Working Paper

*Technical Paper*

# Allometric Modeling, Biomass Estimation, and Carbon Stock Potential of Highland Bamboo in Natural Forests and Homestead Farms in the Sidama Region, Ethiopia

Dagnew Yebeyen[a], Jayaraman Durai[b], Melaku Anteneh[a], Gudeta W. Sileshi[c], Yashwant S. Rawat[d], Belachew Gizachew[e], Selim Reza[a], Fikremariam Haile[f], and Kassa Toshe[g]

[a]International Bamboo and Rattan Organization, East African Regional Office, Addis Ababa, Ethiopia
[b]International Bamboo and Rattan Organization, Global Program, Beijing, P.R. China
[c]Addis Ababa University, Addis Ababa, Ethiopia
[d]Federal Technical and Vocational Training Institute, Addis Ababa, Ethiopia
[e]Norwegian Institute of Bioeconomy Research, Ås, Norway
[f] Forest Products Innovation Center of Excellence, Ethiopian Forestry Development, Addis Ababa, Ethiopia
[g]Environment, Forest and Climate Change Authority, Sidama National Regional State, Hawassa, Ethiopia

2025

International Bamboo and Rattan Organization

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*About this Working Paper*

This work is an INBAR publication produced as part of the Building Circular Economy and Climate Change Resilience through Bamboo Supply Chain Development in Ethiopia, funded by the Spanish Agency for International Development Cooperation (AECID) to develop bamboo-based pro-poor reliable supply chains and technological and institutional innovations contributing to poverty reduction and climate change mitigation in Ethiopia. For more information about this project, please visit https://www.inbar.int/project/ethiopia-bamboo-supply-chain-development/.

*International Bamboo and Rattan Organization*

Beijing 100102, China

Tel: +86 10 64706161; Fax: +86 10 6470 2166

Email: info@inbar.int



www.inbar.int

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## Acronyms

| | |
|---|---|
| AGB | Aboveground Biomass |
| AGBC | Aboveground Biomass Carbon |
| AECID | Spanish Agency for International Development Cooperation |
| AICc | Akaike Information Criterion |
| BGB | Belowground Biomass |
| BGBC | Belowground Biomass Carbon |
| CSA | Central Statistical Agency |
| DBH | Diameter at Breast Height |
| FAO | Food and Agriculture Organization of the United Nations |
| INBAR | International Bamboo and Rattan Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| REDD+ | Reducing Emissions from Deforestation and Forest Degradation |
| RMSE | Root Mean Square of Error |
| SDGs | Sustainable Development Goals |
| UNFCCC | United Nations Framework Convention on Climate Change |

# Executive Summary

Highland bamboo (*Oldeania alpina*) is an important natural resource with significant ecological, economic, and climate change mitigation potential given the increasing concerns over deforestation and the urgent need for sustainable land management practices. Understanding this crop's growth patterns, biomass accumulation, and carbon storage capacity are therefore essential for optimizing its management and integrating it into climate change mitigation strategies. Accordingly, this study explores the allometric modeling, biomass estimation, and carbon stock potential of highland bamboo in the Sidama Regional State, Ethiopia.

The study was conducted in two key highland bamboo growing areas within the Sidama Regional State: a natural bamboo forest in Garamba and homestead bamboo farms in Hula. In Garamba, highland bamboo forms pure stands at elevations higher than other tree species, while in Hula, it is cultivated in discrete stands within farmlands, mainly for bamboo pole production. We selected these sites to compare biomass accumulation and carbon sequestration potential in both natural and managed bamboo systems. We aimed to provide species- and site-specific allometric models to accurately estimate bamboo biomass and assess the contribution of these bamboo stands to carbon sequestration and climate change mitigation.

We employed a systematic sampling approach to collect data on bamboo stand density, structure, and biomass. A total of 12 sample plots (10 × 10 m) were established along transects in the bamboo stands. Dry biomass was estimated using oven-dried samples of bamboo stems, branches, and leaves. Various predictive models were tested to determine the best allometric equations for estimating aboveground biomass (AGB), with two primary models (DBH-based, or diameter at breast height, and volume-based) evaluated for accuracy. Belowground biomass (BGB) was calculated using established root-to-shoot ratios (0.2). Carbon storage was determined by applying the standard carbon fraction (0.47) to the total biomass estimates.

The findings revealed significant differences in bamboo stand structure and biomass accumulation between the two study sites. Homestead bamboo farms exhibited higher stand density (21,775 culms $ha^{-1}$) than natural forests (19,425 culms $ha^{-1}$), likely due to active management practices. Bamboo culm DBH was slightly larger in natural forests, but total biomass was greater in farm-

based stands. The estimated AGB was 92.3 Mg $ha^{-1}$ in the Garamba natural bamboo forest and 118.3 Mg $ha^{-1}$ in the Hula homestead bamboo farms, with corresponding total biomass values of 110.8 Mg $ha^{-1}$ and 141.9 Mg $ha^{-1}$, respectively. Carbon stock assessments indicated that homestead farm stands stored more total biomass carbon (66.7 Mg C $ha^{-1}$) compared to natural forests (52.1 Mg C $ha^{-1}$), underscoring the role of managed bamboo plantations in climate change mitigation.

These results highlight the significant potential of highland bamboo for carbon sequestration, land rehabilitation, and economic development, thereby contributing to climate change mitigation and the United Nations' Sustainable Development Goals (SDGs). Bamboo's rapid growth and ability to regenerate after harvesting make it a valuable resource for sustainable forest management. Moreover, the economic benefits of bamboo are increasingly recognized, as the growing bamboo-based industries in Ethiopia create opportunities for income generation, job creation, and value-added product development. The global shift toward sustainable and eco-friendly products presents a unique opportunity for Ethiopian bamboo to capture a significant share in emerging markets. This in turn can drive regional economic development, support the global circular economy, promote biodiversity conservation, and enhance climate change resilience. Given its ecological and economic advantages, integrating bamboo into national climate policies, land restoration programs, and carbon trading initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) could enhance its contribution to sustainable development.

In conclusion, this study provides a strong scientific basis for the promotion of highland bamboo as a nature-based solution for climate change mitigation, sustainable land use management, and rural economic development. Effective management strategies, coupled with policy support and investment in the bamboo value chain, are crucial for unlocking its full potential. Future research should focus on optimizing bamboo biomass estimation models, assessing its carbon sequestration potential, and expanding value chain development to further enhance its environmental and economic benefits.

# 1. Introduction

## *1.1. Background*

Forests are integral to maintaining ecological biodiversity, safeguarding local livelihoods, carbon sequestration, habitats for pollinators and wildlife, and providing many ecosystem services to humankind (Bonan, 2008; Chazdon, 2008; IPCC, 2019). Forest ecosystems overall are crucial to the global terrestrial carbon cycle and carbon sinks, which are considered a crucial climate change mitigation strategy to reduce global warming due to atmospheric carbon dioxide (Kaushal et al, 2016; Xu et al, 2018). Sustainable forest management and utilization of forest resources therefore contribute to environmental sustainability and broaden livelihood options for local communities (FAO, 2020). Addressing forest-stored carbon both above ground and below ground, litter, and soil pools can help further tackle climate change (FAO, 2018).

Bamboo forests in particular are characterized by fast growth and high biomass productivity in a short period of time, thereby contributing to biodiversity conservation, biomass production, and carbon sequestration (Nath, Sileshi and Das, 2018). Bamboo forests are considered effective in controlling soil erosion, regulating water levels, and reducing flood damage. They also improve site conditions due to their early colonizers' moisture retention capacity, thus enhancing water holding capacity and soil fertility. They have huge potential for climate change mitigation as well, as they store a significant amount of carbon in their ecosystems, thus sequestering carbon from the atmosphere (Huy and Long, 2019).

Carbon stock reduction is alarming due to deforestation in Ethiopia (Rawat and Tekleyohannes, 2021), but bamboo forests provide a permanent carbon sink and multiple other ecosystem services (Yiping et al, 2010). The fast-growing nature of bamboo forests offsets the carbon dioxide in the atmosphere by accumulating mass and carbon stock, resulting in climate change mitigation, adaptation, enhanced livelihood, and biodiversity conservation. Sustainable bamboo forest management and utilization deepen the carbon sink through carbon sequestration by different carbon pools, including soil carbon (Yebeyen, Nemomissa, Sileshi et al, 2022).

Bamboo forests sequestrate carbon faster than tree forests. However, optimum carbon sequestration occurs with increased rates of photosynthesis through land use management

approaches, such as reforestation, afforestation, and sustainable bamboo forest management practices. According to INBAR (2011), approximately 22 million hectares of bamboo forests sequestered about 727.08 teragrams of carbon globally in 2011. Therefore, bamboo forests are considered to have significant carbon sequestration potential (Yebeyen, Nemomissa, Sileshi et al, 2022).

Additionally, bamboo forests are recognized as a key element of nature-based solutions and contribute to the circular economy. The utilization of bamboo is increasing day by day for multiple purposes (Kumar et al, 2023; Silie et al, 2024). In the same line, engineered bamboo structures and products are rapidly developing in the small, medium, and large business sectors, further contributing to carbon sequestration. Other uses of bamboo include new chemical and electrical bamboo-based biomaterials ("bambootronics"), cosmetics, pharmaceuticals, foods and food additives, fabrics, and bio-composites. The demand for bamboo products is increasing in both domestic and international markets. At the domestic level specifically, there is growing interest in bamboo furniture, construction-related products such as floorboards and tiles, processed bamboo poles, woven bamboo mats for interior design and decoration, kitchenware, stick-based products, and alternatives to plastic (Silie et al, 2024). Furthermore, high-end engineered bamboo products are gaining traction as eco-friendly options that appeal to both domestic and international markets.

There are over 1,600 bamboo species throughout the world (Vorontsova et al, 2016) that cover more than 35 million ha of land, with about 71% of these resources found in Asia (FAO, 2020). The total coverage of bamboo in Africa is estimated to be 4.65 million ha and contributes 13.26% of the global bamboo resource (FAO, 2020). Ethiopia possesses 1.44 million ha of bamboo (Zhao et al, 2018), equating to 31.55% of the total bamboo resources of the African region (Bahru and Ding, 2021) and 4.1% of the world's resources. There are two indigenous species of bamboo in Ethiopia: highland or African alpine bamboo (*Oldeania alpina* K. Schum Stapleton, formerly *Arundinaria alpina* or *Yushania alpina*) and a monotypic genus, lowland bamboo (*Oxytenanthera abyssinica* (A. Rich.) Munro). These species are restricted to limited agro-ecological regions, specifically highland areas with an altitude of 2,400–3,500 m above sea level (ASL) and lowland areas with an altitude of 500–1800 m ASL (Mulatu et al, 2022). A large number of additional bamboo species have been introduced in Ethiopia for sustainable forest management, climate change mitigation, and the promotion of bamboo resources for various purposes (Mulatu,

Alemayehu and Tadesse, 2016). In Ethiopia, bamboo is commonly used for furniture, household utensils, handicrafts, construction materials, charcoal, and food (Desalegn and Tadesse, 2014; Embaye, 2000; Mekonnen et al, 2014; Mulatu, Alemayehu and Tadesse, 2019).

Highland bamboo is a fast-growing perennial bamboo species that occurs in natural forests and small holder plantations with a wide range of values and uses in Ethiopia (Kidane et al, 2023). In Ethiopia, highland bamboo is distributed in the south, southwestern, central, and northwestern highland regions with altitudes between 2200 and 4000 m ASL (Yebeyen, Nemomissa, Hailu et al, 2022). Although the species grows well in the altitudinal gradient, better yields can be achieved at elevations of 2300–3500 m ASL with a mean annual rainfall of > 1200 mm, temperatures of min. 6ºC and max. 30ºC, and slopes at 0–60% (Kidane et al, 2023).

Highland bamboo is untapped in Ethiopia as well as in greater Africa, having various socioeconomic, cultural, and ecological significances (Mulatu and Fetene, 2013; Bahru and Ding, 2021). Various industries and factories are also emerging to process and produce bamboo products such as toothpicks and chopsticks, parquet flooring, window blinds, curtains, bioenergy (charcoal and briquettes), and other products for local and international markets. However, limited research has been conducted on the potential of this species for carbon sequestration and its role in climate change mitigation (Abebe et al, 2023; Teshoma, 2019; Yebeyen, Nemomissa, Sileshi et al, 2022). Thus, it is possible to achieve greater economic, ecological, and social benefits from highland bamboo by promoting the species for broader socioeconomic development and environmental sustainability.

### *1.2. Resource Base, Management, and Utilization of Bamboo in Ethiopia*

#### *1.2.1. Bamboo Resources in Ethiopia*

Ethiopia, endowed with diverse agro-ecological zones, hosts significant bamboo resources, positioning it as one of Africa's leading nations in natural bamboo coverage (Silie et al, 2024). A recent remote sensing–based study conducted by Zhao et al (2018) reported that Ethiopia possesses 1.44 million ha of bamboo resources. About 92% (1,332,243 ha) of these natural bamboo resources are lowland bamboo mainly located in Benishangul-Gumuz, western Amhara, and the western Oromia Regional States, while the remaining 8% is covered by highland bamboo, which grows in

the south, southwestern, southeastern, central, and northwestern highlands of Ethiopia (Figure 1) (Ahmed, 2021). Table 1 presents the bamboo distribution in Ethiopia by zone and region.

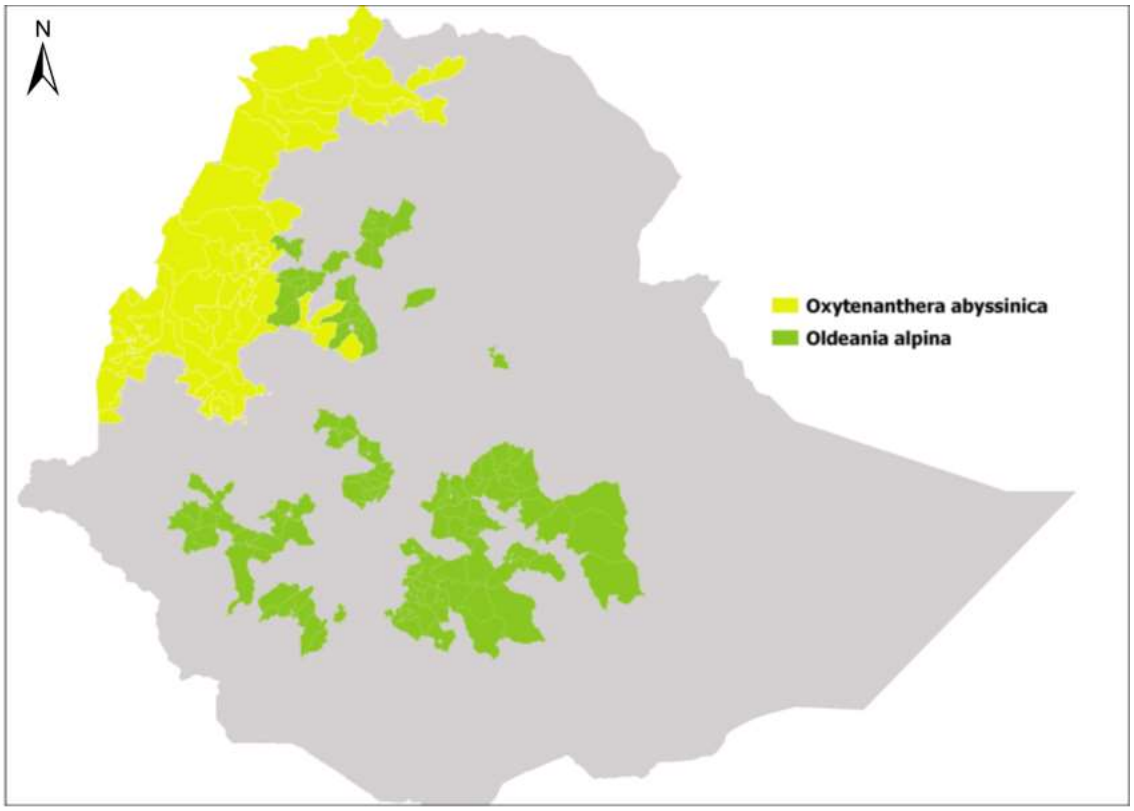


***Figure 1.*** *Bamboo species coverage in Ethiopia (Ahmed, 2021)*

Highland bamboo occurs mostly in high mountains (Hall and Inada, 2008), which also host some of the most essential water towers in Africa. Highland bamboo is limited to elevations of 2000–4000 m (Hall and Inada, 2008), but it is a conspicuous element of the vegetation of most East African mountains, including the Ethiopian highlands and the southern highlands of Tanzania and Malawi (Grimshaw, 1999). It also grows in the Bamenda Mountains of Cameroon (Grimshaw, 1999). In the Virunga transboundary protected area (East-Central Africa), highland bamboo provides important habitat and food for the critically endangered eastern mountain gorillas (Sheil et al, 2012, Stapleton, 2013) and African golden monkeys. In Kenya, highland bamboo provides habitat for the endangered (International Union for Conservation of Nature Red List) mountain bongo in the Aberdare Mountains. The conservation of highland bamboo forests on mountains is

critical for the protection of the remnant populations of these endangered species. In Ethiopia, highland bamboo is an ecologically and economically important indigenous plant species. Nevertheless, its natural regeneration is usually hampered due to human interference, mass flowering, and climate change (Demissew et al, 2011; Embaye, 2000).

***Table 1.*** *Major distribution areas of indigenous bamboo species (Oldeania alpina and Oxytenanthera abyssinica) in Ethiopia (Desalegn and Tadesse, 2014)*

| **Bamboo Species** | **Regional State** | **Zone (Specific Locality)** |
|---|---|---|
| *Oldeania alpina* (Highland bamboo) | Oromiya | Jima (Agaro, Gera), Bore/Gujji/Hagere Selam, Western Shewa (Tikure-Inchini, Shenen, Jibat Mountain), Bale/Harena forest, Western Aris (Degaga, Munesa, Shashemene) |
| | Amhara | Awi Zone/Injibara, Gojam/Choke Mountains, South Wello (Denkoro forest) and South Gonder (Debere Tabor), Debresina/Wofwasha |
| | Southwest | Kefecho Shekecho (Ameya, Wushwush, Baha-Chapa, Gada, Gecha-Masha, Andracha, Mizan Teferi/Kulish), Dawaro |
| | South | Gurage/Indibir-Jembero, Chencha/Arbaminch |
| | Sidama | Agere Selam |
| *Oxytenantheria abyssinica* (Lowland bamboo**)** | Benishangul Gumuz | Assosa (Anbesa Chaka, Kurmuk), Kamashi, Mambuk, Mandura, Bambasi, Dibate, Guba, Begi, Demi, Pawe, Sherkole |
| | Gambella | Gambella |
| | South | Gamo, Gaelebena Hamer Bako |
| | Southwest | Benchi and Maji, Majina Goldiya |
| | Oromiya | West Walega (Begi, Nejo, Gimbi, Guten, Didessa, Kelem), north of Nekemte/Hinde |
| | Amhara | North Gondar (Metema, Dansha, Humera, Chilga, Wegera) |
| | Tigray | Shire |

Lowland bamboo (*Oxytenanthera abyssinica*) is predominantly distributed in the northwestern regions of Ethiopia, primarily in Benishangul-Gumuz, the western part of Amhara, and Oromia. It thrives at elevations ranging from 540 to 1,750 m ASL. Known for its drought resistance, this

species is commonly found in expansive savanna woodlands, along river valleys, and on hillsides. The total distribution area of lowland bamboo is estimated to cover approximately 14,415.04 $km^2$ (Zhao et al, 2018). It is a valuable resource for local communities, offering materials for construction, furniture, farming tools, handicrafts, and fuelwood (Bahru and Ding, 2021).

### *1.2.2. Bamboo for Land Restoration*

Bamboo is a short rotation forestry crop with the potential to sequestrate atmospheric carbon, rehabilitate degraded land, and mitigate climate change. Bamboo is known for its potential in re-greening, slope stabilization, and soil and water conservation. Its unique ecological and physiological characteristics make it ideal for landscape rehabilitation, combating climate change, and biodiversity conservation. Bamboo is considered a superior wood substitute that is cheap, efficient, fast-growing, and holds high potential for environmental protection and wide ecological adaptation (Lombardo 2022). Currently, the world's forest resources are shrinking, though alternative species such as bamboo have the potential to counter this loss (Mekonnen et al, 2014; Lombardo 2022). Bamboo restoration creates livelihood opportunities through sustainable harvesting, processing, and value-added product development. It supports rural communities by providing raw materials for construction, handicrafts, and energy. Ethiopia's 2019–2030 Bamboo Development Strategy and Action Plan alone aims to rehabilitate 42,500 ha of land for landscaping and conservation purposes through the use of bamboo (EFCCC, 2020).

### *1.2.3. Bamboo for Climate Change Mitigation and Adaptation*

From the Stockholm Conference on Environment in June 1972 to the Earth Summit in Rio de Janeiro in June 1992 and 2012, some definitive international actions have been suggested through the United Nations Framework Convention on Climate Change (UNFCCC) to reduce the carbon dioxide concentration in the atmosphere (Nath, Sileshi, and Das, 2020). To reduce greenhouse gases like carbon dioxide in the atmosphere, two key activities are relevant: reduce the anthropogenic emissions of carbon dioxide and create or promote carbon sinks in the biosphere (IPCC, 2007). Carbon research, covering global to local scales, informs our understanding of the potential role of ecological sequestration in offsetting carbon emissions. In this perspective, the contribution of plants to sequestering carbon is inevitable. Plants play an important role in the global carbon cycle, including accumulation and storage of carbon that limits the concentration of

carbon dioxide in the atmosphere (Yen, Ji and Lee, 2010). Forests in particular have the capacity to sequester carbon from the atmosphere in large amounts. The Kyoto protocol recognizes forests as the potentially best land use system for carbon sinks (Sohel et al, 2015). Indeed, the world's forests store an estimated 662 gigatons of carbon (FAO, 2020).

While climate policies have prioritized the potentiality of forestry and agroforestry systems in carbon sink management, bamboo-dominated systems in particular remain little explored (Nath, Sileshi and Das, 2020). Most studies have assessed the contributions of large woody plants to carbon storage, but few have focused on bamboo plants (Yen, Ji and Lee, 2010). Bamboo forests provide important ecosystem services and play an important role in terrestrial carbon cycling. They are one of the most important terrestrial forest ecosystems with a high potential for carbon fixation (Zhuang et al, 2015). Many bamboo species studied so far have notable carbon storage potential (Abebe et al, 2021; Chen et al, 2009; Nath, Sileshi and Das, 2018; Sohel et al, 2015; Teshoma, 2019; Yen and Lee, 2011; Zhuang et al, 2015). Climate change affects us all, but will affect the poorest the most. Thus, bamboo has the potential to mitigate and adapt to the effects of climate change by absorbing and storing carbon, protecting forests and watersheds, insulating environments against extreme weather, providing low-cost green housing and infrastructure, providing cleaner biofuels, offering renewable and sustainable resources to generate income, and increasing the range and season of food sources (INBAR, 2011).

Bamboo has intrinsic characteristics of rapid growth and short harvesting periods (Han et al, 2014), with individual culms possible to harvest after 3–6 years, depending on the species (INBAR, 2011). As fast-growing, high-yield plants, bamboo species are capable of sequestering 5–12 t $CO_2$ $ha^{-1}$ $year^{-1}$ (Venkatappa et al, 2020). Accordingly, bamboo has a large capacity for biomass accumulation within a short period of time and a high potential for carbon storage (Nath, Sileshi and Das, 2020). Bamboo forests have powerful carbon sequestration abilities and play an important role in the global carbon sink due to their large biomass and carbon stock (Han et al, 2014). Indeed, biomass carbon stock and sequestration rates in woody bamboos are quite comparable with those in agroforestry and forest ecosystems (Nath, Sileshi and Das, 2020; Figure 2). Owing to its high crown density and developed underground stems and roots, bamboo has stronger carbon sequestration and water absorption capabilities than wood forests (Li et al, 2016; Zhou et al, 2011). The soil organic carbon generated by bamboo is more stable than that generated by other tree

species because of its high phytolith concentration (Li et al, 2016; Parr et al, 2010). Given its numerous advantages over other woody plants, such as its rapid growth, high production, and versatility (Zhang et al, 2014), there is a strong likelihood of a future directed toward bamboo.

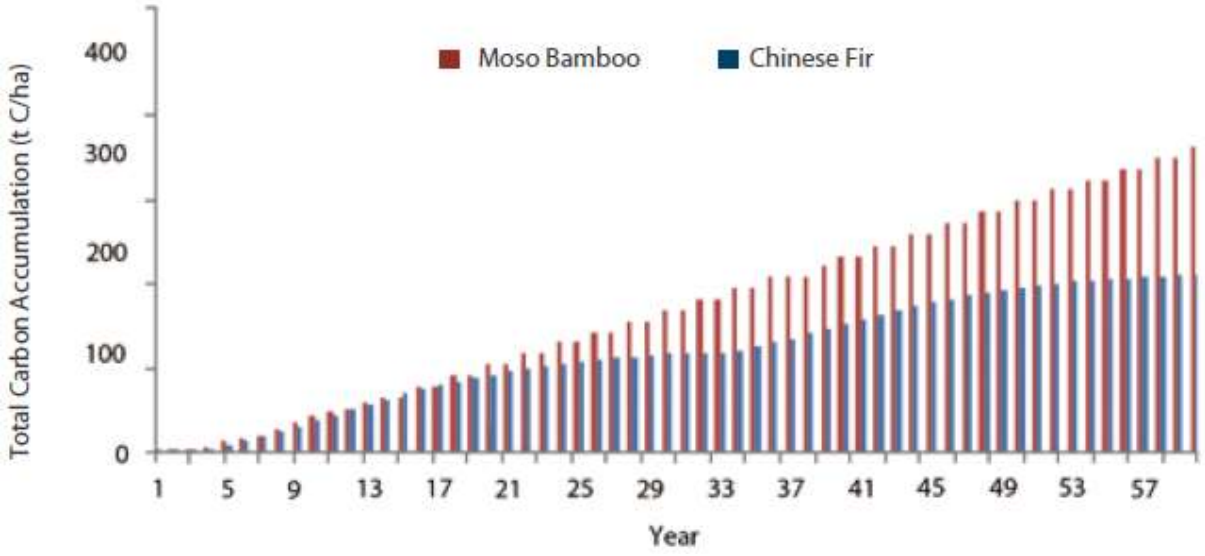


***Figure 2.*** *Comparison of carbon accumulation in Moso bamboo and Chinese fir in managed stands (Yen and Lee, 2011)*

Despite their potential, unmanaged bamboo stands do not store high levels of carbon, as their productivity is low and the accumulated carbon returns quickly to the atmosphere as older culms decompose (INBAR, 2011). In a managed stand, however, mature bamboo culms are harvested before they decay, so the total amount of carbon stored by the ecosystem increases, as new culms will emerge in subsequent years and sequester additional carbon. Studies have shown that appropriately managed and regularly harvested bamboo forests can sequester more carbon than if left in their natural state; moreover, they can sequester more carbon than fast-growing tropical and sub-tropical trees in comparable conditions (Yen and Lee, 2011; Figure 2). Sustainable bamboo management, utilization, and afforestation/reforestation as a potential carbon sink to address the impacts of climate change is relevant to the United Nations' 2030 Agenda for Sustainable Development Goals (SDGs; Ahmed, 2021; Venkatappa et al, 2020). The management of bamboo forests is also an eligible method under the Reducing Emissions from Deforestation and Forest Degradation (REDD+) scheme of the United Nations Framework Convention on Climate Change

(UNFCCC; Yiping et al, 2010). Considering its role in climate change adaptation and mitigation, its noteworthy contribution to the socioeconomic aspects of rural life, and numerous other environmental services, woody bamboo warrants serious consideration for carbon farming and carbon trading (Nath, Sileshi and Das, 2020).

## *1.3. Objectives of the Study*

### *1.3.1. General Objective*

The primary objective of this study was to quantify the biomass and carbon stock potential of highland bamboo in the Sidama Regional State, Ethiopia to support sustainable management practices and enhance the role of this species in climate change mitigation.

### *1.3.2. Specific Objectives*

1. To develop species- and site-specific allometric models for highland bamboo biomass estimation in the Garamba natural highland bamboo forest, Arbegona district, Sidama Regional State.
2. To quantify the biomass and carbon storage capacity of highland bamboo stands in natural and homestead farms in the Sidama Regional State.

## 2. Materials and Methods

### *2.1. Study Area*

This study was conducted in the Arbegona and Hula districts of the Sidama Regional State, Ethiopia (Figure 3). These districts were selected due to their availability of bamboo resources, with Arbegona featuring natural bamboo forests and Hula showcasing homestead bamboo plantations established by local communities.

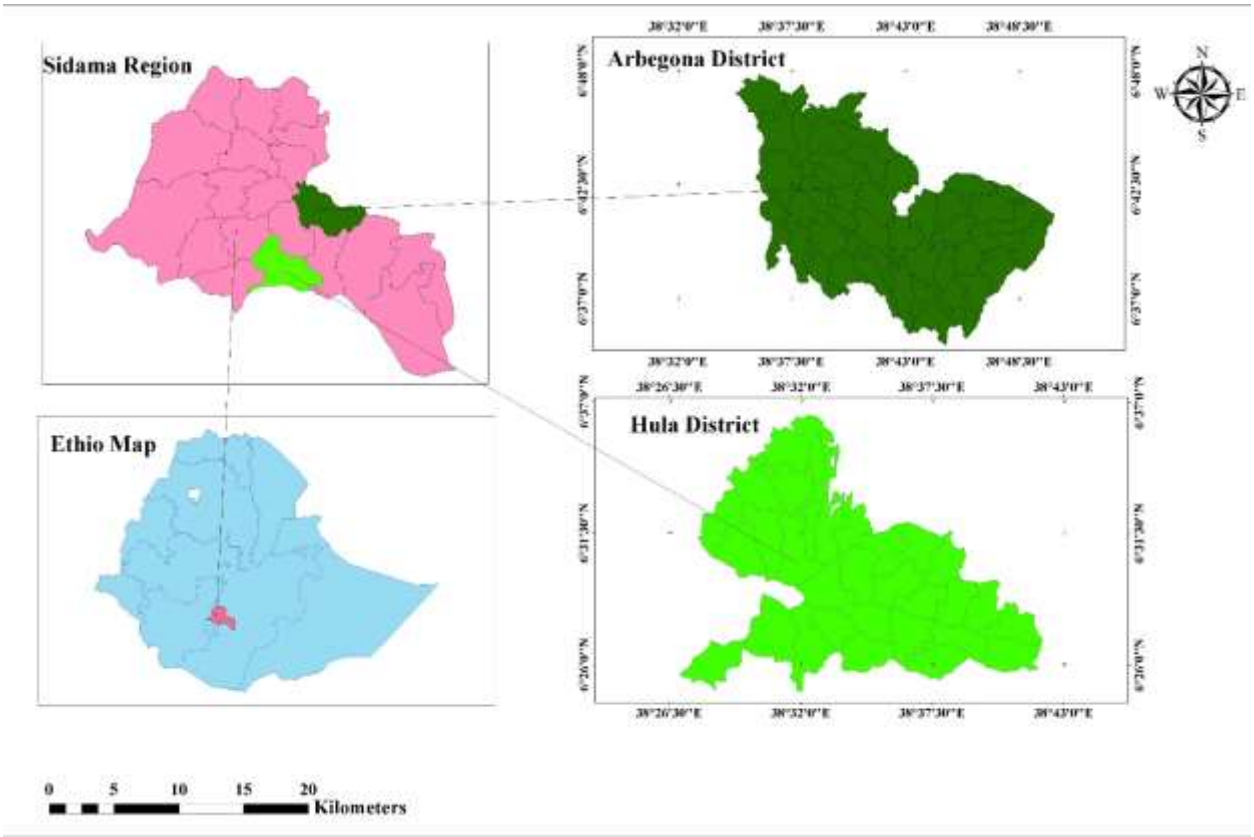


***Figure 3.*** *Map of the study areas*

Arbegona is one of 36 districts in the Sidama National Regional Government, located 77 km from Hawassa, the regional capital. The district geographically lies between 6°35’18” to 6°56’37” N latitude and 38°35’60” to 38°53’36” E longitude (Girma, Beyene and Biazin, 2017). It borders the Bura and Kokosa districts of the Oromia Regional Government. The district comprises 32 kebeles, 30 of which are rural and 2 are urban settlements. The total land area of the district is 235.51 km$^2$,

with 80% of the terrain being mountainous and 20% of the land flat. Of the 32 kebeles, 8 are classified as highland and 24 as sub-alpine climates. The district's total population is 174,731, with 87,336 males and 87,395 females. According to the district's forestry department, Arbegona is home to 235 ha of natural bamboo forests and 3,975.5 ha of bamboo plantations, equating to 4,210.5 ha of total bamboo forests. The study site was situated at an altitude of 2,780 m ASL, with annual rainfall ranging from 1,400 to 1,800 mm and temperatures between 14°C and 21°C. Mount Garamba, located in Fode Folish kebele (12 km from the district capital), spans 250 ha at an altitude of 3,360 m ASL. Approximately 95% of the mountain is covered in highland bamboo, with a few indigenous tree species scattered throughout. The mountain is a crucial source of natural water springs and provides numerous environmental and social benefits to the local community.

Hula is located in the Southern Sidama Zone of the Sidama Regional State at approximately 6°35' N latitude and 38°35' E longitude. It shares borders with the Bura district (Oromia Region) to the south, the Dara district to the west, the Bursa district to the north, and the Bona Zuria district to the east. Hula's capital, Agere Selam, is situated 24 km from the zonal capital, Aleta Wendo, and 94 km from the regional capital, Hawassa. Covering a total area of 159.61 $km^2$, Hula comprises 18 kebeles (16 rural and 2 urban). The district's terrain is predominantly mountainous, accounting for about 80% of the land area, while the remaining 20% is flat. Key agricultural crops include corn, wheat, barley, local cabbage, and potatoes. Hula experiences a bimodal rainfall pattern, with most precipitation occurring during the Kiremt (June–September) and Belg (March–May) seasons. The average annual rainfall is approximately 1,331 mm, and the mean annual temperature is 13.4°C, indicating a cool temperate climate (Yona, Matewos and Sime, 2024). According to the district forestry department, 59.6% of the land is arable, while 36.2% of the land is pastureland, 2.3% is forest, and the remaining 1.8% consists of swampy, degraded, or otherwise unusable land. Of the total forest cover, 38% (1,400 ha) consists of highland bamboo, primarily cultivated on homestead farmlands. Based on the 2007 census by Ethiopia's Central Statistical Agency (CSA, 2008), the district has a total population of 129,263, with 64,551 males and 64,712 females. Urban residents make up 4.96% of the total population.

### *2.2. Survey and Sampling*

A survey was conducted in the Garamba forest during the full growing season of highland bamboo to obtain data on the stand density, structure, biomass, and carbon sequestration potential of the bamboo stands (Figure 4). Transects were laid down 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 m from each other in the bamboo stands. Sample quadrants measuring 10 × 10 m were laid down at 200 m distances along line transects (Yebeyen, Nemomissa, Sileshi et al, 2022). A total of 12 plots (4 plots per transect) were established in the study area.

***Figure 4****. Field photos of the data collection*

### *2.3. Data Collection*

Within the sample plots, data were collected on structural attributes—including diameter at breast height (DBH), basal diameter, total height, culm density, and culm age—as well as environmental factors such as slope, aspect, and altitude (Xu et al, 2018). Bamboo culms were categorized into four age groups: Group 1 (1-year-old culms), Group 2 (2- and 3-year-old culms), Group 3 (4- and 5-year-old culms), and Group 4 (culms older than 5 years) based on specific indicators (Table 2) (Xu et al, 2018; Yebeyen, Nemomissa, Sileshi et al, 2022). A total of 96 culms were randomly selected and harvested—two from each age group per plot—for biomass estimation (Embaye et al, 2005; Yebeyen, Nemomissa, Sileshi et al, 2022). Destructive sampling was employed to obtain data on the fresh weight of highland bamboo for aboveground biomass (AGB) estimation following the methods outlined by Singnar et al (2021).

***Table 2.*** *Criteria for age group classification of highland bamboo (Yebeyen, Nemomissa, Sileshi et al, 2022)*

| **Age Group Classification** | **Age Group Description** | **Indicators** |
|---|---|---|
| Age group 1 | 1 year old | Dark green and smooth stem fully or partly covered by fresh-looking sheath, with poor strength; small leaf size and no or few branches; internode covered with white flour, nodes are hairy; free from any spots or signs of infestation by moss or lichen |
| Age group 2 | 2–3 years old | Pale green stem with no sheath or dirty and ragged sheath slightly rough to the touch; branches and leaves fully developed; no or very little lichen |
| Age group 3 | 4–5 years old | Strong yellowish green stem with dry appearance and rough surface; little lichen |
| Age group 4 | > 5 years old | Gray stem that is hard to cut; moss and lichen are prevalent on nodes and internodes |

### *2.4. Bamboo Sample Collection and Analysis*

Bamboo subsamples (stems, branches, and leaves) were collected and transported to the Forest Products Innovation Center of Excellence at Ethiopian Forestry Development in Addis Ababa, Ethiopia. In the laboratory, the subsamples were dried at 85°C until a constant weight was achieved (Embaye et al, 2005). The mean absolute dry-to-fresh weight ratio was then calculated to estimate the dry biomass of the various bamboo parts across age groups, following Yebeyen, Nemomissa, Sileshi et al (2022).

### *2.5. Modeling Allometric Relationships*

#### *2.5.1. Height-Diameter Allometry*

Various functions were explored to model the height-diameter (H-D) relationships of the bamboo samples to identify the best functional form that predicts asymptotic height ($H_{max}$). Several non-linear models have previously been considered for H-D relationship prediction, of which the following functions were chosen to identify the best model; in all but the Power law, $a$ is asymptotic height ($H_{max}$):

Power law: $$H = aD^b \quad (1)$$

Chapman-Richards: $$H = a\left(1 - exp(-bD)\right)^c \quad (2)$$

Weibull: $$H = a - b\left(exp(-cD^d)\right) \quad (3)$$

Monomolecular: $$H = a\left(1 - exp(-b(D - c))\right) \quad (4)$$

Gompertz: $$H = a\left(-exp(b - cD)\right) \quad (5)$$

Richards function: $$H = \frac{a}{(1+\exp(b-cD))^{1/d}} \quad (6)$$

Logistic: $$H = \frac{a}{(1+\exp(b-cD))} \quad (7)$$

Exponential model (2 parameter): $$H = a(exp(bD)) \quad (8)$$

Exponential model (3 parameter): $$H = a + b(exp(cD)) \quad (9)$$

Hyperbolic models: $$H = a + \frac{b}{D} \quad (10)$$

### *2.5.2. Biomass Estimation Models*

The two models were tested to estimate bamboo AGB, that is, Models 1 and 2. Model 1 used the natural logarithm of DBH alone [ln(D)], while Model 2 used the natural logarithm of volume [ln($D^2H$)] as a predictor. Model 1 followed a simple allometric function using DBH:

$$ln(AGB) = ln(a) + b(lnD) + \varepsilon \quad \text{Model 1}$$

Previous studies (e.g., Singnar et al, 2017; Singnar et al, 2021) have demonstrated that $D^2H$ is a better predictor of bamboo AGB than D or H alone. Strictly speaking, a model with $D^2H$ is not allometric in nature, as it involves a compound variable (Sileshi, 2014) given in the following form:

$$ln(AGB) = ln(\alpha) + \beta(\ln(D^2H)) \quad \text{Model 2}$$

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

The models were compared using the common model selection criteria, namely $R^2$, root mean square of error (RMSE), and the bias-corrected Akaike information criterion (AICc; Singnar et al, 2021). The best species-specific model for AGB was deemed to be that with the largest $R^2$ and the smallest RMSE and AICc.

### *2.5.3. Estimating Plant Biomass and Carbon Stocks*

AGB was estimated using the developed allometric equation based on DBH, whereas biomass density (kg $ha^{-1}$) was calculated by adding together all bamboo biomass values within the sample unit area and converting to hectares (Yebeyen, Nemomissa, Sileshi et al, 2022). Belowground biomass (BGB) was determined by multiplying AGB using a ratio of 0.20, as prescribed by the Intergovernmental Panel on Climate Change and previous studies (Eggleston et al, 2006; Meragiaw et al, 2021). Total plant biomass was then computed by summing aboveground and belowground biomass.

The amount of carbon in each biomass was determined by multiplying the default carbon fraction of 0.47 provided by the Intergovernmental Panel on Climate Change (IPCC) by oven-dried biomass conversion (Eggleston et al, 2006). The carbon storage of all bamboo within a unit area

according to age group was added to determine carbon stock. Finally, one-way analysis of variance was used to compare aboveground and total biomass carbon among the age groups. When $p < 0.05$, differences between age groups were deemed significant. Tukey's HSD (Honestly Significant Difference) test was used to compare the means of the various age groups post-hoc when an omnibus F-test revealed significance.

## 3. Results

### *3.1. Stand Structure*

Highland bamboo displays distinct growth patterns in pure stands in the Garamba natural forest, thriving at elevations higher than those of other tree species (Figure 5). Conversely, in Hula homestead farmlands, it grows in discrete stands within each farm for bamboo pole production. Stand characteristics, including age-specific mean DBH, basal area, height, and culm density, are summarized in Table 3.

***Figure 5.*** *Bamboo stands in Garamba's natural bamboo forest (top) and Hula's homestead bamboo farms (bottom)*

In the natural forest, the proportion of bamboo culms within the total stand density for Age Groups 1, 2, 3, and 4 was 5.2%, 13.3%, 19.6%, and 61.9%, respectively, resulting in a stand density ratio of 1:1:2:6. In turn, in homestead bamboo farms, the proportions were 32.2%, 35.6%, 30.1%, and 2.1% for the same age groups, leading to a stand density ratio of 3:4:3:0. These differences highlight distinct growth patterns, with natural forests favoring older culms and homestead farms maintaining a more balanced age distribution for optimal pole harvesting.

***Table 3.*** *Stand structure of highland bamboo in the study areas*

| Variables | Age Group | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | All | |
| | Forest | Farm | Forest | Farm | Forest | Farm | Forest | Farm | Forest | Farm |
| Density (culms $ha^{-1}$) | 1,008 | 7,008 | 2,583 | 7,742 | 3,817 | 6,558 | 12,017 | 467 | 19,425 | 21,775 |
| DBH (cm) | 5.0 | 4.5 | 5.2 | 4.7 | 4.5 | 5.2 | 4.3 | 5.6 | 4.5 | 4.8 |
| Height (m) | 10.3 | - | 10.1 | - | 9.9 | - | 9.0 | - | 9.8 | 10.8 |
| Basal area ($m^2$ $ha^{-1}$) | 1.99 | 11.79 | 5.67 | 14.20 | 6.47 | 14.36 | 18.56 | 1.16 | 32.68 | 41.52 |

Culm density (culms $ha^{-1}$) varies across age groups, with natural forest stands again dominated by older bamboo and homestead farms having a more balanced age distribution. In forest stands, density increases with age, ranging from 1,008 culms $ha^{-1}$ in Age Group 1 to 12,017 culms $ha^{-1}$ in Age Group 4, with a total stand density of 19,425 culms $ha^{-1}$. In contrast, homestead farms exhibit higher culm densities in younger age groups with 7,008 culms $ha^{-1}$ (Age Group 1), peaking at 7,742 culms $ha^{-1}$ (Age Group 2) before declining sharply to 467 culms $ha^{-1}$ in Age Group 4, resulting in a total stand density of 21,775 culms $ha^{-1}$. This indicates that culm density ($ha^{-1}$) is higher in the homestead farms compared to natural stands in forests.

DBH varies between the two environments as well, with the natural forest showing a relatively stable trend (4.3–5.2 cm). In contrast, DBH increases with age in homestead farms from 4.5 cm (Age Group 1) to 5.6 cm (Age Group 4), suggesting active selection of larger culms for harvesting. The number of bamboo plants in diameter classes 2–4 cm, 4–6 cm, and 6–8 cm account for 29.1%, 57.3%, and 13.1% of the total samples for the natural bamboo forest and 16.2%, 64.4%, and 19.4% for the homestead bamboo farms, respectively.

Bamboo height in the natural forest decreases with age from 10.3 m (Age Group 1) to 9.0 m (Age Group 4), whereas in homestead farms, height data are not available for individual age groups, but they do show an overall average of 10.8 m. Basal area values show significant differences between the two environments, with higher values generally found in homestead farms compared to the natural forest (Table 3). The natural forest exhibits increasing basal area with age, reaching 18.56 $m^2\ ha^{-1}$ in Age Group 4, contributing to a total basal area of 32.68 $m^2\ ha^{-1}$. In homestead farms, basal area is significantly higher in younger age groups, peaking at 14.36 $m^2\ ha^{-1}$ (Age Group 3) before dropping to 1.16 $m^2\ ha^{-1}$ (Age Group 4), resulting in a total of 41.52 $m^2\ ha^{-1}$.

### *3.2. Dry-to-Fresh Weight Ratio of Highland Bamboo Components*

The dry-to-fresh weight ratio of highland bamboo varies across different age groups and plant components, as shown in Table 4. The culm exhibits a slightly higher dry-to-fresh weight ratio compared to branches and leaves, indicating a greater proportion of dry matter content in the main structural component. For culms, the dry-to-fresh weight ratio ranges from 0.53 (Age Group 1) to 0.55 (Age Group 3), with a slight decline to 0.54 in Age Group 4. This pattern suggests a gradual increase in dry matter accumulation with age, stabilizing in older culms. In contrast, the branch and leaf components have lower ratios, ranging from 0.42 (Age Group 1) to 0.46 (Age Group 3) before slightly decreasing to 0.45 in Age Group 4.

***Table 4.*** *Average dry-to-fresh weight ratio for different parts of highland bamboo per age group*

| Age Group | Dry-to-Fresh Weight Ratio | |
|---|---|---|
| | **Culm** | **Branch and Leaf** |
| Age group 1 | 0.53 | 0.42 |
| Age group 2 | 0.54 | 0.45 |
| Age group 3 | 0.55 | 0.46 |
| Age group 4 | 0.54 | 0.45 |

### *3.3. Allometric Scaling for Quantifying Bamboo Biomass and Carbon*

#### *3.3.1. Height-Diameter Allometry*

The H-D relationships using different predictive models are presented in Table 5 and Figure 6. The algorithms for most models we tested did not converge, so we were unable to identify a suitable model for the asymptotic height of highland bamboo in the natural forest at Arbegona. However, among the models tested, the Exponential (2-parameter) model performed best with the lowest AICc (15.8) and RMSE (1.06), indicating superior predictive accuracy and efficiency. The Logistic (3-parameter) model and Gompertz model also showed strong performance, with AICc values of 18.0 and 18.4, respectively and identical RMSE values (1.07). These models could serve as alternative options, particularly in scenarios where a logistic growth pattern is expected. Conversely, the Hyperbolic model exhibited the weakest performance with the highest RMSE (1.14) and AICc (30.1), suggesting poor predictive capability. The Power law model, while widely used in forestry, had a moderate fit with an AICc of 19.0, performing similarly to the Weibull, Monomolecular, and Richard models.

***Table 5.*** *Comparison of height-diameter (H-D) models using the Akaike information criterion (AICc), pseudo $R^2$, and root mean square of error (RMSE) criteria*

| | Parameters | | | | Criteria | | |
|---|---|---|---|---|---|---|---|
| Model | a | b | c | d | $R^2$ | RMSE | AICc |
| Power law | 3.89 (2.95, 4.82) | 0.59 (0.44, 0.75) | -- | -- | 0.384 | 1.08 | 19.0 |
| Chapman-Richard | N/A | N/A | N/A | -- | 0.383 | 1.09 | 21.3 |
| Weibull | N/A | N/A | N/A | N/A | 0.407 | 1.07 | 19.8 |
| Monomolecular | N/A | N/A | N/A | N/A | 0.393 | 1.08 | 19.8 |
| Gompertz | N/A | N/A | N/A | N/A | 0.401 | 1.07 | 18.4 |
| Richard | N/A | N/A | N/A | N/A | 0.402 | 1.08 | 20.6 |
| Logistic (3-p) | N/A | N/A | N/A | N/A | 0.404 | 1.07 | 18.0 |
| Exponential (2-p) | 5.5 (4.7, 6.3) | 0.12 (0.09, 0.15) | -- | -- | 0.404 | 1.06 | 15.8 |
| Exponential (3-p) | 5.3 (-1.6, 12.3) | 1.4 (-2.9, 5.7) | 0.25 (-0.09, 0.58) | -- | 0.395 | 1.07 | 18.9 |
| Hyperbolic | 14.5 (13.0, 15.9) | -21.8 (-28.4, -15.1) | -- | -- | 0.308 | 1.14 | 30.1 |

-- Parameter not applicable

N/A: parameter estimates not available because algorithm did not converge

When the difference between the AICc of two models is less than 10, one model is not considered better than the other. Thus, we further explored and refined the Power law model using three different regression techniques, namely ordinary least square, reduced major axis, and major axis regression. We regressed H against ln(D) after removing two outliers and estimated the uncertainty around the coefficients using bootstrapping. Table 6 presents the coefficients and their 95% confidence intervals.

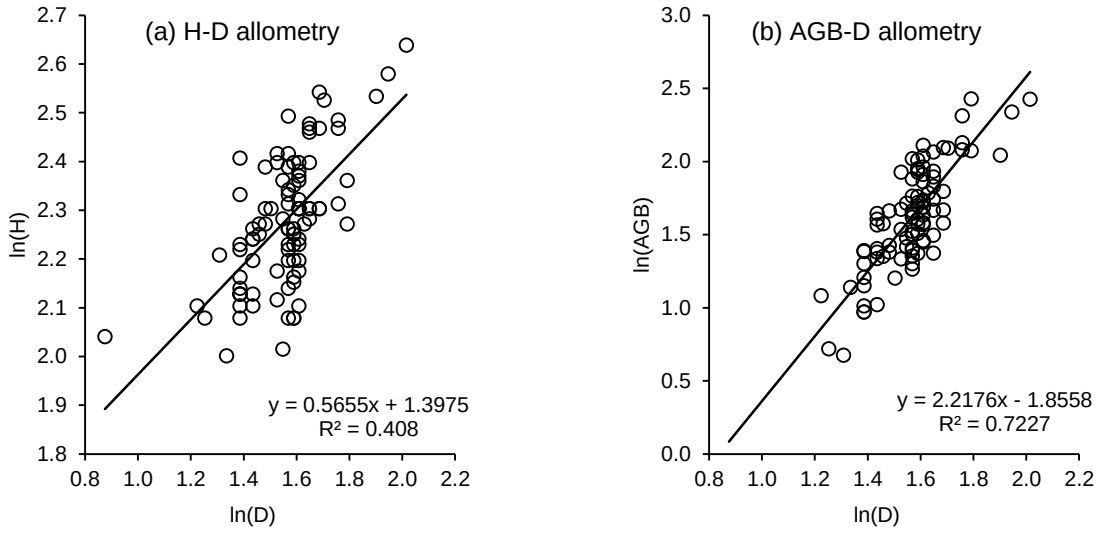


***Figure 6.*** *Allometric scaling of bamboo (a) stem height (H) and (b) aboveground biomass (AGB) with diameter at breast height (D) in the logarithmic domain*

***Table 6.*** *Comparison of H-D models after removing two outliers*

| Model | a | b | $R^2$ |
|---|---|---|---|
| Ordinary least square | 1.39 (1.20, 1.64) | 0.57 (0.41, 0.69) | 0.408 |
| Reduced major axis | 0.90 (0.66, 1.05) | 0.88 (0.66, 1.05) | |
| Major axis | 0.99 (0.65, 1.60) | 0.83 (0.44, 1.04) | |

Values in parentheses are 95% bootstrapped confidence intervals (N = 1,999)

### *3.3.2. Biomass Estimation Models*

We compared the two biomass estimation models (Model 1 and Model 2) for bamboo AGB estimation. For Model 1, Bartlett's test of equality of variances does not reveal significant differences between the age groups ($\chi^2 = 1.40$; $p = 0.706$). The test of equality of slopes also does

not reveal significant differences between the exponents ($F$ = 0.88; $p$ = 0.453), but the test for quality of elevations shows differences between age groups ($F$ = 3.12; $p$ = 0.0297). Similarly, for Model 2, Bartlett's test of equality of variances does not reveal significant differences between the age groups ($\chi^2$ = 2.66; $p$ = 0.447). The test of equality of slopes also does not reveal significant differences between the exponents ($F$ = 1.48; $p$ = 0.2245), but the test for quality of elevations shows differences between age groups ($F$ = 4.51; $p$ = 0.0054). Since the variances were homogeneous and the slopes were equal in Models 1 and 2, separate data analyses for each age group were not warranted. The models and their parameters are given in Table 7 and Figure 6. Based on the model evaluation criteria (lowest RMSE and AIC), Model 1 is more appropriate than Model 2 for estimating highland bamboo AGB in the study areas:

$$ln(AGB) = -1.85 + 2.22(\ln(D)) \quad \text{Model 1}$$

$$ln(AGB) = -2.90 + 0.83(\ln(D^2H)) \quad \text{Model 2}$$

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

***Table 7.*** *Comparison of age-specific biomass models (Model 1 and Model 2) using the $R^2$ and RMSE*

| Model* | Intercept | Slope | $R^2$ | RMSE | AIC |
|---|---|---|---|---|---|
| 1 | -1.85 (-2.30, -1.41) | 2.22 (1.93, 2.50) | 0.723 | 0.208 | -288.0 |
| 2 | -2.90 (-3.49, -2.30) | 0.83 (0.72, 0.94) | 0.708 | 0.213 | -283.1 |

*The models were fitted after removing three outliers with standardized residuals > 2.

### *3.4. Bamboo Biomass and Carbon Stocks on Homestead and Natural Bamboo Stands*

The distribution of biomass across different age groups in highland bamboo stands varies significantly between natural forests and homestead farms (Table 8). AGB is significantly higher in farmland bamboo stands compared to natural forest stands across age groups except for Age Group 4 (Figure 7). In the natural forest, AGB increases with age from 5.7 Mg ha$^{-1}$ in Age Group 1 to 51.9 Mg ha$^{-1}$ in Age Group 4, culminating in a total AGB of 92.33 Mg ha$^{-1}$. Conversely, in farmland stands, younger age groups (Age Groups 1–3) have higher AGB values ranging from

33.2 Mg ha$^{-1}$ to 41.4 Mg ha$^{-1}$, but there is a sharp decline to 3.4 Mg ha$^{-1}$ in Age Group 4, resulting in a total AGB of 118.28 Mg ha$^{-1}$. We record a similar trend in BGB, with forest stands accumulating 1.1 Mg ha$^{-1}$ in Age Group 1 and increasing to 10.4 Mg ha$^{-1}$ in Age Group 4, contributing to a total BGB of 18.47 Mg ha$^{-1}$. In farmland stands, BGB is higher in younger age groups, ranging from 6.6 Mg ha$^{-1}$ (Age Group 1) to 8.3 Mg ha$^{-1}$ (Age Group 3), but sharply declining to 0.7 Mg ha$^{-1}$ in Age Group 4. The total BGB in farmland stands is 23.7 Mg ha$^{-1}$, exceeding that of the forest stands (Table 8). The total highland bamboo biomass (AGB + BGB) in natural forest stands follows a continuous accumulation pattern, increasing from 6.8 Mg ha$^{-1}$ (Age Group 1) to 62.3 Mg ha$^{-1}$ (Age Group 4), resulting in a total of 110.79 Mg ha$^{-1}$. In contrast, farmland stands exhibit a biomass peaking in younger age groups (reaching 49.7 Mg ha$^{-1}$ in Age Group 3) before dramatically declining to 4.1 Mg ha$^{-1}$ in Age Group 4. However, farmland stands still maintain a higher total biomass of 142.0 Mg ha$^{-1}$ compared to natural forest stands.

***Table 8.*** *Variation in aboveground, belowground, and total biomass carbon per age group in forest and farmland bamboo stands*

| | Age Group | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | All | |
| Variable | Forest | Farm | Forest | Farm | Forest | Farm | Forest | Farm | Forest | Farm |
| AGB (Mg ha$^{-1}$) | 5.71 | 33.16 | 16.41 | 40.31 | 18.30 | 41.41 | 51.91 | 3.39 | 92.33 | 118.28 |
| BGB (Mg ha$^{-1}$) | 1.14 | 6.63 | 3.28 | 8.06 | 3.66 | 8.28 | 10.38 | 0.68 | 18.47 | 23.66 |
| Total biomass (Mg ha$^{-1}$) | 6.85 | 39.80 | 19.69 | 48.37 | 21.96 | 49.70 | 62.29 | 4.06 | 110.79 | 141.93 |

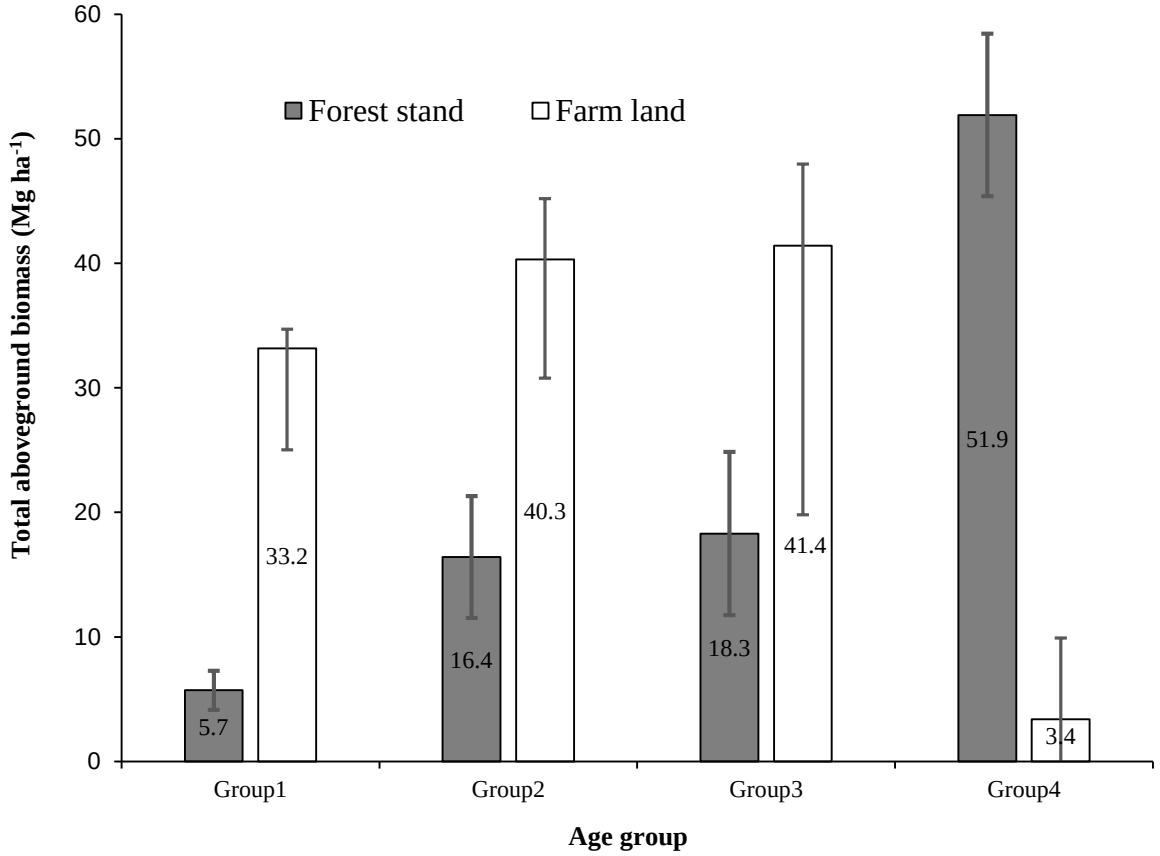


***Figure 7****. Variation in total aboveground biomass (Mg ha$^{-1}$) per age group in forest and farmland bamboo stands*

The distribution of biomass carbon in highland bamboo varies between natural forests and farmland stands across different age groups (Table 9). AGB carbon (AGBC) is significantly higher in farmland compared to forest stands in younger age groups. In forests, AGBC increases progressively with age, from 2.7 Mg ha$^{-1}$ (Age Group 1) to 24.4 Mg ha$^{-1}$ (Age Group 4), leading to a total AGBC of 43.4 Mg ha$^{-1}$. In contrast, farmland stands accumulate more AGBC in early stages, with values peaking at 19.5 Mg ha$^{-1}$ (Age Group 3) before experiencing a sharp decline to 1.6 Mg ha$^{-1}$ in Age Group 4. The total AGBC in farmland stands is 55.07 Mg ha$^{-1}$, surpassing that of forest stands. A similar trend occurs in BGB carbon (BGBC). In forest stands, BGBC increases gradually from 0.5 Mg ha$^{-1}$ (Age Group 1) to 4.9 Mg ha$^{-1}$ (Age Group 4), contributing to a total of 8.7 Mg ha$^{-1}$. In farmland stands, BGBC follows an early peak, reaching 3.9 Mg ha$^{-1}$ in Age Group 3 before dropping to 0.3 Mg ha$^{-1}$ in Age Group 4, resulting in a total BGBC of 11.1 Mg ha$^{-1}$. Total biomass carbon (AGBC + BGBC) in forest stands steadily accumulates, increasing

from 3.2 Mg ha$^{-1}$ (Age Group 1) to 29.3 Mg ha$^{-1}$ (Age Group 4), leading to an overall total of 52.07 Mg ha$^{-1}$. Conversely, farmland stands show rapid carbon accumulation in younger age groups, peaking at 23.4 Mg ha$^{-1}$ in Age Group 3 before declining sharply to 1.9 Mg ha$^{-1}$ in Age Group 4, resulting in a total of 66.71 Mg ha$^{-1}$ (Table 9).

***Table 9.*** *Variation in aboveground, belowground, and total biomass carbon per age group in forest and farmland bamboo stands*

| | Age Group | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | All | |
| Variable | Forest | Farm | Forest | Farm | Forest | Farm | Forest | Farm | Forest | Farm |
| AGBC (Mg ha$^{-1}$) | 2.7 | 15.6 | 7.7 | 18.9 | 8.6 | 19.5 | 24.4 | 1.6 | 43.4 | 55.6 |
| BGBC (Mg ha$^{-1}$) | 0.5 | 3.1 | 1.5 | 3.8 | 1.7 | 3.9 | 4.9 | 0.3 | 8.7 | 11.1 |
| Total biomass C (Mg ha$^{-1}$) | 3.2 | 18.7 | 9.3 | 22.7 | 10.3 | 23.4 | 29.3 | 1.9 | 52.1 | 66.7 |

## 4. Discussion

### *4.1. Highland Bamboo Stand Characteristics*

The present study revealed that in Ethiopia, homestead bamboo stands exhibit higher density, DBH, height, basal area, and biomass compared to natural bamboo forests. The greater density in homestead stands suggests intensive management practices, whereas natural forests follow a more self-sustaining growth pattern influenced by ecological factors and anthropogenic pressures. Overall, stand structure, productivity, and biomass accumulation of bamboo are shaped by ecological conditions, human activities, and management strategies. Notably, well-managed bamboo stands in homestead farmlands showed higher biomass, highlighting the role of farmers' active cultivation and care. The culm density (per hectare) recorded in the study area (19,425 in forests and 21,775 in farms) was comparable or even higher than values reported so far for highland bamboo in Ethiopia (e.g., Embaye et al, 2005; Mulatu, 2012; Nigatu et al, 2020; Teshoma, 2019; Yebeyen, Nemomissa, Sileshi et al, 2022). The average DBH observed in this study was lower than the reported values of highland bamboo in other studies in southwest Ethiopia (Abebe et al, 2023; Embaye et al, 2005; Teshoma, 2019; Yebeyen, Nemomissa, Sileshi et al, 2022), but greater than *Oxytenanthera abyssinica*, the other indigenous bamboo species in Ethiopia (Abebe et al, 2023; Gurmessa et al, 2016; Darcha and Birhane, 2015).

Variations in the dry-to-fresh weight ratio of highland bamboo components indicated that as bamboo matures, the proportion of dry matter in both culms and foliage increases, with culms showing a more consistent trend. The relatively lower dry-to-fresh weight ratio in branches and leaves suggests higher moisture content, which may influence drying and utilization processes for different bamboo products. This provides useful insights for bamboo management, particularly in estimating dry biomass yields and optimizing harvesting strategies for different age classes.

### *4.2. Allometric Scaling, Biomass, and Carbon Stock Potential*

By optimizing the Power law model with various regression techniques, we effectively captured the H-D relationship, demonstrating allometric scaling between culm height and stem diameter in highland bamboo. This finding aligns with previous studies (Yebeyen, Nemomissa, Sileshi et al, 2022) and provides valuable insights for improving bamboo growth modeling and forest

management strategies. The Power law (Model 1) was also more appropriate than Model 2 for estimating highland bamboo AGB in the study area. This is consistent with findings from other parts of Ethiopia on highland bamboo (Yebeyen, Nemomissa, Sileshi et al, 2022). Compared to a study on three bamboo species in northeast India, our findings suggest that volume (Model 2) provides more accurate biomass predictions than diameter (D) or height (H) alone (Model 1; Singnar et al, 2017).

This study established that AGB stocks are higher on homestead farm stands than in natural forest stands. The greater total biomass carbon stocks on homestead bamboo farms compared to natural forest bamboo stands may be attributed to higher stand density, particularly in Age Groups 1–3, which benefit from improved stand management. The exception was in Age Group 4, where the reverse was true. This likely indicates that bamboo stands in the natural forest are dominated by large, mature culms and low recruitment. In turn, AGB in Age Group 4 was lowest on homestead bamboo farms probably because bamboos are ready to harvest in 3–5 years (Durai and Long, 2020). Thus, this study suggests that farmland bamboo stands accumulate biomass more rapidly in early growth stages, likely due to intensive management and faster harvesting cycles. However, the sharp decline in biomass in Age Group 4 suggests frequent removal of mature culms for commercial purposes. In contrast, forest stands exhibit a more gradual and continuous biomass accumulation. These findings highlight the trade-off between biomass productivity and sustainability in managed versus natural bamboo ecosystems, providing insights for optimizing bamboo cultivation and carbon sequestration strategies.

The AGBC (43–55.6 Mg $ha^{-1}$) and BGBC (8–11 Mg $ha^{-1}$) recorded in this study are comparable with values reported for highland bamboo in other parts of Ethiopia and elsewhere in Africa (Embaye et al, 2005; Yebeyen, Nemomissa, Sileshi et al, 2022; Yuen, Fung and Ziegler, 2017). For example, Yebeyen, Nemomissa, Sileshi et al (2022) estimated aboveground and belowground biomass carbon stocks at 43.7 Mg $ha^{-1}$ and 8.7 Mg $ha^{-1}$ in highland bamboo in southwestern Ethiopia. Elsewhere in Ethiopia and in Kenya, highland bamboo was reported to store 68.4 Mg $ha^{-1}$ in AGBC and 12.8 Mg $ha^{-1}$ in BGBC (Embaye et al, 2005; Yuen, Fung and Ziegler, 2017). According to a global review, plausible carbon storage in bamboo ranges from 16 to 128 Mg $ha^{-1}$ in AGB and from 8 to 64 Mg $ha^{-1}$ in BGB (Yuen, Fung and Ziegler, 2017). The total biomass carbon stock recorded in this study (52–67 Mg $ha^{-1}$) is also comparable with values reported for

highland bamboo in southwestern Ethiopia (Yebeyen, Nemomissa, Sileshi et al, 2022). In addition to biomass, bamboo stores significant amounts of soil organic carbon. For example, in southwestern Ethiopia, highland bamboo stands were previously reported to store 263–581.5 Mg C $ha^{-1}$, with an average value of 388.1 Mg C $ha^{-1}$ (Yebeyen, Nemomissa, Sileshi et al, 2022).

### *4.3. Opportunities for Land Rehabilitation, Livelihood Improvement, Value Chain Development, and Climate Change Mitigation*

Bamboo is increasingly recognized as a valuable resource for land rehabilitation due to its unique characteristics and environmental benefits. Its fast growth, extensive root system, and ability to thrive in degraded soils make it highly effective for restoring disturbed landscapes. Bamboo rapidly colonizes degraded lands, demonstrating adaptability and nutrient conservation (Mishra et al, 2014; Peprah et al, 2014). The plant's dense root network stabilizes soil, preventing erosion and landslides, particularly in steep and degraded areas. Additionally, bamboo improves soil fertility by increasing organic matter content and promoting microbial activity (Mishra et al, 2014). It also plays a crucial role in regulating water cycles by enhancing soil permeability and reducing surface runoff.

As an annual yielding and versatile crop, bamboo offers opportunities for added value in various product ranges. There are over 10,000 products and utilities of bamboo. Traditionally, bamboo has been used by communities in the form of food, fodder, firewood, construction, fencing, utility and handicraft products, and furniture that provide livelihood for the forest and rural dependent communities. Since the 1980s, with the development of industrial processing and technological innovations in bamboo utilization as well as an increased need for eco-friendly materials, bamboo has become a value-added, high-quality durable material. In the past two decades alone, numerous value-added bamboo products in the form of wood substitutes, cloth, charcoal, bio-ethanol, plastic composite products, and pharmaceutical applications have been developed.

A key advantage of bamboo is that it is easier to process than timber because of its linear fiber and light weight. Thus, the value addition of bamboo products requires little or no investment in comparison to other enterprises and handicraft activities (Rao, Kumar et al, 2009; Rao, Motukuri and Karpe, 2009). Due to this inherent capacity for accessible and widespread use, bamboo provides opportunities for poorer communities to participate in the wood products market and earn

sustainable on- and off-farm income through resource generation as well as enterprise activities. With annual regrowth, bamboo grants further opportunities for selective harvesting of mature bamboo culms, which can derive regular returns for growers. Furthermore, this selective harvesting increases the productivity of bamboo plantations (Durai and Long, 2020).

Bamboo has been used in the development of various products since time immemorial. Nowadays, bamboo is one of the most important traded non-timber forest products, generating over USD 3 billion per annum. China is the world leader in bamboo development and accounts for more than 70% of bamboo trade. There is a difference in the bamboo sector, product, and technology development within continents, across countries, and even within countries. Asia overall leads in bamboo development, with China, Viet Nam, India, Indonesia, Malaysia, and Thailand having considerable bamboo-based economies. Similarly, Colombia, Ecuador, Peru, and Brazil in South America have relatively advanced bamboo industries. In Africa, with its bamboo development projects and programs, industries for the production of bamboo sticks, laminated boards, and bio-energy products are coming up in Ethiopia, Kenya, Uganda, Madagascar, and Ghana. With abundant bamboo resources in Ethiopia especially, most traditional bamboo products are low value-added products mainly used for sustenance and domestic applications. With innovations in the past decades, however, the utilization of bamboo in Ethiopia is continuously diversifying, allowing the country's bamboo sector to advance as well into the production of other bamboo products. Even so, there are still gaps and imbalances in Ethiopian and global bamboo developments.

The results of the present study have demonstrated the high potential of bamboo stands to sequester carbon and mitigate climate change. Unlike traditional plantation forestry, loss of bamboo biomass carbon due to harvesting is balanced by the production of new culms in each stand every year (Nath and Das, 2011). Bamboo also produces a stable form of carbon known as phytolith-occluded carbon, which results from decomposing vegetation (Huang et al, 2014). Phytolith-occluded carbon is highly resistant to decomposition and remains in the soil for several thousand years. In addition, harvested bamboo is often used to produce durable products such as furniture, flooring, and construction materials, which results in the long-term storage of carbon (Huang et al, 2014; Song et al, 2011). This highlights the potential role of bamboo in the long-term sequestration of carbon to mitigate climate change. It is a highly effective renewable and sustainable carbon sink

and landscape restoration plant, contributing to climate change mitigation by absorbing significant amounts of carbon dioxide, reducing pressure on natural forests through the provisioning of ecosystem services, and strengthening climate resilience by improving microclimates and water retention. Bamboo's full potential can be harnessed for both ecological and economic benefits in current development scenarios to achieve broader socioeconomic development goals, climate change mitigation, and environmental sustainability (Silie et al, 2024).

## 5. Conclusion and Recommendations

This study provides novel insights into the variations of stand structure, biomass, and carbon stocks of highland bamboo in the Sidama Region, Ethiopia across natural bamboo forests and homestead bamboo farms. The findings indicate that bamboo stands on homestead farms have higher density, culm diameter, height, basal area, and biomass carbon stocks compared to those in natural forests. This disparity is likely due to better management practices in homestead farms, which promote optimal growth and regeneration. A Power law model using DBH was the most suitable for estimating the bamboo stands' AGB, allowing greater understanding of the plant's significant role in climate change mitigation.

Integrating highland bamboo into initiatives like REDD+ is crucial for promoting sustainable carbon stock management and improving local livelihoods. Raising community awareness about bamboo's role in climate change mitigation is essential as well for conserving natural bamboo forests and expanding bamboo cultivation on farmlands, thereby supporting sustainable forest management and environmental sustainability. Expanding the use of bamboo in construction, furniture, and packaging can also help reduce deforestation and carbon emissions. Additionally, incorporating bamboo into reforestation and afforestation programs as part of climate adaptation and mitigation plans can support biodiversity conservation and greater sustainable forest management.

As a short-rotation forestry crop, bamboo offers substantial potential for carbon sequestration, climate change mitigation, land rehabilitation, and livelihood enhancement. The development of the bamboo sector is crucial for green economic growth, industrial transformation, and biodiversity conservation. Effective silvicultural management of bamboo stands in both forests and farmlands is key to maximizing the crop's biomass production and supporting the development of diverse bamboo-based products.

Based on our findings, we propose the following recommendations to enhance the management and utilization of highland bamboo for effective climate change mitigation and adaptation:

1. Sustainable Management and Conservation
    - Implement silvicultural practices in natural highland bamboo forests to enhance recruitment and biomass accumulation.
    - Promote sustainable harvesting techniques to maintain a balance between utilization and regeneration.
2. Value Chain Development and Economic Opportunities
    - Invest in highland bamboo processing industries to expand the crop's utilization in furniture, bioenergy, construction, and handicrafts.
    - Support smallholder farmers and entrepreneurs in developing bamboo-based enterprises through capacity-building programs.
3. Climate Change Mitigation and Land Rehabilitation
    - Encourage large-scale highland bamboo plantation programs to rehabilitate degraded lands and increase carbon sequestration.
    - Integrate highland bamboo into agroforestry systems to enhance biodiversity, soil fertility, and water conservation.
4. Research and Policy Support
    - Conduct further studies on soil carbon storage in highland bamboo forests to gain a comprehensive understanding of bamboo's carbon sequestration potential.
    - Develop policies that recognize highland bamboo as a key resource for climate change mitigation and provide incentives for sustainable bamboo farming.

By implementing these recommendations, highland bamboo resources in Ethiopia can be effectively managed to enhance the crop's ecological, economic, and climate benefits.

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