Advances in Bamboo Science 2 (2023) 100008

Contents lists available at ScienceDirect

Advances in Bamboo Science

journal homepage: www.journals.elsevier.com/advances-in-bamboo-science

Original article

Allometric models for estimating biomass storage and carbon stock potential of *Oldeania alpina* (K. Schum.) Stapleton forests of south-western Ethiopia

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ARTICLE INFO

Keywords:
Allometric model
Bamboo
Biomass estimation
Destructive sampling
Ethiopia
Oldeania alpina

ABSTRACT

Ethiopia has the largest bamboo resource base in Africa. However, due to the lack of species-specific models, little is known about the biomass storage, carbon stock and sequestration potential of bamboo forests. Here, species-specific allometric models are presented and the potential biomass and carbon storage of the *Oldeania alpina* (K. Schum.) Stapleton forests of Ethiopia are quantified. A total of 42 bamboo culms covering the full range of sizes were destructively sampled, with a diameter at breast height (DBH) ranging from 3 to 7.1 cm, height (H) of 7.8 – 14.2 m, and age 1 – 6-year-old. Allometric equations were formulated in the form of power models for estimating the total aboveground biomass (TAGB) of *O. alpina*. TAGB was regressed against DBH and H individually and in combination. Finally, the allometric models were validated and selected based on model performance statistics. Allometric equations for estimating TAGB with higher coefficient of determination (adj.R^2), lower residual standard error (RSE), and low Akaike information criterion (AIC) values fitted best. Relationships between observed and predicted TAGB were statistically significant ($p \leq 0.05$) for the selected models. The developed allometric models can be applied to the estimation of the biomass storage potential of *O. alpina* forests of Ethiopia.

1. Introduction

Bamboo forests, which cover 35 million hectares worldwide (FAO, 2020), are an important component of tropical and subtropical forest ecosystems, and they play an important role in mitigating climate change (Abebe et al., 2021a; Bahru and Ding, 2021; Zhou et al., 2011). Bamboo has a higher carbon stock per hectare than fast-growing tropical and subtropical trees under similar conditions (King et al., 2021; Thokchom and Yadava, 2017; Van der Lugt et al., 2018). For example, Yuen et al., (2017) found that the aboveground carbon of bamboo forests ranged from 16 to 128 Mg C ha^{-1}, which is significant when compared to tropical rain forests in Asia, which contain 56–320 Mg C ha^{-1}. Similarly, Abebe et al. (2021c) and Nfornkah et al. (2021a, 2021b) reported that 29.7–69.6 Mg C ha^{-1} is stored by the aboveground biomass of bamboo forests in Africa.

Africa has 7.2 million hectares of bamboo with over 115 species (International Bamboo and Rattan Organization (INBAR), 2022). Ethiopia has the greatest bamboo forest cover (1.45 million ha) in Africa, indicating that the country has a big potential to mitigate climate change through its bamboo resources (Solomon et al., 2020; Zhao et al., 2018). With its two indigenous bamboo species, *Yushania alpina* (K. Schum.) W.C. Lin and *Oxytenanthera abyssinica* (A. Rich) Munro, the country accounts for approximately 67 % and 7 % of Africa's and the world's total bamboo forest cover, respectively (Abebe et al., 2021a, 2021b; Minale and Abebe, 2020). However, due to the lack of species-specific models, little is known about the biomass storage, carbon stock and sequestration potential of the bamboo forests.

Globally, different methods, ranging from generic to species-specific allometric models, have been developed to estimate the biomass and C storage potential of bamboo (Amoah et al., 2020; Huy et al., 2019; Inoue et al., 2018a, 2018b; Inoue and Suga, 2009; Nfornkah et al., 2021a, 2021b; Singnar et al., 2015, 2017; Sohel et al., 2015; Sujarwo, 2016; Thokchom and Yadava, 2017; Xayalath et al., 2019). However, these models are not representative of all bamboo species and the environmental conditions of Ethiopia. As there are many bamboo species and because site conditions vary from place to place, using a general

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https://doi.org/10.1016/j.bamboo.2022.100008
Received 11 July 2022; Received in revised form 10 November 2022; Accepted 10 November 2022

model or a model developed in another country may not accurately estimate the biomass and carbon storage potential of bamboo (Abebe et al., 2021c). Site-specific models produce more accurate results than general models (Yuen et al., 2016) as local climatic conditions, soil properties, topographic nature, and land-use history and management practices all influence plant growth characteristics (Aneseyee et al., 2021; Feyisa et al., 2018).

In Ethiopia, several studies have been conducted on the organic carbon stock and sequestration potential of forests (Aneseyee et al., 2021; Daba and Soromessa, 2019; Gebeyehu et al., 2019). However, the studies that have been conducted to date have mostly focused on tree species while much less emphasis has been given to bamboo species (Abere et al., 2017; Eshetu and Hailu, 2020; Manaye et al., 2021; Tesfaye et al., 2020; Toru and Kibret, 2019). Although bamboo forests are a unique ecosystem with significant carbon storage capacity, quantifying their biomass and carbon stock potential is a great challenge in Ethiopia. This is because direct measurement or estimation of biomass using destructive methods require significant human and financial resources and is unfriendly to the environment (Huy and Long, 2019), while the non-destructive or allometric models (indirect method) are yet to be developed (Abebe et al., 2021c).

The *Oldeania alpina* bamboo forest reserve of Masha district is part of the Sheka Forest Biosphere Reserve of south-western Ethiopia that was established to conserve natural forest and wildlife. Despite the abundant bamboo resource base at the reserve, few efforts have been made to assess the biomass and carbon sequestration potential of bamboo forests. Therefore, it is important to develop species and site-specific allometric models that can be used for future research to estimate the biomass and carbon storage capacity of *O. alpina* bamboo forests. In light of this backdrop, the current study was conducted in the bamboo forest reserve of Masha district, a typical *O. alpina* (alpine bamboo) producing area in southern-western Ethiopia. The objectives of the study were (i) to develop an allometric equation to estimate *O. alpina* forest biomass and (ii) to estimate the aboveground carbon storage and sequestration potential of *O. alpina* forest reserve of Masha district, southern-western Ethiopia.

2. Materials and methods

2.1. Description of the study area

This study was conducted in the *Oldeania alpina* forest reserve of Masha district in south-western Ethiopia. The district is located between 7° 34' 20" to 7° 51'40" N and 35° 19' 35" to 35° to 36' 25" E in south-western Ethiopia (Fig. 1). It covers about 816 km^2 and is situated between 1406 and 2624 m above sea-level in the south-western highlands of Ethiopia. The district's relief is characterized by a rugged terrain comprising hilly areas where the underlying basement rock is of Precambrian origin and is most directly covered by tertiary volcanic rocks that dominate the geology of the area (Beccaluva et al., 2011). The major soil groups of the district are Nitisols, Vertisols, Leptosols, Regosols, Cambisols, and Acrisols. The district has seasonal and perennial rivers, such as the Meneshi, Wonani, Tatamayi, and Gahamayi, that drain. The annual average temperature ranges from 12.2 °C to 28 °C. The district receives all-year-round rainfall, ranging from approximately 1400–3000 mm, and maximum rainfall is received between April and October (Gole and Getaneh, 2011).

The district has various vegetation resources, dominantly Afromontane tree species including *Polyscias fulva (Hiern) Harms*, *Astropanax myrianthus* (Baker) Lowry, G.M.Plunkett, Gostel & Frodin (syn. *Schefflera myriantha* Drake), *Astropanax volkensii* (Baker) Lowry, G.M.Plunkett, Gostel & Frodin (syn. *Schefflera volkensii* Harms), *Dracaena afromontana* Mildbr., *Euphorbia ampliphylla* Pax, *Ekebergia capensis* Sparrm., *Bersama abyssinica* Fresen., *Syzygium guineense* DC, *Prunus Africana* (Hook.f.) Kalkman, *Zanha golungensis* Hiern and *Allophylus abyssinicus* Radlk.. Small trees and shrubs include *Ilex mitis* Radlk., *Maytenus adat* (Loes.) Sebsebe, *Alsophila manniana* (Hook.) R.M.Tryon (syn. *Cyathea manniana* Hook.), *Noronhia mildbraedii* (Gilg & G.Schellenb.) Hong-Wa & Besnard (syn. *Chionanthus mildbraedii* (Gilg & G.Schellenb.) Stearn), *Mitragyna rubrostipulata* (K.Schum.) Havil. (syn. *Hallea rubrostipulata* (K.Schum.) J.-F.Leroy)), *Maesa lanceolate* Forssk., *Oxyanthus speciosus* DC., *Galiniera saxifraga* (A.Rich.) Bridson, *Deinbollia kilimandscharica* Taub. and *Brucea antidysenterica* J.F.Mill. The herbaceous layer vegetation and climbers are diverse (Friis, 1992; Wakjira, 2006). The alpine bamboo (*Oldeania alpina*) groves are one of the vegetation resources predominantly found in Gada, Kanga, Ateso, Yina, Atile and Gatimo villages (*kebeles*) in the district. These bamboo groves are almost monoculture stands, except for a very few scattered trees. It is monopodial/leptomorphic rhizome bamboo, and a hollow species, growing at elevation ranging from 2200 to 4000 m in the south, southwest, central, and northwestern highlands of Ethiopia (Mulatu et al., 2016). This bamboo resource covers about 4856 ha in the southwestern highlands of Ethiopia (Zhao et al., 2018).

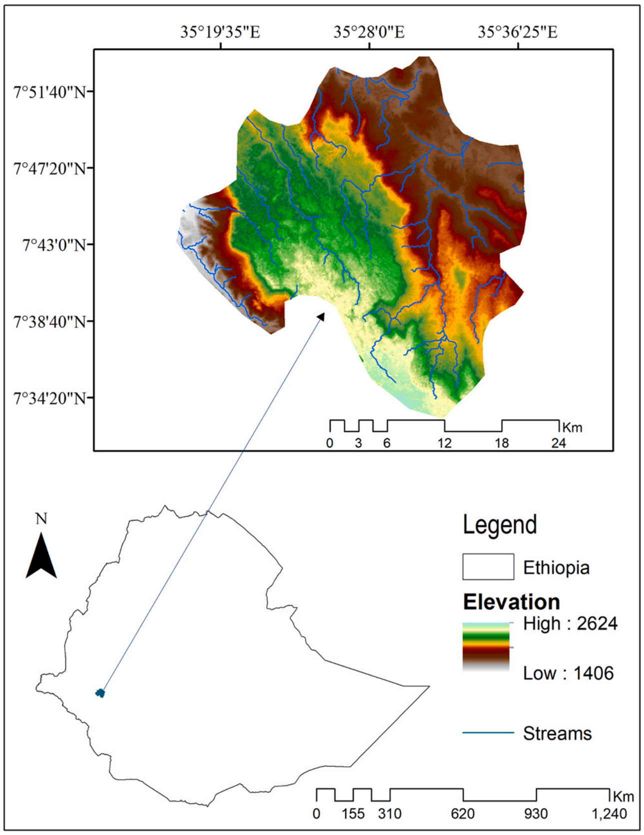

Fig. 1. Location map of the study area.

The majority of people in the district are engaged in mixed farming. Potato (*Solanum tuberosum* L.), enset (*Ensete ventricosum* (Welw.) Cheesman), cereals such as maize (Zea mays L.), barley (*Hordeum vulgare* L.), and common bean (*Phaseolus vulgaris* L.), field pea (*Pisum sativum* L.), are the major crops. In addition, various kinds of spices, coffee, chat, and honey are the major cash crops. Cattle and sheep are the main livestock resources kept in the study area.

2.2. Methods

2.2.1. Data collection

A destructive sampling method was employed for harvesting bamboo culms in the bamboo forest in September 2021. Harvesting a larger number of culms is not recommended when developing a model due to negative ecosystem impacts and the high cost, whereas a small sample size may result in biased equations (Duncanson et al., 2015).

According to INBAR's manual for bamboo forest biomass and carbon assessment (Huy and Long, 2019), a total of 30–50 sample culms must be harvested to develop site-specific allometric models, with 2 – 3 culms in each age- group being taken in a plot. Accordingly, we selected six sample culms from seven circular plots (each measuring 100 m^2 with a radius of 5.64 m) for three age groups (1 – 2, 3 – 4, and 5 – 6-year-old culms). In this case, a total of 42 culms were harvested to develop the model. Circular plots are more efficient because the actual perimeter of the plot is smaller than square or rectangular plots; so, the number of bamboo culms on the edge is limited (Huy and Long, 2019). In each plot, diameter at breast height (DBH) and height (H) were recorded.

Age (A) was identified directly from the culm's morphological features as follows (Singnar et al., 2017): (a) 1-year-old bamboo culms are those that emerged in the current year and have only a few leaves, the sheath on the culm, and the culm has a pale surface colour covered with a white powder; (b) 2-year-old bamboo culms have a few sheaths at the base of the culm with some beginning to rot, well-developed branches on the 5th and 6th internodes, and the white powder on the culm surface is beginning to disappear while the culm is turning dark green; (c) 3-year-old bamboo culms have no sheaths, and the culm bottom has turned dark green, symbolizing near maturity, and characterized by the appearance of a few lichens and mosses on culm surfaces; and (d) 4-year-old culms have no sheath and a light yellowish green culm with an abundance of lichens and mosses, and (e) 5-year-old or older bamboo culms have a brownish green culm surface covered with an abundance of lichens and mosses.

The sampled culms covered the full range of sizes, with DBH ranging from 3 to 7.1 cm, H of 7.8 – 14.2 m, and bamboo culms of 1 – 2, 3 – 4, and 5 – 6 -year-old. After harvesting, samples of the aboveground plant parts were divided into culm, branch and leaf, and then their respective fresh weights were measured in the field. Sub-samples weighing 110 g were taken from each component of culms (at three positions on the culm: root collar, middle and top) and branches and leaves (Huy and Long, 2019). The sub-sample fresh weights were sealed with a plastic bag, labeled, and transported to laboratory at Assosa University, Ethiopia for analysis.

2.2.2. Laboratory analysis and biomass calculations

All sub-samples of culm aliquots and leaves collected from the field were transported and stored in the laboratory. The culm, branch, and leaf were sealed with aluminum foil and placed in an oven separately at an adjusted temperature of 105 °C to remove moisture content and determine the dry matter. The dried culm and branch and leaf aliquots were weighed after two days to stabilize the condition. Then, we weighed the dry culm and branch and leaf aliquot using an electronic balance and recorded their values in the datasheet. The aboveground biomass (AGB/ kg) of the whole bamboo was calculated as the sum of the dry biomass of all compartments. For each sample *i* of branches and leaves taken, the moisture content (MC) was calculated as:

$$\text{MC branch and leaf, i} = \frac{B\text{aliquot dry branch and leaf, } i}{B\text{aliquot fresh branch and leaf, } i}$$

Where *B* aliquot dry branch and leaf*, i* is the oven-dry biomass of the branch and leaves in sample *i,* and *B* aliquot fresh branch and leaf, *i* is the fresh biomass of branch and leaves in the sample, *i.*

The moisture content of the culm, MC, was obtained from the ratio of fresh biomass (B) aliquot of a culm and its dry biomass (B) aliquot dry culm.

$$\text{MC culm, i} = \frac{B\text{aliquot dry culm, } i}{B\text{aliquot fresh culm, } i}$$

Where *B* aliquot dry culm*, i* is the oven-dry biomass of the culm in sample *i,* and *B* aliquot fresh culm, *i* is the fresh biomass of culm in the sample. The total dry weight or biomass for each component of the sampled bamboos was calculated based on FAO (2012) as follows:

$$\text{TDW} = \text{TFW}*\frac{\text{SDW}}{\text{SFW}}$$

Where, TDW = total dry weight or biomass; TFW = total fresh weight; SDW = sub-sample dry weight; SFW = sample fresh weight. The sum of the entire components represents the oven-dried weight or biomass of the bamboo plant. Then, the total stand biomass of the *Oldeania alpina* forest was determined and computed on a per hectare basis.

2.2.3. Model construction

The allometric models were constructed based on measured dendrometry variables such as DBH and H as predictors and AGB of bamboo as the response variable. The normality test for the model development was performed using a Shapiro–Wilk test to examine whether the datasets were normally distributed. The DBH was first tested as an independent variable to develop the allometric models for aboveground biomass (Y) estimation as $Y = ax(DBH)^b$ and subsequently, H and the combination of DBH and H were performed stepwise. The newly developed allometric model for biomass estimation of bamboo species was also compared with previously developed allometric models in Ethiopia and other countries.

2.2.4. Data analysis and model selection

The raw data were organized, arranged, and entered into a Microsoft Excel spreadsheet. Data analysis was conducted with R statistical software and decided at a significant level (α) of 0.05. Analysis of variance (ANOVA) was performed to examine variation in AGB across bamboo components and age classes. The model selection and validation were based on the statistical significance of model parameter estimates, Akaike Information Criterion (AIC), adjusted coefficient of determination (adj.R^2), residual standard error (RSE), and mean relative error (MRE) (Chave et al., 2005). Akaike information criterion (AIC) was used for model selection and calculated as follows:

$$\text{AIC} = 2p - 2\ln(L) \tag{1}$$

L is the likelihood of the fitted model, p is the total number of parameters, and ln is the natural logarithm. The lowest AIC value shows the best estimator.

The adj. R^2 value indicates the total variation of the data explained by the validated equations. It lies between 0 and 1, and the closer it is to 1, the better the fit quality. This was used for testing model performance and calculated as:

$$\text{adj.}R^2 = [1 - \frac{\sum_{i=1}^{n}(\text{AGBesti} - \text{AGBobs})^2}{\sum_{i=1}^{n}(\text{AGBobs} - \text{mAGBobs})2}] \tag{2}$$

where AGB esti is the estimated aboveground biomass in kg; AGB obs is the observed aboveground biomass in kg and mAGB obs is the mean observed individual aboveground biomass in kg.

The residual standard error (RSE) was computed to evaluate the model performance as:

$$\text{RSE} = \sqrt{\sum_{i=1}^{n}\frac{(\text{AGBesti} - \text{AGBobs})2}{n - p}} \tag{3}$$

where, RSE is the residual standard error, and AGB esti is the estimated aboveground biomass in kg; AGB obs is the observed aboveground biomass in kg; n is the number of sampled bamboo species; and, p is the number of parameters in the model. The smaller the RSE values, the greater the accuracy of the regression models in predicting biomass.

For each model evaluation, two measures of average errors were calculated: the root means square error (RMSE, in cm) and the relative systematic error (or bias, in %). The mean relative error (MRE) and root mean squared error (RMSE) were calculated for validation criteria of model performance. It was computed to test model validations as follows:

Table 1

Stand structure of *Oldeania alpina* forest in the study area.

Age (year)	Culm density (ha^{-1})	Clump density (ha^{-1})	Mean DBH (cm)	Mean height (m)
1 – 2	3500		5.86 ± 0.89	10.68 ± 2.48
3 – 4	4043		5.41 ± 0.84	10.95 ± 1.70
5 – 6	11800		5.09 ± 0.98	9.35 ± 1.60
Total	19343	429	5.45 ± 0.94	10.33 ± 2.05

$$\mathrm{MRE}(\%) = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{\mathrm{AGB\ esti} - \mathrm{AGB\ obs}}{\mathrm{AGB\ obs}}\right) \tag{4}$$

where AGB esti and AGB obs are aboveground biomass estimated and observed, respectively, and n = number of sampled trees.

The root means squared error (RMSE) was calculated to validate variation of estimated AGB from observed AGB as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\mathrm{AGB\ esti} - \mathrm{AGB\ obs}}{\mathrm{AGB\ obs}}\right)^2} \tag{5}$$

where AGB esti and AGB obs are the estimated and observed aboveground biomass, respectively, and n is the total number of bamboo species. The plots of observed and predicted AGB values were also employed for assessing model performance.

3. Results

3.1. Culm density and stand structure of Oldeania alpina forest

The culm density of the *O. alpina* stand was 19,343 culm ha^{-1} in the bamboo forest. In terms of culm age composition, 5 – 6-year-old culms were the most common (11,800 culms ha^{-1} = 61 %) in the bamboo stand, while 1 – 2 and 3 – 4-year-old culms made up 18 % (3500 ha^{-1}) and 21 % (4043 ha^{-1}), respectively. The 1 – 2-year-old culms had the highest mean DBH (5.86 cm), while 5–6-year-old culms had the lowest mean DBH value of 5.09 cm. As age increased, the thickness of the bamboo culms decreased (Table 1). Similarly, the greatest mean height of *O. alpina* was recorded for the 1 – 2-year-old culms while 5–6-year-old *O. alpina* had the lowest mean height.

3.2. Aboveground biomass storage by Oldeania alpina

The measured aboveground biomass varied among components ($P < 0.05$). The culm contributed the highest proportion of biomass proportion (59.0 %), while branches and leaves together contributed the remaining 41.0 % and showed a significant difference at $P < 0.05$ (Table 2). In contrast, the total aboveground biomass did not significantly vary ($P > 0.05$) among the bamboo age classes. Generally, the study found that a total of 64.1 Mg ha^{-1} of AGB was stored in *O. alpina* bamboo forests of the study area.

3.3. Allometric model for the prediction of aboveground biomass of Oldeania alpina forest

DBH predicted AGB better as a single parameter than height with the lowest AIC (−27.551) and RSE (0.166). In contrast, height as a single predictor had an AIC of 46.841 and RSE of 0.403. Also, the DBH explained the variation in the total aboveground biomass of the bamboo with significantly higher values of adj.R^2 (0.861) when compared to height (0.183).

Diameter at breast height (DBH) was the most common predictor variable strongly related to the aboveground biomass (Fig. 2). In contrast, height showed a weak linear relation with aboveground biomass (Fig. 2D). Incorporating height as the second predictor variable to DBH did not significantly improve the model: the present allometric model (M1) showed that using DBH alone as a predictor variable provided a similar result to that obtained when using both DBH and H (M2). However, the model developed using DBH alone had lower AIC and RSE (Table 3). In terms of model comparison, the power model performed better for biomass estimation than the exponential or log models (Fig. 3).

3.4. Model evaluation and validation

The result of the cross-validation statistics showed that the constructed model 1 (M1) and model 2 (M2) performed the best for the prediction of the AGB of bamboo (Table 4). However, of the two models, model 1 (M1) did not show a significant difference ($p > 0.05$) between observed and predicted biomass. Moreover, model 1 had a lower MRE of 0.03 and RMSE of 0.866 than model 2, with values of 1.52 and 4.188 for MRE and RMSE, respectively. Based on the 1:1 relationship between the observed and predicted AGB for the validation data set, model 1 predicted well and had a less scattered plot. Hence, it can be concluded that model 1 was the best predictor of *O. alpina* AGB and had the least error when compared to the other models.

3.5. Comparison with previously published allometric models

The newly developed models were compared with previously developed allometric models for biomass estimation of bamboo species (Table 5). The observed biomass of *O. alpina* was not significantly different from the biomass estimated by our allometric models ($p > 0.05$). However, it was significantly different to the biomass estimated from the allometric models developed by Mulatu and Fetene (2013). The allometric models developed by Mulatu and Fetene (2013)

Table 2

Biomass distribution of components and age classes of *Oldeania alpina* bamboo forest.

Age (year)	N	DBH (cm)	Height (m)	Biomass (Mg ha^{-1})		
				Branches and leaves	Culm	Total
1 – 2	14	5.86 ± 0.89	10.68 ± 2.48	8.16 ± 2.23	13.57 ± 3.59	21.73
3 – 4	14	5.41 ± 0.84	10.95 ± 1.70	9.19 ± 3.24	12.84 ± 4.73	22.03
5 – 6	14	5.09 ± 0.98	9.35 ± 1.60	8.91 ± 3.12	11.23 ± 4.32	20.34
Total	42	5.45 ± 0.94	10.33 ± 2.05	26.26 ± 6.60^a	37.84 ± 10.86^b	64.10

Mean ± standard deviation and the different letters show significance at $p < 0.05$.

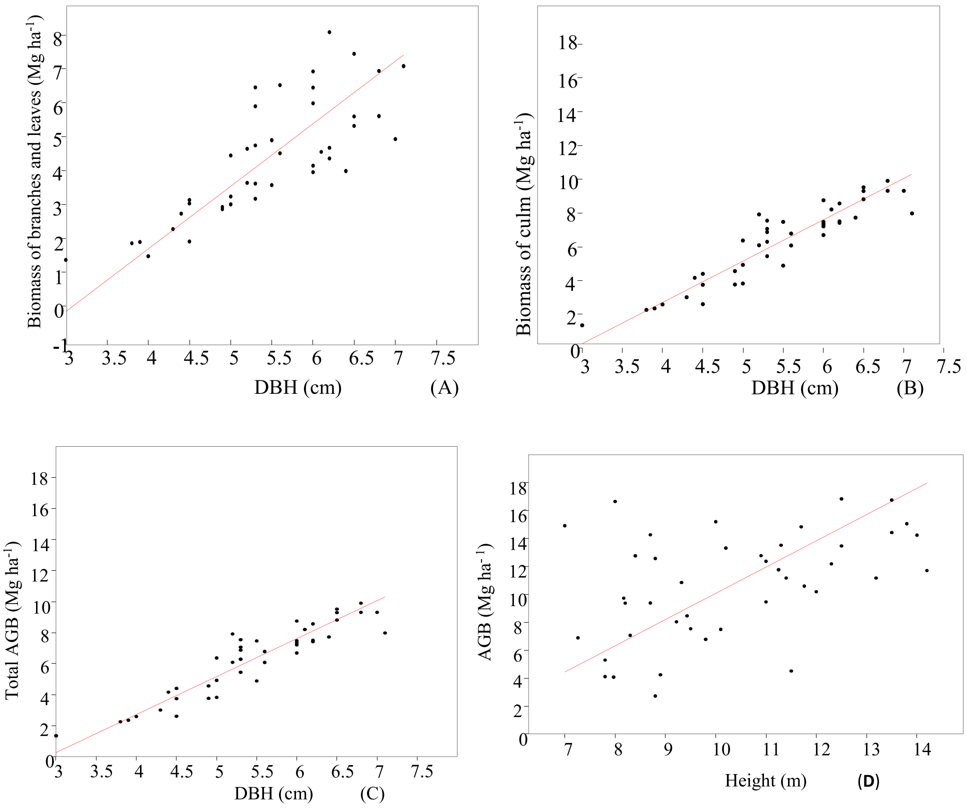

Fig. 2. A, B and C: the relationship between DBH and AGB relationship and D, the relationship between height and AGB.

underestimated the biomass of *O. alpina* (MRE value ranges −5.204 to −3.358 %) when compared to the present study (MRE value ranges 0.01–0.444 %) for the 5 – 6-year-old culms. In contrast, when the allometric models developed for *Bambusa vulgaris* and *Oxytenanthera abyssinica* were applied, the biomass of *O. alpina* was overestimated, as indicated by the higher MRE value. The solid stem structure of *O. abyssinica* particularly might be contributing greater biomass than a hollow stem structure of *O. alpina.*

Table 3
Allometric model relation between predictors and *Oldeania alpina* AGB.

Model code	Age (year)	Power equation	Model performance statistics			
			adj.R^2	AIC	RSE	P-value
M1	1 – 2	$Y = 0.259 \times (DBH)^{2.098}$	0.925	-21.747	0.097	< 0.001
	3 – 4	$Y = 0.139 \times (DBH)^{2.577}$	0.856	- 6.586	0.167	< 0.001
	5 – 6	$Y = 0.165 \times (DBH)^{2.487}$	0.922	-9.152	0.152	< 0.001
	Total	$Y = 0.229 \times (DBH)^{2.237}$	0.861	-27.551	0.166	< 0.001
M2	1 – 2	$Y = 0.296 \times [(DBH)^{2.187} + (H)^{0.885}]$	0.924	- 20.799	0.097	< 0.001
	3 – 4	$Y = 0.232 \times [(DBH)^{2.769} + (H)^{0.697}]$	0.857	-5.834	0.167	< 0.001
	5 – 6	$Y = 0.168 \times [(DBH)^{2.492} + (H)^{0.989}]$	0.915	- 7.153	0.159	< 0.001
	Total	$Y = 0.279 \times [(DBH)^{2.319} + (H)^{0.866}]$	0.861	-26.473	0.167	< 0.001
M3	1 – 2	$Y = 0.287 \times (DBH^2 \times H)^{0.612}$	0.691	-1.994	0.196	< 0.001
	3 – 4	$Y = 0.069 \times (DBH^2 \times H)^{0.869}$	0.713	3.113	0.236	< 0.001
	5 – 6	$Y = 0.049 \times (DBH^2 \times H)^{0.956}$	0.849	0.123	0.212	< 0.001
	Total	$Y = 0.759 \times (DBH^2 \times H)^{0.133}$	0.732	0.101	0.231	< 0.001
M4	1 – 2	$Y = 0.478 \times (DBH \times H)^{0.749}$	0.505	4.620	0.249	= 0.003
	3 – 4	$Y = 0.076 \times (DBH \times H)^{1.206}$	0.578	8.487	0.286	< 0.001
	5 – 6	$Y = 0.037 \times (DBH \times H)^{1.436}$	0.736	7.936	0.280	< 0.001
	Total	$Y = 0.158 \times (DBH \times H)^{1.034}$	0.597	17.193	0.283	< 0.001
M5	1 – 2	$Y = 0.869 \times (DBH \times H^2)^{0.384}$	0.335	8.753	0.288	= 0.017
	3 – 4	$Y = 0.117 \times (DBH \times H^2)^{0.694}$	0.423	12.882	0.334	= 0.007
	5 – 6	$Y = 0.043 \times (DBH \times H^2)^{0.885}$	0.569	14.810	0.358	= 0.001
	Total	$Y = 0.253 \times (DBH \times H^2)^{0.580}$	0.443	30.778	0.333	< 0.001
M6	1 – 2	$Y = 0.869 \times (H)^{0.384}$	0.335	8.753	0.288	= 0.017
	3 – 4	$Y = 0.499 \times (H)^{1.267}$	0.146	18.366	0.406	= 0.098
	5 – 6	$Y = 0.227 \times (H)^{1.567}$	0.193	23.593	0.489	= 0.065
	Total	$Y = 0.938 \times (H)^{1.014}$	0.183	46.841	0.403	= 0.003

M = model, Y = Aboveground biomass, DBH = diameter at breast height, H = height, adj.R^2 = Adjusted coefficient of determination, AIC = Akaike Information Criterion, and RSE = Residual standard error.

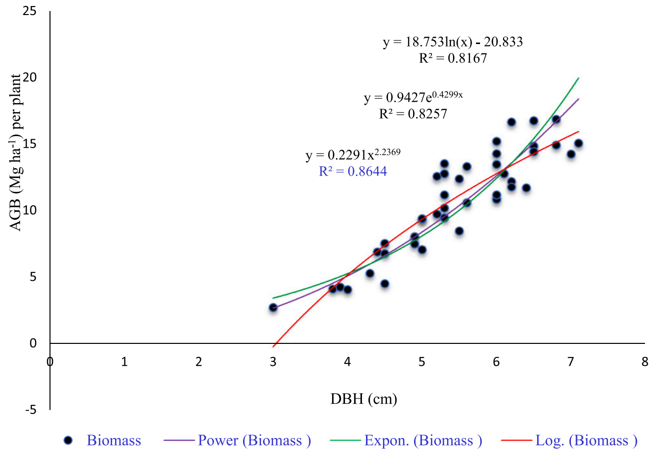

Fig. 3. Models showing the relationship between AGB and DBH (X = DBH in cm and Y = AGB in Mg ha^{-1}).

4. Discussion

4.1. Culm density and stand structure of Oldeania alpina forests

The *O. alpina* forest sampled in the study area has a density of 19,343 culms ha^{-1}. A much lower density of 4374 culms ha^{-1} was recorded for *Oxytenanthera abyssinica* from Cameroon (Nfornkah et al., 2021a, 2021b), and 6267 culms ha^{-1} was reported for the same bamboo species from Ghana (Amoah et al., 2020), while 8840 culms ha^{-1} has been reported for highland bamboo (*O. alpina*) from Ethiopia (Embaye et al., 2005). Comparable densities of 20,467 culms ha^{-1}have been reported by Mulatu and Fetene (2013) and 20,748 culms ha^{-1} (Nigatu et al., 2020) for *O. alpina* from Ethiopia. The higher stand density found in the Sheka Biosphere Reserve can be attributed to the absence of harvesting. Old (5 – 6-year-old) and matured (3 – 4-year-old) culms comprised most (82 %) of the stand density. Another factor influencing bamboo stand density is species variation. Harvesting mature culms stimulates shoot production, the emergence of young shoots, and the growth of rhizomes and roots (Amoah et al., 2020; Inoue et al., 2018a, 2018b; Singnar et al., 2017). Likewise, other studies (for example, Inoue et al., 2018; Xu et al., 2018; Yen, 2015) recommend that to maintain the vigour of bamboo forests, one-fifth of older culms from the entire stand should be harvested selectively every year, as this improves sprouting. Mature and old culms should therefore be harvested to promote shoot production and enhance the productivity of the bamboo forest.

We found that the youngest (1 – 2-year-old) culms had the highest DBH (5.9 ± 0.24). As the age of bamboo culm increased, DBH tends to decreased. This is because young bamboos have a much higher water and starch content that supports the rapid growth rate of young shoots in the first years. This water and starch content declines with age. The increase in silica deposits with culm age decreases the water and starch content, increasing the strength of the culm.

4.2. Biomass and carbon storage potential of Oldeania alpina forests

Aboveground biomass distribution varied among bamboo plant components. Culms contributed the highest proportion of the aboveground biomass. Previous studies have also reported a greater proportion (> 60 %) of biomass allocated to bamboo culms (Amoah et al., 2020; Singnar et al., 2017; Sohel et al., 2015; Yen, 2015; Yen and Lee, 2011; Zhang et al., 2014; Zhuang et al., 2015).

We estimated that 64.0 Mg ha^{-1} AGB was stored in *O. alpina* bamboo forests. In comparision, lower values 4.2 Mg ha^{-1} AGB from Ghana (Amoah et al., 2020). Alower value 28 Mg ha^{-1} ABG has also been reported from Cameroon (Nfornkah et al., 2021a, 2021b), with both the Ghana and Cameroon values being for *Oxytenanthera abyssinica*. In contrast, our value is much lower than the reported values of 100 Mg ha^{-1} AGB (Wimbush, 1947), 110 Mg ha^{-1} (Embaye et al., 2005), 99 Mg ha^{-1} (Mulatu & Fetene, 2013) and 108 Mg ha^{-1} (Nigatu

Table 4
Model internal validation between observed and predicted biomass of *Oldeania alpina*.

Paired Test	Age (year)	Mean of Predicted AGB (Mg ha^{-1})	MRE (%)	RMSE (Mg ha^{-1})	t-value	p-value
Observed – M1	1 – 2	21.66	0.01	0.258	0.143	0.889
Observed – M1	3 – 4	22.57	0.29	0.452	0.189	0.853
Observed – M1	5 – 6	20.11	1.27	0.444	-7.344	< 0.001
Observed – M1	Total	63.57	0.03	0.866	0.316	0.754
Observed – M2	1 – 2	33.86	4.12	2.160	-10.77	< 0.001
Observed – M2	3 – 4	55.00	10.92	5.722	- 8.58	< 0.001
Observed – M2	5 – 6	23.72	1.60	4.743	-9.124	< 0.001
Observed – M2	Total	101.97	1.54	4.188	-13.65	< 0.001

Table 5
Model validation for prediction of biomass of different bamboo species at age level.

Source	Species specific	Model	adj.R^2	Age (year)	MRE (%)	RMSE (Mg ha^{-1})	t-value	p-value
Present study (M1)	*Oldeania alpina*	$Y = 0.259 \times (DBH)^{2.098}$	0.925	1 – 2	0.010	0.258	0.143	= 0.889
		$Y = 0.139 \times (DBH)^{2.577}$	0.856	3 – 4	0.294	0.452	0.189	= 0.853
		$Y = 0.165 \times (DBH)^{2.487}$	0.922	5 – 6	1.267	0.444	-7.344	< 0.001
Mulatu and Fetene (2013)	*Oldeania alpina*	$Y = \exp(0.172 \times DBH)$	0.870	1 – 2	-5.204	2.726	11.030	< 0.001
		$Y = \exp(0.289 \times DBH)$	0.870	3 – 4	-3.692	1.934	7.817	< 0.001
		$Y = \exp(0.30 \times DBH)$	0.990	5 – 6	-3.358	1.759	6.076	< 0.001
Amoah et al. (2019)	*Bambusa vulgaris*	$Y = 0.763 \times (DBH)^{1.84}$	0.971	1 – 2	6.267	3.282	-13.740	< 0.001
		$Y = 0.291 \times (DBH)^{2.26}$	0.926	3 – 4	2.018	1.093	-5.765	< 0.001
		$Y = 0.061 \times (DBH)^{2.883}$	0.955	5 – 6	-2.096	1.097	6.134	< 0.001
Amoah et al. (2019)	*Oxytenanthera abyssinica*	$Y = 2.632 \times (DBH)^{1.881}$	0.955	1 – 2	42.553	22.291	-13.600	< 0.001
		$Y = 1.910 \times (DBH)^{2.410}$	0.855	3 – 4	70.118	36.730	-10.460	< 0.001
		$Y = 2.304 \times (DBH)^{2.233}$	0.919	5 – 6	59.731	31.289	-9.373	< 0.001

et al., 2020), from Ethiopia for the same species (*O. alpina*). The location of the bamboo stand within the Sheka biosphere reserve means that it has not been managed or harvested since the establishment of the reserve, enabling the presence of old culms ($>$ 5 years old). As a result, the productivity of the bamboo culms has decreased. Furthermore, it was learned from senior bamboo experts that the bamboo forests in the Masha district experienced mass flowering and mass death of flowered forests after seeding. This implies that the bamboo forest in the study area is in the process of regeneration. The total aboveground biomass that we found was comparable with the values of 47.4 – 58.7 Mg ha^{-1} for Moso bamboo (*Phyllostachys pubescens*) (Zhuang et al., 2015) and 71 Mg ha^{-1} for *B. vulgaris var. vitata* (Amoah et al., 2020).

The *O. alpina* bamboo forests of the study area had accumulated 64.0 Mg ha^{-1} aboveground biomass and were storing 30.0 Mg C ha^{-1} in their aboveground biomass. According to the recent resource assessment report by Zhao et al. (2018), in Southern Nations, Nationalities, and Peoples regional state of Ethiopia, *O. alpina* bamboo forests cover 4856 ha. Hence, the total bamboo forests of the region could accumulate about 146,086 Mg C and sequester 536,071 tons of CO_2 eq. in their aboveground biomass.

4.3. Allometric model for the prediction of aboveground biomass of Oldeania alpina bamboo forest

Species-specific allometric models were formulated, and the relationship between the AGB and dendrometric variables such as DBH and H of culms were examined for *O. alpina* bamboo forest. The models related AGB against predictors in the power function, which was the best in terms of goodness of fit. Amoah et al. (2020); Huy et al. (2019); Singnar et al. (2017); and Yen (2016) have all argued that the power model produced the best goodness of fit and the lowest values of statistical errors. Compared to height, diameter is a more reliable predictor because it can be measured more precisely (Brahma et al., 2021). The relationship between DBH and AGB demonstrated a high coefficient of determination. This indicates that the diameter of the culm accounts for most of the biomass variation observed. So far, several biomass equations have been formulated relating bamboo biomass to the diameter and these perform well.

Cross-validation is crucial for an evaluation of the accuracy and reliability of the models for estimating biomass. In our study, crossed validated with RMSE, Model 1 was the best fit model with a value of 0.258, indicating a realistic biomass estimation when using the model. The residual standard errors of the selected model remained lower than the reference level (RSE < 0.25) (Sileshi, 2014), while the total variation explained by the coefficient of determination (adj.R^2) was above 0.86, comparing favourably to the recommended value of 0.85 (UNFCCC, 2011).

5. Conclusion

Species-specific allometric models were formulated for *Oldeania alpina* bamboo forest. The relationship between total aboveground biomass and dendrometric variables, diameter and height, were examined individually and in combination. Compared with height, the diameter was a more reliable predictor. We conclude that using DBH alone (model 1) as a predictor variable outperforms height alone or a combination of height and DBH, with a higher coefficient of determination (adj. R^2), lower residual standard error (RSE), and low Akaike information criterion (AIC) values. Crossed validating with RMSE, Model 1 was the best fit model with a value of 0.258. Thus, the model can be considered to be statistically reliable and suitable for estimating the biomass storage and carbon stock potential of *O. alpina* bamboo forests in Ethiopia.

In general, in a milieu where there is limited knowledge about the carbon sequestration potential of bamboo forests, this study should provide bamboo growers, policymakers, and professionals with useful information about the carbon storage potential of bamboo, paving the way for the sustainable management of bamboo forests in Ethiopia.

Funding

This study was financially supported by International Bamboo and Rattan Organization (INBAR) under the Dutch Sino East Africa Bamboo Development Programme, and CIFOR-FTA.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bamboo.2022.100008.

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