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Assessment of aboveground, belowground, and total biomass carbon storage potential of *Bambusa vulgaris* in a tropical moist forest in Ghana, West Africa

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Abstract. This article reports on a study conducted to assess the carbon storage potential of *Bambusa vulgaris*, the predominant bamboo species in Ghana. The study aimed to fill a knowledge gap on the potential of bamboo to sequester carbon for climate change mitigation in Ghana. Unlike previous studies that only focused on aboveground biomass, this study assessed belowground, litter, and coarse wood carbon pools. Allometric parameters and models were used to measure the aboveground biomass, while other carbon pools were directly measured. The results showed that the aboveground biomass of *B. vulgaris* had a carbon stock of 42.85 ± 9.32 Mg C ha^{-1}, which was 73% of the total biomass carbon stock. The carbon stocks of belowground, coarse wood and litter were 8.57, 3.02, and 4.25 Mg C ha^{-1}, respectively. The study also found that *B. vulgaris* had a high carbon dioxide sequestration potential of 215.39 Mg $\mathrm{CO_{2e}}$ ha^{-1} compared to 147–275 Mg $\mathrm{CO_{2e}}$ ha^{-1} for trees in general. The findings suggest that *B. vulgaris* could contribute to Ghana's transition to a low-carbon economy through carbon stock monitoring, reporting, and policy development to minimise the impact of climate change. Moreover, the inclusion of relevant carbon pools, including coarse wood and litter, in forest carbon estimates should be encouraged to provide a comprehensive understanding of the plant carbon cycle.

Keywords: Bamboo / *Bambusa vulgaris* / biomass estimation / carbon stock / Bobiri Forest

1 Introduction

The carbon cycle has recently become an important global issue due to climate change, and plants serve a major function in carbon storage. This has led to an awareness of estimating the current carbon stocks within the global forests and the stock changes. Forest covers approximately one-third of the terrestrial ecosystem and serves as the most important carbon sink [1]. Forests store vast amounts of carbon, which is transformed into carbon dioxide and released into the atmosphere when destroyed; hence, a change in forest biomass is considered a vital component of climate change [2]. Global warming and climate change are influenced by carbon dioxide (CO_2) and other greenhouse gases, including methane, sulfate fluoride, and water vapour [3]. Anthropogenic activities, like burning fossil fuels for energy and deforestation, have impacted this phenomenon [4,5].

Biomass fuels, on the other hand, reduce reliance on fossil fuels and improve energy sustainability. In developing countries, tree biomass is primarily used as a source of energy for cooking, heating, and electricity generation. Monitoring and reporting forest biomass inventories for bioenergy applications is necessary to ensure sustainable usage of biomass resources. As a result, much attention has been given to biomass estimation in recent years because vegetative biomass grows through photosynthesis [6].

Although estimates of forests' carbon sequestration potential and stocks play an essential role in formulating strategies for reducing CO_2 emissions, most studies of woody species neglect bamboo in assessing the capability of trees to sequester carbon. This neglect had been attributed to bamboo being an invasive giant grass

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growing sporadically on degraded lands, with a few other studies arguing that bamboo is a net carbon emitter [7–9]. There has since been enough data implying that bamboo land covers can absorb enormous amounts of carbon, helping to alleviate the consequences of climate change, due to their broad geographic spread (persists in tropical and subtropical areas between latitude 46 °N and 47 °S) compared to other plant species and their fast growth rates, which favours the storage of organic carbon through photosynthesis [7,10]. Bamboo was officially considered in the same bracket as trees for Clean Development Mechanism (CDM) projects in 2008 during the 39 th meeting of the United Nations Framework Convention on Climate Change (UNFCCC) CDM executive board [11].

Limited information about Ghana's forest biomass makes it essential to accurately inventory of the biomass establish an and carbon stocks of important plant species such as bamboo. Ghana has an estimated 400,000 hectares of bamboo, representing 4.28% of the total forest vegetation, which makes it the leading country in West Africa in terms of bamboo sector development and second to only Ethiopia on the continent as a whole [12]. *Bambusa vulgaris* forms part of the eight (8) indigenous bamboo species and is the most widespread in Ghana, accounting for about 90 to 95% of the bamboo resource [13,14].

Previous studies on carbon assessment for trees in Ghana have only focused on the carbon stored in aboveground biomass, ignoring other carbon pools such as litter and woody debris [6,15], which can contain significant amounts of carbon (around 5% and 8% of bamboo ecosystem carbon, respectively [16]). Comprehensive estimates of forest carbon stocks are required to improve the accuracy and reduce uncertainties in carbon and climate change forecasts at regional and global levels. Therefore, this study aims to estimate the biomass carbon storage of *Bambusa vulgaris* natural stands in the Bobiri Forest Reserve, including aboveground and belowground biomass, coarse woody debris, and litter. To the best of our knowledge from existing literature, no prior research has been conducted on assessing the amount of carbon stored in the biomass of *Bambusa vulgaris*, taking into account litter and coarse woody debris [15,17–23]. This study will be the first of its kind, and the outcomes of this research will be instrumental in quantifying the quantity of CO_2 that *Bambusa vulgaris* can capture from the atmosphere. These findings will also aid in developing future carbon policies and climate change mitigation strategies.

2 Materials and methods

2.1 Study site

The study was carried out in the Bobiri Forest Reserve (BFR) and Butterfly Sanctuary, located in the Moist Semi-deciduous South-East sub-type ecological zone of Ghana, and covers an area of 5445 ha [24]. BFR boasts of a one-and-half-hectare arboretum and a hectare Bambusetum with fifteen provenances, besides several other clumps of *Bambusa vulgaris* at locations scattered throughout the reserve. BFR is interspersed with rivers such as Abobiri, Wurapon, Anwiasu, Abofre and Juabenika [24]. The Bobiri forest, according to the Forestry Commission of Ghana, is divided into 73 compartments categorised into Production and Conservation/Research zones. To assess the carbon sequestration potential of *Bambusa vulgaris*, the study was conducted in four (4) randomly selected compartments representing the four major bamboo zones in the BFR, which are the production (18A), conservation (7), reserve border (70), and the bambusetum (69) (Fig. 1). This grouping of the bamboo was done with the help of local forest rangers familiar with the BFR terrain and knowledgeable of the bamboo stands in the forest reserve.

2.2 Data collection

2.2.1 Aboveground measurements

Five (5) bamboo clumps were randomly sampled for allometric measurements in each compartment. The dendrometric variables were clump basal dimensions, culm diameter, culm age, and the number of culms per clump. Tapes were used to measure the basal dimensions for each clump in meters. Culms were measured for diameter at breast height (1.3 m) using diameter tapes and Vernier callipers. Culms were tagged and categorised into four age classes (1, 2, 3, and ≥4). Culm ages were recorded by observing the morphological features as culms appear light green with sheaths around the base for age one and below, green with sub-branches for two years, dark green with white surfaces due to the presence of lichen for three years, and dense lichen with yellowish colouration for culms that are four years and above [25].

2.2.2 Coarse woody debris (downed dead bamboo) measurements

For each compartment, a 100 × 1-meter transect was established to measure downed dead bamboo culms in various stages of decomposition. Dead culms that fell within the transect were measured for length, diameters at both ends (inner and outer for samples), and the stage of decomposition. The stages of decomposition of dead culms were categorised as sound (the blunt side of a machete bounces back when struck against a culm), intermediate (blunt side of a machete sticks inside a bamboo culm when struck against it), and rotten (blunt side of a machete crumples bamboo culm when struck against it) [26]. Ten culm discs of length 10 cm were sampled in each compartment for the various decomposition categories for wood density determination in the laboratory.

2.2.3 Litter measurements

Sample plots were set up to collect data on ground litter within the bamboo sites covered by the canopy. The size of each sample plot was 30 × 30 m. Within the sample plots, five 50 × 50 centimetres ($0.25\,\mathrm{m}^2$) quadrats were laid close to the four corners and one around the centre of the plot to assess ground litter. The litter in each quadrat was collected, and the total fresh mass was immediately determined with an electronic weighing balance. Subsamples were taken, and fresh mass was measured on-site.

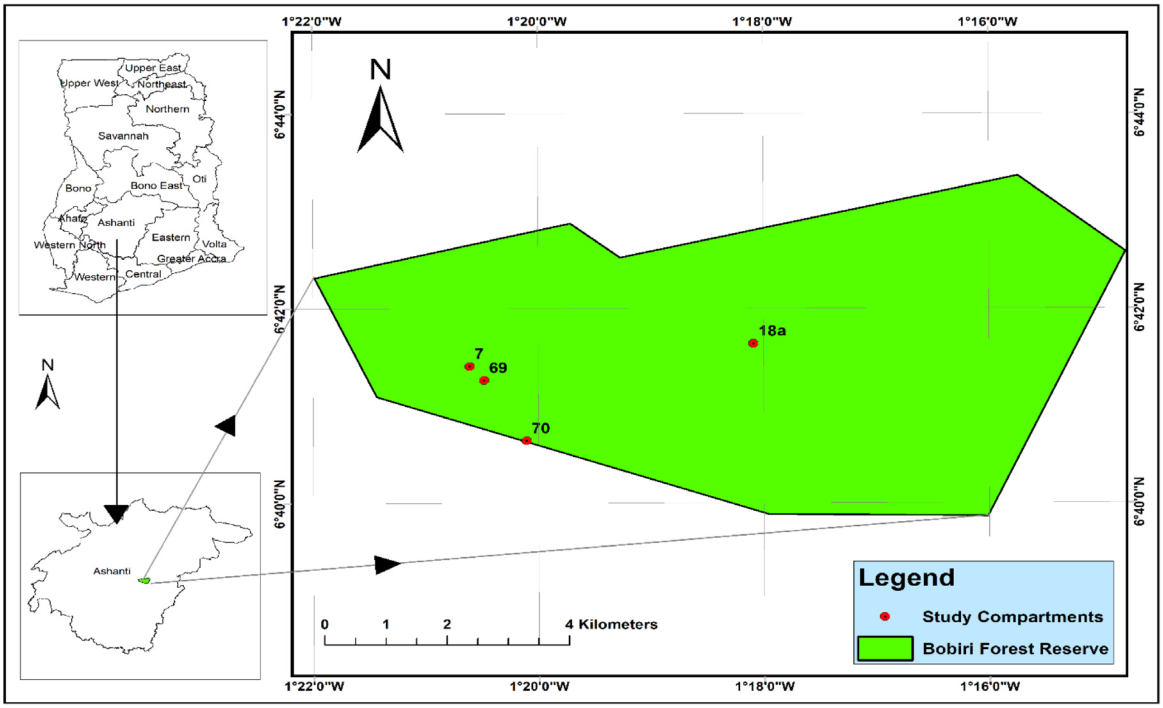

Fig. 1. Map of Bobiri forest reserve showing the compartments understudy.

2.3 Laboratory analyses

Laboratory analysis was carried out to determine the bamboo components' dry-to-fresh mass ratios, volume, density, and carbon content. The dry mass of the samples was determined by oven-drying the leaf litter at 60 °C and the dead culm samples at 105 °C for 48 h to ensure that the samples were bone-dried [27]. The volume of the culm disk samples was determined by the water displacement method. To determine the mass and carbon stock of dead bamboo culms in the transects, average densities and carbon contents were estimated and analysed in the laboratory. Vernier callipers were used to re-measure the dimensions of the culm disc samples to check for field errors due to cutting. The culm disk dry mass and volume were used to determine wood density, whereas the dry mass of the culm disks and leaf litter were used for the dry-to-fresh mass ratio determination. The dry-to-fresh mass and culm disk density analyses were conducted at the Biodiversity, Conservation and Ecosystem Services Division (BCESD) laboratory of the Forestry Research Institute of Ghana (FORIG), while the carbon content analysis of the various plant components was done in the Soil Research Institute (SRI) laboratory in Kumasi.

3 Calculation

3.1 Aboveground mass (AG_M)

The aboveground mass of bamboo was estimated using the most efficient model from the allometric models [28] for *Bambusa vulgaris* in the moist-semi deciduous ecozone in Ghana, where the Bobiri forest lies. The allometric equation is presented as;

$$AG_M = 0.3432\left(\rho \times \mathrm{DBH}^2\right)^{1.1285}, \tag{1}$$

where AG_M = culm aboveground mass, ρ = bamboo culm density, DBH = culm diameter at breast height.

The predictive variables of the allometric equation are diameter at breast height (DBH) and density (ρ).

3.2 Belowground biomass (BG_M)

The below-to-aboveground ratio or root-shoot ratio of 0.20, as prescribed by the Intergovernmental Panel on Climate Change [29,30], was used to estimate the belowground biomass and carbon stock of bamboo for the study since there is no belowground biomass allometric equation for *B. vulgaris* from literature.

$$BG_M = 0.2 \times AG_M. \tag{2}$$

3.3 Bamboo distribution density

The number of clumps and culms was calculated using equations (3) and (4) [31].

$$\mathrm{N_{clumps}ha^{-1}} = \mathrm{N_{clump}} \times \frac{10^4}{\mathrm{plotarea(m^2)}} \tag{3}$$

$$N_{\mathrm{culms}}ha^{-1} = N_{\mathrm{culm}} \times N_{\mathrm{clumps}}\mathrm{ha}^{-1}, \tag{4}$$

where $N_{\text{clumps}}\text{ha}^{-1}$ = number of clumps per hectare, N_{clump} = number of clumps in the study area, $N_{\text{culms}}\text{ha}^{-1}$ = number of culms per hectare, N_{culm} = average number of culms per clump.

3.4 Biomass carbon stock estimation

The litter biomass carbon stock (L_{b}, Mg C ha^{-1}) per plot was estimated by considering the number of quadrats, n, area of quadrat (A, m^2), sample fresh (S_{sw}, g) and dry (S_{dw}, g) mass, total fresh mass (T_{fw}, kg) in the quadrat and carbon fraction or content (CFr) as:

$$L_b = \frac{1}{n}\sum_{i=1}^{n}\frac{S_{sw}}{S_{fw}} \times \frac{T_{fw}}{1000} \times \frac{10000}{A} \times CFr. \tag{5}$$

The coarse woody debris (CWD) of the culm was estimated based on the diameter and length measurements as well as the wood density determination. The diameter and length measurements were used to calculate the inner and outer volumes of the dead culm. Together with the wood density of the decomposition class (ρ_c), the mass of the CWD was estimated. The biomass carbon of the dead culm (DC_b, Mg C ha^{-1}) was thus calculated as;

$$DC_b = \sum_{i=1}^{n}\frac{\pi L}{12}\left(d_1^2 + d_1 d_2 + d_2^2\right) \times \rho_c \times \frac{10,000}{A} \times \frac{CFr}{1,000,000}, \tag{6}$$

where n is the number of samples, d_1 and d_2 (cm) are the diameters at both ends of the CWD having taken cognisance of the hole in the culm, L (cm) is length, A (m^2) is the area of the plot, and CFr is the carbon fraction.

Above or below-ground biomass carbon stock per stand (BB_C, Mg C ha^{-1}) was estimated from the sum of the aboveground mass of the culm (Eq. (1)) or the belowground (Eq. (2)) as:

$$BB_C = \sum_{i=1}^{n} G_M \times \frac{10000}{A} \times \frac{CFr}{1000}, \tag{7}$$

where G_{M} (kg) is the above or below-ground mass of a culm, A (m^2) is the area of the bamboo stand, and CFr is carbon content.

The total carbon stock comprising the woody components of a bamboo ecosystem was estimated by adding the carbon stocks in the various components of the bamboo ecosystem, namely the aboveground bamboo biomass (ABBc), belowground bamboo biomass (BBB_{C}), litter biomass (LB_{C}) and dead culm (DC_{C}). Biomass carbon dioxide equivalent is the long-term storage of CO_2 and other carbon forms in the bamboo ecosystem's biomass components [31]. This was calculated by multiplying the carbon stock by the conversion factor from atomic C to molecular CO_2.

$$\text{TBCO}_2e = (ABBc + BBBc + LBc + DCc) \times \frac{44}{12}, \tag{8}$$

where 44 and 12 are the relative molecular masses of carbon dioxide and carbon, respectively.

3.5 Data analysis

All computations were done using statistical spreadsheets. Tables for analysis were drawn using pivot tables. The data from forest measurements and laboratory analysis were analysed using descriptive statistics, ANOVA, and covariance of the statistical toolpack for data analysis.

4 Results and discussion

4.1 Aboveground biomass and carbon

A summary of bamboo mass results, including bamboo stand areas for the four zones, the number of clumps in stands, mean (± SD) of culm diameter, age, and culm density, have been presented in Table 1. In total, 2114 culms were sampled for allometric measurements.

Uncertainty analysis was performed by calculating the mean, standard deviation, and confidence interval. The mean is the average value of the dataset, while the standard deviation measures the spread of the data around the mean. The confidence interval is a range of values likely to contain the true population mean with a certain level of confidence.

Aboveground mass uncertainty analysis was conducted by considering two main sources of uncertainty: measurement error and sampling error. Measurement error refers to the error that arises from the measurement process itself. For example, suppose the culm diameter (DBH) is measured using a tape that is not accurate. In that case, the diameter value will be incorrect, and this will introduce measurement error into the dataset. Sampling error, on the other hand, refers to the error that arises from taking a sample from a larger population. It was impossible to measure the properties of every single item in the population, so we took a sample to make inferences about the entire population. However, the sample was not perfectly representative of the population, and this introduces sampling error into the dataset.

4.1.1 *B. vulgaris* distribution density

The highest mass of *B. vulgaris* was recorded in compartment 70, representing the forest reserve's border areas. Since borders are naturally demarcated with drainage systems that are natural habitats of bamboo, the border areas in the forest reserve were the most bamboo-populated zone recording a clump density of 145 ± 58 culms per clump and an aboveground mass of 103.32 Mg. This was followed by compartment 7 (128 ± 38 culms per clump), compartment 18 (86 ± 42 culms per clump), and compartment 69 (65 ± 26 culms per clump), respectively (Tab. 1). The total

Table 1. Summary of dendrometric parameters in the selected compartments.

Forest zone	Compt.	Stand area (ha)	No. of clumps	AG_M (Mg)	Variables	Min	Max	Mean	Std. dev.
Conservation	7	0.49	18	45.24	DBH (cm)	2.35	10.94	7.25	1.45
					Age	1	≥4	–	–
					$N_{\text{culm/clump}}$	78	164	128	38
					$\text{mass}_{\text{clump}}$ (Mg)	1.27	3.47	2.51	0.88
Production	18_A	0.29	14	26.59	DBH (cm)	2.23	10.42	7.72	1.30
					Age	1	≥4	–	–
					$N_{\text{culm/clump}}$	39	138	86	42
					$\text{mass}_{\text{clump}}$ (Mg)	0.86	3.26	1.90	1.01
Bambusetum	69	0.34	16	19.36	DBH (cm)	1.12	10.63	7.02	1.78
					Age	1	≥4	–	–
					$N_{\text{culm/clump}}$	33	103	65	26
					$\text{mass}_{\text{clump}}$ (Mg)	0.55	1.91	1.21	0.48
Border	70	1.03	27	103.32	DBH (cm)	0.88	11.53	8.34	1.17
					Age	1	≥4	–	–
					$N_{\text{culm/clump}}$	76	227	145	58
					$\text{mass}_{\text{clump}}$ (Mg)	1.90	6.34	3.83	1.73
Total		2.15	75	194.51					

Table 2. Aboveground bamboo biomass and carbon stock of *B. vulgaris* in the study area.

Parameter	Value (± SD)
N_{clumps} ha^{-1}	35
N_{culms} ha^{-1}	3,710
ABB (Mg ha^{-1})	90.36
Culm Carbon content (%O.C)	47.42 ± 1.29
ABBc (tC ha^{-1})	42.85 ± 9.32

stand density of *B. vulgaris* in the selected zones in the Bobiri forest was 3710 culms ha^{-1} (35 clumps ha^{-1}) (Tab. 2).

Bamboo harvesting for commercial reasons except for research purposes [32] is prohibited in all the forest reserves in Ghana. Therefore, almost all the bamboo stands in the forest are primary stands except for the bamboo species in the bambusetum, which CSIR-FORIG intentionally established for bamboo research. The forest zone with the least bamboo density of 65 culms per clump was recorded in compartment 69, which is the closest natural stand of *B. vulgaris* in the Bambusetum. The bamboo clumps in compartment 69 had notable truncated shoots showing evidence of destructive sampling of culms from past research. Comparatively, the culm density of 3710 culms ha^{-1} for this study is higher than culm densities of 2296 and 2933 culms ha^{-1} reported for *B. vulgaris* from Cameroon [17] and Bangladesh [18] respectively, but lower than 4800 culms ha^{-1} reported in North-East India [33]. The variations in culm densities could emanate from the different silvicultural management practices in other countries.

4.1.2 Aboveground biomass

The study area's estimated aboveground mass of *B. vulgaris* was 194.51 Mg. The highest mass was recorded in compartments 70, 7, 18, and 69, with 103.32 Mg, 45.24 Mg, 26.59 Mg, and 19.36 Mg, respectively, in decreasing order (Tab. 1). The measured overall mass was extrapolated per hectare to give aboveground biomass of 90.36 Mg ha^{-1}, slightly higher than the biomass storage of 81.74 Mg ha^{-1} reported in North-East India [34]. The value recorded in this study somewhat varies from the values of 97.8 Mg ha^{-1}, and 115 Mg ha^{-1} recorded for *B. vulgaris* in a degraded tropical forest in Bangladesh [18] and a moist semi-deciduous ecological zone in Ghana [15]. However, [15] conducted their study using 15 culms in a single stand, while this study used 2,114 culms. It is important to note that accuracy of biomass estimation improves as the number of field samples increases [35]. The aboveground biomass recorded in this study greatly differs from aboveground biomass values of 53.42 Mg ha^{-1} [36] and 63.02 t ha^{-1} [17] recorded for *B. vulgaris* in a school research farm in India and a closed tropical broad-leaved rainforest in Cameroon, respectively. The wide variations may be attributed to the ecological zone, the method of inventory, and the allometric models used for biomass estimation.

4.1.3 Aboveground mass uncertainty analysis

The aboveground mass uncertainty analysis was performed by determining the descriptive statistics of the culm diameter and mass datasets. The results are presented in Table 3.

Table 3. Descriptive statistics of culm diameter and mass.

Statistic	DBH (cm)	AG_M (kg)
Mean	7.684212	22.34927
Mean standard error (SEM)	0.167	0.1.126
Median	8.0165	23.33347
Mode	8.0165	25.11787
Standard deviation	1.485427	8.283504
Sample variance	2.206492	68.61644
Minimum	0.881	0.163842
Maximum	11.525	54.29221
Count	2114	2114
Confidence level (95.0%)	0.063357	0.353312

The sampling error was estimated by calculating the standard error of the mean (SEM). The SEM for diameter indicates that the sample mean diameter is expected to be within 0.167 units of the true population mean diameter, with 95% confidence. The SEM for mass suggests that the mean sample mass is expected to be within 1.126 units of the true population mean mass, with 95% confidence. Finally, the uncertainty was visualised in the data using error bars on a scatter plot in Figure 2. The error bars were calculated using the SEM and measurement error estimates for each point in the dataset.

The error bars show the range of values each point in the dataset could take, given the uncertainty in the measurements and sampling. Although there are a few outliers in the scatter plot, the correlation between diameter and mass is 0.961, indicating a strong positive linear relationship between the two variables. The histogram of the mass suggests that the distribution is approximately normal (Fig. 3). However, the Shapiro-Wilk test suggests that the aboveground mass is not normally distributed at a confidence level of 0.05.

4.1.4 Aboveground carbon stock (ACS)

The carbon content of the various culm components was found to be 49.23% for the culm base, 48.48% for the middle, 48.22% for the top, 47.75% for branches, and 45.78 % for foliage, thus showing a decreasing tendency from the bottom to the top of the culm. Therefore, the weighted average of culm carbon content was 47.42% (Tab. 2), which corresponds to the bamboo carbon content of 47%, as reported by [31], in conformity with IPCC recommendations for tropical forests [31]. The bamboo carbon content was also comparable to the carbon content of 45.38% recorded for the same species in the Bobiri Forest Reserve [15].

4.1.5 Comparison of ACS across various species of bamboo

The carbon stock of *B. vulgaris* found in the study (42.85 ± 9.32 Mg C ha^{-1}) showed a wide variation with carbon stock values reported for the same species in Nigeria, 138.7 Mg C ha^{-1} [23] and Cameroon, 29.62 t C ha^{-1} [17]. However, it compares favourably with values of 38.42 Mg C ha^{-1} in India [33], 50.44 Mg C ha^{-1} in Bangladesh [18], and 50.76 Mg C ha^{-1} in Ghana [15] for the same species. Table 3 thoroughly compares numerous bamboo species from diverse climatic and geographic regions. In this study, *B. vulgaris* was found to have biomass-carbon storage in a manner nearly equivalent to that of other tropical and subtropical bamboo species. For example, *B. vulgaris*, which is a sympodial bamboo, was found to have comparable biomass and carbon storage values with monopodial bamboo species, *P. heterocycla* [37] and *P. pubescens* [38], from Taiwan and China (Tab. 4).

4.1.6 Comparison of ACS with other land-use systems in Ghana

The primary determinants of carbon emissions from tropical forests are land-use change rates and carbon stock changes due to degradation and deforestation [2]. Carbon stock changes in other carbon pools largely depend on the vegetation cover, which is the aboveground biomass [42]; hence, many carbon studies report on the aboveground carbon stock for which inter-plant comparisons can be made. The biomass carbon stock of *B. vulgaris* from the study was compared with other land-use systems in varied ecological zones in Ghana (Tab. 5). Natural forests, teak plantations, fallow land, and cultivated land were four diverse land-use systems considered across Ghana's various ecological zones. It was found that bamboo stands (from the study) accumulated more biomass carbon than both fallow and cultivated land usage across the ecological zones in Ghana. For example, the carbon stock value of 42.85 ± 9.32 Mg C ha^{-1} for bamboo in this study is higher than cocoa agroforestry, 22.9 ± 2.60 Mg C ha^{-1} [43]. The bamboo stands in the study also demonstrated higher biomass carbon accumulation than teak stands in the Savannah and Dry Semi-Deciduous Forest (DSDF) and natural forests in the Savannah zone. This indicates that *Bambusa vulgaris's* fast growth and rapid carbon accumulation can play a vital role in the "Green Ghana Initiative" launched by the Ministry of Lands and Natural Resources in 2021 to plant five million trees annually in the fight against climate change and also contribute to the national development agenda. This is also crucial in targeting plant species for carbon farming in Ghana's attempt to expedite the transition to a low-carbon economy to promote a sustainable environment as well as other ecological benefits.

4.2 Belowground biomass and carbon stock

Below to above-ground biomass ratio of 20% was used per the Intergovernmental Panel on Climate Change (IPCC) recommendation to estimate the belowground biomass of *B. vulgaris* [29,30] The total belowground or rhizome biomass and carbon stocks were 18.07 Mg ha^{-1} and 8.57 Mg C ha^{-1}, respectively. The value of 51.42 Mg C ha^{-1} estimated for the vegetative component consisting of the aboveground biomass carbon stock and belowground biomass carbon stock (ABBc + BBBc) in this study

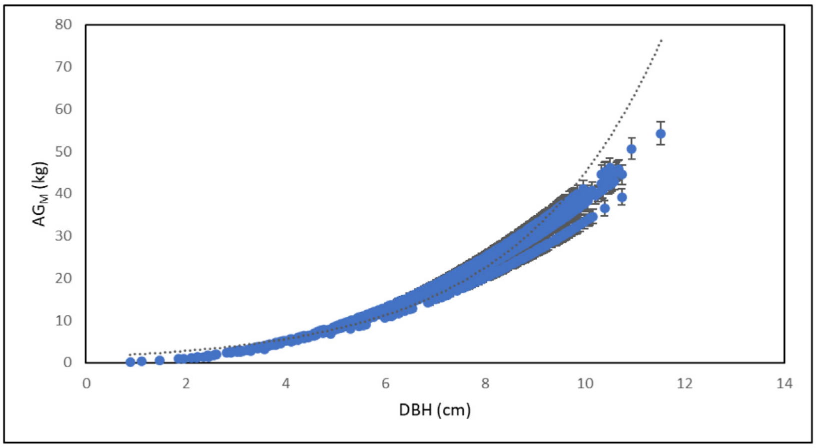

Fig. 2. Scatter plot of aboveground culm mass and diameter.

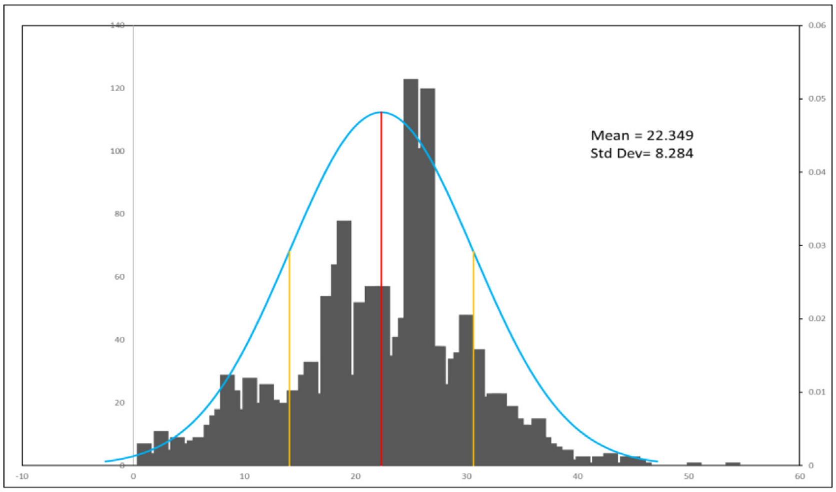

Fig. 3. Aboveground mass normal distribution curve with histogram.

favourably corresponds to plausible ranges of 24 to 192 Mg C ha^{-1} estimated for ABBc + BBBc in 70 bamboo species from 184 case studies globally [46].

4.3 Coarse woody debris (downed dead bamboo) carbon stock

Three hundred and eleven dead bamboo culms were measured within the transects across all four compartments, with 139, 72, and 100 culms representing sound, intermediate, and rotten categories, respectively. Compartment 70 recorded the highest dead culm (DC) carbon stock of 4.71 Mg C ha^{-1}, almost twice the DC carbon stock of the other compartments (Tab. 6). This is probably due to the relationship between DC and carbon stock [47]. Overall mean carbon stock across all four compartments was estimated to be 3.02 ± 1.19 Mg C ha^{-1} (Tab. 5). The sound category recorded the highest carbon stock value of 6.26 Mg C ha^{-1}, roughly double the carbon stocks in the other categories. Densities estimated based on the decomposition category showed a consistent decline trend from sound, intermediate, to rotten, respectively. However, the carbon content showed inverse results to density, with the "rotten" category recording the maximum carbon content of 48.67% organic carbon, followed by intermediate and sound with 48.58% and 48.28%, respectively. This trend of variations could be attributed to the loss of organic matter and carbon build-up as DC transitions from sound to rotten [47].

4.4 Litter pool carbon

Litter biomass (LB) carbon stock in the study area was estimated as 4.25 ± 1.3 Mg C ha^{-1} (Tab. 7). The order of decrease in carbon stocks observed in the forest zones was the bambusetum (5.30 ± 1.6), followed closely by the production zone (4.89 ± 1.0), conservation (4.06 ± 0.9), and border zone (3.45 ± 0.9). An aggregated carbon content of 38.66% organic carbon was recorded for litter from laboratory analysis across all compartments.

4.5 Biomass carbon stock and CO_2 sequestration

Bamboo is known to be an effective method for prolonged carbon storage, and recent literature reviews have investigated its potential to reduce carbon dioxide in the atmosphere [48]. One study suggests that assembled bamboo

Table 4. Comparison of biomass and carbon stock of various bamboo species worldwide.

Bamboo species	Culm ha^{-1}	Sampled culms	Biomass ($Mg\,ha^{-1}$)	C stock ($Mg\,ha^{-1}$)	Location	References
B. vulgaris (From study)	3710	2114	90	43	Ghana	
B. asper	–	5	7	–	India	[36]
B. balcooa	–	5	1045	–	India	[36]
B. bambos	–	5	76	–	India	[36]
B. nutans		5	42	–	India	[36]
B. nutans	8398	18	74	–	Thailand	[39]
B. polymorpha	5434	18	23	–	Thailand	[39]
B. strictus	–	5	13	–	India	[36]
B. tulda	11362	18	59	–	Thailand	[39]
B. tulda	–	5	70	–	India	[36]
B. vulgaris	7904	18	55	–	Thailand	[39]
B. vulgaris	2933	12	97	50	Bangladesh	[18]
B. vulgaris	–	5	53	–	India	[36]
B. vulgaris	2296	–	63	30	Cameroon	[17]
B. vulgaris	6267	15	115	51	Ghana	[40]
B. vulgaris	17900	80	258	139	Nigeria	[23]
B. vulgaris (vitata)	7171	15	71	83	Ghana	[40]
C. pergracile	4940	18	14	–	Thailand	[39]
D. brandisii	8398	18	79	–	Thailand	[39]
D. longispathus	5928	18	17	–	Thailand	[39]
D. strictus	13832	18	41	–	Thailand	[39]
M. baccifera		180	118	58	India	[25]
O. abyssinica	3325	15	4	2	Ghana	[40]
O. abyssinica	4374	–	28	13	Cameroon	[17]
P. aurea	38017	–	144	68	Cameroon	[17]
P. heterocycle	7100	–	89	41	Taiwan	[37]
P. makinoi	21191	–	105	50	Taiwan	[41]
P. polymorphum	–	90	43	21	India	[25]
P. pubescens	3968	–	88	40	China	[38]
S. dullooa	–	132	45	23	India	[25]
T. siamensis	6916	18	32	–	Thailand	[39]

components have a 37% chance of reducing CO2 from the atmosphere, and one tonne of laminated bamboo lumber stores 140 kg more carbon than timber [48]. The total biomass carbon stock of *Bambusa vulgaris* in the Bobiri Forest Reserve was determined to be 58.69 Mg C ha^{-1}. This value compares well with the carbon stock range of 40–75 Mg C ha^{-1} for trees in general [49]. The aboveground carbon pool recorded the highest wood carbon stock, with 42.85 Mg C ha^{-1} representing 73% of the total biomass carbon stock. Carbon stock values of 8.57 Mg C ha^{-1}, 3.02 Mg C ha^{-1}, and 4.25 Mg C ha^{-1} were recorded for belowground, coarse wood, and litter carbon pools, respectively. The carbon dioxide equivalent of *B. vulgaris* in the various forest zones was estimated separately to understand better the carbon sequestration potential of bamboo stands in a tropical forest like Bobiri (Fig. 4).

The research findings showed that bamboo plantations distributed along the edge (border) of the forest reserve sequester more carbon dioxide (238.48 Mg CO_{2e} ha^{-1}) from the atmosphere than bamboo stands located deep inside the production (218.77 Mg CO_{2e} ha^{-1}) and conservation zones (217.63 Mg CO_{2e} ha^{-1}). The border zone recorded the highest aboveground carbon stock, an indication of the potential of this zone to sequester higher CO_2. Therefore, it was not surprising that the highest CO_2 equivalent was recorded in this zone. Furthermore, this variation was ascribed to the “edge effect”, where there is a greater diversity of life in boundary or overlapping regions of two ecosystems [50]. This effect may also account for the high population density of *B. vulgaris* in the border zone. The natural *B. vulgaris* stand closest to the bambusetum

Table 5. Comparison with other land-use systems in varied ecological zones in Ghana.

Land-Use	Eco-zone	Biomass (Mg ha^{-1})	C stock (Mg ha^{-1})	References
Bamboo Stand	MSDF	90.4	42.9	From study
Fallow	Savannah	1.9	1.0	[44]
	DSDF	3.4	1.7	
	MEF	5.1	2.6	
Cultivated	Savannah	–	–	[44]
	DSDF	1.6	0.8	
	MEF	4.5	2.2	
Teak Stand	Savannah	52.2	26.1	[44]
	DSDF	51.2	25.6	
	MEF	195.4	97.7	
Natural Forest	Savannah	31.8	15.9	[44]
	DSDF	356.6	178.3	
	MEF	458.8	229.4	
	EF	284	142	[45]
	MSDF	254	127	
	DF	202	101	
	WS	124	62	

MSDF, Moist Semi-Deciduous Forest; DSDF, Dry Semi-Deciduous Forest; MEF, Moist Evergreen Forest; EF, Evergreen Forest; WS, Woody Savanna.

Table 6. Summary of results for coarse woody debris carbon.

DC Decomposition category	Parameter	Forest Zone				Total DCc (Mg C ha^{-1})
		Conservation	Production	Bambusetum	Border	
		Compt. 7	Compt. 18$_A$	Compt. 69	Compt. 70	
Sound	Density (g cm^{-3})	0.2923	0.2775	0.2519	0.2889	6.26
	Volume (cm^3)	124325.79	68117.67	104728.56	167191.02	
	Mass (g)	36340.28	18902.65	26383.22	48301.49	
	C content (%)	48.28	48.28	48.28	48.28	
	C stock (Mg C ha^{-1})	1.75	0.91	1.27	2.33	
Intermediate	Density (g cm^{-3})	0.2766	0.2562	0.2399	0.2495	2.80
	Volume (cm^3)	26204.52	55215.61	54581.09	92548.23	
	Mass (g)	7248.17	14146.24	13094.00	23090.78	
	C content (%)	48.58	48.58	48.58	48.58	
	C stock (Mg C ha^{-1})	0.35	0.69	0.64	1.12	
Rotten	Density (g cm^{-3})	0.2143	0.2265	0.2338	0.2452	3.00
	Volume (cm^3)	31157.80	37669.32	88982.62	104933.86	
	Mass (g)	6677.12	8532.10	20804.14	25729.78	
	C content (%)	48.67	48.67	48.67	48.67	
	C stock (Mg C ha^{-1})	0.32	0.42	1.01	1.25	
Mean DCc (Mg C ha^{-1})		2.43*	2.02*	2.92*	4.71*	3.02 ± 1.19

* The values marked with asterisks (*) are not means but totals of C stock for the forest zones (last row).

Table 7. Summary of litter mass and carbon analysis.

Forest zone	Compartment	Total dry weight (g)	LBc (tC/ha)
Conservation	7	262.65	4.06 ± 0.9
Production	18	316.26	4.89 ± 1.0
Bambusetum	69	342.70	5.30 ± 1.6
Border	70	223.09	3.45 ± 0.9
Mean		274.53	4.25 ± 1.3

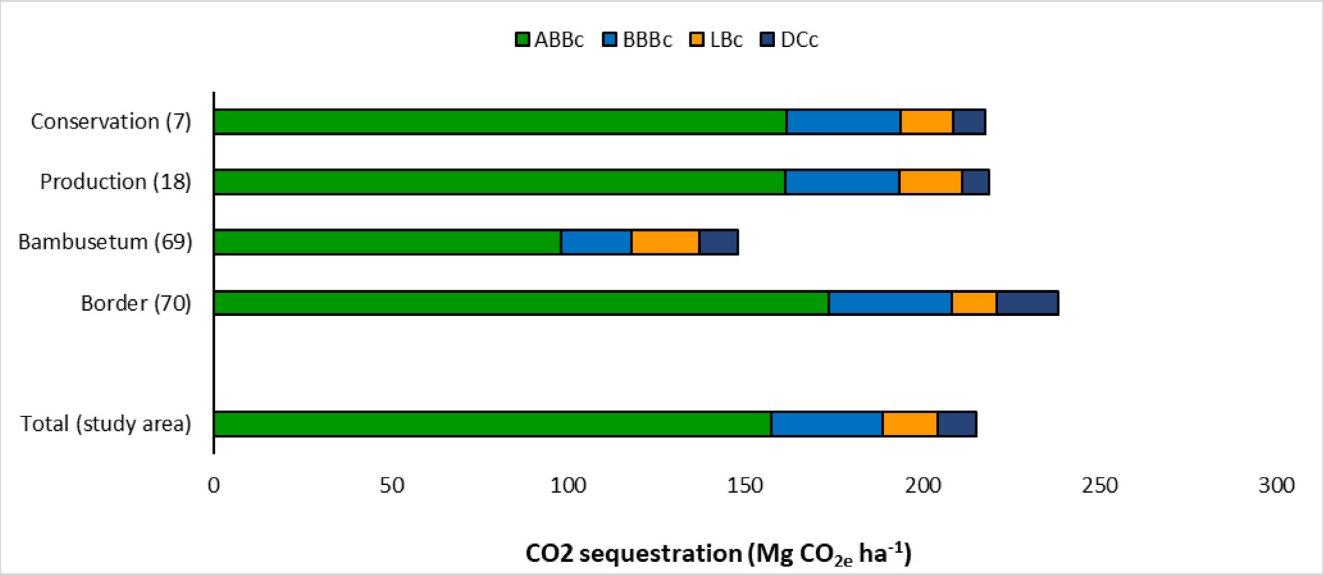

Fig. 4. Biomass CO_2 sequestration of B. vulgaris in the study compartments.

recorded the least carbon dioxide sequestration potential of 147.90 Mg CO_{2e} ha^{-1}, probably due to anthropogenic disturbance due to its ease of accessibility.

The total CO_2 equivalent for the study area was 215.39 Mg CO_{2e} ha^{-1}. Regarding the percentage of CO_2 equivalent for the biomass carbon pools, the contribution was 73, 15, 5, and 7% for aboveground, belowground, dead culm, and litter, respectively.

5 Conclusions and future directions in the field

This study comprehensively assessed the biomass and carbon stock for *Bambusa vulgaris*, a fast-growing bamboo species commonly found in Ghana. The study was carried out to contribute to understanding carbon sequestration potential and the role of bamboo in mitigating climate change.

The results showed that the aboveground biomass and carbon stock of *B. vulgaris* were 5-fold that of belowground, with a value of 90.36 ± 19.65 Mg ha^{-1} and 42.85 ± 9.32 Mg C ha^{-1}, respectively. The aboveground carbon stock was 73% of the total biomass carbon stock, indicating the importance of the aboveground components in carbon sequestration. Carbon stocks for belowground, coarse wood and litter in *B. Vulgaris* stands were also found to be 8.57, 3.02, and 4.25 Mg C ha^{-1}, respectively. These carbon pools are often overlooked in carbon accounting studies, but their inclusion in forest carbon estimates is crucial for accurately assessing the plant carbon cycle. In addition, the study found that the carbon dioxide sequestration potential of *B. vulgaris* was significantly high compared to trees in general, with a value of 215.39 Mg CO_{2e} ha^{-1}.

The study's findings demonstrate that bamboo has considerable potential to contribute to Ghana's transition to a low-carbon economy through carbon stock monitoring, reporting and policy development. Also, it could be a valuable resource for climate change mitigation strategies, and future research should investigate the potential of other bamboo species in this regard. Moreover, the inclusion of relevant carbon pools, including coarse wood and litter, in forest carbon estimates should be encouraged to provide a comprehensive understanding of the plant carbon cycle.

Data availability

The raw and processed data required to reproduce these findings are available to download from https://data.mendeley.com/datasets/2mkx8ht3k8/1 [51].

Conflict of Interest

The authors declare that there is no conflict of interest.

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