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Research Article

Biomass Estimation Models for Combretum-Terminalia Woodlands of Western Ethiopia: Implications for Carbon Accounting, Climate-Change Mitigation, and Biodiversity Conservation

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Abstract

Biomass models play a crucial role in accurately estimating carbon storage potential of forests and evaluate the contribution of forest ecosystem services. However, an allometric model which is specifically tailored to diverse tree species in Ethiopia is currently lacking. Therefore, establishing species-specific allometric models and determining the biomass expansion factor for dry woodland ecosystems is essential for comprehending the role in mitigating climate change impacts. This study tested and validated diffrent allometric models on six dominant tree species in the *Combretum-Terminalia* woodlands of the Benishangul-Gumuz region, which collectively account for approximately 69% of the total basal area. The study applied an explanatory research design method and data were collected through systematic sampling across 40 plots, involving the destructive sampling of 67 representative standing trees. The Allometric models were developed and tested using log-transformed data to satisfy the assumptions of linear regression and ensure statistical rigor. This is done by applying log-transformed data to develop the models to ensure high statistical accuracy. The models performance was validated using key metrics such as R^2, RMSE, and Model Efficiency (EF) to ensure the reliability of the carbon storage and biomass estimations. The study demonstrated that aboveground biomass for all six species is highly predictable using species-specific allometric equations with coefficients of determination (R^2) consistently exceeding 96%. The DBH-based model (M1) was the best fit for five species, notably achieving the highest R^2 (0.985) for *Terminalia laxiflora* and the most stable performance for *Lonchocarpus fruticosa* (EF = 0.953). In contrast, *Syzygium guineense* required the inclusion of height (M2) to reach the study's highest precision (EF = 0.992, MAPE = 3.42%), while *Combretum hartmannianum* showed the greatest individual variability (EF = 69%). Biomass Expansion Factors (BEF) were statistically uniform across all taxa (P = 0.482), with a collective mean of 2.077 ± 0.343. These findings conclude that while DBH is a robust primary predictor for most woodland species, species-specific architecture particularly the vertical growth of *Syzygium guineense* and the high absolute residuals in *Pterocarpus lucens* necessitates tailored models and correction factors to ensure accurate regional carbon accounting and forest management in the Combretum-Terminalia woodlands. Utilizing these models (M1 & M2) can enhance the accuracy of biomass estimations, leading to more effective management practices and conservation strategies via biomass and carbon estimation.

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1. Introduction

Dry land forest and woodlands in Africa provide critical multifunctional benefits across diverse agro-ecological zones forming cornerstone for both ecological stability and rural livelihoods. In East Africa, these woodlands serve as vital refugia for endemic fauna and flora, offering essential ecosystem services that diversify the livelihood strategies of local community [13]. Beyond their socio-economic value, these ecosystems play a pivotal role in global climate change mitigation by sequestering substantial amounts of atmospheric carbon dioxide (CO_2). Covering an estimated 957.6 million hectares across Eastern and Southern Africa, these vast wooded landscapes represent a significant yet frequently undervalued terrestrial carbon sink [10].

In the specific context of Ethiopia, recent reports from the Ethiopian Forestry Development [6] estimate that forest cover now encompasses approximately 23% of the total landmass. Among these formations, dry forests primarily dominated by *Acacia-Commiphora* and *Combretum-Terminalia* woodlands account for more than 50% of the national vegetation cover, surpassing other forest types in spatial extent [21]. These ecosystems are characterized by high species richness and the production of high-value commercial gums and resins. Furthermore, they provide indispensable defensive services against the expansion of desertification while contributing to regional climate regulation through consistent carbon sequestration [30].

Accurate estimation of aboveground biomass (AGB) is fundamental to understanding the structural productivity and functional dynamics, such as nutrient cycling, within these forest ecosystems across broad environmental gradients [17]. Comprehensive biomass data is a prerequisite for assessing economic sustainability and serves as a primary indicator of site productivity. Moreover, precise biomass quantification is essential for assessing carbon stocks and monitoring the impacts of deforestation on the global carbon balance [12]. Consequently, robust biomass assessment tools are urgently required to manage forest carbon effectively from a climate change mitigation perspective.

To meet these needs, allometric biomass models have become indispensable for monitoring carbon storage and flux in terrestrial ecosystems, particularly for reporting greenhouse gas reductions in alignment with international frameworks like the Paris Agreement [9]. While destructive sampling remains the most accurate method for establishing these models, it is often impractical for large-scale applications due to high costs, labor intensity, and ethical concerns regarding tree removal. As a result, empirical relationships relying on easily measurable dendrometric variables such as diameter at breast height (DBH) and tree height (H) are preferred. Despite this, many sub-Saharan African countries still lack appropriate species-specific allometric models due to the historical difficulties in obtaining rigorous field data [7, 2].

Current biomass estimation methodologies have predominantly relied on generic, pan-tropical models, which frequently overlook the unique morphological and ecological traits of specific species [19]. This reliance creates a significant theoretical and practical gap, as the varied growth forms and architectural adaptations of *Combretum* and *Terminalia* species may not be accurately captured by broad-brush equations [8]. Developing tailored biomass equations and biomass expansion factors (BEF) is therefore crucial for accurately estimating the carbon storage potential of dominant species within the *Combretum-Terminalia* woodlands of Ethiopia. This study specifically seeks to evaluate the performance of these new species-specific models against existing site-specific and pan-tropical alternatives [30].

Finally, this research explores how localized factors including climate variability, soil conditions, and inter-species competition influence biomass allocation strategies within the woodland. There remains a notable deficit of localized empirical data for *Combretum* and *Terminalia* species in Ethiopia, hindering the validation of national carbon inventories. This study addresses this gap by providing essential field-validated data to refine biomass estimates and enhance their reliability. This is done by investigating the projection of different tree components on biomass expansion factors. This research aims to develop a superior species-specific allometric model framework with direct implications for biodiversity conservation and climate change mitigation strategies in Western Ethiopia.

2. Material and Methods

2.1. Study Area and Vegetation Types

The research was conducted within the Asosa Zone of the Benishangul-Gumuz Regional State, situated in the westernmost reaches of Ethiopia along the border with Sudan. This region is defined by a complex and rugged topography, transitioning from low-lying river valleys to undulating hills and

high mountain ridges. Elevations across the study site fluctuate significantly, ranging from 600 m to over 2,500 m above sea level (asl), which creates a diverse vertical gradient influencing vegetation distribution [4].

The area experiences a sub-humid tropical climate, primarily governed by the *Kiremt* (main rainy season) from May to October. The mean annual rainfall varies between 800 mm and 2,000 mm, while temperatures remain relatively warm with annual means ranging from 20°C to 28°C. This distinct agro-ecological environment supports extensive bamboo forests and diverse woodland ecosystems, which are increasingly recognized as highly productive yet climate-sensitive landscapes [14, 16]. Benishangul-Gumuz is characterized as one of the most significant repositories of natural woodland vegetation in Ethiopia.

The region hosts three primary vegetation types: dry broadleaved deciduous forests alternatively classified as *Combretum-Terminalia* Woodlands (CTW) and wooded grasslands dry evergreen afro-montane forests, and moist evergreen afro-montane forests. Among these, the dry broadleaved deciduous forest is the most spatially dominant formation (Awas et al., 2007a). This ecosystem is composed of a diverse assemblage of species, including *Combretum* spp., *Terminalia* spp., *Lonchocarpus laxiflorus*, *Lannea* spp., *Albizia malacophylla*, and *Entada africana*. These formations are characterized by fire-tolerant, small-to-medium-sized trees with large deciduous leaves, frequently occurring in association with the lowland bamboo, *Oxytenanthera abyssinica* [14].

2.2. Sample Collection and Preparation

For this study, the Homosha district was selected purposively based on the representativeness of the study site in Beneshangul-Gumuz regional state and accessibility. A reconnaissance survey, ground observation, was conducted to collect basic information about labour accessibility, security, forest coverage, and availability of forest sites to avoid hazards and minimizing time and cost.

2.3. Sample Design

The researcher used an explanatory approach using quantitative data collection techniques. A systematic sampling design were used to ensure representative data collection across different ecological zones within the Combretum-Terminalia woodlands in Western Ethiopia. The studied vegetation was demarcated by using remote sensing tools (Google satellite image) and also we have stratified and clipped out other land use located in the forest to make a homogenous forest, and it covered 21,681.4 ha.

In order to determine the distribution and dominant tree species, parallel line transects were laid in the forest with systematic random sampling using Quantum Geographic Information System (QGIS) software. Along each transect line, 40 sample plots measuring 20*30 meters were laid down following the methods described in the IPCC guideline (Pearson *et al*., 2005). The distance between each plot and transect lines was 2.32 km which were determined based on the size of the forest and plot.

The first transect line was aligned randomly at one side of the forest using QGIS software; then the others were laid at fixed meter intervals from each other. Priory field data collection, the X and Y coordinates were collected by GPS from the map and each sample plot (point) was searched and established a quadrat. Within the quadrats, all woody trees DBH ≥ 5 cm (at 1.3 meters) and total height were recorded using forest caliper and graded bamboo stick, respectively. A total of 2,129 woody species were recorded within 40 sample plots and the species local and scientific names were identified by the manual of Tesfaye (2007). Based on plot inventory data, the dominance of a species was calculated with dominance index or the relative basal area and then six dominant tree species having the highest dominance index were selected for the study.

The diameter at breast height of dominant tree species ranged from 5 to 60 centimeters (cm). Then diameter size class was formulated with a 5 cm interval, and a representative tree was marked for harvesting in each diameter class. Further, the number of individuals in each diameter class was determined with the equation Equ. (1) [18].

$$\mathrm{NTS} = \frac{\mathrm{RD}*\mathrm{TNT}}{100} \quad (1)$$

Where, NTS number of the tree selected from each class, RD relative dominance and TNT is the total number of trees respectively. The diameter classes were 5-10, 11-15, 16-20, 21-25, 26-30, 31-35, 36-40, 41-45 and ≥ 46 cm. A total of 67 sample trees, 9 to 12 individuals in each of the species, were harvested for model development.

A direct destructive sampling method was employed for aboveground biomass measurements. Based on a method described by Picard *et al*., (2012), the selected sample trees were cut at heights of 30 cm from the ground level using a Chainsaw. The felled trees were partitioned into three components, namely stump, stem and branch. The stem and branches were cross-cut into manageable logs to facilitate weight measurements. The fresh weight of branch components was measured immediately with a spring balance scale of (100 kg) measuring capacity. The length and diameter at three positions (lower, middle and upper) of each log were measured. Further, the diameter of the stump and its height were measured for the conversion of volume to biomass by wood density. Then, individual log volumes were calculated by multiplying the basal area of the different diameter sections of each log by its length using Newton's volume formula [27].

$$\mathrm{V} = \mathrm{L} \times (\mathrm{DL}^2 + 4 \times \mathrm{dm}^2 + \mathrm{du}^2) \times \left(\frac{\pi}{24}\right) \quad (2)$$

Where V, H, D, d0.5, d and PI are volume, height, diameter

at breast height, diameter at the middle, diameter at the top and constant number 3.14 respectively. Subsequently, the stem and branch volumes were determined for each tree by summing all individual log volumes and the stump volume was added to the stem volume.

For dry weight determination, 500 grams for the branch with diameter ≥ 5 and 200 grams for the small branch < 5 cm diameter samples were taken. These samples were dried under the oven at 105°C for 24 hours until a constant weight was recorded. The dry weight of the stumps, stems, and branches with the respective diameter was calculated by multiplying the fresh volume of each section by wood density. For the other partitioned branches, diameter less than 5cm, the dry weight was calculated through fresh weight multiplied by dry weight/fresh weight ratio of the corresponding samples. The total dry weight of a tree was obtained by summing the dry weight of the stump, stem, and branches. Leaf data collection in dry woodland was difficult because of the woodland attributes (including tree phenology), the woodland was dominated by tall grasses.

2.4. Wood Density Determination

To determine the specific wood density for each study species, four circular discs were extracted from each sample tree at varying positions along the main stem. These positions included the stump height, diameter at breast height (DBH), and two additional locations selected based on the specific stem architecture and tapering of the individual.

Following field extraction, all discs were transported to the Assosa Agricultural Research Center laboratory for analysis. The wood density for each species was determined following standardized gravimetric procedures. Detailed methodological protocols and specific density values were derived from established regional datasets.

2.5. Biomass Expansion Factors

The total biomass expansion factor was calculated as the total weights (kg) aboveground biomass divided by stem biomass. Branches and twigs and leaves were determined when measurements were carried out in total aboveground biomass estimation. Biomass of the stem was the product of wood density and stem volume. The aboveground biomass expansion factor is expressed as the ratio of total aboveground biomass and the stem biomass, which is BEF is equal to total aboveground biomass divided by the stem biomass with a diameter of ≥5 cm. The typical equation used is as follows;

$$BEF = \frac{TAGB}{SB} \quad (3)$$

Where TAGB is the total aboveground biomass (kg) of all the components and SB is the Stem biomass (kg) of a tree.

2.6. Data Analyses

Biomass Model Development

Before constructing the biomass models, a scatter plot diagram and correlation were used to observe the relationship between independent and dependent variables. The result was a nonlinear relationship and then the data were transformed in to a natural logarithm to use the linear regression method and make homogeneity of the variables (and or residual errors, and variance) (Chave *et al*., 2005). For the reason that the linear form of the variable relationship is easier to work and evaluate than the nonlinear variable of power function and the dispersal of every variable are nearly lognormal [22, 23].

Log-transformed however introduces a systematic bias in biomass estimation when back converting the calculation into original units. This can be corrected through Correction Factor (CF) (Smith, 1993) to modify under-estimated biomass [5]. Thus, a correction factor was calculated using the standard error of the estimate (SEE) for every model and underestimated biomass was multiplied by the value.

$$CF = \exp\left(\frac{SEE^2}{2}\right) \quad (4)$$

Natural log-transformed data of biometric variables including DBH and H well explained the AGB of the species datasets. The scatter plot diagram revealed that the closeness of the data to the regression line indicates the homogeneity of measured variables. Based on this relationship, biomass models were developed using linear regression analysis in the following forms [18].

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(DBH) + Ɛ \text{ M1}$$

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(DBH) + \beta 2 \ln(H) + Ɛ \text{ M2}$$

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(DBH) + \beta 3 \ln(\rho) + Ɛ \text{ M3}$$

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(DBH) + \beta 2 \ln(H) + \beta 3 \ln(\rho) + Ɛ \text{ M4}$$

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(H) + Ɛ \text{ M5}$$

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(DSH) + Ɛ \text{ M6}$$

$$\ln(B) = \ln(\beta 0) + \beta 1 \ln(DSH) + \beta 2 \ln(H) + Ɛ \text{ M7}$$

Where, B, ln, DBH, DSH, H, ρ, Ɛ and β0, β1, β2 and β3 are biomass for stem, branch and total aboveground biomass, natural logarithm, diameter at breast height (cm), diameter at stump height (cm), total tree height (m), wood density (g cm^{-3}), error and regression parameters, respectively.

2.7. Model Evaluation and Selection

The developed biomass models were assessed to measure their performance and accuracy in order to select the best

models. The importance of wood density and total height for the improving biomass estimate was tested for each of the species-specific models. Therefore, several statistical parameters were used for selecting and evaluating the models, which are mentioned and described as follows. Mean absolute prediction error (MAPE). It shows an average error of the estimate which is a pointer of bias in the estimate of single tree parts of biomass values. The adjusted coefficient of determination (R^2), which shows the spread of the data was used to evaluate the best model.

The root means square error (RMSE) evaluates the accuracy of the fitted models. In addition, the model accuracy and appropriateness were also evaluated using model efficiency (EF). Lastly, Akaike Information Criterion (AIC) was used for the selection of the best model. All the statistical parameters were calculated after the estimations were converted to the unit values and multiplied by the correction factor. These statistical parameters were listed as follows:

$$\text{MAPE(kg)} = \frac{100}{n}\left(\sum_{i=1}^{n}\frac{|y-\hat{y}|}{y}\right) \quad (5)$$

$$\text{RMSE (kg)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y-\hat{y})^2} \quad (6)$$

$$\text{AIC} = n * \ln\left(\frac{(\sum y-\hat{y})^2}{n}\right) + 2k \quad (7)$$

$$\text{EF} = 1 - \frac{\sum(y-\hat{y})^2}{\sum(y-\bar{y})^2} \quad (8)$$

Where y, ŷ, ȳ, n and ln are the observed AGB, predicted AGB, mean observed AGB, number of sample trees and natural logarithm, respectively. All collected data were analyzed using Statistical Packages for Social Sciences (SPSS) version 25.0. Using the log-transformed data, linear regression techniques were used to develop biomass models to predict aboveground biomass of tree components from independent variables such as DBH, H and wood density.

3. Results and Discussions

3.1. Species-specific Biomass Models with Parameter Estimates for AGB

Table 1 presents result for the site-specific datasets for each species were tested against existing tropical and regional allometric models for all six species is highly predictable using dendrometric variables, with adjusted coefficients of determination (R^2) consistently exceeding 0.96. The species-specific allometric models developed in this study demonstrate high predictive accuracy ($R^2 > 0.96$), confirming that diameter at breast height (DBH) and tree height (H) are reliable predictors for aboveground biomass (AGB) in the *Combretum-Terminalia* woodlands. This strong correlation aligns with recent findings by [20], who emphasized that species-specific models significantly reduce the uncertainties inherent in generalized pan-tropical equations when applied to Ethiopian dry woodland ecosystems.

Result in Table 1 indicates that *Terminalia laxiflora* in the M1 model (DBH-based) was identified as the best fit. It demonstrated the highest coefficient of determination (R^2 = 0.985) in the study, paired with a high Model Efficiency (EF = 0.943). Despite a relatively high RMSE of 51.45 kg, the MAPE of 11.63% indicates that the model is remarkably consistent for this species across varying diameter classes. The AIC of 90.69 further confirms that the model maintains a strong balance between complexity and predictive power. Predictive Performance and Architectural Influence indicated that the exceptional performance of the DBH-based M1 model for *Terminalia laxiflora*. The exceptional performance of the DBH-based model (M1) for *Terminalia laxiflora* indicates that stem diameter captures the vast majority of the variation in aboveground biomass. This result is strongly supported by the work of [25, 29], evaluated biomass carbon stocks across Ethiopian landscapes, noted that dominant indigenous species often exhibit a "standardized" growth form where DBH alone provides sufficient predictive power for regional inventories. This structural consistency is supported by [25], who noted that *Terminalia* species in Western Ethiopia exhibit predictable biomass accumulation patterns due to their distinct branching architecture.

Result in Table 1 also indicates *Entada africana* was also best represented by the M1 model with R^2 value (0.965) and EF (0.936) shows robust reliability. Notably, it produced a lower RMSE (28.39 kg) compared to *Terminalia laxiflora*, indicating less absolute variance in the predicted versus observed biomass. The Correction Factor (CF) is 1.015 is close to unity, signifying that back-transformation from logarithmic units introduces minimal bias for this species. Similarly, the robust reliability found for *Entada africana* (EF = 0.936) and *Lonchocarpus fruticosa* (EF = 0.953) highlights the stability of diameter as a primary biomass proxy. For these species, the Correction Factors (CF) were near unity (1.015 and 1.012) respectively. The results indicate that log-linear transformations introduce minimal systematic bias as a result consistent with the methodological refinements. The robust reliability found for *Entada africana* (EF = 0.936) and *Lonchocarpus fruticosa* (EF = 0.953) highlights the stability of diameter as a primary biomass proxy. This finding is consistent with the research by [26], who developed allometric equations for several indigenous species in Ethiopia and found that DBH typically explains over 90% of the variation in aboveground biomass for woodland trees. The structural simplicity of these species allows for high-precision modeling without the added labor of height measurements, which is a significant advantage for rapid forest assessments in the Benishangul-Gumuz region.

Result in Table 1 also indicates the model used for *Combretum hartmannianum* which exhibited the most significant statistical challenges among the group. While the R^2 was strong

(0.962), the MAPE was the highest at 25.63%, and the EF was the lowest at 0.69. The result indicates that while the model captures the overall growth trend, there is significant individual variation potentially due to multi-stemmed architecture or irregular wood density that DBH alone that (M1) struggle to capture fully. However, the AIC (60.08) remains competitive, and the low RMSE (12.79 kg) indicates that the absolute errors are small even if the percentage error is higher. The significant individual variation observed in *Combretum hartmannianum* is a characteristic feature of many *Combretum* species in the dry deciduous woodlands of Ethiopia. As noted by [1] in their study of woody species in the Amhara region, members of the Combretaceae family frequently exhibit multi-stemmed architectures and irregular crown development as an adaptive response to frequent disturbances such as fire and livestock browsing. These structural irregularities often weaken the direct correlation between a single stem's diameter and the total tree biomass, explaining the lower EF compared to more "architecturally conservative" species like *Terminalia laxiflora*.

Result in Table 1 also indicates (M1) model for *Lonchocarpus fruticosa* proved to be one of the most stable in the study. It achieved a high EF of 0.953 and a relatively low MAPE of 10.95%. With an R^2 of 0.971 and an AIC of 77.41, this species-specific equation provides a highly accurate tool for biomass estimation with very little systematic error, as evidenced by a CF of 1.012. Abiyu et al. (2024) observed similar complexities in dryland vegetation of Northwest Ethiopia, noting that multi-stemmed architectures often decouple the standard DBH-biomass relationship, necessitating more nuanced modeling approaches or larger sample sizes to capture individual variance.

Result in Table 1 indicates Syzygium. *guineense* was the only species where (M2) incorporating both DBH and height was selected as the superior model. This inclusion of height resulted in the most precise model in the entire dataset, yielding the lowest MAPE (3.42%) and the highest EF (0.992). The exceptionally low AIC (57.22) and RMSE (15.4 kg) confirm that height is a critical predictor for this species, likely due to its more consistent vertical growth form compared to the more spreading woodland associates. A standout result was observed for *Syzygium guineense*, the only species where the inclusion of height (M2) was statistically superior. This model achieved the highest precision in the dataset (EF = 0.992, MAPE = 3.42%). As [3] recently argued, height becomes a critical predictor for species with strong apical dominance or consistent vertical growth forms, such as *Syzygium. guineense*, whereas spreading woodland associates may show more height-growth suppression.

Result in Table 1 indicates the model for *Ptepocarpus lucens* (M1) which shows an excellent fit with R^2 of 0.975 and EF of 0.984. However, it recorded the highest RMSE at 107.57 kg and the highest AIC at 116.28. This indicates that for larger individuals of this species, the absolute biomass is quite high, leading to larger absolute residuals even when the relative accuracy (MAPE 17.31%) is acceptable. The CF of 1.025 is the highest in the study, emphasizing the importance of applying the correction factor when using this specific model to avoid significant underestimation of carbon stocks. Finally, the results for *Pterocarpus lucens* (RMSE = 107.57 kg) underscore the "large-tree effect" often discussed in Ethiopian forestry literature. While the model fit remains excellent (R^2 = 0.975%), the high absolute residuals in larger individuals emphasize the importance of the Correction Factor (1.025). As highlighted by [28], accurate carbon accounting in these ecosystems depends heavily on properly back-transforming data for high-biomass individuals to prevent the systematic underestimation of national carbon stocks.

Table 1. *The best species-specific biomass models with parameter estimates and statistical parameters for AGB.*

Species	Tree com.	Model cod	n	parameter estimates				Statistical parameters					
				β0	β1	β2	β3	R2	CF	MAPE (%)	RMSE (kg)	EF (%)	AIC
Terminalia. laxiflora	AGB	M1	11	-2.786(0.313)***	2.670(0.105)***			0.985	1.012	11.63	51.45	0.943	90.69
Endata. africana	AGB	M1	12	-2.503(0.364)***	2.467(0.123)***			0.965	1.015	12.75	28.39	0.936	84.31
Combretum. hartmannianum	AGB	M1	11	-1.763(0.327)***	2.232(0.139)***			0.962	1.009	25.63	12.79	0.69	60.08
Lonchocarpus. fruticosa	AGB	M1	12	-2.362(0.0.374)***	2.358(0.123)***			0.971	1.012	10.95	22.25	0.953	77.41
Syzigium.	AGB	M2	9	-4.122(0.191)***	1.051(0.122)***	2.664(0.196)***		0.967	1.013	3.42	15.4	0.992	57.22

Species	Tree com.	Model cod	n	parameter estimates				Statistical parameters					
				β0	β1	β2	β3	R2	CF	MAPE (%)	RMSE (kg)	EF (%)	AIC
guineense													
Pterocar-pus. lucens	AGB	M1	12	-2.723(0.389)***	2.657(0.128)***			0.975	1.025	17.31	107.57	0.984	116.28

Where Adj. R^2 adjusted coefficient of determination, CF and n refer to a bias correction factor and the number of sample trees, mean absolute prediction error (MAPE), root mean square error (RMSE), model efficiency (EF) and Akaike Information Criteria (AIC).

3.2. Biomass Expansion Factors (BEF) by Species

Result in Table 2 indicates the analysis of Biomass Expansion Factors (BEF) across the six dominant species in the *Combretum-Terminalia* woodland revealed a high degree of structural similarity in biomass allocation, with a collective mean BEF of 2.077 ± 0.343. Among the individual taxa, *Lonchocarpus fruticosa* exhibited the highest mean BEF of 2.215 ± 0.345 indicating a slightly higher proportion of biomass allocated to branches and non-stem components relative to its stem volume. This was closely followed by *Syzygium guineense*, which recorded a mean BEF of 2.184 ± 0.235. Despite its higher mean *Syzygium. guineense* displayed the lowest standard deviation in the study, indicating a remarkably consistent architectural growth pattern and predictable biomass partitioning across the sampled individuals. The high degree of structural similarity observed across these six species underscores an evolutionary convergence in biomass allocation strategies within the Western Ethiopian woodland. This is consistent with recent findings by [1] in the dry Afromontane forests of Northwestern Ethiopia, where indigenous woody species were found to prioritize crown architecture and branching density as a physiological adaptation to seasonal moisture stress and high light availability.

The analysis of Biomass Expansion Factors (BEF) across the six dominant species reveals that for these taxa, the non-merchantable components (branches and twigs) constitute slightly more than half of the total aboveground biomass. This structural characteristic is consistent with findings by [1] in the dry Afromontane forests of Northwestern Ethiopia, where indigenous woody species were found to allocate significant biomass to crown architecture as an adaptation to the high-light, seasonal environment of Ethiopian woodlands. The highest mean BEF observed in *Lonchocarpus fruticosa* (2.215) and *Syzygium guineense* (2.184) reflects a growth strategy that favors crown expansion over vertical stem accumulation. As noted by [24] in their study of biomass carbon stocks in Ethiopian landscapes, species-specific architecture particularly in indigenous trees can vary significantly based on environmental stressors. Interestingly, *Syzygium guineense* displayed the lowest standard deviation (0.235), indicating a high degree of architectural "predictability." This mirrors the results of [15], who argued that certain Ethiopian species maintain consistent biomass partitioning patterns despite varying site conditions, making them ideal candidates for precise carbon modeling.

In contrast, *Pterocarpus lucens* presented a mean BEF of 2.107, yet it was characterized by the highest degree of variability, with a standard deviation of 0.462 and a wide range extending from 1.547 to 2.884. This broad dispersion indicates that for *Pterocarpus lucens*, factors such as tree age, competitive position, or localized site conditions may exert a more significant influence on the stem-to-total biomass ratio than species-specific genetic constraints. The high degree of variability observed in *Pterocarpus lucens* (SD = 0.462; Range: 1.547-2.884) highlights the plastic nature of this species in response to its environment. This broad dispersion indicates that biomass partitioning in *Pterocarpus lucens* is governed more by external ecological pressures than by rigid genetic templates. This finding resonates with the work of [11], who noted that in Ethiopian dry forests, species often exhibit highly irregular growth forms due to recurring disturbances such as fire, browsing, and selective lopping. Such "stochastic" factors can lead to significant variations in crown-to-stem ratios, even among trees of similar diameters.

In contrast, the intermediate BEF values of *Terminalia laxiflora* (mean 2.017 and SD 0.299) and *Combretum hartmannianum* (mean 1.995 and SD 0.344) reflect the classic architectural blueprint of the Combretum-Terminalia woodland. These values indicate a near-equal distribution between stem and non-stem biomass, a common characteristic of deciduous taxa in the Sudano-Sahelian region of Ethiopia. As observed by [1] in similar woodland ecosystems, these dominant genera often maintain a balanced biomass allocation to support both structural stability and the high photosynthetic demand of the brief wet season.

The relative stability of *Terminalia laxiflora* and *Combretum hartmannianum* compared to *Pterocarpus lucens* indicated that these species may be more "architecturally conservative." Following the logic of [15] regarding Ethiopian indigenous trees, such stability simplifies the development of allometric equations and improves the accuracy of landscape-level carbon estimations in the Benishangul-Gumuz region.

However, the high sensitivity of *Pterocarpus lucens* to localized site conditions implies that for this specific taxon, high-precision biomass modeling may require the inclusion of additional variables such as tree age or crown class to account for its wide range of biomass expansion.

Table 2. *Summary statistics of biomass expansion factor (BEF) of the dominant tree species in the Combretum-Terminalia woodland.*

Species	n	Biomass expansion factor (BEF)		
		Mean	Min-Max	±STD
Terminalia. laxiflora	11	2.017	1.608-2.513	0.299
Endata. africana	12	1.961	1.554-2.569	0.299
Combretum. hartmannianum	11	1.995	1.375-2.469	0.344
Lonchocarpus. fruticosa	12	2.215	1.774-2.747	0.345
Syzigium. guineense	9	2.184	1.696-2.505	0.235
Pterocarpus. lucens	12	2.107	1.547-2.884	0.462

Where n, Min, Max STD is the number of sample trees, Minimum-Maximum and Standard deviation, respectively.

Result in Table 3 indicates statistical evaluation of the Biomass Expansion Factor (BEF) variation among the six dominant tree species was conducted using a One-Way Analysis of Variance (ANOVA), providing critical insights into the structural uniformity of the *Combretum-Terminalia* woodland. The analysis of the variance components revealed a Between-Groups Sum of Squares (SS) of 0.542 across 5 degrees of freedom, resulting in a Mean Square (MS) of 0.108. In contrast, the Within-Groups (Error) Sum of Squares was significantly higher at 7.271 across 61 degrees of freedom (MS = 0.119), indicating that the inherent variability within individual species likely driven by age, size, and micro-site conditions far outweighs the variability attributed to species identity itself.

The resulting F-ratio of 0.908 corresponds to a P-value of 0.482, which is substantially higher than the standard alpha level of 0.05. Consequently, the null hypothesis stating that mean BEF values are equal across all species cannot be rejected. This non-significant (ns) result confirms that there is no statistically significant difference in the biomass expansion rates among *Terminalia laxiflora*, *Entada africana*, *Combretum hartmannianum*, *Lonchocarpus fruticosa*, *Syzygium guineense*, and *Pterocarpus lucens*.

From an ecological and carbon-accounting perspective, this lack of significant variation indicates a high degree of architectural convergence among these dominant taxa. Despite differing botanical families and physiological traits, these species exhibit nearly identical ratios for expanding stem biomass to total aboveground biomass within the sub-humid environment of Western Ethiopia. While species-specific allometric models remain the gold standard for high-precision Tier 3 reporting, these ANOVA results demonstrate that for broader landscape assessments where individual species identification may be challenging, a pooled expansion factor can be utilized without introducing significant taxonomic bias into the final carbon stock calculations.

The statistical evaluation presented in Table 3 also provides a robust scientific foundation for landscape-level biomass modeling in the *Combretum-Terminalia* woodlands of Western Ethiopia. The non-significant ANOVA results (F = 0.908, P = 0.482) reveal that the inherent variability within individual species likely driven by age, size, and micro-site conditions far outweighs the variability attributed to species identity itself. This indicates a powerful "architectural convergence" among the six dominant taxa, where species from differing botanical families exhibit nearly identical ratios for expanding stem biomass to total aboveground biomass within the sub-humid environment of the Benishangul-Gumuz region.

This lack of significant taxonomic variation aligns with findings by [1] in the dry forests of Northwestern Ethiopia, where indigenous woody species were found to share similar biomass allocation strategies as an evolutionary response to seasonal moisture stress and frequent fire cycles. Such environmental filters often dictate a uniform growth form, where trees prioritize crown development and branching to maximize resource capture during the brief growing season. Furthermore, the high within-group variance (MS = 0.119) underscores the observations of [11], who noted that in Ethiopian deciduous woodlands, localized site conditions and anthropogenic disturbances often exert a more profound influence on tree structure than genetic constraints.

Table 3. Variation of biomass expansion factor BEF among Six Dominant Tree Species.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-ratio	P-value
Between Species	0.542	5	0.108	0.908	0.482ns
Within Species (Error)	7.271	61	0.119		
Total	7.813	66			

Note: ns = non-significant at P > 0.05

4. Conclusion

The present study underscores that species-specific allometric equations are highly effective for estimating aboveground biomass in the *Combretum-Terminalia* woodlands, with all selected models achieving an adjusted R^2 above 0.96. The diameter-based model (M1) emerged as the most versatile and robust tool for the majority of the species studied, particularly for *Terminalia laxiflora* and *Lonchocarpus fruticosa*. These results underscore that diameter at breast height (DBH) remains the most reliable and practical dendrometric predictor for biomass in these deciduous woodland environments, effectively balancing field-effort efficiency with high statistical accuracy.

However, the research highlights that architectural differences among species can necessitate more complex modeling approaches to ensure precision. *Syzygium guineense* was a notable exception where the inclusion of tree height in model M2 significantly improved predictive power, yielding the lowest error margins in the entire study (MAPE = 3.42%). Conversely, the irregular growth forms of *Combretum hartmannianum* and the high absolute biomass of large *Pterocarpus lucens* individuals introduced greater variability. This indicates that while DBH is a strong general predictor, accounting for vertical growth and applying bias correction factors is essential for minimizing systematic underestimation in carbon stock assessments across diverse forest ecosystems.

The development of species-specific biomass models for *Terminalia laxiflora*, *Entada africana*, *Combretum hartmannianum*, *Lonchocarpus fruticosa*, *Syzygium guineense*, and *Pterocarpus lucens* provides a highly reliable framework for carbon accounting, with diameter-based models explaining over 96.2% of above-ground biomass variation. While these models offer strong statistical performance for stem and total biomass, the notable bias observed in branch biomass estimates underscores the necessity for component-tailored equations and further refinement through the inclusion of environmental variables. Ultimately, integrating these specific models into forestry management and conservation strategies in the Combretum-Terminalia woodlands will significantly enhance the accuracy of carbon sequestration assessments, though future efforts must prioritize field validation and the exploration of ecological interactions to ensure long-term resilience across diverse forest ecosystems.

5. Recommendations

Based on the findings of this study, it is recommended that regional forest authorities and climate policy stakeholders in the Benishangul-Gumuz region adopt the developed species-specific allometric models for future carbon accounting and forest inventory protocols. Given that diameter at breast height (DBH) serves as a robust primary predictor for most species, practitioners should prioritize the use of the validated DBH-based models (M1) for routine assessments. However, to account for architectural variability, the height-integrated model (M2) must be applied specifically to species like Syzygium guineense to maintain high precision and minimize estimation errors.

Furthermore, these findings suggest that the calculated mean Biomass Expansion Factor (BEF) of 2.077 be integrated into national forest carbon monitoring systems to standardize biomass calculations across similar Combretum-Terminalia dry woodland ecosystems. Moving forward, policymakers should shift away from using generalized pantropical equations which often fail to capture local ecological nuances in favor of these site-specific tools. Expanding this research to include a broader range of successional stages and underrepresented species will be essential to further refine these models and ensure the long-term effectiveness of regional climate change mitigation and conservation strategies.

6. Mandatory Ethical & Policy Declarations

For custom workflows such as building automated data analysis tools, writing scripts, or generating specific reporting templates developers use the Google AI Studio or Vertex AI platforms. These allow users to connect directly to Gemini models via an API. This means you can feed specialized datasets (like forestry measurements or survey data) into a secure environment and prompt the model to generate specific

outputs, such as structured code, automated summaries, or statistical interpretations.

Abbreviations

AGB	Aboveground Biomass
TAGB	Total Aboveground Biomass
SB	Stem Biomass
DBH	Diameter at Breast Height (1.3 M)
DSH	Diameter at Stump Height
H	Tree Height
BEF	Biomass Expansion Factor
CTW	Combretum-Terminalia Woodlands
EFD	Ethiopian Forestry Development
M1, M2	Model 1, Model 2 (Allometric Model Configurations)
CF	Correction Factor
R^2 (Adj. R^2)	Coefficient of Determination (Adjusted R^2)
RMSE	Root Mean Square Error
EF	Model Efficiency
MAPE	Mean Absolute Prediction Error
AIC	Akaike Information Criterion
SEE	Standard Error of the Estimate
asl	Above Sea Level
IPCC	Intergovernmental Panel on Climate Change
QGIS	Quantum Geographic Information System
SPSS	Statistical Packages for Social Sciences

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Conflicts of Interest

The authors declare that this research was conducted in the absence of any commercial, financial, or personal relationships that could be construed as a potential conflict of interest. All participating authors have directly contributed to the study ranging from the explanatory research design and destructive sampling in the *Combretum-Terminalia* woodlands to the statistical validation of the allometric models and collectively agree on the findings and conclusions presented. No funding sources or institutional affiliations had any role in the design of the study, data collection, model analysis, interpretation of the biomass metrics, or the decision to submit this manuscript for publication.

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