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Remote sensing, allometry, and carbon stocks of *Phyllostachys aurea* in the Western Highlands of Cameroon

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ABSTRACT

The fight against climate change is one of the major concerns of the international community and has led to a search to identify cost-effective ways to manage ecosystems in a way that removes atmospheric carbon-dioxide while providing essential societal benefits. As bamboo ecosystems in Cameroon are poorly known, this study sought to evaluate the distribution of bamboo, develop allometric equations for it and estimate carbon stocks associated with bamboo in the Western Highlands of Cameroon. Landsat 8 OLI imagery was used to increase data on the distribution and carbon stocks of *Phyllostachys aurea* Carrière ex Rivière & C. Rivière in the study area. *P. aurea* is reportedly the most exploited species for ecological, socioeconomic and cultural activities in the region, posing a challenge for the sustainability of the species. Twelve circular plots were established in *P. aurea* stands in the Western Highlands. Five per cent of the bamboo stems were harvested. Every stem was sorted into leaves, branches, and culms. These were weighed, and sub-samples taken to the laboratory. Sub-samples were oven-dried for biomass estimation. Regression analysis was used to develop the allometric equations. The best equation was used to estimate the carbon stocks. The Western Highlands region of Cameroon is estimated to have 241,296 ha of bamboos. The dominant bamboo species identified in the study area include *Oldeania alpina* (K. Schum.) Stapleton (syn. *Yushania alpina* K.Schum.), *Bambusa vulgaris* Schrad. ex J.C.Wendl. and *P. aurea*. Focusing on *P. aurea* the best fit equation with a bias of − 6.98%, Adj.$R^2 = 0.711$, AIC = 17 and RSE = 0.262, was selected. The mean density of *P. aurea* was 38,017 ± 4510 culms.ha^{-1}. The mean culm aboveground biomass was 3.15 ± 0.94 kg. The AGB of *P. aurea* was estimated at 119.05 ± 3.63 t.ha^{-1}, mean AGC was 55.95 ± 5.81 t C.ha^{-1} and mean aboveground carbon dioxide equivalence ($AGCO_{2eq}$) was 205.35 ± 58.01.22 t CO_2.ha^{-1}. *P. aurea* constitutes a significant carbon sink in the Western Highlands of Cameroon. Policymakers and development planners should therefore recommend this species for carbon markets, international initiatives such as AFR100, and the Nationally Determined Contribution addressing the United Nations Sustainable Development Goal 13 (SDG13) to combat climate change.

1. Introduction

Anthropogenic activities have caused global temperatures to increase by 0.8 to 1.2 °C as compared to pre-industrial levels (Leung et al., 2019). This reflects the unprecedented rise in the atmospheric concentrations of greenhouse gases in recent decades (Patricio and Dumago, 2014). Efforts to identify cost-effective ways to sustainably manage ecosystems to remove atmospheric carbon dioxide (CO_2) while providing essential societal benefits have gained momentum since the Kyoto Protocol of 1997 (Jyoti et al., 2009; Arun et al., 2015; Nath et al., 2015). Bamboo ecosystems could help significantly in the protection of our environment, while the processing of bamboo is known to provide social benefits to communities. Bamboo ecosystems thus have the potential to contribute to both combating climate change and improving livelihoods.

Bamboos belong to the Gramineae family and Bambusoideae

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subfamily (Ohrnberger, 1999), with approximately 1662 species, about 128 genera and 14% living beyond their natural ranges (Canavan et al., 2017). Bamboo is mostly distributed in Asia, the Americas, Oceania and Africa (Goyal et al., 2012). The global cover of bamboo is estimated to be 37 million ha, equivalent to 1% of world's forest area, with India having more than 13 million ha and China having 6.5 million ha (FAO and INBAR, 2018).

Bamboo is one of the fasted growing plants and has the potential to contribute to the restoration of degraded forest landscapes (Nfornkah et al., 2023), soil fertility (Ananfack et al., 2023), water and wastelands conservation. It can act as a carbon sink as it stores large quantities of carbon (Nath et al., 2015; Yuen et al., 2017; Xu et al., 2018; Terefe et al., 2019, Kaam et al., 2023). Based on a review of 184 studies, Yuen et al. (2017) estimated the above-ground biomass (AGB) carbon stocks of 70 bamboo species to be in the range 16–128 tC.haIPCC, 2006. Trade statistics indicate that bamboo contributes more than USD 60 billion per year to world trade and that China earns more than USD 39.5 million per year (International Bamboo and Rattan Organisation, 2019). Socially, bamboo is a great driver of poverty alleviation within local communities. This has led to suggestions that bamboo is an excellent pro-poor resource, especially in remote, mountainous areas with limited off-farm income opportunities (Hogarth and Belcher, 2013).

Over the past decade, the Government of Cameroon has identified bamboo as one of the resources that should be developed (involving the sustainable management of the resource and the development of the value chain). It is seeking to substitute some uses of wood and reduce deforestation in an effort to fight against climate change. However, reliable information on the distribution and carbon sequestration capacity of the bamboo resource in Cameroon is limited. Past studies of the distribution of bamboo in Cameroon include Ingram et al. (2010) and Nfornkah et al. (2020). A few studies have been conducted on bamboo carbon stocks in Cameroon, including Nfornkah et al., (2020,a), Kaam et al. (2023), Nfornkah et al., (2020,b), Chimi et al. (2022); these deal with *Oxytenanthera abyssinica* (A.Rich.) Munro, *Bambusa vulgaris* and *Phyllostachys aurea.* Only one study has developed allometric equations, namely Nfornkah et al. (2020c), dealing with *Bambusa vulgaris*. This study presents the general distribution of bamboo in Cameroon, highlighting the dominant species in the Western Highlands (*Phyllostachys aurea*). Owing to its important socio-economic value for riparian populations (Chimi et al., 2021), we also develop allometric equations for the species and estimate its carbon storage capacity. Thus, the objectives of this study are threefold: (1) to evaluate the distribution of bamboo, (2) to develop allometric equations for *Phyllostachys aurea* in the Western Highlands of Cameroon (Agroecological zone 3), and (3) to estimate the carbon stock capacity of *P. aurea* in the Western Highlands of Cameroon.

2. Methodology

2.1. Study area

This study was carried out in the Western Highlands of Cameroon, also referred to as Agroecological zone 3 (AEZ 3) according to the classification of MINEPAT (2015). This region is estimated to account for 8.2% of Cameroon's national territory. It comprises the West and Northwest Regions of Cameroon. The Western Highlands are situated between 9°00′ and 12°00′ E; and 4°00′ and 7°00 N (Nfornkah et al., 2021). The climate is generally the Sudano-Guinean type, experiencing rainfall ranging from 1800–2500 mm. Altitude ranges from 1500–3000 m a.s.l (Toukam et al., 2009), with the Bamboutos Mountains reaching 2679 m a.s.l and Mount Oku reaching 3011 m a.s.l. The temperature ranges from 20–27.5 °C with an average of 21 °C. Two seasons characterize the AEZ 3: the short dry season beginning from mid-November and lasting until mid-March and the long rainy season from mid-March through mid-November.

The soils of the Western Highlands of Cameroon are clayey-sandy in texture and rich in laterites with a base where granite predominates. The soils in the lowlands and along river banks are rich in organic matter and have alluvium present. There are numerous rocky outcrops or blocks of stones of various sizes throughout the area. The soils have a brown colour and are quite leached (PCD, 2011).

Four types of relief characterize the AEZ 3: mountains, plateaux, large plains, and lowlands. The two prominent mountains include the Bamboutos Mountains in the West Region and Kilum/Ijim (Mount Oku) in the North West Region. The vegetation of the Western Highlands consists of montane forests, gallery forests, and Guinea savannah. It presents three distinct aspects. On the slopes of hills overlooking the lowlands, there is a type of secondary mountain forest, along the rivers gallery forests allow the production of robusta coffee, and in the lowlands, there is a herbaceous type dominated by *Imperata cylindrica* (L.) Raeusch. The savannah favours the cultivation of oil palm, cocoa, and coffee. The flora is not very diverse. The herbaceous stratum consists of a grassy carpet dominated by *Imperata cylindrica* and *Cenchrus purpureus* (Schumach.) Morrone. The main woody species identified in AEZ3 include: Iroko (*Milicia excelsa* (Welw.) C.C.Berg), Bibolo (*Lovoa trichilioides* Harms), Mahogany (*Swietenia macrophylla* King in Hook.), Sapeli (*Entandrophragma cylindricum* Sprague), Bété (*Mansonia altissima* (A. Chev.) A.Chev.), and Fraké (*Terminalia superba* Engl. & Diels). Swampy areas are colonized by Raphiales and Sterculiaceae and bamboo (PCD, 2011). Important rivers include the Mbam, Noon, Nde, Menoua, Haut Nkam, Mezam, Momo and others.

2.2. Data collection

2.2.1. Bamboo distribution

Landsat 8 Operational Land Imager (OLI) – Thermal Infrared Sensor (TIRS) (Oli-TIRS) satellite images from November and December 2018 with 30 m resolution were used for this study. These images were downloaded from www.glovis.usgs.gov in GEOTIFF format.

Image pre-processing consisted of de-archiving and assembling the strips (layer stacking), repositioning the 1 m pixel offsets, georeferencing and performing radiometric and geometric corrections (clouds, atmospheric particles). Once the corrections had been made, it was necessary to mosaic the different image scenes to have a continuous landscape of the area under study.

The plant reflectance spectrum is determined by its leaf characteristics, which is mostly controlled by the photosynthetic pigments and water absorption properties. These two features are always different amongst plant species. Different mathematical combinations (indices) of the multi-spectral bands have been found to be sensitive indicators of the present conditions in specific types of green vegetation (Goswami et al., 2010).

Within the context of this study, the methods used by Jensen (1996) and Lillesand and Kiefer (2000) to define vegetation indices were exploited. These consisted of calculating the Normalised Difference Vegetation Index (NDVI) and the Water Stress Index (SI) to derive the Bamboo Index (BI). This BI was delineated on the maps to find the reflectance associated with bamboo vegetation on the map. The demarcation of bamboo areas using water stress index (SI) was possible because of the leaf water content of plants. The leaf water content of bamboo is less than that of other plant species. However, the index value difference of bamboo leaves with other land-use classes is less. To increase this difference, a normalized (double) difference bamboo index (BI) was prepared using NDVI and SI in the bamboo vegetation. The resultant imagery was then used to identify bamboo areas based on the index values.

Ground truthing and verification was undertaken by searching for indicative bamboo areas found on map on land. The team used the assistance of informants and existing literature to locate bamboo stands or forests.

Image validation was achieved by an external evaluation of accuracy through field visits. A hand-held Global Positioning System (GPS)

Table 1
Ecological characteristics of sample plots in AEZ 3.

Factors/variables	Values
Mean annual rainfall (mm)	2000
Mean annual temperature (°C)	21
Bedrock	Igneous rocks
Soil colour	Red, grey, dark
Soil type	Volcanic soils (clay, rocky)
Source:Toukam et al., (2009); Institut de Recherche Agricole pour le Développement (I.R.A.D), (2005); Yerima and Van Ranst (2005); Jiotsa, et al., (2015)	
Altitude range (m a.s.l.)	1124 to 1349
Soil layer depth range (cm)	5 to 70
Slope gradient range ($m.s^{-1}$)	10 to 40
H_{culm} (m)	9.9 to 11.2

receiver was used to confirm the position of the different bamboo vegetation. Very high-resolution imagery from Google Earth was also used to control the various maps produced. Specimen vouchers for the dominant bamboo species were sent to the National Herbarium to confirm their identity, and also checked using online sites dedicated for bamboo species documentation and identification. Landsat 8 Operational Land Imager (OLI) – Thermal Infrared Sensor (TIRS) (Oli-TIRS) satellite images can not differentiate one bamboo species from another in the study area and so the result is based on all bamboo species captured by images.

2.2.2. Bamboo carbon stocks and allometric equation for Phyllostachys aurea

Based on the preliminary bamboo distribution maps elaborated in the AEZ3 with the help of the satellite images and the ground-truthing field work, three sites were identified as having the highest densities of *P. aurea*. The biomass data for *P. aurea* were collected in three villages and divisions: Koupara in the Noun, Babou in the Nde and Balack in the Haut-Nkam. After locating the sample sites, the ecological characteristics of *P. aurea* were collected from each plot. These ecological parameters were considered to be conditions that influence or affect the growth and development of the plants. Table 1 shows a summary of the ecological parameters retrieved from the literature and from field observations.

Four plots were setup at each of the three sites. The plots were circular, with an area of 100 m^2, and followed the method proposed by Huy and Trinh (2019). This is the most appropriate plot type for monopodial bamboo. The total number of bamboo culms within each plot was counted. Bamboo culms were divided into different age classes following Angom et al. (2018): $\leq$ 1year; 2 year-old and $\geq$ 3-year-old culms. For each age class, 5% of the bamboo culms were felled and separated into culms, branches and leaves. The fresh weights of the culms, branches and leaves were then obtained using an electronic balance with a capacity 300 kg. Sub-samples were collected, and their weights determined with a precision 0.1 g. Sub-samples were coded, sealed in plastic bags, and transported to the laboratory and oven-dried at a temperature of 105 °C until constant weight was obtained and recorded on data sheet. Leaves were oven-dried at 70 °C. As recommended by Huy and Trinh (2019), the following dendrometric parameters were measured: the height of the culm, diameter of culm at breast height (1.50 m), and an estimated age. These dendrometric parameters were added to the biomass values obtained by oven-drying the bamboo components (culm, branches, and leaves) to develop allometric equations for *P. aurea* in the Western Highland zone. In total, 75 bamboo stems were sampled in 12 plots for this study.

2.2.3. Data analysis

2.2.3.1. Bamboo remote sensing. Envi 5.3 was used to mosaic the different image scenes into one continuous landscape. Bamboo-growing areas (magenta) were spectrally differentiated using a combination of red, near Infrared (NIR) and green (SWIR). Table 2 shows the bands used.

Table 2
Main characteristics of the sensors used.

Characteristics		Landsat 8
Satellite Status		Operational
Mass		2600 kg
Instruments		OLI et TIRS: radiometer
Spectral bands	Short wave Infrared (SWIR) band	0.433-0.453 µm 0.45-0.515 µm - Blue 0.525-0.6 µm - Green 0.63-0.68 µm - Red
	Near Infrared Short wave Infrared (SWIR 1) band Short wave Infrared (SWIR 2) band	0.845-0.885 µm 1.56-1.66 µm 1.36-1.39 µm 2.1-2.3 µm
Thermal infrared		10,3-11,3 µm 11,5-12,5 µm
Panchromatic		0,5-0,68 µm
Resolution		General: 30 m Panchromatic: 15 m Thermal infrared: 100 m
Imaging technique		Push broom
Orbit		Altitude: 705 km cycle: 16 days time: 10 a.m.

The indices of Jensen (1996) and Lillesand & Kiefer (2000) were defined as:

$$\text{Normalised Difference Vegetation Index(NDVI)} : NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

$$\text{Water Stress Index(SI)} : SI = \frac{NIR - SWIR}{NIR + SWIR} \tag{2}$$

$$\text{Bamboo Index(BI)} : BI = \frac{NDVI - SI}{NDVI + SI} \tag{3}$$

where NIR is near infrared; RED is red and short-wave infrared (SWIR) is green.

2.3. Carbon and allometric analysis

Data were keyed into Excel sheets and analysed using R software (version 4.1.1).

The number of *P. aurea* culms and their biomass per hectare were estimated.

The total dry bamboo biomass was the sum of biomass from each bamboo:

$$TAGB_{bamboo} = AGB_{bamboo}1 + AGB_{bamboo}2 + AGB_{bamboo}3._{+}\ AGB_{bamboo}75 \tag{4}$$

where.

$$AGB_{bamboo} = \text{culm } (AGB_{cl}, \text{kg}) + \text{branches } (AGB_{br}, \text{kg}) + \text{leaves } (AGB_{le}, \text{kg}) \tag{5}$$

Huy and Trinh (2019) recommend using a default value of 47% (IPCC, 2006) for the carbon fraction in bamboo. Bamboo carbon stocks per hectare were estimated using the formula:

$$\text{Carbon stock } (\text{t C}\cdot\text{ha}^{-1}) = \text{biomasses } (\text{t ha}^{-1}) \text{ x } 47\% \tag{6}$$

For the allometry, the predictive variables considered in this study were the diameter of the culms (D in cm); total height of the culms (H in m) and age class of the culms (A in year). This is consistent with the

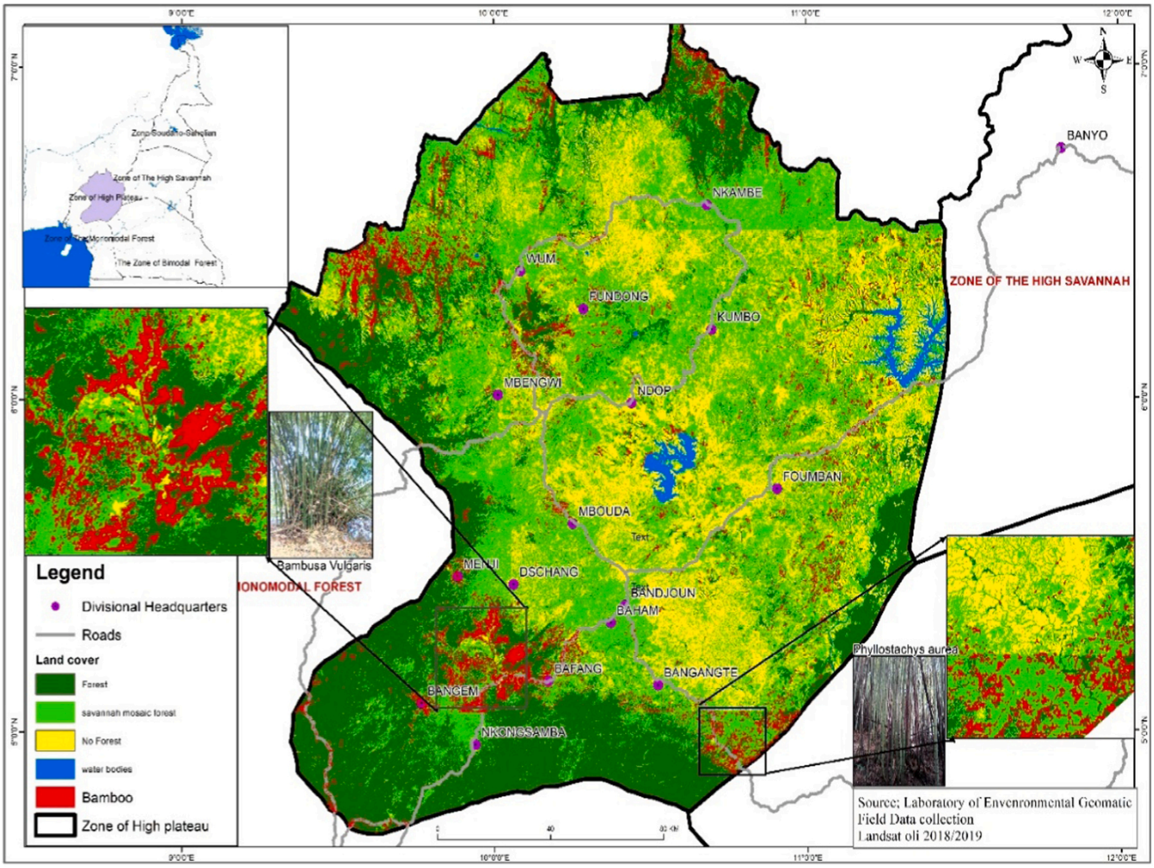


Fig. 1. Mapping of bamboo-growing areas using BI on the High Plateau.

approach of Li et al. (2016a).

A logarithm function was used for the allometric equations as a logarithmic transformation in most cases accounts for the heteroscedascity in the data on the original scale, and satisfies the requirements for normality of the residuals and homogeneity of the variances (Xiao et al., 2011; Picard et al., 2015; Huy et al., 2019). Several log-transformed models were tested. Models with one predictive variable (diameter, height, or age class) were tested first, then models with two variables and finally, models with 3 predictive variables. These models are presented as follows:

$$\ln AGB = a + b \times \ln(D) \tag{7}$$

$$\ln AGB = a + b \times \ln(H) \tag{8}$$

$$\ln AGB = a + b \times \ln(A) \tag{9}$$

$$\ln AGB = a + b \times \ln(D) + c \times \ln(A) \tag{10}$$

$$\ln AGB = a + b \times \ln(D) + c \times \ln(H) \tag{11}$$

$$\ln AGB = a + b \times \ln(D) + c \times \ln(H) + d \times \ln(A) \tag{12}$$

The adjusted coefficient of determination (adj. R^2) was used to assess the model performance. An adj. R^2 coefficient with a p-value of < 0.05 and closer to 1 was considered better. For comparison, the model with the highest adj. R^2 statistical parameter was taken as the best model. In addition, the Akaike Information Criterion (AIC) (Akaike, 1973) and the Residual Standard Error (RSE) were used to select the optimum models. The model with the lowest AIC and RSE value was considered to be the best-fit model.

$$AIC = -2\ln(L) + 2p \tag{13}$$

where L is the likelihood of the model, and p is the number of parameters in the model.

As a logarithmic transformation introduces systematic bias into the model, a correction factor was used to correct this bias for each model developed. It took the form:

$$(CF) = (RSE^2)/2 \tag{14}$$

Models were cross-validated by comparing the estimated biomass of each model with the observed or measured biomass in the field. Two statistical tests carried out including the calculation of the relative root mean square error (RRMSE):

$$RRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{M_{pi} - M_i}{M_i}\right)^2} \tag{15}$$

and the bias:

$$Bias(\%) = 100 \times \frac{1}{n}\sum_{i=1}^{n}\left(\frac{M_{pi} - M_i}{M_i}\right). \tag{16}$$

where M_{pi} is the predicted biomass, M_i is the observed or measured value and n is the number of sizes. The validation of these models focused on the value of the bias (%) for each model.

The best allometric equations were used to estimate the carbon stocks of *P. aurea* in the study area. The model that included all 3 variables (D, H and A) provided the best adjustment. These were then used for estimation of the *P. aurea* biomass. The following relationship was used:

$$AGB = e^{\left(-3.623 + 0.466 \times \ln\left(D^2 \times A\right) + 1.428 \times \ln(H)\right)} \tag{17}$$

However, for culms that were difficult to age, only the diameter and height were available, and the following model was:

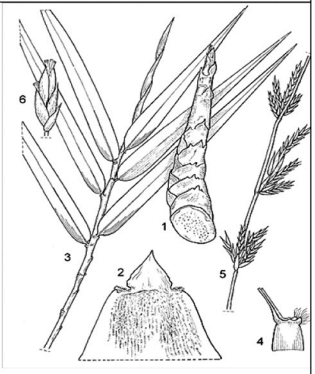
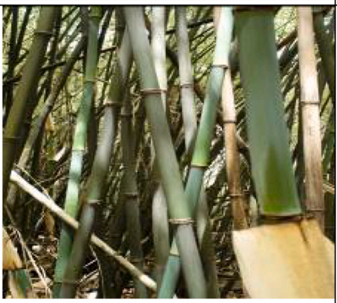
Dominant bamboo species	**Photographs**		
	a	**B**	**C**
P. aurea (field data, *P. aurea* - Search Images (bing.com))			
B. vulgaris var. *green* (field, Ingram *et al*. 2010)			
O. alpina (Ingram et al. 2010)			

Fig. 2. Photographs of the three dominant bamboo species in the Western Highlands of Cameroon.

$$AGB = e^{(-5.166+0.873\times\ln(D)+2.269\times\ln(H))} \tag{18}$$

3. Results

3.1. Remote sensing of bamboo in the Western Highlands (Agro-ecological Zone 3)

Bamboo covered 241,296 ha of land in the Western Highlands of Cameroon, with an image accuracy of 91%. The dominant bamboo species encountered during ground-truthing were *Oldeania alpina*, which was found in the West Regions, and *Phyllostachys aurea* found in Koupara (Noun), Babou (Nde) and Balack (Upper Nkam) of the West region (Fig. 1). *Bambusa vulgaris* was found in the Northern and Northwestern Highlands, in Bui (Mt. Kilum of Oku), Ndonga Mantung and Menchum Divisions of the North West Region and in abundance in Menoua, West Region. The three dominant bamboo species are shown in Fig. 2.

3.2. Allometry for Phyllostachys aurea in the Western Highlands

The diameter of *P. aurea* was considered to be the main variable for predicting its biomass, in view of the general relationship that existed between the main predictive variables in developing allometric equations. The explanatory graphs illustrate the linear relationship that exists between leaves, branches, culms and AGB bamboo biomass with the diameter of this bamboo, with and without logarithmic transformation.

For the development of the allometric equations for *P. aurea*, the results of the adjustments showed that the quality of the model was best when all three predictive variables (diameter, height, and age) were considered in the models. The adj.R^2 varied from 0.073 to 0.737 for leaves, 0.232 to 0.432 for branches, 0.2247 to 0.659 for culms and 0.267 to 0.711 for AGB (Table 3).

When the bamboo components were analysed separately, the results of the supplementary test of the adjustments showed that bamboo leaves and the age class components were the best predictive variables (adj. R^2=0.714, AIC=156 and RSE=0.668) compared to height (adj. R^2=0.365, AIC=216 and RSE=0.996) and, finally, to the diameter (adj. R^2=0.073, AIC=245 and RSE=1.203). Taking two variables at a time, diameter and age were better than diameter and height. The same tendency was obtained for branch components. For culms and AGB, when considering only one variable, the models using height were the best followed by the models with age class, with the poorest fit being with diameter.

Using Bias (%) for model validation of AGB biomass, the following

Table 3
Allometric equations for *P. aurea* bamboo biomass components estimation in agroecological zone 3 in Cameroon.

Equations	N	D range	a	b	c	d	RRSME	RSE	Adj. R^2	AIC	CF	Bias (%)	P-value
Leaves biomass													
$\ln AGB_{le}= a + b \times \ln(D)$	75	1.7-4.4	-4.151^{***}	2.176^{*}			9.917	1.203	0.073	245	0.72	-410.76	0.011
$\ln AGB_{le} = a + b \times \ln(H)$	75	1.7-4.4	-15.158^{***}	5.783^{***}			1.375	0.996	0.365	216	0.50	-190.60	<0.001
$\ln AGB_{le} = a + b \times \ln(A)$	75	1.7-4.4	-3.587^{***}	2.607^{***}			1.432	0.668	0.714	156	0.22	-56.96	<0.001
$\ln AGB_{le} = a + b \times \ln(D) + c \times \ln(A)$	75	1.7-4.4	-4.574^{***}	0.865^{***}	2.530^{***}		1.38	0.657	0.724	155	0.22	-56.84	<0.001
$\ln AGB_{le} = a + b \times \ln(D) + c \times \ln(H)$	75	1.7-4.4	-15.221^{***}	0.577^{ns}	5.513^{***}		4.66	0.999	0.361	217	0.50	-190.36	<0.001
$\ln AGB_{le} = a + b \times \ln(D) + c \times \ln(H) + d \times \ln(A)$	75	1.7-4.4	-7.666^{***}	0.547^{ns}	1.561^{*}	2.270^{***}	1.57	0.641	0.737	152	0.21	-56.02	<0.001
Branches biomass													
$\ln AGB_{br}= a + b \times \ln(D)$	75	1.7-4.4	-2.790^{***}	1.698^{***}			2.588	0.507	0.232	115	0.13	-148.09	<0.001
$\ln AGB_{br} = a + b \times \ln(H)$	75	1.7-4.4	-5.922^{***}	2.199^{***}			1.322	0.504	0.242	114	0.13	-35.20	<0.001
$\ln AGB_{br} = a + b \times \ln(A)$	75	1.7-4.4	-1.331^{***}	0.752^{***}			1.049	0.495	0.269	111	0.12	-30.74	<0.001
$\ln AGB_{br} = a + b \times \ln(D^2 \times A)$	75	1.7-4.4	-2.838^{***}	0.654^{***}			0.76	0.440	0.421	94	0.10	-23.11	<0.001
$\ln AGB_{br} = a + b \times \ln(D \times H)$	75	1.7-4.4	-5.703^{***}	1.392^{***}			1.03	0.467	0.349	103	0.11	-28.20	<0.001
$\ln AGB_{br} = a + b \times \ln(D^2 \times H) + c \times \ln(A)$	75	1.7-4.4	-4.168^{***}	0.631^{***}	0.525^{***}		0.77	0.436	0.432	93	0.10	-22.90	<0.001
Culm biomass													
$\ln AGBc_{l}= a + b \times \ln(D)$	75	1.7-4.4	-0.793^{*}	1.456^{***}			1.02	0.417	0.247	86	0.09	-57.78	<0.001
$\ln AGBc_{l} = a + b \times \ln(H)$	75	1.7-4.4	-5.275^{***}	2.647^{***}			0.49	0.332	0.523	51	0.06	-12.90	<0.001
$\ln AGB_{cl} = a + b \times \ln(A)$	75	1.7-4.4	0.372^{***}	0.752^{***}			0.63	0.373	0.396	69	0.07	-16.26	<0.001
$\ln AGB_{cl} = a + b \times \ln(D^2 \times A)$	75	1.7-4.4	-1.004^{***}	0.614^{***}			0.55	0.326	0.541	49	0.05	-12.13	<0.001
$\ln AGB_{cl} = a + b \times \ln(D) + c \times \ln(H)$	75	1.7-4.4	-5.361^{***}	0.796^{***}	2.275^{***}		0.44	0.310	0.584	42	0.05	-10.84	<0.001
$\ln AGB_{cl} = a + b \times \ln(D^2 \times A) + c \times \ln(H)$	75	1.7-4.4	-4.060^{***}	0.391^{***}	1.599^{***}		0.44	0.281	0.659	27	0.04	-9.03	<0.001
AGB biomass													
$\ln AGB= a + b \times \ln(D)$	75	1.7-4.4	-0.616^{***}	1.531^{***}			0.64	0.417	0.267	86	0.09	-20.37	<0.001
$\ln AGB = a + b \times \ln(H)$	75	1.7-4.4	-5.076^{***}	2.677^{***}			0.48	0.338	0.520	54	0.06	-13.11	<0.001
$\ln AGB = a + b \times \ln(A)$	75	1.7-4.4	0.578^{***}	0.831^{***}			0.52	0.354	0.473	61	0.06	-13.67	<0.001
$\ln AGB = a + b \times \ln(D) + c \times \ln(A)$	75	1.7-4.4	-0.738^{***}	1.153^{***}	0.729^{***}		0.40	0.301	0.620	37	0.05	-10.16	<0.001
$\ln AGB = a + b \times \ln(D) + c \times \ln(H)$	75	1.7-4.4	-5.171^{***}	0.873^{***}	2.269^{***}		0.40	0.311	0.593	42	0.05	-10.61	<0.001
$\ln AGB = a + b \times \ln(D^2 \times A) + c \times \ln(H)$	75	1.7-4.4	-3.628^{***}	0.466^{***}	1.428^{***}		0.33	0.262	0.711	17	0.03	-6.98	<0.001

Note: Statistical analyses were significant at 95% confidence interval. * **p $<$ 0.001; * *p $<$ 0.01; *p $<$ 0.05; and ns (non-significant) p $>$ 0.05
AGB: Aboveground biomass of bamboo; AGB_{cl}: biomass of culm; AGB_{br}: biomass of branches; AGB_{le}: biomass of leaves; D: Diameter of culm; H: total height of culm; A: Age of culm; N: the sample size; a, b, c and d are the model's fitted parameters; RRMSE: Relative root mean square error; RSE: residual standard error of the estimate; Adj R^2: coefficient of determination; AIC: Akaike Information Criterion and CF: Correction Factor.

Table 4
Descriptive statistics of density of culms, AGB.plant^{-1} of *P. aurea* in the Western Highlands of Cameroon.

Descriptive statistic		Mean	Min	Max	Sd
Culm (N.ha^{-1})	12	3,8017	31,200	42,500	4510
Average AGB_{plant} (kg)	12	3.15	1.82	4.35	0.94
AGB_{bamboo} (t.ha^{-1})	12	119.05	69.26	153.20	33.63
AGC_{bamboo} (t C.ha^{-1})	12	55.95	32.55	72.00	15.81
AGC_{bamboo} (t CO_2.ha^{-1})	12	205.35	119.47	269.25	58.01

models with values nearest zero (0) were best for AGB biomass estimation with a bias (%) of − 6.98% (Bias with values nearest zero are more efficient). However, it was also noted that all the models have negative biases (Table 3).

The allometric equations for AGB for *P. aurea* were:

$$AGB=\exp\cdot(-3\cdot623+0\cdot466\times InD^2\times A+1\cdot428\times InH) \tag{19}$$

with the bias of − 6.98%, Adj.R^2= 0.711, AIC = 17 and RSE= 0.262.

And $$AGB=\exp\cdot(-5\cdot166+0\cdot873\times InD+2\cdot269\times InH) \tag{20}$$

3.3. Mean bamboo density, biomass, Carbon, and Carbon dioxide equivalence of Phyllostachys aurea in Western Highlands

The mean N_{culm} per 100 m^2 for *P. aurea* was 380 ± 45 and mean N_{culm} per hectare was 38,017 ± 4510 culm.ha^{-1}. For AGB, the mean AGB per culm for *P. aurea* was 3.15 ± 0.94 kg. *P. aurea* mean AGB was estimated at 119.05 ± 33.63 t.ha^{-1}, mean AGC was 55.95 ± 15.81 t C.ha^{-1} and mean $AGCO_2$eq was 205.35 ± 58.01 t CO_2.ha^{-1} (Table 4).

4. Discussion

The natural vegetation in the Western Highlands has, over the years, experienced anthropogenic pressures due to land-use patterns. Bamboo has a place in the Western Highlands as it is naturally widely distributed in the zone. All bamboo here is natural and unmanaged. Bamboo is exploited by the local population for their local uses (Chimi et al. (2021). The three dominant species are exploited by the local population for various uses; however, some members of the local population who do not appreciate the value of bamboo are cutting and burning them down to free the land for other land uses. The projection of the cover by hectares (241,296) and dominant species (*O. alpina*, *B. vulgaris* and *P. aurea*) is very important at a time when the Government of Cameroon is diversifying wood for consumption and restoring degraded forest landscapes with the aim to increase forest vegetation and to fight against climate change. Our results will inform policy makers and development planners to prioritize bamboo and consider it when selecting species for controlled and well-managed restoration (Nfornkah et al., 2023). Bamboo is one of the fastest growing plants on earth and vital for conserving soils. It produces fibrous root systems that hold soil firmly thus contributing to fighting against soil erosion, while the rapid growth of the plants favours the rapid sequestration of considerable amounts of carbon dioxide. Bamboo forests are known as a habitat for rare and endangered species, thus contributing to biodiversity conservation (Nath et al., 2015; Yuen et al., 2017; Xu et al., 2018; Terefe et al., 2019, Nfornkah et al., 2020a, 2020b, Chimi et al., 2022; Kaam et al., 2023; Nfornkah et al., 2023; Ananfack et al., 2023). *P. aurea* is wide spread and adapted in AEZ3 in Cameroon. This potential can be harnessed upon by

Table 5
Carbon stocks of *P. aurea* and other ecosystems in the different forest strata in Cameroon.

Different Agro-ecological zones	Ecosystem types	Carbon stocks (t.ha^{-1})	References
Western Highlands (WH)	*Phyllostachys aurea*	55.95	This study
	Coffee agroforestry	24.28–41.20	Temgoua et al. (2018)Ngomeni et al. (2021)
	Sacred forest	129.78	Lounang et al. (2018)
High Guinea Savannah (HGS)	Savannah grassland	10.78	Noumi et al. (2018a)
	Shrubby savannah	40.89–45.03	Tchobsala et al. (2016)
	Cashew agroforest	40.02	Noumi et al. (2018a)
	Neem agroforest	28.24	Noumi et al. (2018b)
	Eucalyptus agroforest	64.46–108.51	Noumi et al. (2018a, b)
Tropical humid semi-Deciduous Forest (TDF)	Semi deciduous Forests	235.88	etal.,2020
	Semi deciduous Forests	369.77	Kabelong et al. (2020)
	Coffee agroforest	20.67	Ngomeni et al. (2021)
	Traditional cocoa agroforest	113.5	Madountsap et al. (2019)
	Cocoa agroforest	78.43	Noumi et al. (2018a, b)
Tropical Evergreen Forest (TEF)	Coastal/ mangrove	189.31	Ngueguim et al. (2017)
	Evergreen secondary forest	327.35	Kabelong et al. (2020)
	Coffee agroforestry	34–45	Ngomeni et al. (2021)

decision makers who can use bamboo as a tool to restore degraded forest under initiatives such as the REDD+ strategy, Bonn Challenge (Afr100 initiative), the Convention on Biological Diversity (CBD), National Climate change adaption and mitigation initiatives and Nationally Determined Contributions (Paris agreement), amongst others.

Generally, the best allometric equation was obtained when all three plant variables were included in the model. The supplementary tests indicated an adj. $R^2 = 0.711$, AIC= 17 and RSE= 0.262 for the equation that was developed. The value of the adjusted coefficient was higher when compared to other studies. The adj. R^2 for this study was higher than that obtained by Nfornkah et al.,. (2020), with adj. $R^2 = 0.6$, or those of Huy *et al.* (2019) who found a relationship between branch biomass (Bbr) and leaf biomass (Ble) with covariates D and D^2H, with an adj. R^2 of about 0.5. The results of Melo et al. (2015) and Li et al. (2016) were similar to those of Huy *et al.* (2019). Yuen et al. (2017) reported that the relationship between the biomass of foliage and branches of Makino bamboo species (*Phyllostachys makinoi* Hayata) using the variable D had an adj. $R^2 = 0.5–0.6$. This suggests that our allometric equation predicts well in comparison to previous studies, irrespective of the bamboo species.

A value for bias of − 6.98% was obtained. This was closer to zero than the bias found for *B. vulgaris* in evergreen rain forest in Cameroon (Nfornkah et al., 2020). The negative value indicates that the equation will underestimate the biomass of *P. aurea*. This may be attributable to the hollow structure of bamboo, which means that it will have a lower fibre (lignin) density than trees. However, it is important to develop this equation, as it is the only way that future carbon stocks will be estimated without involving destructive sampling that will damage the local ecosystem.

P. aurea has a higher number of culms per hectare (38,017 ± 4510 culm.ha^{-1}) than *Bambusa vulgaris* (13,330 culm.ha^{-1}) (Chimi et al., 2022). The higher culm density can be explained by its growth form (monopodial). The monopodial bamboo's rhizome grows horizontally in the soil, producing many underground that which eventually grow into young shoots (Vorontsova et al., 2016), *P. aurea* in AEZ in Cameroon is unmanaged with no selective or clear cutting, thus, allowing majority of young shoots to grow into individual plants, and finally, the soils and the climate affecting the species maybe its favorite (Canavan et al., 2017). The result is that a very dense bamboo stand may expand continuously to form a dense bamboo forest. The density that we found differs significantly from the values reported by, who recorded 2296 ± 631 culms.ha^{-1} for *O. abyssinica* in the agroecological zone 2 and 4374 ± 2604 culms.ha^{-1} for *B. vulgaris* in the evergreen rain forest of Cameroon. The differences in density may have arisen because *B. vulgaris* and *O. abyssinica* are sympodial (rhizomes and buds grow vertically forming bamboo in clusters).

For aboveground biomass (AGB), the mean value per culm was small (3.79 ± 0.54 kg). Ironically due to the very high density, the AGB of bamboo per hectare was very high (144.21 ± 21.58 t.ha^{-1}). This may be explained by the power of numbers of *P. aurea* per hectare. Small biomass per culm of bamboo but high individual culms per hectare. When this result is compared to the findings of, the difference is significant. *B. vulgaris* and *O. abyssinica* have higher mean culm biomass (29.80 ± 6.96 and 6.39 ± 3.44) but their numbers are very small when compared to *P. aurea.* Kaam et al. (2023) reported that bamboo AGC varies from 53.83–93 t C.ha^{-1}. Table 5 compares the carbon of *P. aurea* to those of other ecosystems in the Western Highlands and other Agro-ecological zones in Cameroon. The results show that carbon stock of *P. aurea* was both greater than and less than some ecosystems. Considering the carbon storage capacity, it should be considered for degraded and/or marginal forest landscape restoration as a tool for climate change adaptation. In similar studies globally, Nath et al. (2015) reported that mean carbon storage and sequestration rate in woody bamboos ranged from 3–121 tC.ha^{-1} and 6–13 tC.ha^{-1} yr^{-1}, respectively in the Asian Pacific Region. Yuen *et al.* (2016) reviewed 184 studies of bamboo carbon in 70 species in the Asian Pacific Region, finding that the above-ground carbon (AGC) biomass ranged from 16–28 t C.ha^{-1}. It should be noted that bamboo carbon stocks in the world vary with respect to bamboo species as their numbers, sizes, morphologies differ (Jyoti et al., 2009; Nath et al., 2012; Patricio & Dumago, 2014; Yuen et al., 2017).

5. Conclusions

The Western Highlands of Cameroon has a bamboo resource covering 241,296 ha. The dominant species included *Oldeania alpina*, *Bambusa vulgaris* and *Phyllostachys aurea*. The mean density of *P. aurea* was 38,017 ± 4510 culms.ha^{-1}. The mean culm aboveground biomass was 3.15 ± 0.94 kg. The AGB of *P. aurea* was estimated at 119.05 ± 3.63 t.ha^{-1}, the mean AGC was 55.95 ± 5.81 tC.ha^{-1} and the mean AGCO$_2$eq was 205.35 ± 58.01.22 t CO$_2$.ha^{-1}. The best fit allometric equation for *P. aurea* biomass prediction had a bias of − 6.98%, adj. $R^2 = 0.711$, AIC = 17 and RSE= 0.262. *P. aurea* constitutes a significant carbon storage capacity in the Western Highlands of Cameroon. Policymakers and development planners should recommend this species for the Nationally Determined Contribution AFR100 initiative, the Great Green Wall (GGWI), the COMIFAC Convergence plan, the Yaoundé Declaration 2022, the African Union Agenda 2063, and responding to Sustainable Development Goal 13 to combat climate change.

CRediT authorship contribution statement

Chimi Djomo Cedric: Data curation, Investigation, Methodology, Software, Validation. **Neba Nfornkah Barnabas:** Data curation, Investigation, Methodology, Software, Validation. **Tchamba Martin:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision. **Kaam Rene:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rene Kaam reports financial support, administrative support, and equipment, drugs, or supplies were provided by International Network for Bamboo and Rattan. Rene Kaam reports a relationship with International Network for Bamboo and Rattan that includes: employment.

Data Availability

The authors do not have permission to share data.

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Further reading

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