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Biomass, Carbon Stock and Sequestration Potential of Oxytenanthera abyssinica forests in Lower Beles River Basin, Northwestern Ethiopia

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Biomass, Carbon Stock and Sequestration Potential of *Oxytenanthera abyssinica* forests in Lower Beles River Basin, Northwestern Ethiopia

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Abstract

Background: Ethiopia is endowed with abundant bamboo resources. However, little is known about biomass, carbon sequestration and storage potential of bamboos. Therefore, this study was conducted to estimate the carbon sequestration and storage potential of *Oxytenanthera abyssinica* forests in Lower Beles River Basin, Northwestern Ethiopia. To this end, A total of 54 circular plots of 100 m^2, with plots having a radius of 5.64, were established to conduct the inventory in Assitsa and Eddida bamboo forests, the typical bamboo sites in Lower Beles River Basin. Biomass accumulation of bamboo was estimated using an allometric equation based on diameter at breast height (DBH) and age. Soil samples were taken from two different soil depths (0 – 15 and 15 – 30 cm) to determine soil organic carbon.

Results: Results indicate that a total of 1,620 bamboo culms were measured in the bamboo forests. The mean biomass of the bamboo forests in the study area accounted for about 140.11 $\pm$ 2.55 Mg ha^{-1}. The mean biomass carbon and soil organic carbon stock of the bamboo forests were 65. 85 $\pm$ 1.19 and 69.70 $\pm$ 1.83 Mg C ha^{-1}, respectively. Therefore, the mean carbon stock of the *O. abyssinica* bamboo forests was 135.63 $\pm$ 2.33 Mg C ha^{-1} with 497.8 $\pm$ 8.55 CO_2 equivalents.

Conclusion: Generally, the *O. abyssinica* bamboo forests of the study area have significant role in climate change mitigation. Therefore, sustainable management of these crucial vegetation resources will enhance their role in carbon sequestration and thereby, climate change mitigation.

Key words: Biomass; Carbon storage; Ethiopia; Lower Beles Basin; *O. abyssinica;* Soil carbon

Introduction

Climate change is generally recognized as one of the greatest challenges for humankind. Consequently, climate change mitigation has received the earnest attention of scientists, resource managers and policy makers [1]. In this regard, carbon (C) sequestration by growing and managing forests has been recognized as a major mitigation strategy for the changing climate [1–3]. Forests are one of the most important terrestrial C sinks, because they store a large amount of C in vegetation and soil, and interact with atmospheric processes through the absorption and

respiration of CO_2 [4–7]. Currently, forest resources, particularly tropical forests, are experiencing increasing pressure due to the growing population [8]. Hence, the increasing rate of tropical deforestation makes the search for alternative natural resources critical. The characteristics of bamboo make it a perfect solution for the environmental and societal consequences of tropical deforestation [9].

Bamboo forests are an integral component of the tropical forest ecosystems, which play an important role in mitigating climate change [10]. Obviously, every plant sequesters CO_2 to prepare food, thereby, plays a great role in regulating climate. However, some plants, like bamboo, have a special capacity in absorbing CO_2 from the atmosphere [11–13]. Bamboos are recognized as one of the fastest growing plants in the world, with growth rates estimated at 30 to 100 cm per day, and harvesting cycle of 3 to 5 years compared with the 10 to 50 years for most timber species [14–17]. On account of their fast growth and short harvesting cycle, bamboos have been known to have a higher carbon stock per hectare than fast-growing tropical and sub-tropical trees under comparable conditions [7,11,16].

Furthermore, bamboo harvesting does not remove the entire plant, therefore, preventing CO_2 lib eration at post-harvest period [18]. Appropriately managed and regularly harvested bamboo can sequester more carbon than bamboo in the natural state [19,20]. In contrast, deforestation of ba mboo forests could lead to significant losses of carbon to the atmosphere, thus, causing a negati ve feedback to climate change [10].

In addition, due to their intrinsic characteristics and growth habits, bamboo forests have crucial ecological and environmental functions in soil erosion control, water conservation, land rehabil itation, and carbon sequestration [9]. Bamboos are adaptive to climate calamites and adverse sit e conditions [18] so that they can be planted in the degraded landscapes. The bamboos regenera te annually through an extensive rhizome system, and lend themselves to soil stabilization, redu cing erosion, increasing slope stability and contributing significantly to restoration of degraded lands, which are essential to combat desertification [1,11,13,20].

Because of its suitable climate and environment for bamboo growth, Ethiopia is rich in bamboo resources. The country possesses about 67 and 7% of the total bamboo forest areas in Africa and the world, respectively [21–23]. It has two indigenous species of bamboo, namely the Afro-alpine bamboo, *Yushania alpina* (K. Schum.) W.C. Lin (a mono-podial/ leptomorphic rhizome bamboo), and the Savanah or lowland bamboo, *Oxytenanthera abyssinica* (A. Rich) Munro (a

sympodial/ pachymorphic rhizome bamboo). Growing in the vast savannah lowlands of northwestern Ethiopia [24], the lowland bamboo takes the lion-share (85%) of bamboos resources of the country [22,25]. The highland bamboo, which grows in the south, south-west, central and northwestern highlands of Ethiopia, comprises the remaining 15% of bamboo resources [23,26].

Globally, bamboo forests are receiving a glutted attention for their high potential to sequester CO_2 from the atmosphere. Several studies have been carried out on carbon stock and sequestration potentials of bamboos in Asia, especially in China and India [1,3,32–40,13–15,27–31]. But, little research has been undertaken elsewhere, particularly in Ethiopia. Therefore, this study was conducted to estimate the biomass, carbon sequestration and storage potential of *Oxytenanthera abyssinica* forests in Lower Beles River Basin, northwestern Ethiopia.

Materials and Methods

Description of the study area

Mandura District is located between 10º 50' 55" to 11º 10' 10" N and 36º 02' 48" to 36º 32' 42" E in northwestern Ethiopia (Fig. 1). It covers an area of about 1,045 km^2 and situated between 808 to 2186 m in the savannah lowlands of northwestern Ethiopia. The largest portion of the District (lowland) is covered with basement complex rock when the plateau basalts cover few areas in north-eastern part, specifically, the Kar Mountain escarpments [41]. The nitosols, cambisols, luvisols and leptosols are the main soils of the sub-basin [42]. Temperatures range between a maximum of 35 to 40 °C and a minimum of 18 to 20 °C [43]. The rainfall shows a unimodal distribution and ranges, approximately, from 1,300 to 2,000 mm [42]. Generally, the District has a wet tropical climate (wet *kolla*) except few areas around the Kar Mountain, which is wet sub-topical (wet *woynadega*).

About 81.5% of the population is rural dweller [44]. According to the Central Statistical Agency (CSA) report [44], Gumuz, Amhara, Agew and Shinasha are the major ethnic groups in the area whereas the Oromo represent a minority. Mixed farming is the main means of livelihood in the study area.

Most people in the study District are engaged in both traditional crop production and livestock rearing practices. Dominant crops are maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench.], sesame (*Sesamum indicum* L.) and groundnut (*Arachis hypogaea* L.). Cattle and goats

are the main livestock resources kept in the study area. The major land use/covers are woodlands, grassland, shrub/bushland, bamboo, agricultural land and barren land settlement [45].

The Vegetation type of the study area falls under *Combretum-Terminalia* Woodland Ecosystem category, which encompasses the lowland bamboo. This ecosystem is characterized by small to moderate-sized trees with fairly large deciduous leaves. These include *Boswellia papyrifera* (Del.) Hochst., *Anogeissus leiocarpa* (DC.) Guill. & Perr., *Stereospermum kunthianum* Cham. and the species of *Terminalia*, *Combretum* and *Lannea*. The solid-stemmed lowland bamboo, locally known as *Shimel* [*Oxytenanther abyssinica* (A. Rich.) Munro] is prominent vegetation in river valleys and on the escarpment [46].

Sampling and data collection techniques

The study District was selected purposely [39] for good bamboo coverage in the basin. Having selected the study District, Assitsa and Eddida bamboo forests were selected for the inventory based on their forest coverage and accessibility to transportation service. According to Huy and Long [47], if the forest investigation area is small (< about 20 ha) with discrete distribution, the application of random, systematic or cluster layouts is not feasible and necessary, rather, typical sampling is applicable. In this case, 2-3 plots may be established in each of the forest blocks based on, e.g. average density and bamboo size. Accordingly, a total of 54 circular plots, measuring100 m^2 with a radius of 5.64 m, were established to conduct the inventory. Circular plots are more efficient because the actual perimeter of the plot is smaller than the square or rectangular plots in relation to the area and, thus, the number of the bamboo culms on the edge is limited [47].

In each plot, culms were classified based on their ages and, then, counted. Caliper and graduate stick (graduated bamboo culm marked at 1 m intervals) were used to measure the diameter and height of the bamboo culms, respectively. The culm age was determined based on the exterior color of the culm, features of culm sheath, and the development of branches and leaves [36]. Hence, culm ages were determined as follows: (a) 1 year old bamboo culms are those that emerged in the current year and have only a few leaves, sheath on the culm, and the culm has pale surface color covered with a white powder; (b) 2 years old bamboo culms have few sheaths at the base of culm with some beginning to rot, well-developed branches on 5^{th} and 6^{th} internodes, and the white powder on the culm surface also begging to disappear while the culm is turning dark green in color; (c) 3 years old bamboo culms have no sheaths and the culm bottom had turned dark green, symbolizing near maturity, and characterized by the appearance of few lichens

and mosses on culm surfaces; and (d) 4 years old culms have no sheath, and the culm color is light yellowish green with abundance of lichens and mosses; and (e) 5 years old or older bamboo culms have the culm surface covered with an abundance of mosses and lichens, and had turned brownish green in color [16,36].

Soil carbon is likely to vary with depth. As a result, most soil carbon samplings, thus, define one or more layers of soil, usually by the distance in centimeters from the soil surface [48]. Bamboo is a shallow-rooted plant where the average depth of dense roots is 30 cm [10,30]. It, therefore, makes sense to define the top layer as 0 – 30 cm or further subdivide it into 0 – 10 and 10 – 30 cm layers [49]. Accordingly, in this study, a total of 108 (54 plots x 2 depths) soil samples were taken from two different soil depths: 0 – 15 cm and 15 – 30 cm for determining the soil texture, moisture, pH, concentrations of organic carbon (OC), and total nitrogen (TN). The soil samples collected from each depth were composited separately, labeled and placed in durable plastic bags. Similarly, a total of 108 (54 plots x 2 depths) undisturbed soil samples were taken at the middle of each plot using a soil core sampler to estimate soil bulk density.

Soil laboratory analyses

Soil samples were analysed in the Agricultural Research Laboratory of the Ethiopian Institute of Agricultural Research in Pawi, Ethiopia. Before conducting the chemical analyses, soil samples were air-dried and pounded with pestle and mortal, and passed through a 2 mm sieve. Then, moisture content in the soil was determined by the percentage loss of soil sample after it was oven-dried at 105 °C divided by the dried soil weight in gram [50], while soil texture was determined through the hydrometer method [51]. The bulk density analysis was carried out by using the core sampling method [52], where each sample was dried at 105 °C for a minimum of 48 hours. The volume of core sampler (VC) was determined by using the formula: $\mathrm{VC} = \pi r^2 \mathrm{h}$, where r is the radius and h is the height of core sampler [$\mathrm{VC} = 3.14 \text{ x } (2.5 \text{ cm})^2 \text{ x } 5 \text{ cm} = 98.125\ cm^3$]. Soil pH was determined in 1:2.5 pH-H_2O ration using the Beckman Zeromatic-II pH meter. The Walkley and Black [53] and micro-Kjeldahl methods [54] were used to determine the soil organic matter (SOC) and TN concentrations, respectively.

Data analyses

Estimation of Biomass, Carbon Stocks and CO_2 Sequestration

An allometric model developed by Amoah et al. [16] was used to estimate the above ground biomass (AGB) and carbon (C) storage potential of *O. abyssinica* forest. The model has a robust

predictive power with R^2 in the range between 0.868 – 0.916. In this model, the relationship between AGB and DBH were predicted by a simple allometric function:

$$Y = a \text{ x } DBH^b$$

Where, Y= above ground biomass, and a and b are parameters.

$$AGB\ (1-2 \text{ years}) = 2.105 \text{ x } DBH^{1.890}$$

$$AGB\ (3-4 \text{ years}) = 1.590 \text{ x } DBH^{2.408}$$

$$AGB\ (5-6 \text{ years}) = 1.853 \text{ x } DBH^{2.256}$$

Then, the total above ground biomass (TAGB) was calculated by summing up of above ground biomass of each age class as follows: $TAGB = AGB_1 + AGB_2 + AGB_3$

Estimating the belowground biomass is much more difficult and time consuming than estimating aboveground biomass. To simplify the process, ratio of root-to-shoot ratio of 1: 5 [55], which is 20% of the above ground biomass, is commonly used. Hence, below ground biomass (BGB) was computed as follows: $BGB = AGB \text{ x } 0.2$. Then, total below ground biomass $(TBGB) = BGB_1 + BGB_2 + BGB_3$. Finally, C storage and CO_2 equivalent potential of the bamboo forest was calculated from total biomass (TB) (total above ground and below ground), respectively, as follows [56]:

$$Carbon\ (C) = C \text{ fraction } (0.47) \text{ x TB; and } CO_2 = C \text{ x } 3.67$$

Soil carbon and nitrogen stock

The amount of carbon and nitrogen stored per hectare was derived from soil depth (cm), bulk density (g cm^3), and the percentage of soil organic carbon (SOC) and total nitrogen (TN) based on the following formula [55]:

$$SOC \text{ stock or TN stock} = BD * d * \%\ SOC \text{ or } \%\ TN$$

where, SOC stock = Soil organic carbon stock per unit area (Mg ha^{-1}), TN stocks = total nitrogen stocks (Mg ha^{-1}), BD = soil bulk density (g cm^3), d = depth of the sampled soil layer (cm), % SOC = percentage organic carbon and NT (%) = total nitrogen concentration. Then, CO_2 equivalent potential of bamboo forest soil was calculated by multiplying C with 3.67 [56]. Bulk density (BD) was calculated from the following formula [55]: $BD = \frac{MS}{VC}$, where, BD = Bulk density (g cm^3); MS = Mass of the dried soil (g); VC = volume of core sampler (cm^3).

Statistical analysis

The study considered culm height, diameter, age and density as stand structures [26]. Independent t-test was used to examine the mean difference in culm density and biomass across

the studied bamboo forests while, pairwise comparison was conducted to assess the mean difference of bamboo forests and soil depth depending on soil properties. In addition, multiple mean comparison was employed at for each variable (texture, soil moisture, pH, bulk density, nitrogen content, organic carbon content, soil organic carbon and nitrogen stock) at $\alpha = 0.05$ using DUNCAN test. Correlation analysis was carried out to test the association between soil bulk density and soil organic carbon along with soil depth.

Results

Culm density and stand structure of *O. abyssinica* forests

The culm density of *O. abyssinica* stand showed significant variation between the study sites, Assitsa (12,364.28 $\pm$ 490.19) and Eddida (15,025.64 $\pm$ 766) bamboo forests, $t(51) = -2.92$, $P = 0.005$ (Table 1). Regarding the culm age composition, matured (2 years) bamboo culms comprised the highest stand density (5,921 culms ha^{-1} = 47.9%) followed by older culms (3,236 culms ha^{-1} = 26.1%) and young culms (3207 culms ha^{-1} = 25.9%) in Assitsa forest. In the case of Eddida forest, the older (6,035 culms ha^{-1} = 40.17%) and matured (5,505 culms ha^{-1} = 36.64%) culms comprised most (76.81%) of the bamboo stand, while young culms shared the remaining proportion (3,485 culms ha^{-1} = 23.19%) (Table 1). In the study District, harvesting intensity and season play great role in determining the overall culm density and age composition. During the field survey and inventory in Assitsa forest, a number of harvested culms were observed, with some clumps having fewer numbers of culms.

The youngest bamboo has the highest thickness (DBH) both in Assitsa (4 $\pm$ 0.41 cm) and Eddida (4.5 $\pm$ 0.27 cm) bamboo forests, while the oldest bamboo culms had the lowest DBH value of 3.5 $\pm$ 0.4 and 3.8 $\pm$ 0.23 cm for Assitsa and Eddida bamboo forests, respectively (Table 2). As age increases, the thickness of bamboo culm decreases. Alike the DBH, the height of bamboo culms slightly decreased as age increased (Fig. 2). The mean culm heights were 11.4 $\pm$ 0.12, 11.0 $\pm$ 0.12 and 10.8 $\pm$ 0.12 m in Assitsa and 12.2 $\pm$ 0.47, 11.5 $\pm$ 0.52 and 11.1 $\pm$ 0.53 m in Eddida bamboo forests for 1-, 2- and 3-year bamboo culms, respectively.

Biomass and carbon storage potential of *O. abyssinica* forests

As the stand density varied across sites, there was also significant variation in the total biomass (above and below ground biomass) stored by the bamboo forests, $t(52) = -5.08$, $P = 0.001$(Table 3). The mean total biomass stored was higher in Eddida (146.43 $\pm$ 2.44 Mg ha^{-1}) than Assista (122.03 $\pm$ 4.14 Mg ha^{-1}) bamboo forests. The mean biomass value of the bamboo

forests in the study area accounted for about 140.11 ± 2.55 Mg ha^{-1}. The total mean biomass (above and below ground) and, then, biomass organic carbon stock in the studied bamboo forests were 268.47 ± 6.58 Mg ha^{-1} and 126.17 ± 3.08 Mg C ha^{-1}, respectively (Table 4).

Physicochemical properties of soils of *O. abyssinica* forests

The sand fraction was the dominant (63.26 ± 0.96) textural class while the silt textural class shared the smallest (14.17 ± 0.45) proportion on both topsoil (0 – 15 cm) and sub-soil (15 – 30 cm) in the study area (Table 5). However, the soil textural fractions of clay, silt and sand showed little variation across the study sites. Soil organic carbon and nitrogen content decreased, while bulk density and moisture content increased along soil depth. Likewise, soil PH decreased as soil depth increased. The concentration of SOC decreased from 5.3 to 2.8 in the Eddida forest and 3.4 to 2.4 in the Assitsa bamboo forests for 0 – 15 to 15 – 30 cm soil depths, respectively. Similarly, TN concentration on topsoil to sub-soil layer decreased from 0.38 to 0.21 and 0.25 to 0.18 in the Eddida and Assitsa bamboo forests, respectively. The analysis indicates that the concentration of SOC and TN varied significantly ($P < 0.05$) across soil depth.

While associating soil bulk density and SOC content, a strong correlation ($r = -0.7$) was found in the study. The result indicated that as bulk density increases, organic carbon tends to decrease, and vice-versa (Fig. 3). SOC concentration decreased from 4.8 on topsoil to 2.6 on sub-soil layer, while bulk density increased from 1.19 to 1.36 g cm^{-3} on the topsoil to subsurface soil. Soil bulk density was significantly different ($P < 0.05$) across soil depths. Soil PH values decreased on the topsoil to sub-soil from 5.88 to 5.66. Conversely, soil moisture increased from 9.57 (0 – 15 cm) to 11.13 in 15 – 30 cm soil depth. The lower moisture content in the topsoil could be due to the exposure of the surface soil to solar radiation and disturbances, which would lead to loss of soil moisture through evapotranspiration process.

Total carbon stocks and sequestration potential of *O. abyssinica* forests

Mean biomass (above and below ground) carbon and soil organic carbon stocks (0 – 30 cm) were 57.35 ± 1.94and 61.73 ± 1.94 Mg C ha^{-1} for Assitsa bamboo forest, respectively, and 68.82 ± 1.14 and 141. 57 ± 2.38 Mg C ha^{-1} for Eddida bamboo forest, respectively (Table 6). The mean total biomass carbon and soil organic carbon stock of the two forests were 65. 85 ± 1.19 and 69.70 ± 1.83 Mg C ha^{-1}, respectively. Therefore, the mean carbon stock of the *O. abyssinica* forests in February 2020 was 135.63 ± 2.33 Mg C ha^{-1} with 497.8 ± 8.55 CO_2 equivalents.

Discussion

Culm density and stand structure of *O. abyssinica* forests

In Ethiopia, bamboo growing in natural forests is under the protection of the State and, hence, banned from harvesting by law. This works for Eddida Bamboo Forest Reserve, where bamboo harvesting is only allowed for research purposes. Hence, most of the bamboo culms have been in their natural stand since the establishment of the bamboo forest reserve. However, it does not mean that the bamboo culms were not harvested at all; there have been an act of illegal and improper bamboo harvesting. In the case of the privately owned Assitsa Bamboo Forest, the bamboo culms have been harvested regularly though the harvesting practice is traditional. The present study found that the bamboo stand density was 12,364 and 15,025 culms ha^{-1} in Assitsa and Eddida bamboo forests, respectively, during February 2020.

Compared to the present study, a much lower density of 2,933.33 culms ha^{-1} was recorded for *Bambusa vulgaris* Schrad. ex J.C.Wendl. from Bangladesh [1]. Densities of 3,400 – 4,722 culms ha^{-1} was reported for Moso Bamboo [*Phyllostachys pubescens* (Pradelle) Mazel ex J.Houz.] in China [37]. Similarly, Inoue et al. (2018) reported 5,222 culms ha^{-1} for Moso Bamboo from Japan. Amoah et al. (2020) also found 3,325 and 6,267 culms ha^{-1} for *O. abyssinica* and *B. vulgaris*, respectively, in Ghana. A total of 7,190 culms ha^{-1} from a bamboo forest in Bali, Indonesia [15], 8,840 culms ha^{-1} for highland bamboo (*Y. alpina*) from Ethiopia [58] and 9,760 culms ha^{-1} for *Schizostachyum pergracile* (Munro) R.B.Majumdar were reported from India [11]. On the other hand, higher densities of 20,467 culms ha^{-1} for highland bamboo (*Y. alpina*) [59] and 20,748 culms ha^{-1} [60] were reported for the same species from Ethiopia. Furthermore, significantly higher densities of 32,376 – 43,000 culms ha^{-1} were reported for *Schizostachyum dullooa* (Gamble) R.B.Majumdar, *Pseudostachyum polymorphum* Munro and *Melocanna baccifera* (Roxb.) Kurz in India [36]. Generally, stand density of bamboo is dependent up on plant species, tending operations, harvesting intensity and site conditions [16,33,36].

Moreover, this study indicated that the youngest culm has the highest DBH (4.25 ± 0.34) and height (11.8 ± 0.29 m). As age of bamboo culm increases, DBH and height tend to decrease. Unlike trees, bamboos have no secondary meristem, the cambium, thus, lack special tissues to accumulate or shade metabolic residues [61,62]. Consequently, the existing tissues of bamboo have to function for many years without forming any new tissues [63]. Moreover, aging of bamboo culms is associated with significant structural and chemical changes in the parenchyma and fiber tissues, which is manifested with declining moisture content, cell wall thickening,

decrease in the percentage of cellulose and sugars, accumulation of silicon and increase or decline in certain nutrient ions [26,63].

Biomass and carbon storage potential of *O. abyssinica* forests

The results revealed that total biomass stored by bamboo forests was higher in Eddida (146.44 $\pm$ 2.44 Mg ha^{-1}) than Assista bamboo forest (122.03 $\pm$ 4.14 Mg ha^{-1}) at $P = 0.001$. The total mean biomass of 140.11 $\pm$ 2.55 of the present study is greater than the corresponding reported values of 108.71 Mg ha^{-1} [60] and 110.7 Mg ha^{-1} [58] for *Y. alpina*, 105 Mg ha^{-1} for *Phyllostachys makinoi* Hayata [3], 89 Mg ha^{-1} for *Phyllostachys heterocycla* (Carrière) Matsum. [35], 87.35 Mg ha^{-1} for six bamboo species [15], 88.23 Mg ha^{-1} for *P. pubescens* [29], 43 – 45 Mg ha^{-1} for *S. dullooa Pseudostachyum polymorphum* [36]. The results were comparable with those reported by other authors [11,32,38]. However, the total biomass recorded in this study is lower than the values reported for *Chusquea culeo* Desvaux. (156 – 162 Mg ha^{-1}) [64] and *Bambusa bambos* (L.) Voss (286 Mg ha^{-1}) [28]. Generally, the results indicated that bamboo stand biomass accumulation depends up on culm age, size (culms diameter) and density.

The mean above and belowground carbon storage of the studied bamboo forests (65.85 $\pm$ 1.19 Mg ha^{-1}) is higher than the values reported for six different bamboo species [15], *Bambusa cacharensis* R.B. Majumdar*, B. vulgaris* and *B. balcooa* Roxb. (25.8 Mg ha^{-1}) [65], *B. vulgaris* (52.96 Mg ha^{-1}) [1], *P. pubescens* (54.6 Mg ha^{-1}) [31] and *P. pubescens* (40.45 Mg ha^{-1}) [29]. But, it was comparable with the aboveground carbon values of 61 and 64 – 91.45 Mg ha^{-1} reported by Nath et al. (2009) and [11], respectively, in Northeast India.

Soil organic carbon content of *O. abyssinica* forests

Soils of the study landscape are slightly acidic and sandy clay loam in texture. Soil pH ranged between 5.88 and 5.66 in the topsoil and sub-surface soil layers, respectively. Soil bulk density and moisture content increased with increasing soil depth. Conversely, the quantity of C and N stored in the bamboo forest soil decreased along with increasing soil depth. This indicates that the concentration of organic matter is higher at the topsoil (0 – 15 cm) than the sub-surface soil layer. In this regard, similar studies conducted so far confirmed that soil organic carbon decreased while bulk density increased with increasing depth in bamboo forest soils [1,11,29,32,37].

Soil organic carbon storage (0 – 30 cm) ranged from 61.73 – 72.57 Mg ha^{-1} with mean of 70 Mg ha^{-1} for bamboo forests of the study area. The amount of carbon stored in the bamboo forest soils (70 Mg ha^{-1}) is greater than that of carbon stored in the above- and below-ground biomass (65.85 Mg ha^{-1}). Similar to the present study, in studies conducted so far, forest soils have been reported to accumulate higher carbon than vegetation biomass [48,65–67]. In general, the results indicated that bamboo forest soils have an important role in the sequestration of atmospheric CO_2 as do the soils of tropical forests.

The total carbon stocks (119.09 $\pm$ 2.70 – 141.57 $\pm$ 2.38 Mg ha^{-1}) in the studied bamboo forests are comparable with the values of 134.14 Mg ha^{-1} [11], 120.75 Mg ha^{-1} (Nath et al. 2009), 145.4 Mg ha^{-1} [29]. But, they were higher than the reported values of 87.83 – 119.5 Mg ha^{-1} [37] and 77.67 Mg ha^{-1} [1].

Enhancement of bamboo stands to maximize biomass carbon storage

It is estimated that about 30 billion tons of CO_2 equivalent are produced each year by human activities [68]. Bamboos offer one of the quickest way to remove vast amounts of that CO_2 from the atmosphere [68,69]. Several studies have provided evidences that CO_2 sequestration potential of bamboo equals or surpasses that of fast-growing trees over short periods [11,19,35,68,70]. Indeed, studies have reported that regularly managed Moso bamboo accumulates higher biomass and, hence, more carbon by a factor of 2.39 than fast growing tree species, such as Chinese fir [35,69,71].

Bamboo forests of the study area have the capacity to accumulate 268.47 Mg ha^{-1} biomass and store 260.66 Mg ha^{-1} of carbon. As a result, these forests could sequester 956.63 ton ha^{-1} of CO_2 equivalents and, thus, generate a considerable amount of carbon credit which signify their actual and potential roles in climate change mitigation. The results indicated that if properly managed, the bamboo forests could store more carbons.

During field survey and inventory, it was possible to observe that the bamboo management in the study area was, mostly, improper and unsustainable. In Assitsa forest, bamboo was harvested and managed traditionally by farmers based on the lesson they got from their fathers and forefathers as well as their personal experiences. In this regard, earlier studies also reported that the quality of bamboo management and harvesting is limited by the relatively low level of knowledge and skills of farmers [24]. In the state-owned Eddida forest, where bamboo harvesting is prohibited except for research purposes, most of the bamboo culms have been in their natural stand since the establishment of the Bamboo Forest Reserve. In this forest, the old

and matured culms comprised most (76.34%) of the bamboo stand, while young culms shared the remaining proportion of the stand. In this respect, harvesting of matured and old culms has been suggested as a requirement to stimulate the growth of rhizomes and roots as well as to increase shoot production in the clump [4,16,19,36]. Unless mature culms are harvested, the emerging shots will be challenged by lack of growing space and competition for resources, such as nutrients, light and water [26].

Moreover, in the studied bamboo forests, there were improper practices, such as harvesting of young and immature culms, cutting of bamboo culms at higher positions and from root base, and unseasonal harvesting, mainly, during the wet seasons. Nevertheless, it is only matured culms of age three and above that are recommended for harvest [72]. Besides, bamboo should be harvested during dry season when moisture content of the culm is low and no damage of underground shoot growth that happens by the time soil is moist. Cutting bamboo culms at higher positions does not relive bamboo stands from belowground congestion, rather it hinders the possible robust newly coming shoots [26]. Similarly, harvesting of culms by using primitive and blunt tools damages the stand and cause wastage. Therefore, culms should be cut using a sharp machete, in slanting positions as low as possible and leaving one internode aboveground.

Generally, adopting scientific management techniques could play a key role for enhancing the productivity of bamboo stands and their carbon storage potential. Application of improved management practices, such as soil loosening and deep tilling, selective thinning of old and malformed culms, fertilizing, weeding and adopting seedlings after mass flowering of bamboo stands increase productivity of bamboo stands. In addition, protecting bamboo stands from fire and human as well as animal interferences is reported to increase culm yield of previously unmanaged communal bamboo stands by 158 – 519% more than unmanaged bamboo stands [26]. Lastly, providing short-term training sessions to technical experts, farmers and other development practitioners is crucially important to enhance, and build their skills on sustainable bamboo management.

Conclusions

Tropical forests potentially contribute to global climate change mitigation through carbon sequestration, hence, serve as global carbon pools. In this regard, bamboos are invaluable plant species for mitigating climate change. Bamboos mature, mostly, within 3 – 6 years, while most

timber species need a decade or more to reach maturity. Likewise, even when harvested regularly, bamboos sequester carbon equivalent to fast growing tree species.

Bamboo forests of the present study area have the potential to accumulate 268.47 Mg ha^{-1} biomass and store 260.66 Mg ha^{-1} of carbon. Hence, these forests could sequester 956.63 ton ha^{-1} of CO_2 equivalents. The present study confirms the critical role of lowland bamboos in carbon sequestration and, thus, climate change mitigation. At the same time, the study revealed that bamboos have been managed rudimentarily, in a way that hinders their sustainability and role to sequester more carbon, and provide other ecosystem services. Therefore, it is strongly recommended to promote their sustainable management for enhancing the productivity of bamboo stands and enhancing their roles in the provision of ecosystem services, including climate change mitigation.

Declarations

Availability of data and materials: We have deposited the necessary data.

Conflict of interest

The authors declare that they have no conflict of interest.

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Authors contribution

Shiferaw Abebe, Amare Sewnet Minale and Demel Teketay contributed to the study conception and design. Material preparation, data collection and analysis were performed by Shiferaw Abebe. The first draft of the manuscript was written by Shiferaw Abebe, and Amare Sewnet Minale, Demel Teketay and Durai Jayaraman commented on the previous version of the manuscript. All authors read and approved the final manuscript.

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Figures

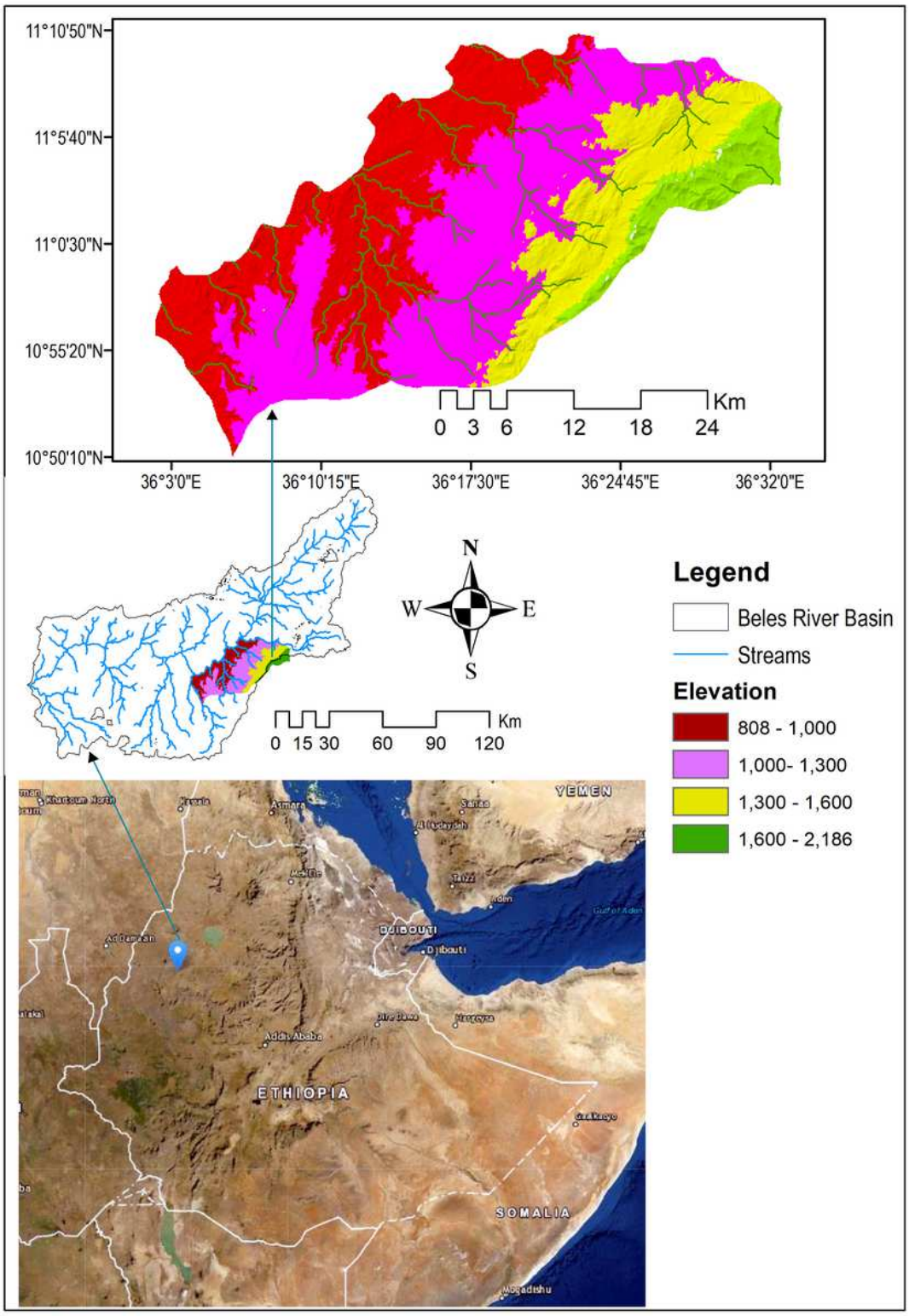


Figure 1

Mandura District is located between 10° 50' 55" to 11° 10' 10" N and 36° 02' 48" to 36° 32' 42" E in northwestern Ethiopia (Fig. 1). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square

concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

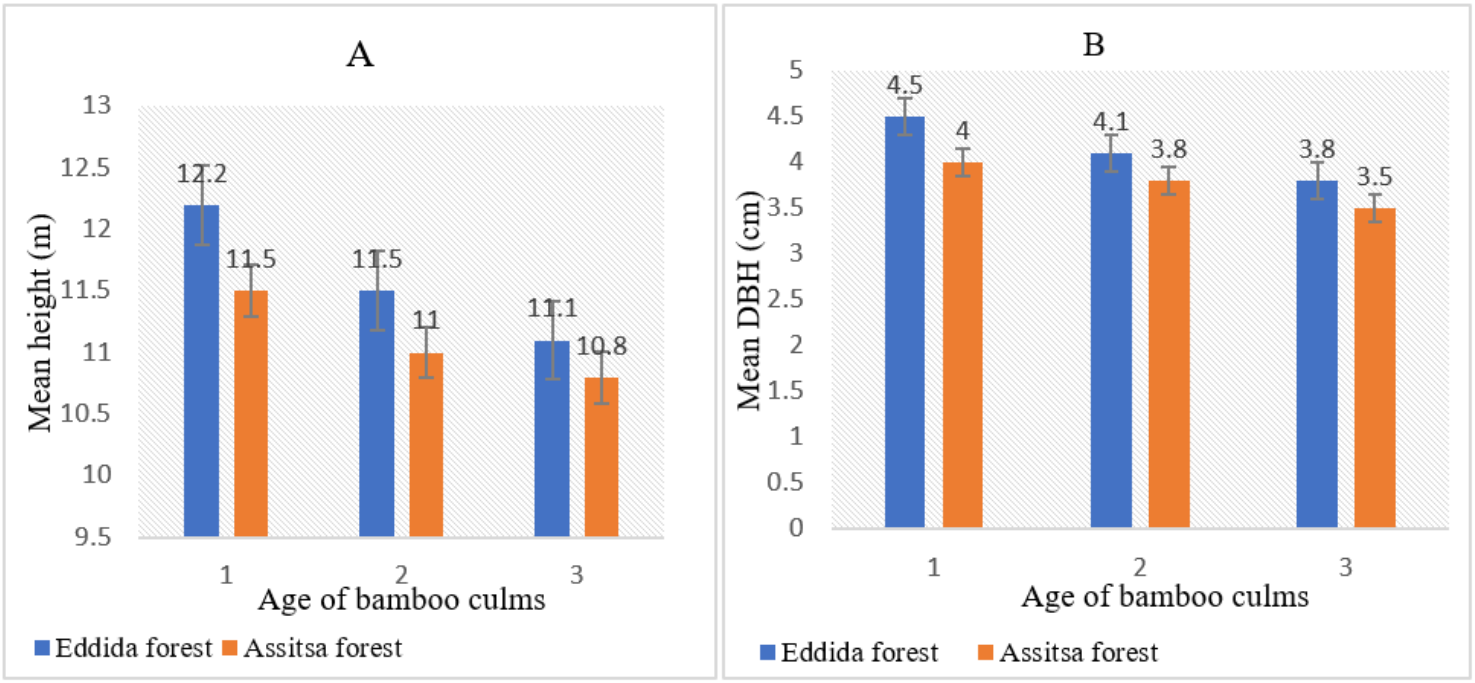


Figure 2

Height (A) and DBH (B) characteristics of bamboo culms along age groups.

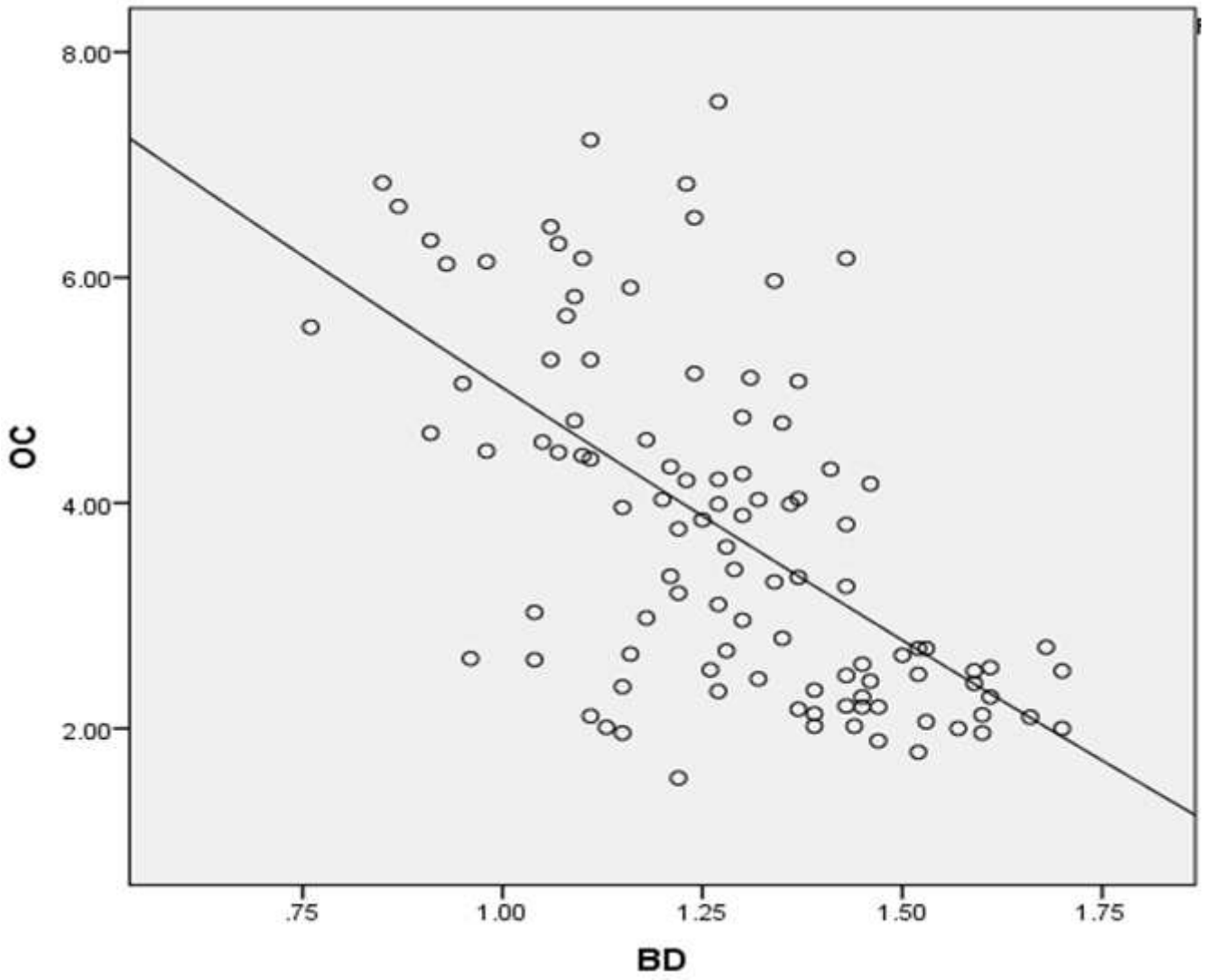


Figure 3

The relationship between soil organic carbon (OC) and bulk density (BD).