Allometric scaling, biomass accumulation and carbon stocks in natural highland bamboo (Oldeania alpina (K. Schum.) Stapleton) stands in Southwestern Ethiopia

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ABSTRACT
Bamboos provide a number of ecosystem services, including the provision of a permanent carbon (C) sink. The present study was undertaken in the Sheka forest, currently recognized as a UNESCO Biosphere Reserve. The objectives of this study were to: (1) develop species- and site-specific allometric models for biomass estimation and (2) quantify the carbon storage capacity of highland bamboo stands. A total of 12 plots each measuring 10 m x 10 m were established at a distance of 200 m in the forest. 96 culms were harvested for the development of biomass estimation equations. Litter samples were collected in 1 m x 1 m subplots, while soil samples were collected at 0 – 10, 10 – 20, 20 – 40, and 40 – 60 cm soil depths for determination of soil organic carbon (SOC) contents. The estimated mean DBH, basal area and plant height were 7.0 cm, 53.2 m² ha⁻¹ and 12.9 m, respectively. The study has established allometric scaling of plant height with stem diameter in highland bamboo. It has also established that the allometric model is superior to commonly used non-linear H-DBH models. Aboveground biomass was estimated at 93 Mg ha⁻¹ with mean C stocks of 43.7 Mg ha⁻¹. The estimated below-ground biomass was 18.6 Mg ha⁻¹ with C stocks of 8.7 Mg ha⁻¹. The C stocks in the litter layer were estimated at 1.57 Mg ha⁻¹. Soil organic C stock of highland bamboo stands was 388.1 Mg ha⁻¹ within the 0 – 60 cm soil depth. In total, the natural highland bamboo stands store approximately 442.1 Mg C ha⁻¹. The estimated C stocks were comparable with values reported for bamboos in Ethiopia and elsewhere. It is concluded that natural highland bamboo stands play a significant role as carbon sinks. The insights gained in this study are expected to be applicable to Afromontane ecosystems where highland bamboo occurs in Africa.

HIGHLIGHTS
- Highland bamboo (Oldeania alpina) is a conspicuous element of Afromontane vegetation in Africa
- We developed models for estimating biomass carbon (C) stocks in highland bamboo stands
- We estimated biomass C stock of highland bamboo stands at 52.5 Mg ha⁻¹ and litter C at 1.6 Mg ha⁻¹
- Soil organic C stock of highland bamboo stands was 388.1 Mg ha⁻¹
- Total system C in highland bamboo stands was over 442 Mg ha⁻¹

Introduction
Forests play an important role in the global terrestrial carbon cycle, and their potential to sequester additional atmospheric carbon dioxide is considered a mitigation strategy to reduce global climate warming [1,2]. Following the “Kyoto Protocol,” many studies have focused on evaluating the contributions of forests to the accumulation and storage of carbon worldwide [3]. The ability of forests to store large amounts of carbon in their aboveground and belowground biomass, litter and soils represents one of the path ways for confronting climate change [4].
In recent decades, bamboo has become a globally important biomass resource in tropical regions [5]. Due to their fast growth, ability to produce a large amount of woody biomass and sequester C, bamboo can play a significant role in climate change mitigation, adaptation, and rural livelihoods [6,7]. In 2011, bamboo was estimated to cover 22 million hectares globally, which translates into a sequestration potential of 727.08 teragrams of carbon [8]. Many bamboo species studied thus far have notable carbon storage potential [7,9]. The carbon stocks in bamboo stands are nearly equal to or higher than those in many fast-growing timber species [3]. Ecosystem carbon storage of 94–392 Mg ha\(^{-1}\) and sequestration rate of 8–14 Mg ha\(^{-1}\) yr\(^{-1}\) for woody bamboos are comparable with agroforestry and forest ecosystems [7].

The versatility and unique characteristics of bamboo provide communities with options to diversify their economies and increase resilience. Bamboos can be a tool in local coping strategies that aim to increase the resilience of livelihoods [8]. Moreover, they provide important ecosystem services like water conservation, erosion control, habitats for plants and wildlife (biodiversity) and soil fertility improvement [6,7,10–16]. Carbon markets will offer an additional opportunity to increase incomes. As such, bamboos can generate tradable amounts of carbon under CDM and REDD schemes.

Nonetheless, past climate change negotiations have overlooked the role bamboos can play in carbon sequestration [6]. Hence, bamboos were missed in the forest definitions under the CDM, and they were ignored in IPCC Assessment Reports and guidelines for greenhouse gas emission inventories [9]. The CDM Executive Board, in its 39\(^{th}\) meeting, decided that “Palm (trees) and bamboos are equivalent to trees in the context of afforestation and reforestation” [17,18]. In line with this, programs like Bamboo for Africa of the Food and Trees for Africa were certified under the verified carbon standard [19]. However, in reducing emissions from deforestation and land degradation (REDD) programmes bamboo ecosystems have not been given due recognition [17]. Not considering bamboo stands as forests in a future regime of REDD\(^+\) in developing countries would neglect significant carbon stores, undermine highly effective carbon sinks, and constrain proven pillars of rural livelihoods [20]. Thus, there is a strong need to recognize the ecosystem services of woody bamboos for the well-being of society and nature conservancy and for considerations towards trading of carbon credits [7]. The estimation of biomass is an important step in monitoring changes in carbon stocks in natural stands of bamboo ecosystems [21]. Bamboo biomass is highly heterogeneous in space and time [22], and it can vary with species, climate, soil fertility, plant density and age [23].

Highland bamboo (*Oldeania alpina*) (formerly known as *Arundinaria alpina*, *Sinarundinaria alpina*, and *Yushania alpina*) is one of the poorly studied species. In 2013, *Arundinaria alpina* was transferred from the genus *Yushania* (now treated entirely as an Asian genus) to *Oldeania* by Stapleton [24]. The species is widely distributed in Afrotropical forests across tropical Africa (Figure 1) from Cameroon in the west to Ethiopia in the east and Malawi in the south [27], mostly occurring on high mountains (2000–4000 m altitude) [28–30], which

Figure 1. (a) The distribution of Afrotropical vegetation zones covering West African and Cameroon highlands (I), Ethiopian highlands (II), Western (Albertine) Rift (III), Eastern Rift (IV), Southern Rift (V), Eastern Highlands (VI) and Drakensberg (VII); (b) Eastern Afrotropical forests; and (c) distribution of *Oldeania alpina* in the Afrotropical vegetation zones. Source [24–26].
are some of the most important water towers in Africa [31]. It also occurs at lower altitudes of 1600 m in the Uluguru Mountains in Tanzania. It is a conspicuous element in Afromontane vegetation cover Ethiopia, Kenya, DR Congo, Rwanda, Uganda, Tanzania and Malawi in eastern Africa, and the Bamenda Mountains of Cameroon [27]. Its area of potential occurrence is estimated at approximately 20.2 million ha [10, 32]. This species forms dense stands on the high mountains of significant conservation status, including Mt. Kivu in Zaire, the Virunga transboundary protected area that includes parks in the Democratic Republic of Congo, Uganda and Rwanda [33], the Aberdares and Mau ranges and Mt. Kenya in Kenya, the highlands of Ethiopia, Mt. Uluguru in Tanzania, Mt. Mulanje in Malawi, and Mt. Cameroon in Cameroon [24, 31, 33,34]. It provides habitat and food for the critically endangered eastern Mountain Gorilla in the Virunga transboundary protected area and mountain bongo in the Aberdare Mountains [24, 33].

In Ethiopia, highland bamboo naturally occurs in the southern and central parts of Ethiopia, mainly in the Oromia, Southern Nations, Nationalities, and Peoples, South West Ethiopia Peoples and Amhara Regional States [35]. As part of agroforestry practices, highland bamboo is also planted and managed by farmers in various niches in Ethiopia [32]. It is a very useful plant species for both rural and urban dwellers in Ethiopia [11–13].

Accurate estimation of carbon sequestration by highland bamboo stands at the local, national and continental scales is important for improving the understanding of forest carbon dynamics and the potential of Afromontane forests to mitigate future climate change. However, the biomass estimation and carbon sequestration potential of highland bamboo remain poorly understood in Africa. This severely limits our understanding of the important role of highland bamboo in national and regional carbon sequestration and climate change mitigation. Therefore, the main aim of this study is to (1) develop species- and site-specific allometric models for biomass estimation and (2) quantify the carbon storage capacity of highland bamboo stands. Although the study focused on the Sheka forest, the insights gained through this study are expected to be applicable to the Afromontane ecosystems where highland bamboo occurs in Africa.

**Materials and methods**

**Study area**

The study was conducted in parts of the Sheka forest located in the Andracha district of the Sheka Zone, South West Ethiopia Peoples’ Region (Figure 2). The district lies between 7°22'–7°45' N latitude and 35°6'–35°35' E longitude. It covers an estimated area of 1,011.7 km². The altitudinal range of the area falls between 838 and 2756 m asl, and it receives a high amount of rainfall, with an average of 1800–2200 mm annually [36] for approximately nine months. The mean annual temperature of the zone is approximately 17.6 °C. The soil type of the selected bamboo site is clay soil. The vegetation is mostly characterized by typical Afromontane forests, which constitute a unique forest type occurring on high African mountains [37–39].

The forest received the status of a Biosphere Reserve, according to the UNESCO MAB Program in 2012 [40]. The Sheka forest constitutes one of the few remaining pristine moist afromontane
forests in Ethiopia. As such, it is highly regarded as important for the conservation of afromontane forest vegetation types including alpine bamboo thickets [41]. The reserve represents a unique biogeographic unit extending from cold and very wet highlands bordering the Illubabor zone of the Oromia regional state and Kafa zone to hot lowland areas bordering the Gambella regional state and the Bench-Sheko zone. Highland areas above 2000 m asl are mostly covered by highland bamboo. The bamboo thickets form monoculture stands, except for very few scattered trees.

Data collection and processing

For data collection, line transects were laid out systematically from the top ridges of the mountain to the bottom edge. The first transect was aligned randomly on one side of the forest using a compass. Thereafter, the other transects were laid at intervals of 300 meters from each other in the bamboo stands. Sample quadrants measuring 10 m by 10 m were laid down at 200 m distance [42,43] along line transects. A total of 12 plots (four plots per transect) were established in the study area.

In the sample plots, data on structural variables, including diameter at breast height (DBH), basal diameter, total height, culm density and culm age, and environmental factors, such as slope, aspect and altitude, were recorded [2]. Bamboo culms were grouped into four age classes: age class 1, one-year-old culms; age class 2, two- and three-year-old culms; age class 3, four- and five-year-old culms; and age class 4, culms more than five years old [2] using indicators (Table 1). A total of 96 culms were randomly selected and harvested (two culms from each age class and plot) for biomass estimation [42]. Destructive sampling was employed to estimate the above and belowground biomass of highland bamboo following methods used in Singnar et al. [46]. The rhizomes and roots were excavated by digging trenches to a depth of 60 cm in a circular pattern around the culm. Then rhizomes and roots were manually extracted from the soil surface to bottom of the trench [46]. Each bamboo plant was separated into culm, branch and leaf, and rhizome and root parts and fresh weights were recorded on the spot in the field. In addition, plant litter on the forest floor was collected and measured in a 1 m x 1 m subplot per plot. Subsamples were taken from each part for dry matter determination.

Soil samples were collected for organic carbon content analysis from the 0–60 cm depth divided into four layers: 0–10, 10–20, 20–40, and 40–60 cm [43, 47]. The soil samples were taken from five spots, i.e. four in the corners and one in the center of the plot. All the samples from each layer were aggregated, and a composite sample was taken. Soil bulk density was determined using the soil core-ring method in each layer [43]. The textural classes of the soil in the study area are clay, clay loam, sandy clay and sandy clay loam. The average soil bulk densities in the bamboo stands based on the entire profile depths (0–60 cm) are shown in Table 2. There was a gradual increase in the soil bulk density with increasing soil depth. In contrast, soil organic matter (SOM) and soil organic carbon (SOC) contents decreased with increasing soil depth, where the upper soil layer contained most of the soil organic matter and carbon (Table 2). However, different sites in the study area showed slight variations in soil bulk density and soil organic matter.

Plant and soil analysis

Plant subsamples were dried to constant weight at 85 °C, and mean values of the dry to fresh weight ratios for different parts were computed [42]. The dry biomass of the different bamboo components in each age-class category was determined by the ratio of absolute dry weight-to-fresh weight ratio

| Table 1. Criteria used for age determination of highland bamboo [15, 42, 44, 45]. |
| Bamboo age group | Description of age group | Indicators |
|------------------|--------------------------|------------|
| Age group 1      | 1 year old               | Stem dark green and smooth with fully or partly covered by fresh looking sheath and have poor strength; smaller leaf size and no or few branches; internode covered with white flour, nodes are hairy; free from any spot or sign of infestation by moss or lichen |
| Age group 2      | 2–3 years old            | Stem pale green with no sheath or dirty and ragged sheath and slightly rough to the feel; branches and leaves are fully developed; no or very small lichen |
| Age group 3      | 4–5 years old            | Stem strong yellowish green with dry appearance and rough surface; small lichen |
| Age group 4      | >5 years old             | Stem gray color and hard to cut; moss and lichen are prevalent on nodes and internodes |
of samples [9, 48]. The average dry-to-fresh weight ratio for different parts is summarized in Supplementary Table S1. Litter dry weight was determined in a similar way to the plant biomass [49].

Soil bulk density was determined from the oven-dry weight of soil from a known volume of sampled material. In analyzing bulk density, samples are dried in an oven at 105 °C for a minimum of 48 h [49]. The SOC concentration was determined by wet digestion following Schumacher [50].

### Statistical analysis

#### Modelling allometric relationships

This study looked into allometric relationship between plant height (H), stem diameter (DBH) and aboveground biomass (AGB) of *Oldeania alpina*. The analysis examined H-D scaling in light of allometric theory, which provides competing prediction scaling [51]. The theoretical models are the geometric similarity, stress similarity, elastic similarity and metabolic theory of ecology [52,53]. The geometric similarity model predicts a scaling exponent of 1. The stress similarity hypothesis predicts an exponent of 0.50, while elastic similarity and metabolic theory predict an exponent of 0.667 [54]. Similarly, different allometric scaling theories predict different exponents for the scaling between plant biomass (M) and D. The stress similarity hypothesis predicts a scaling exponent of 2.50, while elastic similarity and metabolic theory predict a common scaling exponent of 2.667 between M and D [51]. The elastic similarity hypothesis assumes biomechanical constraints, while metabolic theory assumes metabolic constraints and resource transport in scaling relationships [53,54]. Empirical studies suggest that scaling relationships may vary across species due to species-specific differences in biomass partitioning patterns and ecological responses to different environmental conditions [51, 54]. Although the scaling exponent is stochastic in nature, it is expected to converge around its theoretical values as the sample size increases [51]. In this analysis, we tested hypotheses regarding the allometric scaling relationships using the H, D and M data for highland bamboo. The allometric model is based on a power function [3, 55], which takes the following form: $Y = ax^b$ where $Y$ is either plant height or biomass, $a$ is the normalization (proportionality) constant, $b$ is the exponent (slope) and $X$ is stem diameter at breast height (1.3 m). For ease of analysis, the linear form of the above function is often used [16], which involves logarithmic transformation of both the $Y$ and $X$ variables as follows:

$$\ln(Y) = \ln(a) + b(\ln X) + \varepsilon$$

(1)

It is well known that the value of the exponent can be biased due to the presence of outliers, measurement errors and inadequacy of sample size [51]. Differences in the exponent and deviations from theoretical values may arise simply due to the differences in the way measurement errors and outliers are handled by the regression technique used. Therefore, we estimated the exponent using ordinary least square (OLS), reduced major axis (RMA), major axis (MA) and robust regression analysis (RRA). OLS regression is known to produce biased estimators of the exponent when measurement errors in the $X$ variable are large in a dataset. In such situations, RMA and major axis regressions are recommended to account for measurement error. After comparing different regression techniques, Hu et al. [56] found that RMA is the least biased method. According to Taskinen and Warton [57], neither OLS nor RMA are robust to outliers and leverage points. RRA provides more stable coefficients than OLS and RMA if there are outliers in either the $X$ or $Y$ variable [57].

Initially, we explored the data for each age group separately. Since the sample sizes ($N = 24$) in each age group were too small, we also explored the analysis after combining the data for the different age groups. If the residual variance is heterogeneous, the validity of statistical tests from combined data can be severely undermined. The comparison of slopes also becomes legitimate only when homogeneity of residual variance has been established. Therefore, we first tested for the homogeneity of residual variances between the four age groups using Bartlett’s test. Then, we performed a null hypothesis (Ho) test for equality of

| Soil Depth (cm) | Bulk Density (g/cm³) | SOC content (%) | SOC stocks (Mg C ha⁻¹) |
|----------------|----------------------|----------------|------------------------|
| 0–10           | 0.81                 | 11.80          | 95.31                  |
| 10–20          | 0.92                 | 9.46           | 86.30                  |
| 20–40          | 0.98                 | 6.63           | 130.44                 |
| 40–60          | 0.99                 | 3.82           | 76.07                  |

Table 2. Soil bulk density, SOC content and SOC stocks at different soil depths in the natural highland bamboo forest.
the slopes (Ho: $b_1 = b_2 = b_3 = b_4$) and elevation (Ho: $a_1 = a_2 = a_3 = a_4$) as recommended by White [58].

The OLS, RMA and robust regression analyses do not take into account nesting in the data when different age groups are combined. Ignoring nesting in data can impact estimated variances and the resulting parameters. Therefore, we applied a linear mixed model (LMM) with a random intercept where the subject was an age group. The rationale for the use of LMM is that both fixed and random parameters can be entered in the model simultaneously, thus providing more consistent estimates of parameters and their standard errors than conventional methods such as OLS and RMA.

In addition, non-linear models that have been commonly used for modelling H-D relationship [1, 5] were compared with the power law function. For this comparison, the Chapman, Gompertz, logistic, monomolecular and Richarl functions were used as they have been used frequently [1, 5, 46]. Finally, the performances of the various models were compared using the $R^2$ and root mean square of error (RMSE) and the mean absolute error (MAPE). Since $R^2$ is not applicable to LMM and the $R^2$ of linear and non-linear models cannot be directly compared. The $R^2$ is inappropriate for such comparisons because the residual variance and explained variance do not add up to total variance in no-linear models. As such, the $R^2$ does not necessarily fall between 0 and 1, and that is why it is called pseudo $R^2$ in non-linear models. The $R^2$ can also remain close to 1.0 even when the model is poor and unable to distinguish between bad and good models [51]. Therefore, the comparison of LMM and non-linear models was entirely based on RMSE and MAPE. Ideally, the values of RMSE and MAPE should be close to zero, indicating no error or perfect simulation. A model is deemed valid for the data when it yields MAPE ≤ 20% [51].

The 95% confidence intervals (CIs) were used to represent the uncertainty around estimates of the allometry parameters. The calculation of 95% CIs assumes normality of residuals and independence between the variables and the variance of residuals. For 95% CIs to be reliable, the sample sizes (N) should also be greater than 28 [59]. However, the sample sizes were only 24 in each age group. Therefore, the 95 CIs were estimated using 1999 bootstrap replicates performed in PAST 3.14 software [60].

For each analysis, we conducted various diagnostics to check whether certain observations have undue influence on the coefficients. These diagnostics included tests of normality, homogeneity, outliers and leverage points. The normality of residuals was ascertained using the Shapiro–Wilks W statistic and examination of the normal probability plots. The Breusch–Pagan test was used to check for heterogeneity of residuals.

**Biomass estimation models**

Tree biomass is often estimated from equations that relate biomass to DBH only [49]. Although the combination of DBH and height as the independent variables is often superior to using DBH alone, measuring height in bamboos is difficult owing to culm density and can be time consuming and liable to error. Thus, many models for bamboo AGB use DBH alone [1, 61, 62], and these are given as follows.

$$\ln(AGB) = ln(a) + b(\ln D) + \epsilon$$

Previous studies (e.g. [5, 46]) have demonstrated that $D^2H$ is a better predictor of AGB of bamboos than $D$ or $H$ alone. Strictly speaking, a model with ($D^2H$) is not allometric in nature, as it involves a compound variable [51] given in the following form:

$$\ln(AGB) = \ln(\alpha) + \beta(\ln(D^2H))^\epsilon$$

where $AGB$ is aboveground biomass, $D$ is diameter at breast height, and $H$ is plant height.

We also cross-validated Eqs. (2) and (3) using the K-fold cross-validation method. We implemented cross-validation using macros written in the SAS system and the procedure PROC SURVEYSELECT to generate the samples and the REG procedure to estimate the parameters. We used the cross-validation $R^2$, RMSE and the mean absolute error (MAE) for comparing the two models. In the arithmetic scale, the RMSE is more sensitive to occasional large errors as the squaring process gives disproportionate weight to very large errors. Therefore, we did all cross-validation on the log-transformed data.

**Estimating plant biomass and carbon stocks**

The aboveground biomass was estimated using the developed allometric equation based on the diameter and age class, whereas biomass density (kg ha$^{-1}$) was calculated by summing all bamboo biomass values in different age classes within the unit area (ha) [48]. Below-ground biomass was calculated using the average sample ratio of below-ground biomass to aboveground biomass [63].
Table 3. Stand structure of highland bamboo in the study area. Values in parentheses are the 95% confidence limits.

| Age group | Variables | 1 | 2 | 3 | 4 | All |
|-----------|-----------|---|---|---|---|-----|
| Density (culms ha$^{-1}$) | | 1,067 | 2,442 | 4,425 | 5,367 | 13,301 |
| DBH (cm) | | 7.4 (7.1, 7.6) | 6.8 (6.6, 7.0) | 6.8 (6.7, 6.9) | 7.2 (7.1, 7.3) | - |
| Height (m) | | 13.2 (12.5, 14.0) | 12.9 (12.1, 13.6) | 12.5 (11.9, 13.2) | 13.0 (12.3, 13.7) | - |
| Basal area (m$^2$ ha$^{-1}$) | | 4.7 (3.3, 6.0) | 9.2 (6.6, 11.9) | 16.7 (12.0, 21.4) | 22.7 (16.9, 28.4) | - |
| AGB (Mg ha$^{-1}$) | | 6.2 (–0.8, 13.2) | 17.1 (10.1, 24.1) | 29.8 (22.9, 36.8) | 39.9 (32.9, 46.9) | 93.0 (78.6, 107.4) |
| BGB (Mg ha$^{-1}$) | | 1.2 (–0.2, 2.6) | 3.4 (2.0, 4.8) | 6.0 (4.6, 7.4) | 8.0 (6.6, 9.4) | 18.6 (15.7, 21.5) |
| Total biomass (Mg ha$^{-1}$) | | 7.4 (–1.0, 15.8) | 20.5 (12.1, 28.9) | 35.8 (27.4, 44.2) | 47.9 (39.5, 56.3) | 111.6 (94.4, 128.9) |

Litter biomass was calculated in accordance with Pearson et al. [49], which was given by:

\[
\text{Litter biomass (t ha}^{-1}\text{)} = (\text{litter oven dry weight(g)/sampling frame area (cm}^2\text{)}) \times 100
\]

The quantity of biomass carbon was estimated by converting oven-dried biomass to units of carbon by multiplying the Intergovernmental Panel on Climate Change (IPCC) default carbon fraction of 0.47 [64]. The carbon stocks were calculated by summing the carbon storage of all bamboos at different age classes within a unit area [48].

Estimating soil carbon stocks

The soil organic carbon stock was computed using the following equation [65]:

\[
CS_{\text{soil}} \text{ (Mg C ha}^{-1}\text{)} = \sum_{i=1}^{n} BD_i \times C_{\text{conc}_i} \times D_i \times 0.1
\]

where $CS_{\text{soil}}$ is the C stock of soil (Mg C ha$^{-1}$), $BD_i$ is the soil bulk density in layer i (Mgm$^{-3}$), $C_{\text{conc}_i}$ is the SOC concentration in layer i (g kg$^{-1}$), $D_i$ is the thickness of layer i (cm), and i is the soil layer number.

Finally, the aboveground biomass carbon, soil organic carbon and total biomass carbon pools in the different age groups were compared using one-way analysis of variance. Differences between age groups were considered significant when $p < 0.05$. When the omnibus $F$ test showed significance, Tukey’s HSD test was used for post-hoc comparisons among means of the different age groups.

Results

Stand structure

In the study area, highland bamboo grows in pure stands. The stand characteristics in terms of age-specific mean diameter at breast height (DBH), basal area, height and culm density are summarized in Table 3. Examination of the 95% CI of DBH and stem height did not reveal a significant difference between age groups (Table 3). The percentages of culms to the total stand density in age groups 1, 2, 3, and 4 were 8.0, 18.4, 33.3 and 40.4%, respectively. This resulted in a stand density ratio of 1:2.3:4. The number of bamboo plants in diameter classes 5–7 cm and 7–9 cm accounted for 37.9 and 48.5% of the total samples, respectively. The mean DBH was 7.0 cm, the basal area was 53.24 m$^2$ ha$^{-1}$, the plant height was 12.9 m and the plant density was 13,301 culms ha$^{-1}$ (Table 3). The dry-to-fresh weight ratio was highest for branches and foliage, followed by culms and rhizomes/roots. The dry-to-fresh weight ratio (0.39) of leaves and branches in age group 3 was slightly higher than that in the other age groups (0.35–0.37).

Allometric scaling

Height-diameter allometry

Parameters of the H-D allometric scaling are summarized in Table 4. Bartlett’s test of equality of variances did not reveal significant differences between the age groups ($\chi^2 = 1.74$; $p = 0.629$). The test of equality of variance also did not reveal significant differences between the exponents ($F = 2.13$; $p = 0.1020$) and elevations ($F = 0.36$; $p = 0.7815$). The analysis of data separately for each age group also produced severely biased parameters with large uncertainty. Therefore, fitting the H-D models for each age group was deemed inappropriate. Accordingly, the data combined for all age groups were subjected to OLS, LMM, RMA, major axis and robust regression analysis (Table 4). With the smallest RMSE and MAPE, robust regression gave the best estimate of parameters of the H-D allometry (Table 4). The estimates of the exponents generated using OLS, LMM and robust regression were not significantly different from the theoretical value of 0.50, as their 95% CI
Table 4. The H-DBH and biomass-DBH allometric scaling in highland bamboo stands.

| Method   | Intercept (95% CL) | Slope+p (95% CL) | R² | RMSE+p | MAPE |
|----------|--------------------|------------------|-----|--------|------|
| H-DBH    |                    |                  |     |        |      |
| OLS      | 1.84 (1.55, 2.15)  | 0.37 (0.21, 0.52) | 0.207 | 0.1107 | 3.6  |
| RMA      | 1.00 (0.74, 1.28)  | 0.81 (0.67, 0.94) | 0.207 | 0.1298 | 4.1  |
| MA       | 1.33 (0.85, 1.88)  | 0.64 (0.35, 0.88) | 0.207 | 0.1180 | 3.8  |
| Robust   | 1.81 (1.46, 2.16)  | 0.39 (0.20, 0.57) | 0.170 | 0.1106 | 3.6  |
| LMM      | 1.84 (1.54, 2.14)  | 0.36 (0.21, 0.52) | NA   | 0.1120 | 3.7  |
| AGB-DBH  |                    |                  |     |        |      |
| OLS      | −0.23 (−0.74, 0.23) | 1.00 (0.86, 1.37) | 0.477 | 0.1784 | 8.1  |
| RMA      | −1.17 (−1.56, −0.72) | 1.59 (1.36, 1.80) | 0.477 | 0.1940 | 8.5  |
| MA       | −1.79 (−2.43, −0.99) | 1.92 (1.50, 2.25) | 0.477 | 0.2188 | 9.4  |
| Robust   | −0.21 (−0.78, 0.35) | 1.10 (0.80, 1.39) | 0.349 | 0.1785 | 8.1  |
| LMM      | −0.56 (−1.26, 0.15) | 1.26 (1.04, 1.49) | NA   | 0.1812 | 8.2  |

† Values of the exponent in bold face are not significantly different from the theoretical values of 0.50 and 0.667, while values in red are highly biased.
‡ RMSE values in bold represent the best regression techniques.
N for H-DBH was 85, and 84 for AGB-DBH.

encompassed 0.50 (Table 4). Therefore, the hypothesis of stress similarity could not be rejected. The RMA estimate of the exponent was higher than the theoretical values of 0.50 and 0.667 but consistent with elastic similarity (exponent = 0.667). Based on the 95% CI of the major axis regression estimate of the exponent, the stress similarity and metabolic scaling could not be rejected. The predictions produced using the OLS and MA regression tended to underestimate H in the higher DBH range (Figure 3a). RMA and MA regression tended to underestimate H in the lower DBH range and overestimated H in the higher DBH range (Figure 3a).

Comparison of the non-linear H-DBH models with the power law model did not reveal significant improvement in predictive ability of non-linear models. The algorithms also did not converge for most non-linear regression models except for the power law, and the four-parameter Gompertz and logistic functions. The asymptotic height could also not be correctly estimated (Table S2). Therefore, presenting these comparisons was deemed superfluous, and these are now summarized in Supplementary Table S2.

Biomass allocation in different components of highland bamboo

DBH was moderately correlated with aboveground biomass (R² = 0.48) for all age groups using both Model 1 and 2 (Table 4, Figure 3b and Figure 4) but when the analysis was performed separately for each age group better correlation was observed especially for age groups 1 and 2, where R² was greater than 0.80 (Table 5). Bartlett’s test of equality variances did not reveal significant differences between the age groups (p = 0.125) for both models 1 and 2. The test of equality of variance also did not reveal significant differences between the slopes (p = 0.204 for Model 1 and p = 0.428 for Model 2). However, the elevations significantly differed (P = <0.001) with age group for both models (Table 5). The estimated exponents were all below the theoretical values (Table 4). RMA and major axis regression tended to underestimate AGB at lower DBH, but it tended to overestimate AGB as DBH increased (Figure 3b).

Ordinary least square regression gave the best prediction (smallest RMSE) of AGB from DBH (Tables 4 and 5). Therefore, the estimated intercept and exponent from OLS (Table 5) were used to estimate AGB from DBH (Model 1 below).

\[
\ln(AGB) = -0.23 + 1.10\ln(D) \quad \text{Model 1}
\]
\[
\ln(AGB) = -1.02 + 0.46\ln(D^2H) \quad \text{Model 2}
\]

Although graphical exploration did not reveal visible differences (Figure 4), cross-validation revealed that the model given in Eq. (2) was slightly better than the model given as Eq. (3). The model given as Eq. (2) had cross-validation R² of 0.479, RMSE of 0.185 and MAE of 0.151, while Eq. (3) had R² of 0.473, RMSE of 0.186 and MAE of 0.153. Model parameters of the AGB-DBH allometric scaling for each age groups of highland bamboo are presented in Table 5. When the models were applied for separate age groups, the R² and RMSE showed better performance than all age groups combined (Table 5).
age (Table 3). Aboveground biomass was estimated at 93 Mg ha$^{-1}$, while belowground biomass was estimated at 18.6 Mg ha$^{-1}$ (Table 3). The total plant dry biomass was estimated at 111.6 Mg ha$^{-1}$ (Table 3). Litter layer biomass ranged between 1.2 and 8.2 Mg ha$^{-1}$ with an average value of 3.1 Mg ha$^{-1}$.

**Table 5.** Comparison of age-specific biomass models (Model 1 and Model 2) using the $R^2$, RMSE and MAPE.

| Age group | Model | Intercept       | Slope          | $R^2$ | RMSE  | MAPE |
|-----------|-------|-----------------|----------------|-------|-------|------|
| 1         | 1     | $-0.58 (-1.30, 0.14)$ | 1.17 (0.82, 1.53) | 0.775 | 0.103 | 4.5  |
|           | 2     | $-1.92 (-2.93, -0.91)$ | 0.56 (0.41, 0.71) | 0.810 | 0.095 | 4.2  |
| 2         | 1     | $-1.22 (-1.83, -0.60)$ | 1.64 (1.32, 1.96) | 0.820 | 0.123 | 4.0  |
|           | 2     | $-1.94 (-2.74, -1.15)$ | 0.61 (0.48, 0.73) | 0.805 | 0.128 | 4.4  |
| 3         | 1     | $-0.28 (-1.21, 0.65)$ | 1.14 (0.65, 1.63) | 0.484 | 0.168 | 5.7  |
|           | 2     | $-1.18 (-2.39, 0.03)$ | 0.48 (0.29, 0.68) | 0.526 | 0.161 | 5.5  |
| 4         | 1     | $-0.11 (-1.03, 0.84)$ | 1.07 (0.57, 1.58) | 0.463 | 0.176 | 5.7  |
|           | 2     | $-0.80 (-2.03, 0.44)$ | 0.43 (0.23, 0.63) | 0.479 | 0.174 | 5.2  |
| All       | 1     | $-0.23 (-0.71, 0.25)$ | 1.10 (0.85, 1.35) | 0.477 | 0.178 | 8.1  |
|           | 2     | $-1.02 (1.64, -0.40)$ | 0.46 (0.36, 0.55) | 0.504 | 0.174 | 8.0  |

Comparisons

- Variance: $P=0.125$
- Slope: $P=0.204$
- Elevation: $P<0.001$

$P$ value for Bartlett’s test of equality of variances.
$P$ value for comparison of Slopes.
$P$ value for comparison of Elevations.
Carbon stock in different pools of highland bamboo

Figure 6 shows the variation in estimated aboveground biomass C, belowground biomass C and total biomass C (TBC). Across age groups, the average aboveground and belowground (rhizomes and roots) carbon stocks were 43.7 and 8.7 Mg ha\(^{-1}\), respectively. The allocation of carbon was greater in culms (71.59%) than in branches and leaves (11.95%) and rhizomes and roots (16.5%). The litter layer sequestered 0.59–4.1 Mg C ha\(^{-1}\), with an average of 1.6 Mg ha\(^{-1}\). The total soil organic carbon stored in the bamboo stands ranged between 263.0 and 581.5 Mg C ha\(^{-1}\) with average value of 388.1 Mg C ha\(^{-1}\). Based on the carbon storage above- and belowground biomass, litter and soil, the mean carbon storage in bamboo stands in the study area was estimated at 442.2 Mg ha\(^{-1}\). Soil organic carbon stock accounted for 87.8% of the total highland bamboo ecosystem carbon storage, while aboveground carbon stocks accounted for the remaining 9.9%.

Discussion

Carbon management in forest ecosystems requires a better understanding of stand structure and C stock. The variation in aboveground carbon stock is dependent on many factors, such as stand structure and composition, topography, altitude and disturbance [21]. In the present study, the culm density of highland bamboo increased with the age of the stand. The density in age groups 1, 2, 3 and 4 represent one, two, three and four seasons of recruitments. Assuming a simple exponential growth, the expected density in the fourth year is 6344, but the observed density of 5367 is about 18% lower than expected. This indicates a weak recruitment of new bamboo plants in the older stands. This highlights the need for the management of natural bamboo forests to facilitate the sprouting of new culms. Studies elsewhere indicate that silvicultural management can significantly increase culm density and average DBH in managed bamboo [66]. The culm density observed in this study (13,300 culms ha\(^{-1}\)) was comparable with earlier reports of highland bamboo densities by Embaye et al. [42] and Mulatu [14] but lower than values reported by Teshoma [21] and managed stands in northwestern Ethiopia [32]. When compared with other bamboo species, the density recorded in this study is greater than the other indigenous bamboo species in Ethiopia, namely, *Oxytenanthera abyssinica* natural bamboo stands and *Phyllostachys pubescens* in East Asia [55, 66–69], but much lower than thin-walled bamboos of India, *S. dullooa*, *P. polymorphum* and *M. baccifera* [5].

The average DBH and height observed in this study were greater than the values of highland bamboo reported in other studies in Ethiopia [14, 21] except Embaye et al. [42]. When compared with other bamboo species, the DBH was greater than that of *Oxytenanthera abyssinica* [67,68] but lower than that of *Phyllostachys pubescens* [2, 43, 48]. The bamboo stands in the present study were dominated by older culms. This is probably because the stands are in a natural forest with no human intervention. This result is consistent with a previous study by Embaye et al. [42], where the population structure of highland bamboo from Masha forest (in Southwestern Ethiopia) was dominated by older culms, resulting in reduced yield [5]. This suggests that the existing age structure is not optimum for maximum production of the bamboo forest.

This study has established that plant height and stem diameter are allometrically related in highland bamboo, and that the H-DBH scaling exponent is not significantly different from the
theoretical values. Although aboveground biomass and DBH are allometrically related, the exponents are much smaller than their theoretical values [51]. The $R^2$ values were also low for the general model partly due to the high variance in the data, which probably reflects high natural variability. This is evident in the significant differences in elevations among age groups. For the age-specific models the $R^2$ was higher. For the general model larger sample sizes, ideally in the hundreds, are needed to absorb this level of natural variability. However, due to resource limitations we were unable to collect more samples. We believe this is one of the limitations of this study. Other studies on bamboo also indicate that the exponents of AGB–DBH are lower than theoretical values [5]. This may be attributed to the hollow nature of highland bamboo, and a simple allometric model with DBH is probably inadequate for biomass estimation of the species. The RMA and major axis regression yielded H–DBH exponents consistent with elastic similarity, while the OLS, LMM and robust regression yielded exponents consistent with the stress similarity hypothesis. These differences arise due to the differences in the way measurement errors are handled within the different regression techniques. In OLS regression, the $X$ variable is assumed to be under the control of the researcher and measured without error. In most practical situations, however, DBH is measured with some error, and therefore, the exponent is often biased downwards. This regression problem is called attenuation bias. On the other hand, RMA and major axis regression assume that $X$ and $Y$ are measured with some error, but the errors must be proportional. Although the RMA estimators are free from attenuation bias, they are known to overestimate the true regression slope [70]. For some of the non-linear regression models, the algorithms did not converge. This problem has also been noted in Singnar et al. [5]. When the algorithm fails to converge, estimated parameters and their standard errors will be unreliable. This emphasizes the point that regression methods should be selected carefully when testing hypotheses about allometric scaling.

The results show that the aboveground components contribute the majority of the biomass. Much of the bamboo biomass is held in the culm, which constitutes more than 70% of the total plant biomass, followed by rhizome and roots. This is in agreement with other previous studies on highland bamboo [14, 21]. Similar trends were reported for other bamboo species in which the largest proportion of biomass was contributed by the bamboo culm [1, 3, 68, 71].

The aboveground standing biomass recorded in the present study is comparable with other reported values for highland bamboo in Ethiopia [14, 21] but greater than the AGB of *Oxytenanthera abyssinica*, the other indigenous bamboo species in the country [67,68]. The AGB of the highland bamboo was comparable or even higher than values reported for other bamboo species elsewhere [1, 9, 48, 71,72]. We found that biomass production increases with age, and this is consistent with findings in other studies (e.g. [5, 62]). Younger culms (1-yr. old) are expected to have the maximum moisture content and therefore minimum biomass [5, 62].

Carbon stock in bamboos represents a permanent stock, as C export through harvesting of mature culms is balanced by gains from new culms produced in the clump [1, 73]. The short
periodicity of culm growth, rapid elongation rate, brief clump development period and the ability of bamboo to survive in poor-quality soil in comparison to well-managed plantations of trees make bamboo a good sink of CO₂ [71]. The allocation of C in the highland bamboo was highest in the culm component. Previous studies also found that bamboo culms accounted for most of the carbon storage [21, 47, 71]. Mean above-ground C storage of 44 Mg ha⁻¹ in the present study was lower than values reported (72.3 Mg ha⁻¹) for highland bamboo reported by Teshoma [21] but much higher than the 11.47 Mg ha⁻¹ of Oxytenanthera abyssinica [67]. Furthermore, the belowground and litter results indicated that it has an important contribution to enhancing the carbon sequestration potential of the highland bamboo forest.

The SOC in the study area varied greatly with soil depth; the upper soil surface had a higher SOC content. This is consistent with reports from elsewhere [21, 23, 47, 74]. The higher SOC content in the surface soil may be attributed to decomposition of the litter layer [21]. The total SOC stored in the natural highland bamboo forest (388.1 Mg ha⁻¹) was higher than values reported for similar bamboo forest in Adiyo (205.6 Mg ha⁻¹) in Southwestern Ethiopia [21], Moso bamboo in China (79.14 to 96.45) [47], B. philippinensis bamboo plantation in the Philippines (118.19 Mg ha⁻¹) [23]. The advantage of SOC in bamboo stands is that it is a stable form of C known as phytolith occluded carbon resulting from C entrapped within silica bodies [75, 76]. This form of carbon is highly resistant to decomposition and remains in the soil for several thousand years [75, 76].

Total carbon storage of the natural highland bamboo forest in the study area (442 Mg ha⁻¹) was found to be higher than that of other bamboo species in tropical and subtropical regions [23, 47]. The SOC accounted for most of the total carbon stored in the natural bamboo forest. As bamboo stands are known to reach maximum biomass within very short periods, they compare favorably with different types of forests in their ability to quickly store larger amounts of carbon [77]. Previous studies on bamboo from tropical and subtropical countries show that various bamboo species have carbon storage comparable to that of many fast-growing timber species or tropical forest ecosystems [9, 48].

For the first time, this study systematically estimated C stored in the different pools and total system C in highland bamboo. These estimates may be used as baseline data for future carbon management and for emerging payments for ecosystem services projects in Afromontane ecosystems. Given the high potential of highland bamboo for carbon sequestration, it could provide an opportunity for climate change mitigation [9]. It is also expected that a good amount of revenue can be earned by selling carbon credits in the carbon market [78], which can accelerate economic, social and environmental development. Integrating woody bamboos with carbon trading will promote the cultivation and management of bamboos in agroforestry and forest ecosystems and therefore generate another income stream for rural communities [17]. For effective management of the bamboo forest for carbon trading, CDM and REDD⁺ projects may offer an opportunity to increase carbon stocks and give concurrent economic, environmental and social benefits to the community [9].

Conclusion and recommendations

This study has provided evidence that highland bamboo stands can play an important role in carbon management in Afromontane forests. The estimated C stocks were comparable with values reported for bamboos in Ethiopia and elsewhere. The insights gained in this study are expected to be applicable to Afromontane ecosystems where highland bamboo occurs in Africa. We recommend long-term studies to quantify the carbon sequestration potential of highland bamboo to obtain concrete information on the annual carbon stock increment and total carbon stock potential of the species in the area. Further in-depth research is also needed to enhance the contribution of highland bamboo through sustainable utilization of the forest and carbon locking using durable products. We also recommend inclusion of natural bamboo forests in mechanisms such as REDD⁺ to ensure sustainable management and maximize the carbon storage and livelihood benefits to local communities living around bamboo forest. Local community awareness should be raised with regard to the role of the highland bamboo forest for global climate change mitigation so that they will participate in the conservation of the forest.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Kaushal R, Subbulakshmi V, Tomar J, et al. Predictive models for biomass and carbon stock estimation in male bamboo (Dendrocalamus strictus L.) in doon valley, India. Acta Ecol Sin. 2016;36(6):469–476. doi:10.1016/j.chinaes.2016.07.003.
2. Xu L, Shi Y, Zhou G, et al. Structural development and carbon dynamics of moso bamboo forests in Zhejiang province, China. For Ecol Manage. 2018a;409:479–488. doi:10.1016/j.foreco.2017.11.057.
3. Yen T-M, Lee J-S. Comparing aboveground carbon sequestration between moso bamboo (Phyllostachys heterocycla) and China fir (Cunninghamia lanceolata) forests based on the allometric model. For Ecol Manage. 2011;261(6):995–1002. doi:10.1016/j.foreco.2010.12.015.
4. FAO. 2018. FAO’s work on climate change. United Nations Climate Change Conference 2018. Katowice (Poland): Food and Agricultural Organization of the United Nation, Rome, Italy.
5. Singnar P, Das MC, Sileshi GW, Brahma, et al. Allometric scaling, biomass accumulation and carbon stocks in different aged stands of thin-walled bamboos Schizostachyum dullooa, Pseudostachyum polyomorphum and Melocanna baccifera. For Ecol Manage. 2017;395:81–91. doi:10.1016/j.foreco.2017.04.001.
6. Lobovikov M, Schoene D, Yping L. Bamboo in climate change and rural livelihoods. Mitig Adapt Strateg Glob Change. 2012;17(3):261–276. doi:10.1007/s11027-011-9324-8.
7. Nath AJ, Sileshi GW, Das AK. 2020. Bamboo: climate change adaptation and mitigation. Apple Academic Press, Florida.
8. INBAR. 2011. The climate change challenge and bamboo: mitigation and adaptation. Working Paper.
9. Sohel MSI, Alamgir M, Akhter S, et al. Carbon storage in a bamboo (Bambusa vulgaris) plantation in the degraded tropical forests: Implications for policy development. Land Use Policy. 2015;49:142–151. doi:10.1016/j.landusepol.2015.07.011.
10. Embaye K. 2003. Ecological aspects and resource management of bamboo forests in Ethiopia [PhD dissertation]. Uppsala (Sweden): Swedish University of Agricultural Sciences.
11. Kelbessa E, Bekele T, Gebrehiwot A, et al. 2000. A socioeconomic case study of the bamboo sector in Ethiopia. Addis Ababa, Ethiopia.
12. Mekonnen A. 2017. Socio-economic and socio-cultural value of highland bamboo (Fusania alpina) plant and its contribution to rural livelihood in banja district Aw Zone Ethiopia. [MSc thesis]. Addis Ababa University.
13. Mekonnen Z, Worku A, Yohannes T, et al. Bamboo resources in Ethiopia: their value chain and contribution to livelihoods. Ethnobot Res App. 2014;12:511–524. doi:10.17348/era.12.0.511-524.
14. Mulatu Y. 2012. Growth, morphology and biomass of Arundinaria alpina (highland bamboo)[poaceae] as affected by landrace, environment and silvicultural management in the choke Mountain, northwestern Ethiopia [PhD Dissertation]. Addis Ababa University.
15. Mulatu Y, Alemayehu A, Tadesse Z. 2016. Biology and management of indigenous bamboo species of Ethiopia. Ethiopian Environment Forest Research Institute, Addis Ababa, Ethiopia.
16. Nath AJ, Sileshi GW, Das AK. Bamboo based family forests offer opportunities for biomass production and carbon farming in North East India. Land Use Policy. 2018;75:191–200. doi:10.1016/j.landusepol.2018.03.041.
17. Nath AJ, Lal R, Das AK. Managing woody bamboos for carbon farming and carbon trading. Global Ecol Conserv Biol. 2015;3:654–663. doi:10.1016/j.gecco.2015.03.002.
18. UNFCCC. 2008. Thirty-ninth Meeting of the Clean Development Mechanism Executive Board. UN Campus, Langer Eugen, Hermann-Ehlers-Str. 10, 53113 Bonn, Germany: United Nations Framework Convention on Climate Change.
19. FTFA. 2012. World’s first bamboo carbon offset credit issued under the VCS in the voluntary carbon market. Sandton, South Africa Food and Trees for Africa.
20. FAO. 2009. The poor man’s carbon sink: bamboo in climate change and poverty alleviation. Non-Wood Forest Products Working Document.
21. Teshoma U. Carbon storage potential of ethiopian highland bamboo (Arundinaria alpina) plantation in the Eastern Afromontane [Online]. Conservation International. [cited 2021 Nov 8]. https://www.biodiversityhotspots.org/xp/Hotspots/afromontane/.
22. Stapleton CM. 2020. Afromontane [Online]. [cited 2021 Nov 8]. https://en.wikipedia.org/w/index.php?title=Afromontane&oldid=985146803.
27. Grimshaw JM. The afromontane bamboo, *Yushania alpina*, on Kilimanjaro. J East Afr Nat History. 1999; 88(1):79–83. doi:10.2982/0012-8317(1999)88[79: TAYBAY2.0.CO;2]

28. Bekele-Tesemma A, Tengnás B. 2007. Useful trees and shrubs of Ethiopia: identification, propagation, and management for 17 agroclimatic zones. RELMA in ICRAF Project, World Agroforestry Centre, Eastern Africa Region, Nairobi, Kenya.

29. Hall J, Inada T. 2008b. *Sinarundinaria alpina* (K. Schum.) CS Chao & Renvoie. 7, 508–512.

30. Phillips S. 1995. Flora of Ethiopia and Eritrea, poaceae (gramineae). (Vol. 7) The National Herbarium, Addis Ababa University, Addis Ababa, Ethiopia.

31. Katumbi NM, Kinyanjui MJ, Kimondo J, et al. Biomass energy resource of the highland bamboo (*Yushania alpina*) and its potential for sustainable exploitation in Southern abirebdes Forest. JBSB. 2017;07(03):85–97. doi:10.4236/jbsb.2017.73007.

32. Nigatu A, Wondie M, Alemu A, et al. Productivity of highland bamboo (*Yushania alpina*) across different plantation niches in west Amhara, Ethiopia. Forest Sci Technol. 2020;16(3):116–122. doi:10.1080/21580103.2020.1791260.

33. Sheil D, Ducey M, Sassi F, et al. Bamboo for people, Mountain gorillas, and golden monkeys: evaluating harvest and conservation trade-offs and synergies in the virunga volcanoes. For Ecol Manage. 2012;267:163–171. doi:10.1016/j.foreco.2011.11.045.

34. Hall J, Inada T. 2008a. *Sinarundinaria alpina* (K. Schum.), PROTA (Plant Resources of Tropical Africa), Wageningen, Netherlands.

35. Zhao Y, Feng D, Jayaraman D, et al. Bamboo mapping of Ethiopia, Kenya and Uganda for the year 2016 using multi-temporal landsat imagery. Int J Appl Earth Obs Geoinf. 2018;66:116–125. doi:10.1016/j.jag.2017.11.008.

36. Kassa Z, Asfaw Z, Demissew S. An ethnobotanical study of medicinal plants in sheka zone of Southern nations nationalities and peoples regional state, Ethiopia. J Ethnobiol Ethnomed. 2020;16:1–15.

37. Gadow KV, Zhang G, Durrehim G, et al. Diversity and production in an afromontane Forest. For Ecosyst. 2016;3(1):15. doi:10.1186/s40663-016-0074-7.

38. Grimshaw JM. What do we really know about the afromontane archipelago? Syst Geograph Plant. 2001; 71(2):949–957. doi:10.2307/3668730.

39. White F. 1983. The vegetation of Africa.

40. Kostova E. 2015. Income generation in Ethiopian biosphere reserves: promoting alternative livelihoods to preserve the forest [MSc thesis]. University of London.

41. SZA. 2015. Sheka biosphere reserve management plan. Sheka Zone Administration Masha, Ethiopia.

42. Embaye K, Weih M, Ledin S, et al. Biomass and nutrient distribution in a highland bamboo Forest in southwest Ethiopia: implications for management. For Ecol Manage. 2005;204(2–3):159–169. doi:10.1016/j.foreco.2004.07.074.

43. Xie M, Ji H, Zhuang S. Carbon stock of moso bamboo (*Phyllostachys pubescens*) forests along a latitude gradient in the subtropical region of China. PLoS One. 2018b;13(2):e0193024.

44. Mulatu Y, Fetene M. Morphology and biomass variations of *Arundinaria alpina* landraces in the choke Mountain, northwestern Ethiopia. Bamboo Rattan. 2011;10:77–93.

45. Wimbush S. The african alpine bamboo. East Afr Agric J. 1947;13(1):56–60. doi:10.036700741947.11664583.

46. Singnar P, Sileshi GW, Nath A, et al. Modelling the scaling of belowground biomass with aboveground biomass in tropical bamboos. Tree Forest People. 2021;3:100054. doi:10.1016/j.tfp.2020.100054.

47. Zhuang S, Ji H, Zhang H, Sun B. Carbon storage estimation of moso bamboo (*Phyllostachys pubescens*) Forest stands in Fujian, China. Trop Ecol. 2015;56:383–391.

48. Zhang H, Zhuang S, Sun B, et al. Estimation of biomass and carbon storage of moso bamboo (*Phyllostachys pubescens* mazel ex houz.) in Southern China using a diameter–age bivariate distribution model. Forestry Int J Forest Res. 2014;87(5):674–682. doi:10.1093/forestry/cp028.

49. Pearson T, Brown S, Birdsey R. 2007. Measurement guidelines for the sequestration of forest carbon. United States Department of Agriculture-Forest Service, USA.

50. Schumacher BA. 2002. Methods for the determination of total organic carbon (TOC) in soils and sediments. Environmental Sciences Division National Exposure Research Laboratory, United States Environmental Protection Agency, Las Vegas, CA.

51. Sileshi GW. A critical review of Forest biomass estimation models, common mistakes and corrective measures. For Ecol Manage. 2014;329:237–254. doi:10.1016/j.foreco.2014.06.026.

52. Niklas KJ. Size-dependent allometry of tree height, diameter and trunk-taper. Ann Botany. 1995;75(3):217–227. doi:10.1006/anbo.1995.1015.

53. West GB, Brown JH, Enquist BJ. The fourth dimension of life: fractal geometry and allometric scaling of organisms. Science. 1999;284(5420):1677–1679. doi:10.1126/science.284.5420.1677.

54. Niklas KJ, Spatz H-C. 2004. Growth and hydraulic (not mechanical) constraints govern the scaling of tree height and mass. *Proceedings of the National Academy of Sciences*, 101, p. 15661–15663.

55. Lin, M-Y, Hsieh I-F, Lin, P-H, Laplace S, Ohashi, et al. Moso bamboo (*Phyllostachys pubescens*) forests as a significant carbon sink? A case study based on 4-year measurements in Central Taiwan. Ecol Res. 2017;32(6):857–865. doi:10.1007/s11284-017-1497-5.

56. Hui C, Terblanche JS, Chown SL, et al. Parameter landscapes unveil the bias in allometric prediction. Method Ecol. 2010;1(1):69–74. doi:10.1111/j.2041-210X.2009.00005.x.

57. Taskinen S, Warton D. Robust tests for one or more allometric lines. *J Theor Biol.* 2013;333:38–46. doi:10.1016/j.jtbi.2013.05.010.

58. White CR. Allometric analysis beyond heterogeneous regression slopes: use of the Johnson-Neyman technique in comparative biology. Physiol Biochem Zool. 2003;76(1):135–140.
59. Krzywinski M, Altman N. Visualizing samples with box plots. Nat Methods. 2014;11(2):119–120.
60. Hammer Ø, Harper DA, Ryan PD. Past: Paleontological statistics software package for education and data analysis. Palaeont Electron. 2001;4:9.
61. Huy B, Thanh GT, Poudel KP, et al. Individual plant allometric equations for estimating aboveground biomass and its components for a common bamboo species (*Bambusa procera* A. Chev. and A. Camus) in tropical forests. Forests. 2019;10(4):316. doi:10.3390/f10040316.
62. Shanmughavel P, Francis K. Above ground biomass production and nutrient distribution in growing bamboo (*Bambusa bambos* (L.) voss). Biomass Bioenerg. 1996;10(5–6):383–391. doi:10.1016/0961-9534(95)00124-7.
63. Walker S, Murray L, Tepe T. 2016. Allometric equation evaluation guidance document. Winrock International, USA.
64. IPCC. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. IGES, Japan: National Greenhouse Gas Inventories Programme.
65. Li, C, Shi Y, Zhou G, Zhou, et al. Effects of different management approaches on soil carbon dynamics in moso bamboo Forest ecosystems. Catena. 2018;169:59–68.
66. Shi Y, Xu L, Zhou Y, et al. Quantifying driving factors of vegetation carbon stocks of moso bamboo forests using machine learning algorithm combined with structural equation model. For Ecol Manage. 2018;429:406–413. doi:10.1016/j.foreco.2018.07.035.
67. Darcha G, Birhane E. Biomass and carbon sequestration potential of *Oxytenanthera abyssinica* in the homestead agroforestry system of Tigray, Ethiopia. J Nat Sci Res. 2015;5:69–77.
68. Gurmessa F, Gemechu T, Soromessa T, et al. Allometric equations to estimate the biomass of *Oxytenanthera abyssinica* (A. Rich.) Munro. (Ethiopian lowland bamboo) in dicho Forest, Oromia region, Western Ethiopia. Int J Res Stud Biosci. 2016;4:33–48.
69. Yen T. Culm height development, biomass accumulation and carbon storage in an initial growth stage for a fast-growing moso bamboo (*Phyllostachy pubescens*). Bot Stud. 2016;57(1):4–12. doi:10.1186/s40529-016-0126-x.
70. Kilmer JT, Rodriguez RL. Ordinary least squares regression is indicated for studies of allometry. J Evol Biol. 2017;30(1):4–12.
71. Nath AJ, Das G, Das AK. Above ground standing biomass and carbon storage in village bamboos in North East India. Biomass Bioenerg. 2009;33(9):1188–1196. doi:10.1016/j.biombioe.2009.05.020.
72. Yen T-M, Ji Y-J, Lee J-S. Estimating biomass production and carbon storage for a fast-growing makino bamboo (*Phyllostachys makinoi*) plant based on the diameter distribution model. For Ecol Manage. 2010;260(3):339–344. doi:10.1016/j.foreco.2010.04.021.
73. Nath A, Das A. Carbon storage and sequestration in bamboo-based smallholder homegardens of barak valley, Assam. Curr Sci. 2011;100:229–233.
74. Zhao B, Li Z, Li P, et al. Spatial distribution of soil organic carbon and its influencing factors under the condition of ecological construction in a hilly-gully watershed of the loess Plateau, China. Geoderma. 2017;296:10–17. doi:10.1016/j.geoderma.2017.02.010.
75. Parr J, Sullivan L, Chen B, et al. Carbon bio-sequestration within the phytoliths of economic bamboo species. Global Change Biol. 2010;16(10):2661–2667. doi:10.1111/j.1365-2486.2009.02118.x.
76. Song X, Zhou G, Jiang H, et al. Carbon sequestration by chinese bamboo forests and their ecological benefits: assessment of potential, problems, and future challenges. Environ Rev. 2011;19(NA):418–428. doi:10.1139/a11-015.
77. Chen X, Zhang X, Zhang Y, et al. Changes of carbon stocks in bamboo stands in China during 100 years. For Ecol Manage. 2009;258(7):1489–1496. doi:10.1016/j.foreco.2009.06.051.
78. Kassahun K, Soromessa T, Belliethathan S. Forest carbon stock in woody plants of ades Forest. Western Hararghe Zone of Ethiopia and its variation along environmental factors: implication for climate change mitigation. Forest. 2015;5:4–12.