

# Carbon stock of *Oxytenanthera abyssinica* (A.Rich.) Munro forests in northern Uganda: A vital nature-based climate solution

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## ABSTRACT

Recognizing the significant potential of bamboo as a carbon sink, Uganda has strategically incorporated it into its national climate-mitigation and forest-restoration initiatives. However, there is limited information on the carbon storage and sequestration potential of bamboo forests in Uganda. Therefore, this study was conducted to estimate the carbon stock and sequestration potential of natural lowland bamboo (*Oxytenanthera abyssinica*) forests of the Lamwo District, Northern Uganda, to provide the necessary empirical basis for their formal recognition as a vital Nature-based Climate Solution. A total of 50 circular plots, each covering 100 m<sup>2</sup> with a radius of 5.64 m, were set up to gather data. We estimated biomass using an allometric equation considering the diameter and age. The mean biomass of the bamboo forests in the study area was approximately 161.09 ± 4.0 Mg ha<sup>-1</sup>. The mean biomass carbon and CO<sub>2</sub> equivalent were 75.71 ± 1.89 Mg ha<sup>-1</sup> and 277.86 ± 6.95 Mg ha<sup>-1</sup>, respectively. These findings establish the *Oxytenanthera abyssinica* forests as vital, underutilized carbon reservoirs, necessitating their integration as a Nature-based Climate Solution (NbCS) in national mitigation and resilience strategies.

## 1. Introduction

Bamboo forests constitute an essential component of forest ecosystems in tropical and sub-tropical regions, covering 35 million hectares globally (FAO, 2020) and accounting for about 1 % of the global forest area (Du et al., 2018). Beyond their vast area, they play a key role in the global carbon cycle, notably contributing to reducing the increase in greenhouse gas concentration in the Earth's atmosphere (Cheng et al., 2023; Dong et al., 2024; Pan et al., 2023; Tamang et al., 2025). Due to this essential function, bamboo forests are increasingly recognized as a modern nature-based solution for fighting climate change (Ayer, 2025; Innes and Dai, 2024; Pan et al., 2025). For this official recognition to be operationalized and integrated into national climate action, quantifying carbon stocks in bamboo forests is essential to assess their verifiable contribution to mitigation efforts accurately.

Bamboo is one of the fastest-growing plants, with some species having growth rates of 30–100 cm per day and a short harvesting cycle of 3–5 years (Chiti et al., 2024; Qin et al., 2017). Due to this rapid

growth, bamboo offers one of the quickest and most effective ways to sequester large amounts of CO<sub>2</sub> from the atmosphere (Yuan et al., 2021; Yuen et al., 2017), storing up to 392 Mg C ha<sup>-1</sup> in its ecosystem (Yuen et al., 2017). Furthermore, it provides an essential and long-term carbon sink when harvested bamboo culms are converted into durable products such as permanent construction materials, furniture, utensils and art (Abebe et al., 2021b; Atoyebi et al., 2023). Crucially, bamboo harvesting does not remove the entire plant, which prevents the release of CO<sub>2</sub> during the post-harvest period (Nath et al., 2015).

Given this tremendous capacity for carbon sequestration, the global distribution of bamboo is highly relevant. Africa, in particular, holds a significant amount of bamboo resources, accounting for 12.8 % of the global total, with approximately 7.2 million hectares and over 115 species distributed across 48 countries (Abebe et al., 2022; Bahru and Ding, 2021; International Bamboo and Rattan Organisation (INBAR, 2020)). This substantial resource base highlights Africa's significant potential for climate change mitigation through sustainable bamboo management. Moving to the national level, Uganda is one of the

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continent's key bamboo-growing nations, possessing 54,533 ha and 13 species (Kalanzi and Mwanja, 2023; Zhang et al., 2019). While the country's total natural forest extent was approximately 2.44 million hectares in 2020 (Global Forest Watch, 2025), bamboo forests constitute a distinct and essential part of the national forest cover. *Oxytenanthera abyssinica* (A.Rich.) Munro (lowland bamboo) and *Oldeania alpina* (K. Schum.) Stapleton (highland bamboo) are the dominant native species. Among the introduced species, *Bambusa vulgaris* Schrad. ex J.C.Wendl. and *Dendrocalamus giganteus* Munro are the most widely cultivated (Mavito et al., 2023; Ministry of Water and Environment (MWE) and INBAR, 2020).

In Uganda, bamboo forests provide crucial subsistence, socio-economic and ecological services. Bamboo supports soil and water conservation, land rehabilitation, acts as a windbreak and acts as a carbon sink. Culms are vital for construction, furniture, crafts and fuel,

while shoots are a popular delicacy for local communities, thus demonstrating significant potential to reduce poverty and drive sustainable economic growth (MWE and INBAR, 2020; Mbazzira et al., 2018). However, this resource is severely threatened by unsustainable and unregulated harvesting. Pressure stems from local subsistence needs, high housing demands from the refugee population in Northern Uganda, weak enforcement and natural disturbances such as browsing by animals and insect infestations (Mbazzira et al., 2018).

Given the significant socio-economic and ecological importance of bamboo, it is a crucial component of Uganda's national climate strategy. In its pledge to fight climate change, Uganda submitted its first forest reference emission levels (FRELs) to the UNFCCC in 2017. Since then, it has continued to improve on the FREL with financial support from the Forest Carbon Partnership Facility of the World Bank and technical support from the FAO (MWE, 2018). Bamboo is recognized as a key

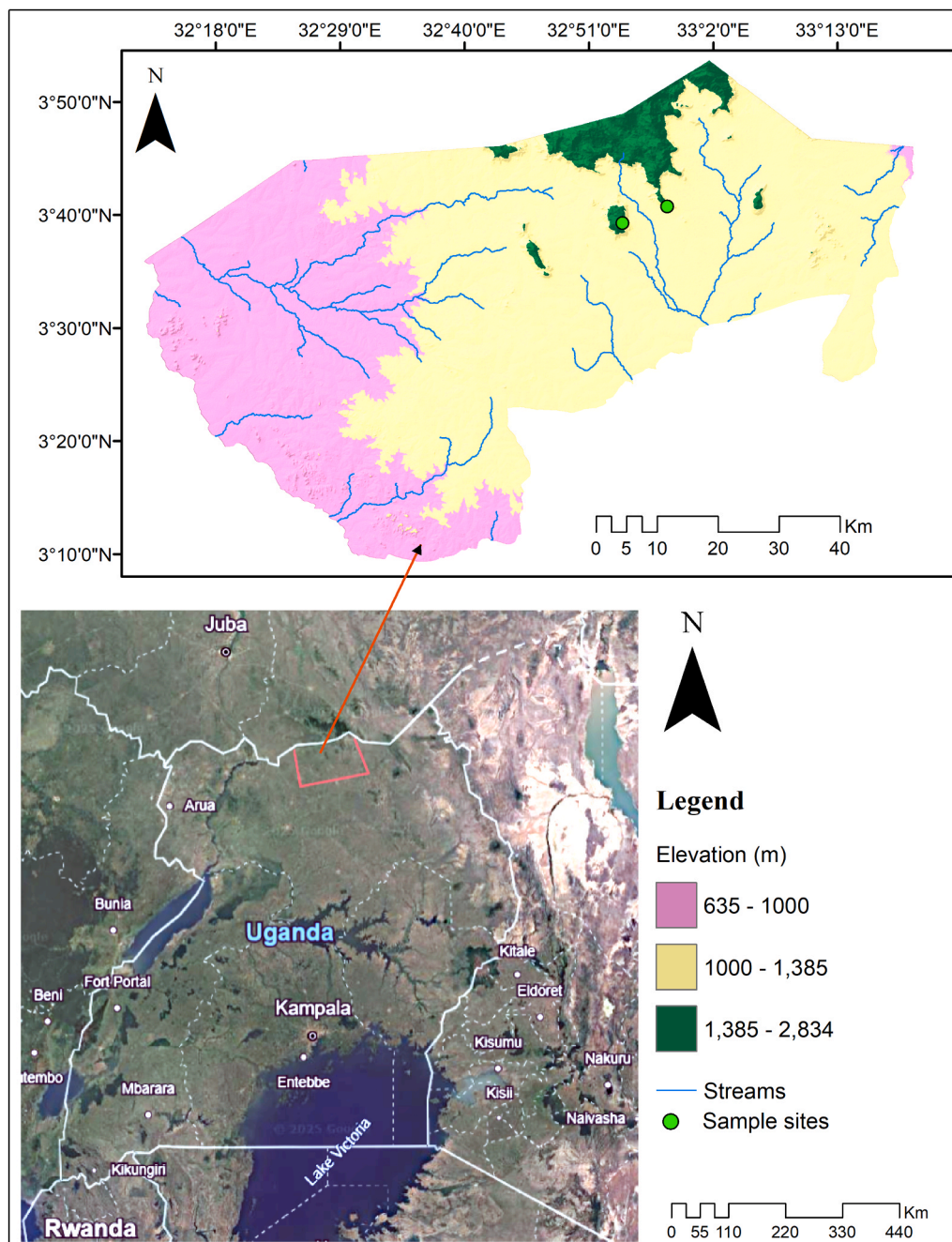


Fig 1. Map of the study area.

carbon-sinking solution under REDD+ and national climate change initiatives (MWE, 2018; MWE and INBAR, 2020). Therefore, quantifying the carbon stock potential of bamboo forests helps to ensure the reporting and verification of Uganda's performance in emissions reduction or carbon removal through its bamboo resources.

Hitherto, several studies have documented the carbon stock potential of various bamboo species globally (Abate et al., 2024; Abebe et al., 2022; Amoah et al., 2020; Jember et al., 2023; Kigomo et al., 2025; Li et al., 2016; Li et al., 2018; Nforinkah et al., 2021; Singnar et al., 2017; Sujarwo, 2016; Yebeben et al., 2022; Zhou et al., 2023). However, little is known about the potential carbon stock of Uganda's bamboo forests. Bamboo stand biomass, carbon storage, and sequestration rates are highly variable due to niche-specific biotic (species composition and diversity) and abiotic (soil, topography, and elevation) factors influencing plant growth and performance (Jember et al., 2023; Tovissodé et al., 2015; Zheng and Lin, 2020). It is, therefore, important to estimate the carbon stock and sequestration potential of bamboo forests in various localities. In this context, this study sought to quantify the carbon stock potential of natural *O. abyssinica* forests in the Lamwo District, Northern Uganda, to establish the empirical basis for their recognition as a vital Nature-based Climate Solution.

## 2. Materials and methods

### 2.1. Description of the study area

This study was conducted in the Agoro-Agu Central Forest Reserve in the Lamwo District of northern Uganda, approximately 460 km from Kampala. Geographically, it is located between 3° 10' 0" – 3° 50' 0" N to 32° 18' 0" – 33° 13' 0" E at an altitude of 1100 – 2600 m above sea level, while the temperature ranges from 20 °C to 28 °C (Fig. 1). It experiences a bimodal rainfall pattern, with the primary wet season spanning late March to early April through August and a secondary peak in November, with annual rainfall ranging from 800 mm to 1000 mm (Birungi et al., 2023). The soil is primarily grey-brown sand overlaying red clay or brown sandy loam (Birungi et al., 2023).

The Agoro-Agu CFR has a gazetted area of approximately 26,508 ha (Mbazzira et al., 2018) and the vegetation is classified as a mosaic, consisting mainly of the dominant *Combretum - Terminalia* woodland, and co-occurring *Acacia* thickets typical of the foothills of the Agoro-Agu hills (IUCN, 2015). The most prominent of the woodland is *O. abyssinica*, which is widely distributed on the slopes between 1170 and 1905 m, covering an area of 7952 ha (Mbazzira et al., 2018). Given the focus on this species, the two bamboo-growing sites in the forest reserve, the Omua and Ongalo villages, were selected purposively for the inventory based on their forest cover and accessibility (Abebe et al., 2021b).

### 2.2. Sampling and data collection techniques

Circular plots are more efficient than rectangular or square plots, as their shorter perimeters minimize the number of bamboo culms left at the edges (Abebe et al., 2021b; Huy and Long, 2019). Accordingly, 50 circular plots, each measuring 100 m<sup>2</sup> with a radius of 5.64 m, were randomly established to collect the stand structure and biomass data in the bamboo forests. In each plot, culms were first classified and counted by age. From the total count, a subsample of 30 culms per plot was randomly selected to ensure representation across all age and size classes. For these selected culms, diameter at breast height (DBH) was measured at 1.3 m using callipers, and culm height was measured with a graduated pole (a calibrated bamboo culm marked at 1 m intervals) by standing the pole vertically against the culm. Finally, physiographic data, including altitude, latitude and longitude, were recorded for each plot using a GPS device.

Culm age was determined using a combination of physical characteristics (exterior colour, sheath features and branch/leaf development)

and local knowledge (Abebe et al., 2021b; Singnar et al., 2017). One-year-old culms are those that emerged in the current year, have only a few leaves, possess the culm sheath, and have a pale surface covered with white powder. By two years old, the culms begin to turn dark green as the white powder disappears, with a few rotting sheaths remaining at the base and well-developed branches appearing on the 5th and 6th internodes. Three-year-old culms are sheath-less, have a dark green base, and show the initial appearance of a few lichens and mosses, symbolizing near-maturity. A light yellowish-green colour and an abundance of lichens and mosses characterize four-year-old culms. Finally, five-year-old or older culms have turned brownish-green and are extensively covered with mosses and lichens.

### 2.3. Stand structure and biomass carbon stocks estimation

Stand density for the *O. abyssinica* forest (ha) was determined using the following procedure (Huy and Long, 2019).

$$\text{Density of culms ha}^{-1} = \frac{\text{Number of culm} \times 10,000}{\text{Plot area (m}^2\text{)}} \quad (1)$$

The above-ground biomass (AGB) storage potential of the bamboo forest was estimated using an allometric approach. While several allometric equations have been developed across Africa (Abebe et al., 2022; Kigomo et al., 2025; Nforinkah et al., 2021; Tesema et al., 2024; Tovissodé et al., 2015; Yebeben et al., 2022), many lack the necessary species- and site-specificity required for accurate estimation. The scientific literature confirms that species-specific models yield the most reliable results (Yuen et al., 2016; Abebe et al., 2021b). Since no species-specific model exists for *O. abyssinica* in Uganda, we ultimately selected the model developed by Amoah et al. (2020) (Ghana), expressed as:  $Y = a x \text{ DBH}^b$ ; Where,  $Y$  = above-ground biomass,  $\text{DBH}$  = diameter at breast height, and  $a$  ( $\alpha$ ) and  $b$  ( $\beta$ ) are parameters.

$$\text{AGB}_1 \quad (1 - 2 \text{ years}) = 2.632x\text{DBH}^{1.881} \quad (2)$$

$$\text{AGB}_2 \quad (3 - 4 \text{ years}) = 1.910x\text{DBH}^{2.410} \quad (3)$$

$$\text{AGB}_3 \quad (5 - 6 \text{ years}) = 2.304x\text{DBH}^{2.233} \quad (4)$$

The model was selected based on two primary methodological criteria: (1) comprehensive sampling: the model was developed using samples and sub-samples from all plant components (culm, leaves and branches), ensuring a holistic biomass estimate; and (2) robust predictive power: it incorporated different bamboo age groups and demonstrated strong statistical performance, with a high  $\text{Adj. R}^2$  (0.855–0.955) and low error metrics, including RMSE (0.022–0.096 %) and MAPE (8.82–21.98 %).

Afterward, the total above-ground biomass (TAGB) was calculated by summing the above-ground biomass of all age classes as follows:

$$\text{TAGB} = \text{AGB}_1 + \text{AGB}_2 + \text{AGB}_3. \quad (5)$$

Estimating below-ground biomass (BGB) is considerably more challenging and time-consuming than estimating AGB. Hence, the root-to-shoot ratio method (Pearson et al., 2007) was employed. Given that *O. abyssinica* has a pachymorphic rhizome, investing more resources in below-ground structures for stability and thus storing higher BGB, a high AGB to BGB ratio of 1:4 was used to estimate BGB (Abebe et al., 2021b; Singnar et al., 2021). Accordingly, BGB was computed as:  $\text{BGB} = \text{AGB} \times 0.25$ . Then, the total below-ground biomass ( $\text{TBGB} = \text{BGB}_1 + \text{BGB}_2 + \text{BGB}_3$ ), and the total biomass ( $\text{TB} = \text{TAGB} + \text{TBGB}$ ). Finally, the C storage and CO<sub>2</sub> equivalent of the bamboo forest were calculated from the TB as follows (IPCC, 2006).

$$\text{Carbon(C)} = \text{C fraction}(0.47) \times \text{TB}; \text{ and } \text{CO}_2 = \text{C} \times 3.67 \quad (6)$$

## 2.4. Statistical analysis

Data were organized in an Excel spreadsheet, and univariate statistics were calculated to determine stand structure and biomass at each of the two bamboo forest locations. The normality of the data distribution was assessed using the Shapiro-Wilk test before proceeding with analysis; data were considered normally distributed if  $p > 0.05$ . The coefficient of variation (CV%) was calculated to determine the relative spatial heterogeneity and precision of the estimates for each forest. A two-way analysis of variance (ANOVA) was then conducted to assess the main and interaction effects of age group and forest site on aboveground biomass. Finally, an independent-samples *t*-test was performed to determine whether there was a significant difference in mean biomass and carbon stock values between the bamboo forests at Ongalo and Omua. All statistical analyses were performed at  $\alpha = 0.05$ .

## 3. Results and discussion

### 3.1. Culm density and population structure of *O. abyssinica* forests in northern Uganda

*O. abyssinica* stand density varied across forest sites and age groups (Table 1). The Ongalo bamboo forest exhibited a higher cumulative culm density (15,254 ha<sup>-1</sup>) compared to the Omua forest (13,634 ha<sup>-1</sup>) across all age classes. Conversely, the Omua bamboo forest had higher clump density (874 ha<sup>-1</sup>) than the Ongalo bamboo forest (717 ha<sup>-1</sup>).

In contrast to this study, lower culm densities for *O. abyssinica* have been reported. Tovissodé et al. (2015) found 2751 culms ha<sup>-1</sup> in Benin, Amoah et al. (2020) reported 3325 culms ha<sup>-1</sup> in Ghana, and Nforankah et al. (2021) found 4374 culms ha<sup>-1</sup> in Cameroon. Comparable densities of 12,364–15,025 culms ha<sup>-1</sup> (Abebe et al., 2021b) and 15,500–17,700 culms ha<sup>-1</sup> (Tesema et al., 2025), have been reported for *O. abyssinica* forests in Ethiopia. On the other hand, higher densities of 20,375–27,945 culms ha<sup>-1</sup> (Jember et al., 2023), 20,467 culms ha<sup>-1</sup> (Mulatu and Fetene, 2013), 20,748 culms ha<sup>-1</sup> (Nigatu et al., 2020) and 19,343 culms ha<sup>-1</sup> (Abebe et al., 2022), have been recorded in other studies of *O. alpina* in Ethiopia. Generally, bamboo stand density is influenced by a range of factors, including species diversity, tending practices, harvesting intensity and prevailing site conditions.

Regarding the age structure, in the Ongalo bamboo forest, 42.9 % (6549 culms ha<sup>-1</sup>) of the culms were mature (3–4 years old), whereas 35.7 % (5452 culms ha<sup>-1</sup>) were older than 4 years and 21.4 % (3235 culms ha<sup>-1</sup>) were younger than 3 years. In contrast, in the Omua forest, old culms constituted the most significant portion of the bamboo stand at 42.4 % (5770 culms ha<sup>-1</sup>), followed by matured culms at 31.4 % (4286 culms ha<sup>-1</sup>), while young culms made up the remaining 26.2 % (3578 culms ha<sup>-1</sup>) (Table 1).

In the study area, bamboo culms were harvested unsystematically, especially in the Ongalo forest, located far from settlements, where harvesters cut culms freely. Moreover, significant issues with harvesting and management, such as premature harvesting of young culms, inefficient cutting of culms high above the root base, and disruptive unseasonal harvesting, predominantly during the wet seasons, were evident in the studied bamboo forests (Fig. 3).

The youngest bamboo culms exhibited the highest thickness (DBH)

in both the Ongalo (4.1 ± 0.12 cm) and Omua (4.0 ± 0.14 cm) bamboo forests. Conversely, the oldest bamboo culms displayed the lowest DBH values of 3.6 ± 0.1 cm for both Omua and Ongalo bamboo forests. Culm thickness was negatively correlated with culm age. We found that the youngest culms were the thickest (culms from older age groups had progressively smaller diameters), while a slight difference was observed in culm height (Fig. 2). Bamboo deteriorates and eventually dies after reaching maturity because it lacks a secondary meristem (the cambium) for tissue renewal, leading ageing culms to undergo structural and chemical changes with fluctuating nutrient levels (Abebe et al., 2021b; Liese and Köhl, 2015).

### 3.2. Variations in the above-ground biomass of the *O. abyssinica* forests in different age classes

Above-ground biomass (AGB) accumulation showed a highly significant main effect for age class (F (2, 144) = 16.985,  $p < 0.001$ ), accounting for 19.1 % of the total variance (Partial  $\eta^2 = 0.191$ ). Neither the main effect of forest site (F (1,144) = 0.555,  $p = 0.457$ ) nor the age x forest interaction (F (2, 144) = 0.308,  $p = 0.735$ ) was statistically significant, indicating a uniform pattern of AGB accumulation across both sites (Tables 2 and 3). Post-hoc analysis using Tukey's HSD test revealed that age class 2 (3–4 years) had significantly higher mean ABG (51.32 t ha<sup>-1</sup>) than either age class 1 (1–2 years) (36.42 t ha<sup>-1</sup>) or age class 3 (5–6 years) (41.14 t ha<sup>-1</sup>) (all  $p < 0.001$ ). No significant difference was found between age class 1 and age class 3 ( $p = 0.171$ ).

These findings indicate that above-ground biomass accumulation was strongly influenced by culm age, peaking in age class 2 (3–4 years old), and that this pattern was uniform across both forest sites. Crucially, the analysis showed that a substantial portion (71.7 %) of the total stand biomass was concentrated in mature (3–4 years old) and old (5–6 years old) culms, which remained largely unharvested in the study sites. This observation is consistent with reports by Embaye et al. (2005) and Abebe et al. (2022, 2021b), who noted that mature and old culms contribute the highest biomass in unmanaged bamboo stands of Ethiopia.

However, the dominance of mature and old culms suggests negative implications for the sustainability and productivity of these forests (Abebe et al., 2021a, 2021b; Yebeyen et al., 2022). Unharvested mature culms lead to congestion and eventual deterioration of both above- and below-ground parts; their presence inhibits new shoot growth by limiting growing space and competing for light and rainwater. Consequently, the physical interference between new and mature rhizomes and culms increases the likelihood of new culms being malformed, aborted, broken or dying (Mulatu et al., 2016). Ultimately, this results in culms of poor quality (thin and short) and low stand value. Generally, management plays a crucial role in biomass distribution across age classes, leading to a more balanced distribution in well-managed bamboo stands (Chiti et al., 2024; Jember et al., 2023; Xu et al., 2024).

### 3.3. Biomass and carbon stock potential of the *O. abyssinica* forests

Following confirmation of equal variances by Levene's test (F = 2.916,  $p = 0.094$ ), the *t*-tests revealed no statistically significant difference in mean values for total biomass (t (48) = -0.736,  $p = 0.465$ ),

**Table 1**  
Stand structure of *O. abyssinica* forests of northern Uganda.

Age (year)	Ongalo bamboo forest				Omua bamboo forest			
	Culm Density (ha <sup>-1</sup> )	Clump density (ha <sup>-1</sup> )	DBH (Cm)	Height (m)	Culm (ha <sup>-1</sup> )	Clump (ha <sup>-1</sup> )	DBH (Cm)	Height (m)
1 – 2	3253 ± 77.1	717 ± 33	4.1 ± 0.10	10.5 ± 0.12	3578 ± 66.3	874 ± 55	4.0 ± 0.11	10.5 ± 0.25
3 – 4	6549 ± 161.6		3.9 ± 0.10	10.4 ± 0.10	4286 ± 155.8		3.8 ± 0.11	10 ± 0.30
5 – 6	5452 ± 145.6		3.6 ± 0.01	10.0 ± 0.13	5770 ± 178.3		3.6 ± 0.10	9.7 ± 0.29
Total	15,254				13,634			

All values are presented as Mean (±) Standard Error (SE). DBH is the diameter at breast-height.

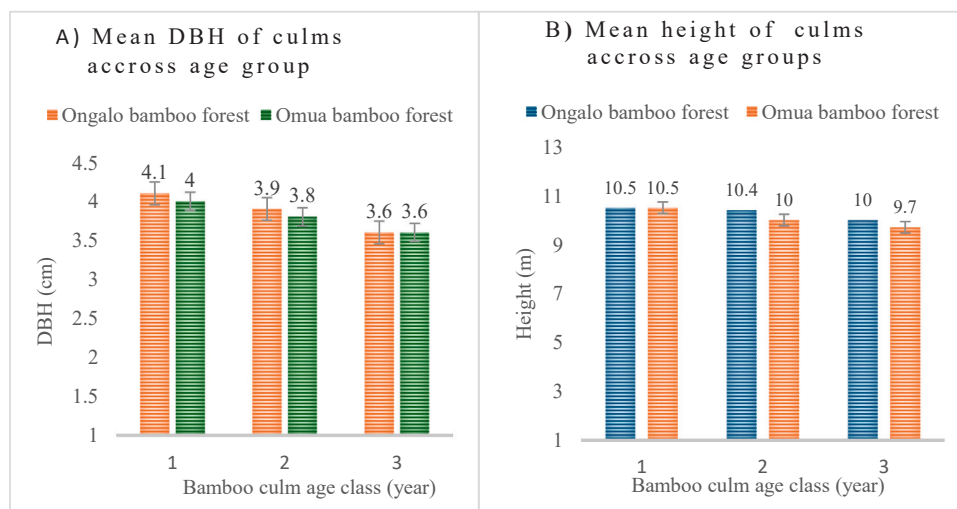


Fig. 2. Mean DBH (A) and height (B) of bamboo culms.

Table 2

Biomass storage among the age classes of *O. abyssinica* forests in northern Uganda.

Bamboo forests	AGB <sub>1</sub> (Mg ha <sup>-1</sup> )	AGB <sub>2</sub> (Mg ha <sup>-1</sup> )	AGB <sub>3</sub> (Mg ha <sup>-1</sup> )	TAGB (Mg ha <sup>-1</sup> )	TBGB (Mg ha <sup>-1</sup> )	TB (Mg ha <sup>-1</sup> )
Omua forest	35.75 <sup>a</sup> ±1.91	49.44 <sup>b</sup> ±3.39	41.30 <sup>a</sup> ±2.52	126.48 ± 5.34	31.62 ± 1.33	158.11 ± 6.67
Ongalo forest	37.08 <sup>a</sup> ±1.74	53.20 <sup>b</sup> ±3.38	40.98 <sup>a</sup> ±2.23	131.25 ± 3.67	32.81 ± 0.91	164.07 ± 4.59
Grand mean	36.41 <sup>a</sup> ±1.28	51.32 <sup>b</sup> ±2.39	41.14 <sup>a</sup> ±1.67	128.87 ± 3.22	32.22 ± 0.80	161.09 ± 4.03

All values are presented as Mean (±) Standard Error (SE). Mg ha<sup>-1</sup> (megagram per hectare). AGB=Aboveground biomass. Numbers 1, 2 and 3 refer to age classes 1–2, 3–4, and 5–6, respectively. TAGB is the total aboveground biomass; TBGB is the total belowground biomass; TB is the total biomass. Different letters in superscripts indicate a significant difference, while similar letters show no significant difference in aboveground biomass based on Tukey's HSD test ( $\alpha = 0.05$ ).

Table 3

Two-way ANOVA results for factorial effects on biomass storage.

Statistical test	df	F	(p-value)
Age group	2, 144	16.985	< .001
Forest	1, 144	0.555	0.457
Age × Forest	2, 144	0.308	0.735

df = degree of freedom; F = F-statistic

carbon ( $t(48) = -0.735$ ,  $p = 0.465$ ), or CO<sub>2</sub> eq. ( $t(48) = -0.736$ ,  $p = 0.465$ ) between the two sites. Although the mean values for Ongalo were numerically higher across all variables (e.g., total biomass: Ongalo = 164.07 Mg ha<sup>-1</sup> vs. Omua = 158.11 Mg ha<sup>-1</sup>), this observed difference was not statistically significant, as indicated by the high p-value ( $p = 0.465 > 0.05$ ) (Table 4).

In contrast to the mean comparison, the coefficient of variation (CV %) analysis revealed a consistent difference in data dispersion across all three variables. The CV% was higher in the Omua forest (21.11 %) than in the Ongalo forest (14.00 %). This suggests that measurements from

the Omua forest exhibited greater relative variability around the mean. The lower CV% in the Ongalo forest indicates that its measurements were more homogeneous, with lower absolute (standard deviation) and relative (CV%) variability across all parameters (Table 4).

The mean total biomass value for the entire study area was 161.09 ± 4.03 Mg ha<sup>-1</sup>, with the Ongalo bamboo forest storing 164.07 ± 4.59 Mg ha<sup>-1</sup> and the Omua bamboo forest storing 158.11 ± 6.67 Mg ha<sup>-1</sup>. Comparing the findings to the existing literature, our result is higher than the corresponding reported values of 108.71 Mg ha<sup>-1</sup> (Nigatu et al., 2020) and 110.7 Mg ha<sup>-1</sup> (Embaye et al., 2005) for *O. alpina*; 105 Mg ha<sup>-1</sup> for *Phyllostachys makinoi* Hayata (Yen et al., 2010). Much lower values were reported, 64.0 Mg ha<sup>-1</sup> for *O. alpina* (Abebe et al., 2022), 87.35 Mg ha<sup>-1</sup> for six bamboo species (Sujarwo, 2016), 88.23 Mg ha<sup>-1</sup> for *Phyllostachys pubescens* (Pradelle) Mazel ex J.Houz. (now known as *Phyllostachys edulis* (Carrière) J.Houz. (Zhang et al., 2014), and 89 Mg ha<sup>-1</sup> for *Phyllostachys heterocycla* (Carrière) Matsum. (now also known as *P. edulis*) (Yen and Lee, 2011). Conversely, the total biomass recorded in this study is lower than the values reported of 177.12 Mg ha<sup>-1</sup> for *O. abyssinica* (Abebe et al., 2021b), 186–237 Mg ha<sup>-1</sup> for *O. alpina*

Table 4

Total biomass, carbon stock and CO<sub>2</sub> sequestration potential of *O. abyssinica* forest in northern Uganda.

Attribute	Bamboo forests	Mean	SD	CV%	t	df	p-value
Total biomass (Mg ha <sup>-1</sup> )	Omua	158.11 ± 6.67	33.38	21.11	-0.736	48	0.465
	Ongalo	164.07 ± 4.59	22.97	14.00			
Carbon stock (Mg ha <sup>-1</sup> )	Omba	74.31 ± 3.13	15.68	21.11	-0.735	48	0.465
	Ongalo	77.11 ± 2.15	10.79	14.00			
CO <sub>2</sub> eq. (Mg ha <sup>-1</sup> )	Omua	272.72 ± 11.51	57.57	21.11	-0.736	48	0.465
	Ongalo	283.00 ± 7.92	39.62	14.00			

± is mean standard error; SD = standard deviation; CV% = coefficient of variation; t = t-statistic (value); df = degree of freedom; Mg ha<sup>-1</sup> = Mega gram per hectare, and CO<sub>2</sub> eq. = CO<sub>2</sub> equivalents.

(Jember et al., 2023) and  $286 \text{ Mg ha}^{-1}$  for *Bambusa bambos* (L.) Voss (Shanmughavel and Francis, 1996). These wide variations reflect that bamboo stand biomass accumulation is fundamentally governed by intrinsic factors such as species composition, age, size (culm diameter) and density.

The total biomass carbon stored by the bamboo forests mirrored the numerical trend observed in total biomass (Table 4). Carbon storage was higher in the Ongalo forests ( $77.11 \pm 2.15 \text{ Mg ha}^{-1}$ ) compared to the Omua bamboo forests ( $74.31 \pm 3.13 \text{ Mg C ha}^{-1}$ ). The overall mean total biomass carbon for the study area ( $75.71 \pm 1.89 \text{ Mg ha}^{-1}$ ) was comparable to values ( $72.5\text{--}87 \text{ Mg ha}^{-1}$ ) reported for the same species (*O. abyssinica*) in Ethiopia (Abebe et al., 2021b). Importantly, the carbon stock of the studied *O. abyssinica* forests was notably higher than values reported for several other bamboo species in tropical and subtropical regions, such as *Dendrocalamus giganteus* ( $47.82 \text{ Mg ha}^{-1}$ , Teng et al., 2016), *B. vulgaris* ( $52.5 \text{ Mg ha}^{-1}$ , Sohel et al., 2015), *P. pubescens* ( $54.6 \text{ Mg ha}^{-1}$ , Zhuang et al., 2015), *Schizostachyum dullooa* (Gamble) R.B. Majumdar ( $69.70 \text{ Mg ha}^{-1}$ , Singnar et al., 2021), *O. alpina* ( $52.4 \text{ Mg ha}^{-1}$ , Yebeyen et al., 2022), and introduced *Phyllostachys edulis* plantations ( $18.5 \text{ Mg ha}^{-1}$ , Chiti et al., 2024).

### 3.4. Policy and sustainability implications of the *O. abyssinica* carbon stock

The *O. abyssinica* forests of the study area could accumulate  $322.18 \text{ Mg ha}^{-1}$  biomass and store  $151.42 \text{ Mg ha}^{-1}$  carbon. As a result, these bamboo forests could sequester  $555.72 \text{ Mg ha}^{-1}$  of  $\text{CO}_2$  equivalents,

thereby generating a considerable amount of carbon credits. These quantitative metrics establish *O. abyssinica* as a vital nature-based climate solution, providing the critical empirical evidence needed to realize Uganda's strategic objectives for mitigation and resilience.

The empirically established sequestration potential directly supports national policy by significantly contributing to Uganda's commitment to achieving a 24.7 % reduction in greenhouse gas emissions by 2030, based on a business-as-usual (BAU) scenario projected at  $148.8 \text{ Mt CO}_2$  eq. for 2030 and  $235.7 \text{ Mt CO}_2$  eq. by 2050 (MWE, 2018). Furthermore, these bamboo resources align with national restoration goals, supporting Uganda's pledge to restore 2.5 million hectares of landscapes by 2030 under the African Forest Landscape Restoration Initiative (AFR100) (MWE, 2018). Reflecting this national focus, the Uganda National Bamboo Strategy and Action Plan (2019–2029) aims explicitly to restore 375,000 ha of degraded forest land with bamboo by 2030 (MWE and INBAR, 2020).

Despite these critical mitigation benefits, the long-term sustainability of *O. abyssinica* forests is compromised by multiple pervasive threats, primarily driven by weak management and high demand. Weak regulatory and enforcement mechanisms characterize management within government-controlled Central Forest Reserves (NFA) in Uganda. Field observations confirm widespread unsustainable harvesting by local communities, including improper techniques such as unrestricted harvesting of young culms, cutting culms too high, the use of blunt machetes and unseasonal harvesting during wet seasons. Paradoxically, this over-utilization of shoots often exceeds the regeneration capacity of clumps, even as many mature and old culms remain unharvested



**Fig. 3.** Field photographs showing improper bamboo harvesting and management in the study area: a) Culms cut at a higher position; b) Unharvested old culms in a clump; c) Clumps with a higher number of unharvested culms; and d) Clump with no culms.

(Fig. 3). Further exacerbating this is the increasing demand for housing materials driven by Uganda's large refugee population (hosting over 1.8 million refugees) (European Union, 2025), which has severely exacerbated indiscriminate harvesting, particularly in northern Uganda where agencies prioritize funding for bamboo poles for shelter. Additional ecological disturbances include wildfire, extensive feeding on young shoots by animals (e.g., mountain gorillas), infestations by borers and insects, and the prevalence of climbers.

#### 4. Conclusion

Our study reaffirms the crucial role of *O. abyssinica* forests as a vital Nature-based Climate Solution. The *O. abyssinica* forests were found to accumulate 322.18 Mg ha<sup>-1</sup> of biomass, store 151.42 Mg ha<sup>-1</sup> of carbon, and sequester 555.72 Mg ha<sup>-1</sup> of CO<sub>2</sub> within their biomass. Proper management and use of harvested bamboo culms for durable industrial products would enhance carbon sequestration and establish a stable, long-term carbon sink. Apart from carbon storage, these bamboo forests provide numerous services that support livelihoods. However, the current mismanagement of *O. abyssinica* forests, driven by weak regulatory enforcement, undermines their sustainability and their capacity to sequester CO<sub>2</sub> and provide other crucial ecosystem services. Therefore, we strongly advocate for the sustainable management of bamboo forests to enhance their productivity and optimize their provision of ecosystem services, including both climate change mitigation and adaptation and regional resilience.

To ensure the continued ecological and socio-economic benefits of this valuable resource, the following critical policy recommendations specific to Uganda's forest management practices are essential. There is a need to empower local stewardship and enforcement. The National Forestry Authority (NFA) should be mandated to establish community-based sustainable harvesting protocols and to grant local Bamboo User Groups (BUGs) formal tenure rights over specific blocks to ensure strict adherence to harvest limits (e.g., 30 % per clump) and proper cutting techniques.

There is a need to develop a value chain to offset pressures. National incentives should be introduced to develop the bamboo value chain via industrial processing and value-addition. This would include partnering with humanitarian agencies to shift procurement from raw poles to certified, durable processed materials, thereby diverting the acute demand pressure (exacerbated by refugee housing needs) away from vulnerable natural stands.

Finally, there is a need to formalize carbon accounting and investment. The existing national recognition of bamboo as a climate solution should be used as a basis to mandate the integration of quantifiable *O. abyssinica* carbon stocks into the national GHG inventory and to require the fast-tracking of bamboo-based carbon project development (e.g., afforestation/reforestation and REDD+). This would ensure that the representative average biomass carbon capacity of this species (75.71 Mg C ha<sup>-1</sup>) is actively leveraged to attract international funding for conservation and meet Uganda's NDC targets.

Implementing these targeted policies is crucial for realizing the full potential of bamboo forests and ensuring Uganda achieves its national restoration and climate change mitigation goals.

#### CRedit authorship contribution statement

**Shiferaw Abebe:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Michael Malinga:** Supervision, Resources, Data curation. **Durai Jayaraman:** Writing – review & editing, Resources, Funding acquisition. **Selim Reza:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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#### 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.

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