.697]	2.103	0.0012
API	21	12.780146333333	[−1.853; 1.844]	−0.004	0.996

4. Discussion

4.1. Differences between Felled Volume and Volume Estimated by TIAMA

The difference found between the two volume estimations aligns with the conclusions of Ligot et al. (2018), which confirm the existence of bias between the volumes measured after felling and the volumes estimated by the volume functions prescribed by the Cameroonian forest administration. It is important to note that this difference could be attributed to errors related to the data collection methodology used for the design of the models. The methodology adopted for the collection of data necessary for the development of TIAMA volume functions included the use of the Relascope formula. However, Rondeux (2021) points out that the density of the structure of tropical forests can hinder visibility and, consequently, the accuracy of data collected using tools such as the Relascope. Furthermore, Massenet (2010) advises against using the Relascope formula to estimate tree volume due to the evaluation errors that may result. Such a constraint could also explain part of the gap observed between the estimated volumes and the felled volumes. It is therefore crucial to revise these methods to ensure greater accuracy in volume estimation, especially considering the diversity of forest species and contemporary harvesting practices.

The 15% increase, as granted by MINFOF, seems to alleviate the underestimation of Ayous volumes, but it leads to a potential overestimation that could harm long-term sustainable forest management. While this increase may be beneficial for operators in the short term, it may create long-term difficulties in resource management, warning against the consequences of using estimation models that are not suited to field realities (Fayolle et al. 2013). These findings are consistent with the complaints from logging concessionaires and the results of previous studies. It therefore becomes imperative to adopt an approach based on more reliable data and improved data collection methodologies to reduce biases in the estimation of timber volumes. To ensure sustainable management of forest resources, it is necessary to use more appropriate volume modeling and assessment tools that take into account the specificities of humid tropical forests (Ligot et al. 2018, Fayolle et al. 2013).

4.2. Adjustment and Validation of Models

The volume functions were developed as part of this study based on dendrometric data from 141 Ayous trees. Although this number of trees is lower than the 400 trees recommended in the literature, it is nevertheless higher than that of most studies conducted on volume functions in tropical forests, which often rely on smaller samples (Purfürst et al. 2023, Seka 2019). Studies have shown that larger sample sizes allow for better representation of biological variability and enhance the accuracy of models. The accuracy of cubic volume models generally varies with sampling effort; therefore, the rates proposed in this study (**Table 3**) may offer better accuracy than some earlier studies, such as those based on more limited samples.

The use of sophisticated fitting methods, such as the least squares method or other advanced statistical techniques, could also contribute to better modeling of the volume-diameter relationships by taking into account other dendrometric variables, such as total height or upper diameters. This supports the recommendations of previous research that highlighted the importance of an integrated approach to improve the accuracy of volume estimates. Thus, even though the results of this study show potential for improvement, rigorous validation and a more comprehensive database are necessary to establish their reliability. Similar studies on other species, possibly by combining different types of data (e.g., photogrammetric and lidar measurements), could enrich knowledge and refine volume estimation models for optimal forest management (Berendt, Wolfgramm, & Cremer, 2021).

4.3. Quality of Estimates

The variability of the 15% increase according to the sample used highlights a critical aspect in the analysis of data on forest volumes. It is clear that this increase does not always translate into a uniform improvement in volume estimation across different samples (**Table 4**). This situation could be explained by the accumulation of errors that decreases as the sample size diminishes, as pointed out by some previous research in the field of forest volume estimation. Therefore, further studies on the maximum values of quota exceedances of Ayous could provide stronger explanations regarding these disparities.

TIAMA volume function often provides biased estimates of volume; however, it is important to clarify that the results should be viewed in the context of the statistical methods used for calibration (Fortin et al., 2007). The conclusion that the API volume function and the adjusted volume function in this study present more accurate estimates must be interpreted with caution, taking into account the specifics of the models (Sghaier & Youssef, 2022).

To maximize the accuracy of Ayous volume estimates, it is essential to adopt an innovative approach to the development of volume models. This could involve improving sampling methods and implementing multidimensional analyses that take into account various dendrometric variables (Daheur, 2023). By integrating additional parameters into the estimation framework, it is likely that the models will provide even more reliable results, thereby contributing to better-informed and more sustainable forest resource management.

5. Conclusion

The study reveals significant biases between the estimates of TIAMA volume and the volumes measured after felling. The 15% increase implemented by MINFOF to correct these biases shows variations depending on the samples, underscoring the need to update the volume functions. The new one-entry volume function proposed in this research is demonstrated to be an unbiased estimator of the volume. This adjusted model improves on TIAMA estimations in the FMU-10035, while the volume estimated with API volume function was closest to felled volume in the external test sample. However, due to the limited number of Ayous included, its application should be restricted to the diameter range or to forests with similar conditions. Continued sampling is crucial to develop a more widely applicable rate. For the revision of TIAMA volume functions, it would be preferable for MINFOF to prioritize ecological zoning for forest classification, as trees of the same species in similar conditions tend to behave comparably. Considering the cost of a new national inventory, utilizing data from inventories conducted by logging companies could be beneficial. Although the API and adjusted volume functions demonstrate better efficiency than TIAMA, large-scale validations are necessary to ensure their applicability and accuracy in forest management in Cameroon, thereby guaranteeing sustainable management of forest resources.

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Conflicts of Interest

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

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