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Fighting climate change with bamboo in Africa: The case of Kyela, Rungwe and Mufindi districts – Tanzania

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Abstract

Responding to the African Forest Landscape Restoration Initiative (AFR100), 32 countries have committed to restoring more than 100 million hectares of land across Africa by 2030. Bamboo is being discussed as one of the nature-based solutions to achieve this ambitious target in the face of climate change. Major advantages are that it is a fast-growing versatile woody grass that can prosper in degraded lands. So far, landscape restoration strategies are driven by climate policy debates where bamboo is largely neglected. Most empirical research on the potential of bamboo for fighting climate change has been conducted in Asia, leaving open questions on the transferability of results to the African context. In this paper, we contribute to the debate by investigating how bamboo can contribute to climate change

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mitigation, especially in degraded ecosystems. Taking Tanzania as an example, we lay a special focus on bamboo carbon sequestration and storage potential and assess the dynamics of carbon stocks: (i) across an elevation gradient, (ii) between indigenous and exotic bamboo species, and (iii) between intensively and extensively managed bamboo ecosystems. We collected data from 60 destructive sample plots and estimated biomass carbon stocks in the aboveground carbon pool. The weighted average biomass, carbon stocks, and sequestration rates obtained were 52.4 t ha^{-1}, 26.2 t C ha^{-1}, and 19 t C $ha^{-1}yr^{-1}$, respectively. The ANOVA revealed a significant variation in carbon stocks across an elevation gradient and between bamboo species ($P < 0.05$), which explained 22% and 11% of the total variation. We also observed a significant two-way-factors interaction between elevation versus species and silvicultural management options ($P < 0.05$), explaining 12% and 5% of the total variation, respectively. Similarly, a three-way interaction between all factors was significant, accounting for 4% of the total aboveground carbon variation. Our results contribute to developing a more nuanced picture of the advantages and disadvantages of incorporating bamboo in landscape restoration efforts. The novel findings may be a first step toward unlocking future climate finance in Africa.

Keywords: Bamboo, carbon sequestration, climate change, landscape restoration, Africa, Tanzania

1. Introduction

Ambitions for forest landscape restoration (FLR) in Africa are substantial. Pledges to the country-led African Forest Landscape Restoration Initiative (AFR100) surpassed the benchmark of 100 million hectares by 128% [afr.org, as of November 22]. In many policy circles, there is a nascent discussion on the role that bamboo could play in landscape restoration and its intimately linked goals of climate change mitigation and poverty alleviation. Bamboo has the potential to contribute to FLR due to its fast growth, versatility, and ability to prosper in marginal and degraded lands (Lobovikov et al., 2009; Rebelo and Buckingham, 2015; Kuehl et al., 2013). By comparison, the duration at which the fastest-growing timber species accumulate a certain amount of carbon (i.e.,100t C ha^{-1}) is twice longer than that taken by bamboo species to accumulate the same amount (Hinkle et al., 2019). However, bamboo has not entered mainstream climate negotiations, mainly due to its classification as woody grass rather than a tree (Yuen et al., 2017). While most research on bamboo's carbon sequestration potential has been conducted in Asia (Yiping et al., 2010; Nath et al., 2015; Yuen et al., 2017), corresponding information on bamboo in Africa is rather scarce. Given the differences in climatic conditions, soil characteristics, and prevalence of bamboo species, many open questions on the transferability of the findings from the Asian to the African context remain. This study contributes to filling the knowledge gap on bamboo's carbon sequestration potential in Africa by empirically investigating bamboo's aboveground carbon stock in Tanzania.

Carbon sequestration is among the environmental benefits anticipated from the eco-restoration of degraded land using the bamboo alternative (Singh et al., 2020). Kumar et al. (2021) studied the phytoremediation of fly-ash dumped sites by bamboo afforestation. They observed a significant increase in all bamboo species' carbon sequestration rates ranging from 0.3 to 0.6 t C $ha^{-1}yr^{-1}$ per plant. Similarly, Singh et al. (2020) studied the development of bamboo diversity on degraded lands. The study reveals a significant increase in bamboo height, diameter, and stand density, suggesting an increase in biomass and carbon sequestration (Singh et al., 2020). Yuen et al. (2017) conducted a global review of woody bamboo species and found that aboveground carbon stocks range from (16 -128) t C ha^{-1} . Furthermore, a 2015 review by Nath et al. reported annual carbon sequestration rates ranging from (6 – 24) t C $ha^{-1}yr^{-1}$ for different bamboo species. Both reviews point to significant variations in carbon densities and annual sequestration rates across different bamboo species, elevation gradients, and silvicultural management options. Comparisons between bamboo species with either sympodial or monopodial root growth patterns suggest that species with sympodial growth patterns have a higher carbon storage potential (Nath et al., 2015; Yuen et al., 2017). However, an assessment of the dynamics in aboveground carbon stock by three bamboo species (*Dendrocalamus asper, Bambusa philippinensis and Schizostachyum lumampao*) in the Philippines revealed that variation in carbon storage exists even between species of the same growth pattern receiving the same silvicultural treatments (Pongon et al., 2017). Similarly, studies from Cameroon and Ghana on carbon sequestration by the same bamboo species (*Oxytenanthera abyssinica*) report substantially different results, 13.3 t C ha^{-1} (Nfornkah et al., 2020), and 1.98 t C ha^{-1} (Amoah et al., 2020). These variations suggest that factors other than species affect bamboo's carbon content. On the other hand, a study conducted in China showed that biomass accumulation in *Phyllostachys edulis* stands increased with elevation, especially from 1000-1400 meters above sea level (m asl.) (Chen et al. 2014). Although research on the relationship between bamboo biomass carbon stock and elevation is scarce, there are indications that variation mostly correlates to an individual species' adaptability to either highland or lowland (Kigomo, 2007; Mulatu and Kindu, 2010).

Other research shows that carbon stock and sequestration rates in bamboo-based ecosystems vary according to management options (Lou et al., 2010). Silvicultural management practices can increase bamboo's productivity and, thus, carbon sequestration (Lobovikov et al. 2009). Lou et al. (2010) differentiate between three management intensities applied in China, where highly intensive management is characterized by fertilization, yearly clearance of the understory, tending, thinning, and harvesting bamboo shoots. Intensive management includes yearly fertilization, tending, thinning, and harvesting shoots, while extensive management involves tending, thinning, and harvesting shoots. Intensively managed bamboo ecosystems tend to have a high storage amount of carbon in the arbour layer compared to their extensive counterpart (Lou et al., 2010). So far, most existing research in China compared carbon sequestration performance between the extensively and intensively managed ecosystems of only *Phyllostachys* species (Zhou & Jiang, 2004; Xiao et al., 2007:2009; Qi et al., 2009). Africa hosts up to 7.3% of the global bamboo species (Bahru & Ding, 2021). Of this, 89.6% are indigenous (Bahru & Ding, 2021), and five are endemic to Africa: *Oxytenanthera abyssinica, Yushania alpina, Hickelia africana, Thamnocalamus tessellatus,* and *Oreobambos buchwaldii* (Bystriakova et al., 2004). However, nearly 90% of the African bamboo species exhibit a sympodial (clumping) root growth pattern (Piazza et al., 2007; Partey et al., 2017). Tanzania has the largest diversity of bamboo species, as four of the five endemic species are native to Tanzania (Bystriakova et al. 2004). Seven more exotic bamboo species exist in Tanzania, with *Bambusa vulgaris* and *Bambusa bambos* being the most common (Lyimo et al., 2019).

In this paper, we contribute to improving the knowledge base on bamboo in Africa by presenting the results of an empirical investigation of bamboo's biomass-carbon stock in Tanzania. In particular, we investigate differences in carbon stock between indigenous and exotic species, variation across an elevation gradient, and variation between different silvicultural management options applied. Our analysis is based on a destructive assessment of aboveground bamboo carbon with samples derived from 60 plots.

2. Materials and methods

2.1. Study sites

We conducted this study in Tanzania, located between 6.3690° S and 34.8888° E in South-Eastern Africa. Tanzania has various climates: tropical along the coast, semi-arid in the central plateau, and temperate in the highlands. We assessed bamboo biomass carbon in the planted bamboo-based ecosystems of the Kyela, Rungwe, and Mufindi districts in the country's southern highlands (Figure 1). Kyela and Rungwe districts are in the Mbeya region, whereas the Mufindi district is in the Iringa region. The two outstanding features, the Eastern arc highlands, and the Mufindi plateau, topographically distinguish the Mufindi district (Nuru et al., 2014). Similarly, the Rungwe district situates on the summit of an extinct volcano, surrounded by varied topographical features, including the Rungwe volcanic mountain and Mount Livingstone escarpments (URT, 2017). On the contrary, the Kyela district lies on the lowland flood plains of Lake Nyasa at the border of Malawi. The dominant bamboo species found in these sites are *Oxytenanthera abyssinica* (syn. *Oxytenanthera braunii*), *Bambusa vulgaris* var. *vitata*, and *Yushania alpina*. The weather condition for all three sites is distinguished by three seasons:

- a hot, dry season from mid-August to the end of October
- a hot, rainy season from November to April
- a cool, dry season from May to mid-August (Mauya et al., 2014).

Detailed descriptions of the study sites' conditions are in (Table 1). The distinctive rainfall patterns in these sites are unimodal, with a single and long rainy season from November to April or May (FAO, 2016).

Table 1: Descriptions of the study sites

District	Climate	Location	Altitude (m)	Mean Annual temperature (^{0}C)		Mean annual rainfall (mm)	
				Low	High	Low	High
Kyela	Tropical	9˚29´S, 330 0´E	495 – 1700	22	29	1600	2400
Rungwe	Tropical highland	9˚15´S, 33˚40´E	770 – 2265	16	25	800	2700
Mufindi	Warm-temperate	8˚36´S, 35˚17´E	1700 -2200	15	27	1200	1400

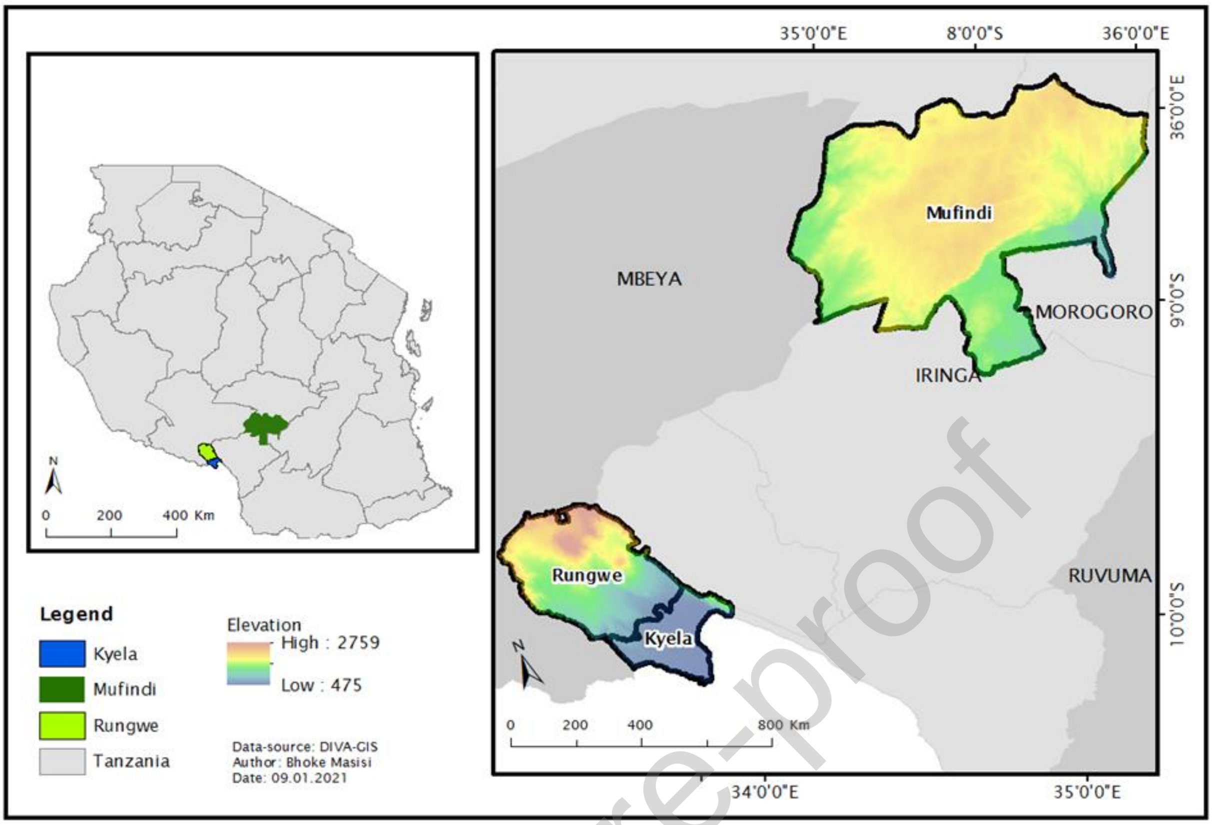

Figure 1: Location of the study sites

2.2. Sampling design and variable measurements

As mentioned in the introduction, previous literature points to three factors that impact bamboo biomass carbon stocks: species, elevation, and silvicultural management options. Considering these factors, we split our sample into 12 strata (see Table 2). Stratification was based on dividing a sample of bamboo ecosystems into subgroups by species, elevation, and management options (e.g., low elevation - extensively managed - *Bambusa vulgaris* spp.). We then randomly selected a proportional number of sample plots from each sub-group, representing their stratum. For the species, we differentiated between indigenous and exotic species (*Bambusa vulgaris* var. *vitata* versus *Oxytenanthera abyssinica*). Regarding elevation, we defined three groups for our study sites: low (< 900 m asl.), medium (900 ≤ 1900; 900 ≤ 1400 m asl.), and high (> 1900; > 1400 m asl.). Finally, we differentiated between intensive and extensive silvicultural management options. This study's context indicates intensive management is characterized by frequent weeding, thinning, and organic fertilization (rare). At the same time, the extensively managed ecosystems were not subjected to tending operations other than planting and harvesting.

Table 2: Description of the sampling design.

Elevation	Extensively managed		Intensively managed	
	O. abyssinica	*B. vulgaris*	*O. abyssinica*	*B. vulgaris*
Low	5	5	5	5
Medium	5	5	5	5
High	5	5	5	5

***** Cells represent strata; the numbers in the cells are sample sizes per stratum

For each of the 12 strata, we sampled bamboo from 5 different sites. In total, we thus derived bamboo samples from 60 different sites. At each site, we laid out a circular sampling plot of $100m^2$ (Huy and Trinh, 2019). We used a simple random sampling technique adopted from Pongon et al. (2016) to select and harvest one bamboo culm from each plot. In addition, we collected the following data:

- Diameter at Breast Height (DBH) of the destructively sampled culm, measured by a calliper at 1.3m above the ground before harvesting,
- Height of the sampled culm, measured on the ground by a measuring tape after harvesting,
- Fresh weight of the sampled culm, measured by a hanging scale,
- DBH of all non-destructively sampled culms within a plot,
- Culms' density, obtained by counting the number of standing culms per plot; and
- The age of the destructively sampled culms (<2 years, 2-4 years, and >4 years), identified based on the aerial stem features by Huy et al. (2013).

2.3. Laboratory measurements

Each of the 60 destructively sampled culms were cut and separated into three components: stems, branches, and leaves. We first measured and recorded each component's total fresh weight in the field. Then, we took subsamples of approximately 100-300g from each sampled component for further oven-dry weight measurements. Due to the probabilities of existing variation in carbon content along the stem, we took four sub-subsamples from each quarter of the stem component to ensure a fair representation. Each sub-subsample included the part of the node and internodes of the stem. All subsamples were oven-dried at 105 ^{0}C until they attained a constant weight.

2.4. Data Preparation

We obtained each component's dry matter values by multiplying the component's fresh weight by the subsample's dry-to-fresh weight ratio (Eqn. i). Moreover, we computed the total dry weight of the culm as the sum of the components' dry weights (Eqn. ii).

$$\text{Component dry weight (kg Component}^{-1}) = \frac{\text{Component fresh weigh t (kg)} \times \text{Subsample dry weight (g)}}{\text{Subsample fresh weight (g)}} \quad \text{(i)}$$

$$\text{Culm dry weights } \left(\text{kg Culm}^{-1}\right) = \sum \text{Component dry weights (kg Component}^{-1}) \quad \text{(ii)}$$

2.5. Data analysis

2.5.1. Development of biomass allometric models

To determine an allometric model (equation) for the two-bamboo species relevant to our case study, we regressed above-ground biomass (AGB), i.e. the culm dry weight, against DBH. We tested four general non-linear regression model forms: logarithmic ($AGB = b_0 + b_1 \times \ln(DBH) + \varepsilon$), exponential ($AGB = b_1 e^{(k \times DBH)} + \varepsilon$), and ($AGB = b_0 \times DBH^{b_1} + \varepsilon$), quadratic ($AGB = b_0\, DBH^2 + b_1 DBH + k + \varepsilon$), with b_0, b_1 and k being parameter estimates and ε is the error term. We assessed the models' performance based on graphical analyses of the scatter plots and considered the R^2 - value as the goodness of fit statistic. Furthermore, we assessed the applicability of allometric models from other regions to our case study by applying four equations from the literature to our data. The rationale was to test whether species and site differences can affect bamboo biomass prediction.

2.5.2. Estimation of biomass, carbon stock and sequestration rate

Using the best fit allometric equation, we estimated the biomass of each non-destructively sampled culm. We then summed their estimated biomass and computed the aboveground biomass density (t ha $^{-1}$). We multiplied biomass density by a 50% biomass to carbon conversion factor to obtain the total Above Ground Carbon (AGC) (Penman et al., 2003). Next, we computed an estimate of the annual carbon sequestration rate by dividing aboveground carbon by the age of bamboo culms (Yen and Lee, 2011). Finally, we ran an ANOVA with a subsequent Tukey's HSD test to investigate whether carbon stock varied across different bamboo species, elevation gradients, and silvicultural management options and tested for interaction effects.

3. Results

3.1. Biomass allometric models

Of the four different model specifications, the quadratic function revealed the best fit for the data on *B.vulgaris* (see Figure 2, iii) and the data on *O.abyssinica* (see Figure 2, iv). The corresponding allometric equations that establish the relationship between AGB and the culm's DBH (cm) are presented in Eqn. (iii) for *B.vulgaris* and in Eqn. (iv) for *O.abyssinica* . Culm DBH explained 77.2% of the variation in AGB for *B. Vulgaris* and 77.6% for *O.abyssinica* ($P < 0.0001$).

$$AGB = 0.23296DBH^2 - 0.07558DBH - 0.438 \ldots\ldots\text{(iii)}$$

$$AGB = -0.1091DBH^2 + 4.481DBH - 10.3 \ldots\ldots\ldots \text{(iv)}$$

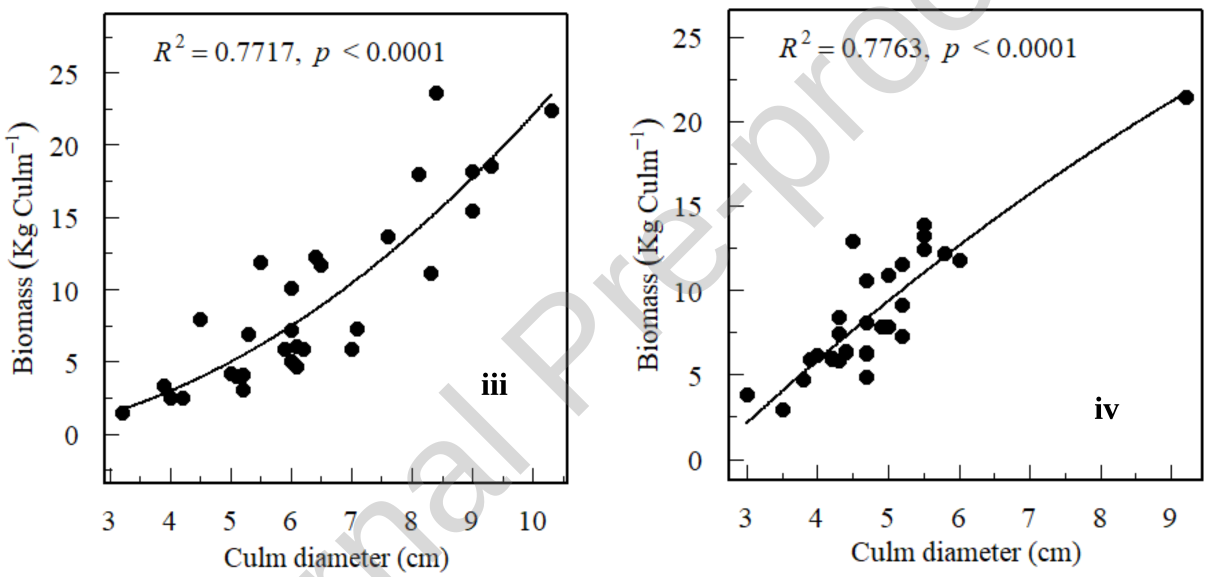

Figure 2: DBH – biomass relationship of the selected 2 nonlinear best-fit equations (iii) and (iv) for *B.vulgaris*, and *O.abyssinica*, respectively.

When applied to our modelling data, allometric models by Huy et al. (2019) and Nath et al. (2009) overestimated biomass values of *B.vulgaris* above 4 cm DBH (Figure 3). In contrast, the equations by Darcha and Birhane (2015) and Gurmessa et al. (2016) underestimated biomass values for *O. abyssinica* species (Figure 3). Similarly, a generalized equation that was developed using the data of both species in this study overestimated biomass on small diameter culms of *B. vulgaris* while underestimating biomass of *O. abyssinica.*

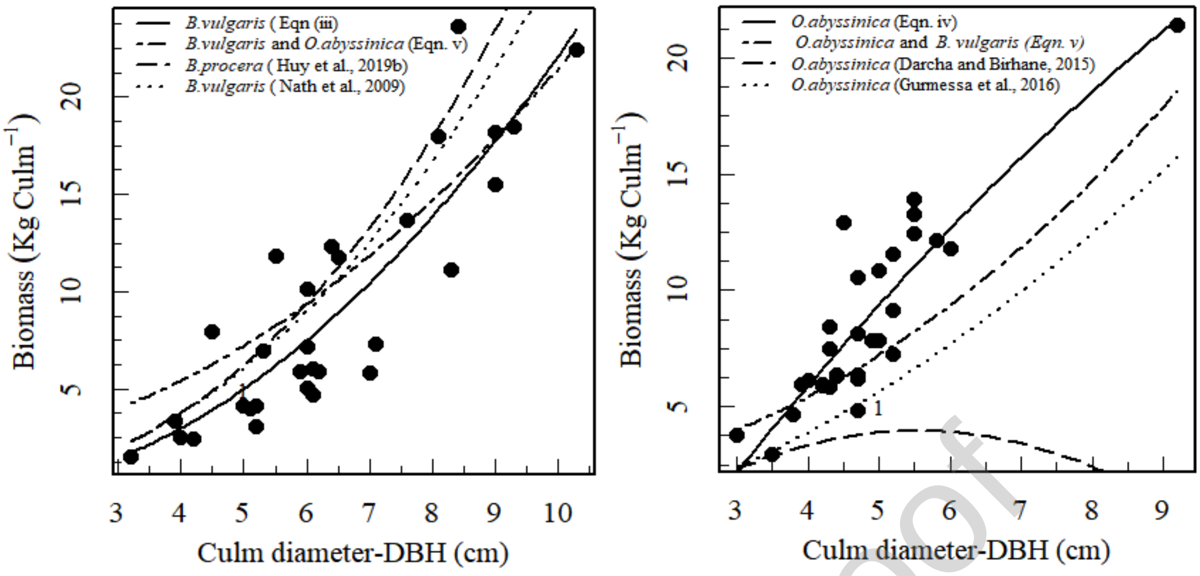

Figure 3: Comparison of generalized and species-specific equations for *Bambusa vulgaris* and *Oxytenanthera abyssinica* (Eqns. iii, iv and v were developed using this study's data)

3.2. Bamboo biomass, carbon stock and sequestration rate

The overall mean bamboo biomass, carbon stock, and sequestration rate obtained in this study were 52.4 t ha^{-1}, 26.2 t C ha^{-1}, and 19 t C ha^{-1}yr^{-1}, respectively (Table 3). The minimum and maximum aboveground carbon stock distributions were 0.06 and 1.17 t plot^{-1}, equivalent to 6 and 117.3 t ha^{-1}, respectively (Figure 4). Results show that bamboo aboveground carbon stocks and annual sequestration rates per hectare decreased with increased culms' age (Table 3). The observed carbon stock and sequestration rates in younger bamboo culms (i.e., less than two years) and matured culms (above four years) were: 30.2 t C ha^{-1}, 19.8 t C ha^{-1}yr^{-1}; and 22.3 t C ha^{-1}, 14.6 t C ha^{-1}yr^{-1}, respectively (Table 3). The percentage of aboveground carbon contribution by individual components of bamboo culms depicted an average of 68% contribution by a stem component followed by branches (17.3%) and leaves (15%). Bamboo branches and leaves showed almost similar annual carbon sequestration capacity in young and medium age culms ranging from (3.6-3.8) t C ha^{-1}yr^{-1}. However, both the leaves and branches of the matured culms showed the relatively lowest carbon sequestration rates of 1.3 t C ha^{-1} yr^{-1} and 2.4 t C ha^{-1}yr^{-1}, respectively (Table 3). Furthermore, the average bamboo aboveground carbon stock for the three study sites, Kyela, Mufindi and Rungwe, was 41.2 t C ha^{-1}, 21.6 t C ha^{-1} and 13.7 t C ha^{-1}, respectively (Figure 4).

Table: 3 Distribution of aboveground biomass, carbon stock and sequestration rate of individual bamboo components across age classes

Age class	Biomass (t ha $^{-1}$)	Carbon (t C ha $^{-1}$)	Biomass C sequestration rate (t C ha^{-1} year^{-1})	Percentage Carbon contribution	Culm density (Culms ha $^{-1}$)
I (≤ 2 years)					
Stem	39.7	19.9	14.4	66%	
Branches	10.0	5.0	3.6	17%	
Leaves	10.6	5.3	3.8	18%	
Total	60.3	30.2	21.8	100%	4947
II- (>2-4 years)					
Stem	36.3	18.2	13.3	63%	
Branches	10.6	5.3	3.8	18%	
Leaves	10.6	5.3	3.8	18%	
Total	57.5	28.8	20.9	100%	909
III- (> 4 years)					
Stem	29.3	14.65	10.6	74%	
Branches	6.7	3.35	2.4	17%	
Leaves	3.5	1.75	1.3	9%	
Total	39.5	19.8	14.3	100%	202
Mean	**52.4**	**26.2**	**19.0**	**100%**	**6057**

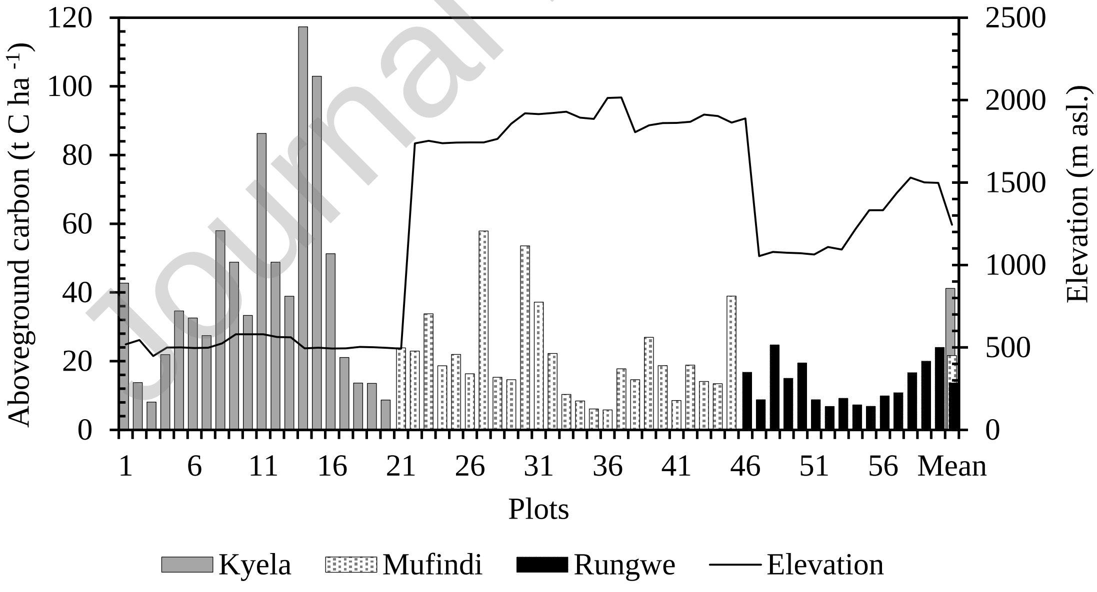

Figure 4: Bamboo aboveground carbon distribution among the three study sites

3.2.1. Variation in carbon stock for studied bamboo variables

The ANOVA revealed significant variation in bamboo aboveground carbon content within two independent variables (factors): species and elevation ($P < 0.05$; Table 4). However, the variation in aboveground carbon content with silvicultural management options applied was insignificant (P > 0.05; Table 4). Of the three factors, elevation was the most significant source of variation, explaining 22% of the total variation, followed by species (11%) and the silvicultural management options 2% (Table 5). The ANOVA further depicted a significant two-way and three-way factors interaction between independent variables. Aboveground carbon stock across an elevation gradient depends on species and silvicultural management options. The two interactions account for 12% and 5% of the total variation, respectively (P < 0.05; Table 4). The ANOVA was also significant in a three-way interaction of all the factors (P < 0.05), explaining 4% of total aboveground carbon variation. However, there was no interaction effect of the ecosystem silvicultural management options on either type of the two-bamboo species (P > 0.05). The data for ANOVA is in the upper part of Table (4).

Table 4: Summarized results of ANOVA and Tukey's HSD test of pairwise comparisons of carbon stocks for studied bamboo variables

ANOVA					
Source of variation	Df	MSE	F	P-Value	Var %
Species	1	222.2	16.2	0.0002**	11
Management option	1	222.2	3.3	0.0747^{ns}	2
Elevation	2	222.2	15.69	5.7E-05**	22
Elevation × Management option	2	222.2	4.644	0.01434**	5
Elevation × Species	2	222.2	9.07	0.00045**	12
Species × Management option	1	222.2	1.736	0.19384^{ns}	1
Elevation × Species × Management	2	222.2	3.4308	0.04049**	4

Tukey's HSD (Honest Significant Difference)				
	Mean differences	q	Significant (P <0.05)?	95% CI of differences
B. Vulgaris vs. *O. abyssinica*	15.5	2.84	0.0002**	7.76 to 23.2
Intensive vs. Extensive	-7.01	2.84	0.0747^{ns}	-14.8 to 0.7
Low vs. High	20.2	3.4	0.00024**	8.8 to 31.6
Medium vs. High	-4.5	3.4	0.5995^{ns}	-15 to 6.8
Medium vs. Low	-24.8	3.4	9.7E-06**	-36.2 to -13.4

MSE is the Mean Square Error; df are the degrees of freedom; q is the Studentized range; P** < 0.05 (significant), P^{ns} is non-significant (P > 0.05), and Var is the proportion of variance explained.

This study's mean elevation was 1127m asl. The minimum and maximum elevations were 448 and 2016 m asl., respectively. Across an elevation gradient, the lower elevation contributed the highest aboveground carbon stock (41.2 t C ha^{-1}), followed by the high elevation (21 t C ha^{-1}), while the medium elevation was the least (16.4 t ha^{-1}) (Table 5). Of the two species, observations showed more aboveground carbon stored in the indigenous *O.abyssinica* (34 t Cha^{-1}) than in the exotic *B.vulgaris* (18.4 t C ha^{-1}). Although non-significant, the extensively managed bamboo ecosystems depicted high biomass carbon storage (29.7 t C ha^{-1}) relative to the intensively managed counterparts (22.7 t C ha^{-1}; Table 5).

Table 5: Mean aboveground carbon stock for the studied bamboo ecosystems' variables.

	Intensively managed		Extensively managed		
Elevation	*B. vulgaris*	*O. abyssinica*	*B. vulgaris*	*O. abyssinica*	Mean
Low	19.2	39.9	24.9	80.7	41.2
Medium	7.8	22.9	17.0	17.8	16.4
High	25.3	20.8	16.3	21.4	20.9
Mean	17.5	27.9	19.4	40.0	26.2

4. Discussion

Our overall objective was to compute aboveground carbon stocks in planted bamboo ecosystems and assess carbon dynamics with different factors such as elevation, species and silvicultural management options.

4.1.Allometric models

Our data revealed a curvilinear DBH-biomass relationship. Graphical analyses showed that models selected in this study (Eqn. iii and iv) are more appropriate for estimating biomass than those transferred from other regions. A comparison between different allometric models showed under and overestimating biomass values by models from other regions and species-generalized models. This pattern provides insight into the unreliability of predicting bamboo biomass with models from different species and regions. Furthermore, such variation may be attributable to differences in DBH classes of sampled data sets as a function of climate and other environmental conditions. We, therefore, recommend using both species- and site-specific allometric models to predict bamboo biomass. Otherwise, one should pre-investigate whether the modelling data of a given equation are within the range of the data to be studied.

4.2. Bamboo biomass, carbon stock and sequestration rate

Our results highlighted the potential of bamboo to sequester and store aboveground carbon in planted bamboo ecosystems. However, the extent to which we realized this potential depends on the species type, elevation, and the applied silvicultural management options. These dynamic aspects of bamboo's carbon content determine the ecosystem's reliability for investment, provided carbon sequestration is concerned (i.e., carbon farming). Results show that the aboveground carbon stock decreased with an increase in the age of bamboo culms, a similar pattern as observed by Amoah et al. (2020) and Darcha & Birhane (2015). These observations complement a report by Yen (2016) that 75% of bamboo biomass and carbon accumulation occurs in the initial 40 days of the entire yield period. A potential explanation for the decrease in carbon stock per hectare with age is that the decrease in the density of culms outweighs the incremental increase of carbon sequestration per culm as the bamboo matures.

The average carbon stock estimated in this study (26 t C ha^{-1}), range (19.8 – 30.2) t C ha^{-1} is higher than the values obtained from most planted land cover types of Tanzania, such as plantation forests (20 t C ha^{-1}) and agroforestry (4 t C ha^{-1}) (Mauya et al., 2019). However, the current carbon stock is lower than the reported 62 t C ha^{-1} and 43.7 t C ha^{-1} for Tanzania's humid montane and lowland forests (Mauya et al., 2019). That is to say, it could take approximately one, three, and four years for a typical bamboo forest to attain the same amount of carbon stocking as Tanzania's plantation, lowland, and humid montane forests, respectively. Furthermore, the annual carbon sequestration rate obtained in this study (av. 19 t C $ha^{-1}yr^{-1}$) lies within the range of (6-24) t C $ha^{-1}yr^{-1}$ for woody bamboo species earlier reported by Nath et al. (2015). However, the sequestration rates presented here for each species are higher than those reported by Amoah et al. (2020) in Ghana for *O.abyssinica* (5.65 t $ha^{-1}yr^{-1}$) and *B.vulgaris* (0.33 t $ha^{-1}yr^{-1}$). Variations in aboveground carbon stock between these studies might be affected by the differences in the sampled culms' DBH, land use, elevation, climate and other site conditions.

4.2.1. Variation in bamboo carbon stock

We compared aboveground carbon stock in the three elevation ranges, namely low, medium, and high elevations. Our results showed that aboveground biomass in lower elevations was superior to others. These findings complement previous studies that reported the best performance of *O.abyssinica* and *B.vulgaris* in lowlands, often below 1750 m asl. (Zhao et al., 2018) and 1200 m asl. (Kigomo, 2017), respectively. This phenomenon explains why our sampling design assigned different elevation limits in medium and higher elevations, as the existence of *B.vulgaris* was limited in elevations above 1700 m asl. We further observed that culms' dimensions were decreasing from a lower to a higher elevation, a phenomenon that has also been found in a previous study (Kigomo, 2007). These findings indicate that the lower elevation is suitable for accumulating carbon biomass in both species. Despite our results showing an existing aboveground carbon variation across an elevation gradient, this variation is species dependent. On average, *O.abyssinica* stores higher amounts of aboveground carbon across elevation gradients than *B.vulgaris*. Although they are both lowland bamboo species, each species showed a different elevation limit of existence and carbon storage. Therefore, we suggest that the optimal elevation for carbon sequestration and storage is below 1800 and 1400 m asl. for *O.abyssinica* and *B.vulgaris,* respectively.

We further compared aboveground carbon stocks between the indigenous (*O.abyssinica*) and exotic (*B.vulgaris*) species and found that *O.abyssinica* stores a significantly higher amount of carbon than *B.vulgaris*. These results contradict studies from Ethiopia, Ghana, and Cameroon that earlier reported bamboo aboveground carbon stock ranging between (1.98-13.1) t C ha^{-1} for *O. abyssinica* and (29.5-33.9) t C ha^{-1} for *B. vulgaris* (Darcha & Birhane, 2015; Amoah et al., 2020; Nfornkah et al., 2020). Similarly, the relative percentage variation explained in this study (11%) is lower than that obtained by Amoah et al. (2020) (49%) for the same species. The observed differences between the two studies could be due to the differences in environmental conditions that caused heterogeneity of the sampled datasets, as DBH affects the biomass carbon stock (Chenge, 2021). Furthermore, the differences in carbon estimates between species could also be due to differences in culm morphology. Typically, bamboo culms have hollow internodes, but the degree of hollowness varies between species. According to Wahab et al. (2010), the culm wall thickness varies between bamboo species and within a single bamboo culm from the base to the top. The average wall thickness of *B. vulgaris* varies between 14, 8, and 5 mm at the base, middle, and top of the culm. Comparably, the *O.abyssinica* culm wall thickness varies from solid (without hole) at the base to 13 and 9 mm at the middle and top parts (Wahab et al., 2010). These variations in culm wall thickness explain why *B.vulgaris* weighs low carbon estimates despite having large DBH values than *O.abyssinica*. In addition, the comparatively high density of culms per hectare in *O.abyssinica* ecosystems may be another factor contributing to such a difference, as previously explained by Wassihun et al. (2019). Although our results suggest that elevation affects each species' aboveground carbon stock, *O.abyssinica* outperformed *B.vulgaris* across an elevation gradient. Therefore, if carbon sequestration is concerned, *O.abyssinica* is the most recommended investment in carbon farming to achieve high land-use efficiency. Furthermore, *O. abyssinica* can help rural livelihoods adapt to the impacts of climate change by generating income from the sales of bamboo wine (Haule, 2015). The latter is in line with Murdiyarso (2005), who emphasises that "climate-related projects should in one way or another be developed to have practical relevance for livelihoods with a broad range of options depending on the local needs".

Silvicultural management options had no significant impact on bamboo aboveground carbon stocks. These findings contradict other studies that observed a significant aboveground carbon variation with varied ecosystem management options (Zhou & Jiang, 2004; Zhou et al., 2006b; Xiao et al., 2007; Xiao et al., 2009; Qi et al., 2009). One of the factors leading to contrasting results is the heterogeneity of management practices and their degree of application between regions or plantations. As described earlier, the degree of intensification in our study is minimal compared to other regions. In contrast to the level of intensification described here, intensive management of bamboo plantations in China includes, among others, annual fertilizer applications (INBAR, 2009). Zhou et al. (2006) find that an intensively managed *Phyllostachys pubescens* plantation in China sequesters approximately 1.6 times more carbon than an extensively managed one. These findings contradict our observations, which showed that carbon sequestration was approximately 1.3 times higher in the extensively managed ecosystem than in the extensively managed counterpart. The first possible reason for this observation could be the high frequency of weeding and litter raking observed in our study's intensively managed ecosystems, especially in *O. abyssinica* species. According to bamboo winemakers, extreme weed control in *O. abyssinica* ecosystems is essential for such species' enormous wine production. These observations suggest that intensive management in our study removes natural fertilizers without replacing them with artificial supplements resulting in insufficient soil nutrients, a well-known aspect already described by Christanty (1996). Second, the non-significantly high carbon content observed in extensively managed ecosystems is due to the high number of culms per hectare compared to intensively managed ones. Similarly, variation in culm density results from the high thinning intensity in intensively managed ecosystems for the same reasons for wine production. However, if well managed, a subsequent low stand density might increase the culms' size, eventually increasing its biomass carbon stock (Schaedel et al., 2017). Furthermore, our results depicted a significant three-factor interaction between variables. This interaction suggests that each bamboo species responds differently to silvicultural management practices at a specified elevation gradient, provided all other factors are kept constant. Our results reveal how bamboo can sequester a considerable amount of carbon even on plantations with minimal silvicultural management operations. Given the prevalence of climate change impact, these observations explain why we should consider bamboo for landscape restoration in Africa.

Apart from the three studied factors, we also observed bamboo aboveground carbon variation between the study sites. This variation indicates that geographic location as a function of climate and other site conditions affects bamboo carbon storage (Dwivedi et al., 2019). Of the three sites, the Kyela district had the highest aboveground carbon stock, almost twice and two-thirds that of the Mufindi and Rungwe districts, respectively. Previous studies found that suitable agroclimatic conditions for lowland bamboo are warm temperatures, mainly between 15 ºC and 35 ºC, and rainfall above 500 mm per year (Battisti et al., 2019; Tanga et al., 2022). These results are comparable to the climatic information described for our study sites (Table 1), suggesting that climate is not a limiting factor for carbon storage in this study. Another site condition that could affect bamboo carbon storage is soil. The three sites studied have different soil characteristics, ranging from volcanic soils in Rungwe to alluvial soils in Kyela to clay loam soils in Mufindi (URT, 2019; Mteta et al., 2022). Literature shows that *B.vulgaris* and *O. abyssinica* thrive in a wide range of soils and moisture conditions, preferring alluvial soils and well-drained sandy and loamy soils (Durai & Long, 2019). However, these species, like many other bamboo species, are tolerant to various soils, including poor and marginal soils (Durai & Long, 2019). Therefore, in this case, soils were not a limiting factor either.

5. Conclusion

Our assessment has provided an overview of bamboo's potential for carbon sequestration and contributing to fighting climate change in Africa. Current findings suggest that bamboo can produce a tradable amount of carbon under carbon offsetting schemes and serve as an effective strategy for forest landscape restoration opportunities. However, for efficient land use, factors that may affect bamboo's biomass carbon accumulation should be considered, including species type, elevation, and silvicultural management regimes. While the selection of these three factors in this study was based on the existing literature, we propose to expand future research on further factors that potentially could impact carbon accumulation, e.g. rainfall, light conditions and industrial processes. Despite its overwhelming potential in sequestering carbon, bamboo utilization in climate change initiatives is still shaped by its taxonomy. Based on these conclusions, countries should consider incorporating a bamboo alternative as a resilient strategy for fighting climate change in their sustainable development plans. This should include upgrading and promoting bamboo resources' status by declaring them equivalent to trees under national forest definitions. This paper revealed that bamboo could more quickly sequester carbon than trees in plantation forestry and can help achieve targets under global and regional commitments such as the Paris Agreement and AFR100. Bamboo could help prevent deforestation, restore degraded lands, and act as an effective carbon sink in Africa. Fortunately, bamboo's significance in providing synergies between adaptation and mitigation strategies aligns well with the objectives of many initiatives such as the REDD+, Forest Landscape Restorations (FLR), and Nature-based Solutions (NBS). As the body of evidence on bamboo’s carbon sequestration potential grows, we expect bamboo to gain recognition as an effective and resilient alternative for climate change mitigation and adaptation in landscapes of the south.

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7. Conflict of Interests

The authors declare no conflict of interest concerning finances, authorship or publication.

8. Data Availability

Datasets related to this article can be found at https://doi.org/10.5281/zenodo.7024827, an open-source online data repository hosted at Zenodo Data sets (Masisi, 2022).

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Appendix A: Culms used in development of DBH-Biomass equation for *Bambusa vulgaris*

Culm No.	Plot number	Species name	DBH (cm)	AGB (kg $Culm^{-1}$)
1	2	*Bambusa vulgaris*	5.5	11.85178
2	4	*Bambusa vulgaris*	9	18.167667
3	5	*Bambusa vulgaris*	6	10.128378
4	6	*Bambusa vulgaris*	8.1	17.993565
5	7	*Bambusa vulgaris*	6	5.08025
6	10	*Bambusa vulgaris*	8.4	23.64393
7	17	*Bambusa vulgaris*	5.3	6.936036
8	18	*Bambusa vulgaris*	7.6	13.697708
9	19	*Bambusa vulgaris*	6.4	12.289486
10	20	*Bambusa vulgaris*	4.5	7.917027
11	27	*Bambusa vulgaris*	3.9	3.365435
12	35	*Bambusa vulgaris*	4	2.493673
13	36	*Bambusa vulgaris*	5.1	3.970458
14	37	*Bambusa vulgaris*	3.2	1.514091
15	45	*Bambusa vulgaris*	6.1	4.670906
16	46	*Bambusa vulgaris*	6.1	6.03867
17	47	*Bambusa vulgaris*	5.2	4.09804
18	48	*Bambusa vulgaris*	10.3	22.399808
19	49	*Bambusa vulgaris*	9.3	18.500719
20	50	*Bambusa vulgaris*	7.1	7.283144
21	51	*Bambusa vulgaris*	5.2	3.050383
22	52	*Bambusa vulgaris*	6.5	11.733416
23	53	*Bambusa vulgaris*	5.9	5.919933
24	54	*Bambusa vulgaris*	7	5.854981
25	55	*Bambusa vulgaris*	6	7.166771
26	56	*Bambusa vulgaris*	8.3	11.103989
27	57	*Bambusa vulgaris*	5	4.148789
28	58	*Bambusa vulgaris*	9	15.491009
29	59	*Bambusa vulgaris*	4.2	2.470527
30	60	*Bambusa vulgaris*	6.2	5.894066

Appendix B: Culms used in development of DBH-Biomass equation for *Oxytenanthera abyssinica*.

Culm No.	Plot number	Species name	DBH (cm)	AGB (kg $Culm^{-1}$)

1	1	*Oxytenanthera abyssinica*	5.5	13.905355
2	3	*Oxytenanthera abyssinica*	5	10.875844
3	8	*Oxytenanthera abyssinica*	4.2	5.958038
4	9	*Oxytenanthera abyssinica*	3.8	4.669944
5	11	*Oxytenanthera abyssinica*	5.8	12.147369
6	12	*Oxytenanthera abyssinica*	9.2	21.428448
7	13	*Oxytenanthera abyssinica*	4.3	8.424179
8	14	*Oxytenanthera abyssinica*	4.5	12.921395
9	15	*Oxytenanthera abyssinica*	5.2	11.539921
10	16	*Oxytenanthera abyssinica*	4	6.115606
11	21	*Oxytenanthera abyssinica*	4.7	10.562931
12	22	*Oxytenanthera abyssinica*	4.7	6.341106
13	23	*Oxytenanthera abyssinica*	4.9	7.848065
14	24	*Oxytenanthera abyssinica*	4.7	8.112524
15	25	*Oxytenanthera abyssinica*	5.2	9.14703
16	26	*Oxytenanthera abyssinica*	5	7.850801
17	28	*Oxytenanthera abyssinica*	3.9	5.937126
18	29	*Oxytenanthera abyssinica*	4.4	6.314001
19	30	*Oxytenanthera abyssinica*	5.5	13.254627
20	31	*Oxytenanthera abyssinica*	3.5	2.945132
21	32	*Oxytenanthera abyssinica*	4.4	6.381377
22	33	*Oxytenanthera abyssinica*	4.7	4.829816
23	34	*Oxytenanthera abyssinica*	4.2	5.874034
24	38	*Oxytenanthera abyssinica*	5.2	7.278784
25	39	*Oxytenanthera abyssinica*	4.3	5.811792
26	40	*Oxytenanthera abyssinica*	3	3.797913
27	41	*Oxytenanthera abyssinica*	6	11.799613
28	42	*Oxytenanthera abyssinica*	4.3	7.476171
29	43	*Oxytenanthera abyssinica*	5.5	12.420476
30	44	*Oxytenanthera abyssinica*	4.7	6.208097

Declaration of interests

☐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.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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HIGHLIGHTS

1. Bamboo is a nature-based solution that can help combat climate change in Africa.

2. In plantation forestry, bamboo can sequester more tradable amounts of carbon than trees.
3. Bamboo carbon sequestration is affected by species, Elevation and Silvicultural management regimes.
4. Bamboo can contribute significantly to restoring degraded landscapes.