Above- and belowground biomass and biomass carbon stocks in homegarden agroforestry systems of different age groups at three sites of southern and southwestern Ethiopia

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ABSTRACT

As the loss of forests over time results in a net flux of carbon (C) into the atmosphere, the practice of agroforestry can combat this and serve as a long-term sink for CO2. Based on the inventory of 93 homegarden agroforestry systems (AFS) in three study sites and using a non-destructive method involving allometric equations, the research assessed aboveground (AG) and belowground (BG) biomass and biomass C stocks across sites and along age groups in homegarden AFS in southern and southwestern Ethiopia. Plant diversity parameters were also gathered on perennial plant species. Results indicate that the mean perennial plant species richness per homegarden agroforestry, and other diversity parameters varied strongly among sites (p < 0.05). Biomass C stocks range from 18.11 at Malo Ezo to 32.86 Mg C ha⁻¹ at Saja Laften for AG, 3.97 to 7.10 Mg C ha⁻¹ for BG, and 22.02 to 39.96 Mg C ha⁻¹ for each respective sites, for the overall biomass C stocks were recorded within the homegarden agroforestry systems. In terms of age groups, the mean total biomass C stock did show numerical change from the initial, <10 years (22.49 Mg C ha⁻¹) to the middle age group, >10 and ≤20 years (39.96 Mg C ha⁻¹), but it was stagnant 20 years onward (28.49 Mg C ha⁻¹). The homegarden agroforestry systems had the potential to store up to 80.81–112.30 Mg ha⁻¹ of CO₂ equivalents across sites, and 82.53–104.55 Mg ha⁻¹ of CO₂ equivalents along age groups. A positive relationship was noted between AG woody biomass C stocks and attributes such as woody species richness, and woody plant density. Considering the involvement of large numbers of homegardeners, future improvements and expansion of homegarden agroforestry to larger areas can enhance to a great extent the potential to sequester C and thereby mitigate climate change.

KEYWORDS
Carbon stocks and biodiversity; climate change mitigation; age groups; perennial plant components; sustainability

Introduction

Global demand for agricultural and forest products caused a net forest loss of 7–11 million km² in the past 300 years [1]. If past trends continue, global cropland would increase by a net of 3.5 × 10⁸ hectares by 2050 [2]. Apart from such continuing pressures, forests store 20–50 times more carbon (C) per unit area than agricultural lands [3], but its loss over time results in net release of C into the atmosphere [3,4]. The emission of C into the atmosphere through the removal of a large volume of biomass affects biomass and soil C sink capacity and causes global warming [4,5]. If the current emission rates continue unabated, global warming is expected to reach 1.5 °C between 2030 and 2052, which rose from about 1.0 °C above the magnitude that was recorded in the pre-industrial level [6].

To alleviate the situation, increasing efforts are needed to offset C emissions either through maintenance of existing C stocks by protecting or enhancing woody vegetation and a continuous supply of organic matter to the soil [7,8]. One option may be tree-based land management systems such as agroforestry that can serve as long-term sink for CO₂ as it involves the production of tree biomass and secure storage of C even in deep soil [8,9]. Agroforestry systems that maintain high tree density and multiple species mix (e.g. homegardens) became recognized as a viable C storage and sequestration strategy, especially under the afforestation and reforestation programs under the Kyoto Protocol [10–12]. Long-term agroforestry...
systems such as homegardens can be defined as sustainable land use system that combines the production of the staple crop *enset* (*Enset ventricosum* (Welw.) Cheesman) with annual crops, livestock, and multipurpose trees surrounding houses and provides environmental services, household needs, and employment and cash-income opportunity to the households [13–15]. These systems are regarded as efficient farming systems, allowing interactions and synergies between different components [15], and they are characterized by a huge diversity of species and complex structure producing sustained yield for centuries [15,16].

Compared to other agriculture systems, higher amounts of C storage were recorded in the above- and belowground (BG) biomass and soils in the agroforestry systems [4,17–19]. For instance, agroforestry systems could potentially be established on 585–1275 x 10^6 ha of technically suitable land on global scale, and could store 12–228 Mg C ha\(^{-1}\) [20,21]. Other previous studies on biomass C stocks for complex agroforestry systems indicated mean values of 99.6 Mg C ha\(^{-1}\) for the neotropical region [4]; 16 Mg C ha\(^{-1}\) for tree-based agricultural landscapes in Kenya, east Africa [22]; 24.32 Mg C ha\(^{-1}\) for homegardens in Kerala, India [23]; and 29.6 Mg C ha\(^{-1}\) for coffee agroforestry system in Costa Rica [24]. Carbon stock estimations in homegarden agroforestry could vary based on factors including, management practices, system age and design [18,25,26], and land use history [18,26]. Given the area currently destined for agriculture, the number of people who depend on land for their livelihood, and the need for integrating food production with environmental services [26], homegardens potential contribution to the global C sequestration has only been recently gaining scientific interest [27–30]. Furthermore, as biodiversity conservation and mitigation of global warming are the two environmental issues of the world today [17], the association between carbon stocks and biodiversity was also emphasized in recent studies [17,24].

As part of tree-based agroecosystems, homegarden agroforestry systems were reported to cover about 576,000 hectares or representing 31% of southern Ethiopia people’s region cultivated land, where it was dominated by perennial staple and cash crops *enset*, coffee, and other companion crops along with tall shade trees [16,31]. Owing to much wider coverage of these systems in southern and southwestern parts of Ethiopia, it is very much important to understand the potential opportunity of these systems and select priority areas at landscape-level and regional levels to sequester C and its eventual use in C sink projects [32]. If agroforestry is to be used in C sequestration schemes such as the clean development mechanisms (CDM), better quantitative information is required about above- and belowground C stocks, and areas under agroforestry practices [33]. Although C storage potential of agroforestry needs studying biomass C stocks over time, few publication report C stocks beyond one-time data [8].

Although the relevance of homegarden agroforestry was considerably recognized for its C storage potential elsewhere in the world [11,33], only few studies have been undertaken concerning biomass C stocks of these systems in southern Ethiopia [28]. Given the highly heterogeneous agroforestry-dominated landscapes [34], and high spatial and temporal variability among farms and farming systems [15,35], those studies related to the biomass and biomass C stock dynamics and relationships of perennial plant species with C stocks under these specific systems were scant in this region. Therefore, the present study was undertaken to investigate the magnitude of above- and belowground biomass and C stocks of homegarden AFS between sites and along age groups. The study also assessed the relationships between woody species and aboveground biomass C stocks in these systems. This study explored the hypothesis that biomass and biomass carbon stocks vary across sites and along age groups. It also hypothesized that there may be positive relationships between taxonomic (woody plants species richness and Shannon index), structural (DBH, height, woody plants density), and farm (homegarden size, total landholding) attributes and woody biomass carbon stocks in these systems.

Materials and methods

**The study sites**

The research was conducted in Yem special woreda (7°37′–8°02′N, 37°40′–37°61′E), and Chencha (6°15′N, 37°34′E) and Daramalo (6°15′N, 37°14′E) woredas of Gamo zone, all located in southern and southwestern Ethiopia (Figure 1). Yem is located at elevations ranging from 920-2939 meters above sea level (m a.s.l.), while Chencha and Daramalo each located at an elevation ranging from 2000–3000 [36], and 1217–2700 m a.s.l. [37]. With bimodal seasonal distribution, both Chencha and Daramalo received mean annual precipitation of 1265 mm and 1031 mm, respectively. The
precipitation for that of Yem was 1365 mm. The mean annual temperature was 15.3 °C for Chencha, 24.9 °C for Daramalo, and 20 °C for that of Yem. The major soil types observed in Chencha and Daramalo areas include Immature Cambisols, Nitisols, Luvisols, Leptosols, Cambisols, and Andosols [38], while that of Yem include Nitisols, Acrisols, Ferralsols, Vertisols, and Planosols [39].

The human population density of Chencha, Daramalo, and Yem woredas in 2021 were 445.57, 326.66, and 166.1 persons/km² respectively [40]. Taking into account the method developed by Gerhardt et al. [41] and adopted by Bekele [42], the native vegetations of Chencha and Daramalo are characterized by dry Afromontane forests in the highlands with extensive areas being changed into bushlands [43]. The ubiquitous existence of individual forest trees such as Juniperus procera Hochst. ex Endl., Olea europaea subsp. cuspidata (Wall. ex G.Don) Cif., and Croton macrostachyus Del., a scattered relict in most highlands of Yem is indicative of a long history of forest exploitation [42]. The study was undertaken in three study sites (kebeles, the lowest Ethiopian administrative unit) selected from three woredas based on a stratified sampling strategy, where enset-based homegarden agroforestry systems are practiced and have similar livelihood patterns (Table 1). A stratified sampling strategy that involves first, purposive sampling technique was applied to select woredas and sites based on the presence and extensive abundance of enset-based homegarden agroforestry systems, and distance/travel time (as a surrogate for accessibility) to major roads, and being disaggregated by major traditional agroecologic subdivisions, namely, Dega (cool and humid highland), Weyna Dega (cool sub-humid midland/midhighland) and Kolla (warm semiarid lowland). From each study

Figure 1. A map showing the study sites.

| Table 1. Main characteristic of sampled homegarden agroforestry sites in southern and southwestern Ethiopia. |
| --- |
| Characteristic | Yoyra /Chencha woreda | Saja Laftern / Yem woreda | Malo Ezo/ Dara Malo woreda |
| Biophysical | | | |
| Altitude (m asl.) | 2695 | 1964 | 1744 |
| Annual rainfall (mm) | 1263 | 1365 | 1031 |
| Slope (%) | 9.32 | 9.82 | 18.82 |
| Geographic location | | | |
| Easting | 37.5307 | 37.4682 | 37.3520 |
| Northing | 6.2832 | 7.9993 | 6.3195 |
| Socioeconomic | | | |
| Woreda population by 2021 | 166,644 | 120,338 | 120,864 |
| (projected based on 2007 census and 2.9% rate of growth for SNNPR) | | | |
| Population density (Km⁻²) | 445.57 | 166.1 | 326.66 |
| Mean farm sizes (ha) | 0.27 | 1.35 | 0.56 |
| Homegarden size (m²) | 2374.88 | 2748.64 | 3455.61 |
| Livelihood zone | Enset and barley are complemented by wheat, sweet or Irish potatoes, horse beans, and field-peas | A cereal and enset Maize and root crop | |
| Distance to major markets (hr) | 0.6 | 1.24 | 1.12 |
| Production system | | | |
| Major food crops | Enset and barley | enset and maize | enset and root crops |
| Major cash crops | Wheat, sweet or Irish potatoes, Teff, maize, sorghum, wheat, Maize, teff |
| Livestock types | Cow, oxen, sheep, horses, mule, Cow, oxen, sheep, goats, Yem | |
| Dominant ethnic group | Gamo | Gamo | |
site, homegarden owners were selected by using systematic random sampling in probability proportionate to size (PPS) [44] taking into account socio-economic variability, and gender ratio of inhabitants.

**Data collection**

A total of 93 household farms/homegardeners were selected randomly out of the total 1878 heads by using the formula defined by [45],

\[
n = \frac{z^2 \cdot p \cdot q \cdot N}{d^2 (N - 1) + z^2 \cdot p \cdot q}
\]

where, \( n \) = sample size in the study site; \( N \) = number of households; \( z \) = the value of the normal variable (20.25 = 1.96) for a reliability level of 0.95; \( q \) = probability of failure (0.5); \( d \) = margin error (0.1), and \( p \) = probability of success (0.5).

Besides considering sites as sampling units, the ages of homegarden agroforestry systems were constructed based on date of establishment of homegardens by interviewing longtime residents and by taking into account significant historic events, e.g. severe drought occurrences, and periods of political unrest and personal life events [46]. The homegardens were classified into three categories (initial (younger) age group ≤10 years; middle age group >10 years and ≤20 years; and older age group >20 years), following previous experience [47,48], but modified to suit the present study sites’ situation. These homegarden agroforestry age groups were also employed for the investigation of variations in above- and belowground biomass and biomass carbon stocks because historic land use patterns associated with human activities were potential sources of variation, apart from sites heterogeneity [49].

In order to assess biomass and biomass carbon stocks, and taxonomic and structural attributes, a survey of perennial plant species (enset, banana, trees and/or shrubs) was conducted in 93 homegarden agroforestry systems. During the survey, the area of homegarden microzones and total landholdings including their altitudinal variations were measured using a handheld Garmin GPS (Geographical Position System) and measuring tapes. Furthermore, household farm characteristics were collected through household questionnaires.

Following the method adopted by Millat-e-Mustafa and Haruni [50], a complete enumeration of individuals of species was carried out in homegarden agroforestry systems. In such a situation a north-south baseline was established to divide a homegarden into two roughly equal parts. Sample centers were demarcated on this line at 10 m intervals until the boundary reached. From the center points, additional lines perpendicular to the baseline were demarcated towards the east and west as far as the homegarden limit. By creating further points at 10 m intervals on these east-west lines, a 10 x 10 m sample grid was generated. Within each grid, the individuals of all perennial species mentioned above, total height, and diameter at breast height (DBH, 1.30 m) were documented [46]. Using a Suunto clinometer, total tree height was measured. Diameter of all woody plants of a minimum diameter and greater (>5 cm) in DBH were measured that were rooted in the grids; the reason is most biomass equations are valid for stems with DBH >5 cm [49,51].

Conventional and commonly used biodiversity indices were used to assess the status of biodiversity in homegarden agroforestry systems. Species richness indices (that is the number of species) were collected in total across sites. Furthermore, data on other diversity indices, namely, Shannon’s diversity and species evenness indices [52] were also computed in this study. Evenness that represents how equally abundant the species [52] were calculated in the homegarden agroforestry systems. Shannon diversity index (H’) was calculated with \( H’ = -\sum p \ln p \) [52], where \( p \) is the proportion of individuals found in the \( i \)th species in the collection and the summation is over all of the species. The proportions \( p \) are given by \( n_i/N \), where there are \( n_i \) individuals of the \( i \)th species. From that the Equitability or Species evenness index (E) was calculated by \( E = H’/H_{max} = H’/\ln S \) [52] where E is contained between 0 and 1, with 1 representing a situation in which all species are equally abundant; \( H_{max} \) is the maximum diversity and \( S \) species number. The degree of similarity of homegardens plant species composition across sites/habitats was calculated using Jaccard’s coefficient (\( S_j \)) of similarity [53], given by \( S_j = a/(a + b + c) \), where \( a \) is the number of species common to both sites, \( b \) is the number of species in site A only, and \( c \) is the number of species in site B only. To identify the importance of species, the summed dominance ratio (SDR) was estimated following McCune and Grace [54], as the averages of at least two of the parameters, namely, the sum of relative density, and relative frequency of species.

In this study, only the above- and BG biomass C stock measurements were considered, but C stocks
in deadwood and litter were ignored [55], because of negligible quantity and soil surface disturbance in the agricultural landscapes, respectively. Soil organic C was not also addressed here due to the fact that this issue went beyond the scope of this paper. Food crops for biomass C were not also considered, because the AG biomass of these annuals was indiscriminately removed after each cropping season [22]. Aboveground measurements of C stock are direct derivatives of aboveground biomass (AGB) estimates [23], assuming that 47% of the biomass is made up of C [4]. The inventories included all non-destructive measurements necessary to use the allometric models introduced (e.g. DBH, height) and the floristic composition of the different plant components [22].

Due to the lack of robust and validated information and methods of biomass for trees on farm [56], and the currently unavailable species-specific models for many tropical tree species, including those found in homegardens [4,9,23], the conventional and commonly used general allometric regression models developed for tropical dry forests [57], and those applied to different agroforestry land uses were applied [23,24,26]. Even country-specific allometric models available for Sub-Saharan African countries represent only less than 1% of the tree species in the region [58]. Thus allometric models developed elsewhere including locally developed ones were also used [28,59,60], as described below. Therefore, among those models developed, specific published allometric regression models were employed to estimate carbon stocks [57,61]. For the AGB, the regression model recommended by Chave et al. [57] was used since it is a result of critical validation of an extensive dataset collected at sites ranging from dry woodlands to hyperhumid closed-canopy forests, from highly seasonal to aseasonal climates, lowland to high-elevation, and old-growth forests in different continents for a total of 2,410 trees \( \geq 5 \) cm in DBH. Hence, based on Chave et al. [57] allometric equation was applied to estimate AGB for dry forests as follows in equation (1),

\[
AGB_{trees/shrubs} = 0.112 \times (\rho D^2 H)^{0.916}
\]  

(1)

where AGB aboveground biomass (kg dry weight), \( \rho \) wood density (g cm\(^{-3} \)), \( D \) diameter at breast height (cm), and \( H \) height (m).

To estimate the aboveground woody biomass of fruit trees without destructive measurements, the following equation given by [59] was used,

\[
AGB_{fruits} = \exp (-2.4090 + 0.9522 \ln (D^2 \times H \times \rho))
\]  

(2)

where AGB is the average aboveground woody biomass dry weight for a fruit tree (kg); \( \exp = \) exponential function; \( D \) the diameter at breast height (cm); \( H \) tree height in m and \( \rho \) wood density. Specific wood densities were compiled from different sources [61].

Similarly, the estimation of AGB stored in coffee and enset plants follows an allometric equation constructed by [28], respectively,

\[
AGB_{coffee} = 0.147 \times d_{40}^2; R^2 = 0.80, n = 31
\]  

(3)

\[
\ln (AGB_{enset}) = -6.57 + 2.316 \ln (d_{10}) + 0.124 \ln (h); R^2 = 0.91, n = 40
\]  

(4)

where \( d_{40} \) (cm) = stem diameter of the coffee plant at 40 cm height, \( d_{10} \) (cm) = the basal diameter of the enset pseudostem at 10 cm height, \( h \) (m) = total height.

At the same time, AGB of banana and bamboo plants were estimated following [60],

\[
AGB_{banana} = 0.03 \times (D)^{2.13}
\]  

(5)

\[
AGB_{bamboo} = 0.131 \times (D)^{2.28}
\]  

(6)

where \( D \) is diameter at breast height (cm).

Following Cairns et al. [62], belowground (root) biomass was estimated from total aboveground biomass using the following allometric equation,

\[
BGB_i = \exp (-1.0587 + 0.8836 \times \ln (AGBi))
\]  

(7)

where BGB, and AGB, represent root biomass and aboveground biomass, respectively, of an individual tree \( i \).

For predicting the belowground biomass (corm plus adventitious roots) component of enset and banana (Musa x-paradisiaca L.), the root: shoot ratio of 35% and 31%, respectively, were used as developed by [63]. The biomass C contents were then summed and divided by the area of the plot to give above- and belowground C density values for the farm plots expressed in Mg C ha\(^{-1} \). The overall above- and BG C stock in the homegarden agroforestry systems was eventually converted into Mg C ha\(^{-1} \) CO\(_2\) equivalent by multiplying this value by 3.67 (this ratio being derived from the molecular weight ratio of CO\(_2\) (44) to C (12)) to understand the climate change mitigation opportunity of the systems in the study area [64].
Table 2. Characteristics of woody and other perennial plant components inventoried for biomass carbon estimation in homegarden agroforestry systems between sites and age groups in southern and southwestern Ethiopia.

| Sites       | Mean DBH (cm) | Mean height (m) | Stems density (ha⁻¹) |
|-------------|---------------|-----------------|----------------------|
|             | Woody plants  | Enset plants    | Banana plants        |
|             |               |                 |                      |
| Yoyra       | 10.68        | 35.65          | –                    |
|             | 7.53          | 4.96           | –                    |
|             | 1396.74²      | 1639.41        | –                    |
| Saja Laften | 14.55²        | 30.33³         | 12.8³                |
|             | 7.07          | 4.55²          | –                    |
|             | 1436.49²      | 1171.13        | 401.40³              |
| Malo Ezo    | 17.65²        | 28.02³         | 18.92³               |
|             | 8.09          | 3.79³          | –                    |
|             | 589.68²       | 1073.99        | 519.18³              |

Significance | *** | ** | NS | *** | NS | NS | NS |

Means followed by different superscript letters in a column are significantly different from each other ($p < 0.05; p < 0.01; p < 0.001$).

Source: Survey data.

Statistical analysis

One-way ANOVA and t-tests were employed to analyze variation in above- and belowground biomass and carbon stocks between sites and along age groups of homegarden agroforestry systems using Statistical Package for Social Sciences (IBM SPSS version 17.0) software. Regression analysis was also run to test the relationships of taxonomic and structural attributes, and household farm characteristics to aboveground woody biomass and woody biomass carbon stocks.

Assumptions of normal distribution and homogeneity of variances were checked by using the Shapiro-Wilk and Levene tests [65]. Where necessary, quantitative data was log-transformed to meet assumptions of normality & homogeneity of variance, otherwise non-parametric Kruskal–Wallis and Mann-Whitney tests were followed when assumptions of normality failed to be satisfied. Appropriate post-hoc pairwise comparisons were made with Fisher’s Least Significance Difference (LSD) tests at $\alpha = 0.05$.

Results

Characteristics of woody and perennial plants inventoried for carbon estimation

Among the parameters considered in the study, DBH of woody plants showed significant variation across sites and age groups. Higher average DBH value (17.65 cm) was recorded for Malo Ezo site, but the density of woody stems (589.68 stems ha⁻¹) in this site was considerably lower than the other sites (1436.49 and 1396.74 stems ha⁻¹) (Table 2). Among the age groups, agroforestry systems under the category of > 20 years have the highest average DBH value and it was significantly higher than the age group of < 10 years, but not that of 10-20 years category. The mean DBH of woody plants in the homegarden agroforestry was found to be progressively increasing with age group, where it ranged from 10.45 cm at the initial age group (≤ 10 years) to 16.24 cm at the older age group (beyond 20 years) (Table 2). No significant differences were detected in height of woody plants in homegardens for the three sample sites ($\chi^2(2)=5.474; p = 0.065$).

For *Enset* plants, mean basal diameter ($d_{10}$) among all homegarden agroforestry systems between sites ranged from 15.39–56.15 cm. Among the sites, Yoyra had significantly larger mean *Enset* basal diameter than did Malo Ezo and Saja Laften (Table 2). Though it varied significantly between sites ($F_{2, 90}=4.425; p = 0.007$), mean *Enset* height did not follow the same pattern between the previously mentioned sites. Rather the opposite holds true, where the mean *Enset* height value was highest at Saja Laften (4.55 m) and a relatively lowest mean value at Malo Ezo (3.79 m) for these homegardens. Despite the occurrence of marginally insignificant difference in *Enset* stem density among homegardens between sites ($F_{2, 90}=2.843; p = 0.063$), a relatively higher stem density was recorded at Yoyra (1639 stems per ha) than Malo Ezo (1073.99 stems per ha) and Saja Laften (1171.13 stems per ha) (Table 2).

For banana plants, it should be noted that these plants were not found in the homegarden agroforestry systems of Yoyra site. Therefore, the statistical focus, in this case, was at Saja Laften and Malo Ezo. Based on these data, DBH of banana plants did show significantly larger values ($t = 2.241, p = 0.007$) for Malo Ezo than Saja Laften, but no significant differences were noted for banana plants density ha⁻¹ in the homegardens between these two sites (Table 2).

No significant differences existed among age groups in mean DBH values for *Enset* and banana plants in the homegarden agroforestry systems.
Similarly, mean height and stem density did show no significant differences for these major live biomass components (woody plants, *enset* and banana) of homegardens along the age groups (Table 2). Stem density of woody and *enset* plants among homegardens were slightly, but not significantly, higher at the initial age group than the older age group (Table 2).

**Plant species composition, richness, and diversity of homegardens**

One hundred seven different perennial plant species that belonged to 84 genera and 42 perennial plant families were identified across all 93 homegardens surveyed, out of which Euphorbiaceae was the dominant family with 6 genera and 10 species. The other families that demonstrate the floristic importance of homegarden AFS included Fabaceae, Rosaceae, Moraceae, and Rutaceae, with 8, 8, 7, and 6 species, respectively. Of the total perennial plant species registered, 71% were native, while the rest exotic species. Based on IUCN (The World Conservation Union) Red List, six species (7.9%) are listed as endemic species to Ethiopia (Appendix A).

The overall mean perennial plant species richness per homegarden agroforestry, mean individual density, and other diversity parameters varied strongly among sites, as shown in Table 3. Differences in mean species richness per homegarden agroforestry at Saja Laften (16.96) showed a markedly higher value than at Malo Ezo (8.88) and Yoyra (6.50) (Table 3). It implies that mean species richness at Saja Laften was about two-fold higher than that of Yoyra. There was also a statistically significant difference in the mean Shannon diversity index between Saja Laften and the rest two sites, but with no significant differences for any of the diversity indices along age groups (Table 3).

The five most dominant perennial plant species in the homegarden agroforestry systems were *Ensete ventricosum* (30.936% of all perennial plants), *Coffea arabica* L. (6.859%), *Musa x-paradisiaca* L. (5.858%), *Arundinaria alpina* K. Schum. (5.543%), and *Cordia africana* Lam. (4.682%) (Table 4).

In the study sites, homegarden agroforestry systems vary in their degree of dissimilarity in perennial crop and woody plant species composition between pairs of sites. The Jaccard index ranged between 0.219 and 0.337 across sites (Table 5). Yoyra and Saja Laften show the lowest degree of similarity, followed by Yoyra and Malo Ezo, implying higher dissimilarity between sites. In respect to age groups, a relatively higher similarity in species composition was observed between the initial age group, ≤10 years, and medium age group, >10 and ≤20 years (Table 5).

**Aboveground- and belowground biomass and biomass carbon stocks in homegarden agroforestry systems**

Comparing biomass fractions in the homegarden agroforestry systems across sites, the above- and belowground and cumulative woody and *enset* biomass fractions did show significant differences (Figure 2a–c). Based on partitioned components of the homegarden agroforestry systems across sites, estimated AG dry biomass stock was 31.61 to 58.23 Mg ha$^{-1}$ for woody plants, 5.22–10.54 Mg ha$^{-1}$ for *enset* plants, and 3.7–4.63 Mg ha$^{-1}$ for banana plants. When considering BG dry biomass stocks, it was 5.87–11.13 Mg ha$^{-1}$ for woody plants, 1.83–3.69 Mg ha$^{-1}$ for *enset* plants, and 1.14–1.46 Mg ha$^{-1}$ for banana plants. When taking into account cumulative AG and BG dry biomass stocks for each partitioned component of these homegardens across sites, woody plants yielded 37.47–69.36 Mg ha$^{-1}$, *enset* plants

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**Table 3.** Perennial plant species diversity of sample homegarden agroforestry in three sites in southern and southwestern Ethiopia.

| Sites     | Species richness | Shannon diversity index | Species evenness index |
|-----------|------------------|-------------------------|-----------------------|
|           | Mean  | Range | Mean  | Range | Mean  | Range |
| Yoyra     | 6.50a | 2–12  | 1.03b | 0.28–1.90 | 0.60 | 0.25–0.99 |
| Saja Laften | 16.96c | 9–28  | 1.65c | 0.64–2.20 | 0.58 | 0.29–0.73 |
| Malo Ezo  | 8.88d | 2–19  | 1.24d | 0.05–2.30 | 0.58 | 0.07–1.00 |

Means followed by different superscript letters in a column are significantly different from each other ($p < 0.05$; $p < 0.01$; $p < 0.001$). NS = not significant. Source: Survey data.
Table 4. The 20 most dominant species out of the 96 trees and shrub species, including perennial crops, encountered in 93 homegarden agroforestry in three study sites of southern and southwestern Ethiopia from highest to lowest summed dominance ratio (SDR) ranking.

| Species name                  | Relative frequency | Relative density | Total    | Rank |
|-------------------------------|--------------------|------------------|----------|------|
| Ensete ventricosum (Welw.) Cheesman | 9.438              | 52.435           | 30.936   | 1    |
| Coffea arabica L.             | 6.681              | 7.037            | 6.859    | 2    |
| Musa x paradisiaca L.         | 5.196              | 6.520            | 5.858    | 3    |
| Arundinaria alpina K. Schum.  | 1.379              | 9.708            | 5.543    | 4    |
| Cordia africana Lam.          | 6.681              | 2.684            | 4.682    | 5    |
| Catha edulis (Vahl.) Forsk. ex Endl. | 2.757         | 6.140            | 4.449    | 6    |
| Persea americana Mill.        | 4.878              | 1.227            | 3.053    | 7    |
| Malus sylvestris Mill.        | 2.333              | 3.660            | 2.997    | 8    |
| Mangifera indica L.           | 4.772              | 0.783            | 2.778    | 9    |
| Croton macrostachyus Del.     | 3.181              | 0.480            | 1.831    | 10   |
| Moringa stenopetala (Bak.f.) Cufod. | 2.651        | 0.974            | 1.813    | 11   |
| Carica papaya L.              | 2.757              | 0.412            | 1.585    | 12   |
| Citrus sinensis (L.) Osb.     | 2.439              | 0.284            | 1.361    | 13   |
| Erythrina brucei Schweinf.    | 2.227              | 0.363            | 1.295    | 14   |
| Ricinus communis L.           | 2.121              | 0.348            | 1.235    | 15   |
| Cupressus lusitanica Mill.    | 1.803              | 0.636            | 1.219    | 16   |
| Grevillea robusta R. Br.      | 2.015              | 0.380            | 1.198    | 17   |
| Eucalyptus camaldulensis Dehnh. | 1.909             | 0.332            | 1.176    | 18   |
| Eucalyptus globules Labill.   | 1.166              | 0.967            | 1.067    | 19   |
| Annona squamosa L.            | 1.803              | 0.227            | 1.015    | 20   |

Source: Field Survey.

A comparison of biomass-derived C stocks for the partitioned components in the homegarden agroforestry systems across studied sites did show significant differences for woody and enset plants (AG-, BG- and total biomass C for woody plants at Malo Ezo site. Although banana plants were not present at Saja Laften, its mean total C value did not vary between the other two sites (t = 1.934, p = 1.72; Figure 2d-f). In general, the AG-, BG- and total biomass C stocks for woody plants were higher at Saja Laften in comparison with Yoyra and Saja Laften (Figure 2d-f). However, relatively lower mean values were recorded for the AG-, BG- and total biomass C stocks for the enset plants at Malo Ezo site. Although banana plants were not present at Yoyra, its mean total C value did not vary between the other two sites (t = 1.934, p = 1.72; Figure 2d-f). Results of mean AG-, BG- and cumulative biomass C stocks did reveal no significant differences with respect to age groups of homegarden agroforestry systems for each plant components (p > 0.05; Table 8). Both woody plants and banana plants; however, showed an increase in biomass C stocks as someone moved from the initial age group (<10 years) to the middle age group (>10 and ≤20 years). But, for enset plants, AG-, BG- and cumulative biomass C stocks declined in the middle as compared to the initial age group of homegardens (Table 8). We observed increased mean biomass C storage in the middle age group as compared to the initial age group of homegardens (Table 8).

Table 5. Similarities (Jaccard similarity index) of crop species composition among sites and age groups in the homegarden agroforestry systems of southern and southwestern Ethiopia.

| Sites          | Yoyra | Saja Laften | Malo Ezo |
|----------------|-------|-------------|----------|
| Yoyra          | 1.000 |             |          |
| Saja Laften    | 0.219 | 1.000       |          |
| Malo Ezo       | 0.205 | 0.337       | 1.000    |
| Age-groups     |       |             |          |
| ≤10 years      | 1.000 |             |          |
| >10 and ≤20 years | 0.492 | 1.000       |          |
| >20 years      | 0.341 | 0.400       | 1.000    |

Source: Field Survey.

7.05–14.23 Mg ha⁻¹, and banana plants 4.77–6.08 Mg ha⁻¹ (Figure 2c).

Except enset, all biomass fractions along age groups of homegarden AFS did show a progressive increase in storage of above- and belowground, and cumulative biomass stocks up to 20 years, but did not increase with increasing homegarden age beyond 20 years, though it was not significant in all cases (Table 6).

For the entire plant components within the homegarden AFS across sites, the mean total AG- and BG- biomass stocks ranged from 39.29–69.93 Mg ha⁻¹, and from 8.47–15.09 Mg ha⁻¹, respectively (Table 7). At the same time, the overall biomass stock across sites ranged from 47.76 at Malo Ezo to 84.93 Mg ha⁻¹ at Saja Laften, with an average value of 60.61 Mg ha⁻¹. Considering the biomass distribution of components to the total biomass stock, woody plant components constituted the largest share of nearly 79.42%, with 16.34% being held in enset, and 4.24% in banana plants.
age group, but unexpectedly it ceased to increase and remained stagnant from age 20 years onward both for those partitioned components as well as for the entire components in the system (Table 7; Table 8). Similar to the pattern observed with total biomass stock, the distribution of biomass C stock for woody plant components did seem to constitute the largest share for nearly 80.05%, with 15.75% being held in enset, and 4.20% in banana plants.

**Table 6.** Estimated aboveground (AG) and belowground (BG) biomass stocks in different components in homegarden agroforestry systems along age group in southern and southwestern Ethiopia.

| Carbon pool | Mean AG biomass stock (Mg ha⁻¹) | Mean BG biomass stock (Mg ha⁻¹) | AG + BG biomass stock (Mg ha⁻¹) |
|-------------|---------------------------------|---------------------------------|--------------------------------|
|             | Woody plants | Enset plants | Banana plants | Woody plants | Enset plants | Banana plants | Woody plants | Enset plants | Banana plants |
| Age groups  |                                  |                                 |                                |                                  |                                 |                 |                                  |                                 |                 |                                |
| ≤10 years   | 29.53          | 9.08             | 0.88            | 5.88           | 3.18          | 0.24           | 35.41          | 12.26          | 1.12           |
| >10 and ≤20 years | 41.77          | 7.62             | 4.83            | 7.91           | 2.67          | 1.53           | 49.67          | 10.29          | 6.36           |
| >20 years   | 40.9           | 7.02             | 4.34            | 7.71           | 2.46          | 1.35           | 48.55          | 9.48           | 5.66           |
| Significance | NS               | NS               | NS              | NS             | NS            | NS             | NS             | NS             | NS             |

Source: Survey data.

**Factors driving variability in the aboveground biomass carbon stocks in homegarden agroforestry systems**

When considering the relationships of taxonomic attributes (woody plants species richness and Shannon index), structural attributes (DBH, height, woody plants density), and household farm characteristics (homegarden size, total landholding) to aboveground woody biomass carbon stocks, there appeared to be mixed results (Figure 3a–g). From
the taxonomic attributes, only woody species richness showed significant patterns to aboveground woody biomass carbon (AGWBC) for the homegarden agroforestry systems that were considered, although not significantly so for woody species Shannon diversity index (Figure 3a). From the structural attributes and farm characteristics, only woody plant density showed stronger positive relationships but remained significant to aboveground woody biomass carbon stocks (Figure 3e). However, homegarden size had revealed insignificant patterns to AGWBC, as do total landholding (Figure 3f and g).

**Discussion**

**Characteristics of woody and perennial plants inventoried for carbon estimation**

The mean DBH and basal d$_{10}$ (cm) values for woody and enset plants recorded in this study (10.41–17.50 and 28.02–30.33 cm, respectively) were comparable to those reported by [28], who found mean values of 10.6–20.1 and 22.4–29.2 cm for woody and enset plants, respectively, in indigenous AFS practiced in Southern Ethiopia. In general terms, DBH as predictor alone provided reliable estimation of total aboveground biomass, explaining well the variability of the data in agricultural landscapes [34]. Though enset in Ethiopia can grow up to a height of 13 m, the values documented for these plants in indigenous AFS in Ethiopia (4.9 m) [66] coincided with the mean height in the present study (3.79–4.55 m). Considering the density of woody and enset plants, some recent studies carried out by Negash et al. [67] under AFS in Ethiopia have suggested comparable mean values of woody plants (625–1505 stems density, ha$^{-1}$) but higher mean values of enset plants (1700–3784 stems density, ha$^{-1}$) as compared to the values documented in this study (589.68–1436.49 and 1073.99–1639.41 stems density (ha$^{-1}$), respectively, for woody and enset plants). In other previous studies carried out under various types of AFS in northern, southwestern and southern Ethiopia, and even elsewhere in Mexico; however, seemingly lower mean values of 364, 475, 589, and 188 woody stems density (ha$^{-1}$) were recorded, respectively [24,31,68,69]. As perennial crop and woody species differ in their growth pattern, specific achievable plant density and age of the plants (that may infer older ones as being big-sized individuals) of each species in each farm can be used as proxy measures for C stock and C sequestration [70], highlighting varying garden management strategies adopted by homegarden owners [23].

Along age groups, woody plants mean DBH value progressively increased from 10.45–16.24 (cm) towards the older aged homegardens, implying that most obvious general stand-level trend such as DBH increased as the age of the stands

| Table 7. Estimated total biomass and biomass C stocks in homegarden agroforestry systems between sites and along age groups in southern and southwestern Ethiopia. |
|---------------------------------------------------------------|
| Carbon pool | Mean AG biomass stock (Mg ha$^{-1}$) | Mean BG biomass carbon (Mg C ha$^{-1}$) | Mean total biomass stock (Mg ha$^{-1}$) | Mean total biomass carbon (Mg C ha$^{-1}$) |
| Sites | | | | |
| Yoyra | 53.13$^{a}$ | 11.97$^{ab}$ | 64.93$^{a}$ | 24.97$^{a}$ |
| Saja Laften | 69.93$^{b}$ | 15.09$^{b}$ | 84.93$^{b}$ | 32.86$^{b}$ |
| Malo Ezo | 39.29$^{a}$ | 8.47$^{ab}$ | 47.76$^{a}$ | 18.11$^{a}$ |
| Significance | * | ** | ** | * |
| Age groups | | | | |
| ≤10 years | 38.75 | 9.09 | 47.84 | 18.21 |
| >10 and ≤20 years | 51.64 | 11.29 | 62.93 | 23.88 |
| >20 years | 50.23 | 10.89 | 61.03 | 23.43 |
| Significance | NS | NS | NS | NS |
| Mean | 47.76 | 11.29 | 59.05 | 23.88 |
| Significance | NS | NS | NS | NS |
| Mean | 47.76 | 11.29 | 59.05 | 23.88 |

Means followed by different superscript letters in a column are significantly different from each other ($p < 0.05, 0.01$).

Source: Survey data.

**Table 8. Estimated AG, BG and AG$+$BG biomass C stocks partitioned by major plant components in homegarden agroforestry systems along age groups in southern and southwestern Ethiopia.**

| Carbon pool | Mean AG biomass carbon (Mg C ha$^{-1}$) | Mean BG biomass carbon (Mg C ha$^{-1}$) | AG$+$BG biomass carbon (Mg C ha$^{-1}$) |
|-------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Woody plants | Enset plants | Banana plants | Woody plants | Enset plants | Banana plants | Woody plants | Enset plants | Banana plants |
| Along age group | | | | | | | | | |
| ≤10 years | 2.76 | 1.49 | 0.24 | 16.64 | 5.76 | 1.12 |
| >10 and ≤20 years | 3.71 | 1.46 | 1.53 | 23.33 | 4.44 | 6.36 |
| >20 years | 3.62 | 1.11 | 1.35 | 22.85 | 4.26 | 5.66 |
| Significance | NS | NS | NS | NS | NS | NS |
| Mean | 3.71 | 1.46 | 1.53 | 23.33 | 4.44 | 6.36 |
| Significance | NS | NS | NS | NS | NS | NS |

Survey data.
increased [71]. With increasing homegarden agroforestry age, woody stem density decreased in the middle age group (>10 and ≤20 years) as compared to the initial age group (<10 years) but remained stagnant 20 years onward. This result is consistent with the results of previous studies [72], where they reported a similar pattern of decreasing shade tree densities over time in coffee agroecosystems in San Ramón, Nicaragua. This may be attributed to consequent intensification effort of homegardeners or focus on selected individuals of any species that serve multiple provisioning services (e.g., timber, food, firewood) of homegarden production systems [72].

Figure 3. a-h. 3. Relationships of aboveground woody biomass carbon (AGWBC) stocks with a) woody plant species richness, b) woody Shannon diversity index, c) DBH, d) height, e) woody plants density, f) homegarden size, and g) total land holding. Numbers in each graph are coefficients of determination ($R^2$ values), trend lines are shown for significant relationships only. *$p < 0.05$, ***$p < 0.001$. 
Plant species composition, richness, and diversity of homegardens

The relatively higher number of perennial species found in the study area might be associated with the integrative management of varying niches meant for addressing different socioeconomic needs within the homegardens [73,74]. Besides this, another reason for high species diversity may be attributed to the predominance of complementary homegarden agroforestry in the present study as compared to integrative homegarden agroforestry where farmers may have no or little additional land allocated to specialized production systems such as cereals [75]. Besides to supporting endemic perennial plant species to Ethiopia, the relatively higher perennial plant diversity in the present study is indicative of what those human-dominated landscapes are valuable for the maintenance of biological diversity [76], and provision of potential food, fruit, timber and other multipurpose species (Table 4). A relatively low Jaccard index which was observed in the present study sites may reflect the low proportion of common species in homegarden agroforestry between pair of sites.

Estimation of aboveground- and belowground biomass and biomass C stocks in homegarden agroforestry systems

The biomass stocks in the current study (47.76–84.93 Mg ha⁻¹) revealed that there were heterogeneity in total biomass stock between homegarden agroforestry systems in different sites may be due to the variation in woody plants density and species richness (Table 2; Figure 3a). The Jaccard similarity index also asserts such differences revealing that there exists heterogeneity in species composition across sites (Table 5). The mean values in the present study were well within the range reported for total cocoa ecosystem biomass stocks in Ghana (26.5–101.6 Mg ha⁻¹) [77], and enset-based indigenous agroforestry systems in southeastern Rift Valley escarpment, Gedeo, Ethiopia (104.7 Mg ha⁻¹) [78]. However, the mean biomass stock values were lower than stocks reported from some types of indigenous agroforestry systems in Gedeo, southern Ethiopia (153.4–173.1 Mg ha⁻¹) [28]. Furthermore, distinct agroecology and management practices might explain the variation in biomass stock between the sites [79].

Considering total biomass C stocks in a range of agricultural and natural ecosystems in different parts of the world, this study matched the range of pre-existing results. The amount of C in biomass that corresponds with the range of values in the present study (22.02–39.96 Mg C ha⁻¹) were those recent estimates from local AFS, such as homegardens (23.52 Mg C ha⁻¹) and pole wood plantations (37.05 Mg C ha⁻¹) studied at the landscape scale around Jimma, southwest Ethiopia [80], and in enset-based indigenous multistrata AFS (46.5 Mg C ha⁻¹) in Gedeo, southern Ethiopia [28]. Similar biomass C mean values were also reported by several others from different ecoregions, by Kumar [23] in the home gardens (24.32 Mg ha⁻¹) of central Kerala, India; coffee AFS (25.5 Mg C ha⁻¹) in Costa Rica, [24]; and cacao monoculture (31.1 Mg C ha⁻¹) in Alto Beni, Bolivia, [81]. As compared to the present study, higher biomass C mean values were reported from Guatemala (coffee agroforests 89.39 Mg C ha⁻¹), [82]; Ethiopia (semi-forest coffee community 91.42 Mg C ha⁻¹), [80]; and Panama (traditional agroforests 145 Mg C ha⁻¹), [4]. In contrast to the average C stocks presently reported, considerably lower mean values were noted in different published reports by Unruh et al. [83] in sub-Saharan Africa AFS (4.5–19 Mg C ha⁻¹); in agricultural landscapes (13–19 Mg C ha⁻¹) in western Kenya, [84]; Mattsson et al. [19] in homegardens (13 Mg C ha⁻¹) in dry zone area of Moneragala district, Sri Lanka, and by Roshetko et al. [85] in the young (9-year old) Sumatran agroforests (14 Mg ha⁻¹). In general, the mean values of biomass carbon stocks in the present study were consistent with the international literature [21], implying the fact that homegarden agroforestry has a large potential in lowering elevated atmospheric CO₂ concentrations and thereby climate change mitigation when combined and extensified as mosaics of land use at landscape and regional scales. The variation in the estimates of these varying agroforestry systems production potential may depend on several factors including site characteristics, land use types, stocking density, plant species, management practices, and age category of plants [11,23,77,86]. This heterogeneity in AG-, BG- and total biomass C stocks in different study sites may have both management and policy implications for extensifying and introducing tree-based land use systems hoping to simultaneously take advantage of the presence of greater number of woody plants for their enormous potential as C sink and C accounting purposes. To attain greater C storage; therefore, it
was suggested to incorporate long rotation tree-based land use systems that maintain higher tree densities, and to convert low biomass species/lands into productive ones by convincing smallholder farmers or otherwise by giving them incentive mechanisms that favor higher C stocks in aggregate [85].

When considering the partitioned components in the present homegarden agroforestry systems, a comparably similar largest share of woody biomass carbon (80–89%), but a contrasting lower percentage value for enset plant components (9%) to the total biomass carbon was recorded in indigenous enset-based agroforestry systems in southern Ethiopia [28]. Another research result strengthens the fact that woody components did contribute a major share (86.95–98.38%), while banana shares the least only 1.61–13.05% of the total biomass carbon in cocoa-based successional agroforestry systems in Alto Beni, Bolivia [81]. Although the SDR in the present study reveals perennial herbaceous crops enset and banana being listed in the top three most dominant species (Table 4), their contribution to total biomass and biomass carbon was low (Table 6; Table 8).

As is the case for other more recent results [72], a non-significant trend of increasing above- and BG and total biomass and biomass C stocks were noted for woody plant components at the middle age group (>10 and ≤20 years), but remained stagnant with negligible change 20 years onward in the present study. Similar to the present findings, Sumaila [87] also found no difference in the biomass carbon stock between the three age groups (new, 1-5 years; medium, 6-10 years; and old, over 10 years) in Shea parkland agroforestry trees in northern Ghana. When considering numerical mean values, several studies have documented increased biomass carbon during the first five to 15 years as compared to the initial ones [86,88]. For instance, an 80.52% increase in total (AG + BG) biomass C has been observed after 8 years of cocoa-gliricidia agroforests in Central Sulawesi, Indonesia [86]. In a study undertaken in West African multistrata agroforestry systems, Isaac et al. [88] demonstrated that C in biomass had increased between two and 15 years. In an evaluation of coffee agroecosystems in San Ramón, Nicaragua, the mean AG shade tree biomass C stocks had increased by about 7.16% after 5 years, but fell to −38.4% after 9 years [72]. Higher C sequestration was observed because of fast tree growth during the initial age group and the middle age group; however, tree growth slows down and C sequestration rate is sustained during the latter age group may be because of tree aging, respiration, and death, and because trees approach maturity [89]. In agreement with the present findings, Mukul et al. [90] and Nair et al. [11] also stated that the ability to accumulate biomass C was maximum at younger ages, but the rate of accumulation decreases with increasing tree age especially after reaching an intermediate age. It was demonstrated that total biomass was significantly dependent on species number and functional group composition [91]. Consistent with the findings of Kirby and Potvin [4], the AG woody biomass in the present result reflected a positive association with woody plant species richness better denoting the rationale for the consequent rapid biomass increment as other additional species are added in the homegardens [4]. This implies that increased number of woody species may infer increased C sequestration potential of these homegardens, and thereby assist in tackling climate change [23]. Furthermore, the relationship between plant species richness and soil organic carbon stocks were also reported in homegardens in Kerala, India [17], which might have been derived from plant biomass that was indirectly sequestered as SOC during decomposition processes [10].

Factors driving variability in the aboveground biomass carbon stocks in homegarden agroforestry systems

In contrast to other studies from smallholder farming systems in western Kenya [22] and in West Africa [92], but consistent with the findings of [23] in central Kerala, India, and [93] in Terai, Nepal, there were positive relationships between woody perennial biomass C stocks and species richness in the present study. Although there were inverse relationships between homegarden size and C stocks as demonstrated by Kumar [23] in central Kerala, India, no relationship was found between these two in the present study, nor do with total landholding of farm households. In conformity with the study undertaken by Goodall et al. [72] in coffee agroecosystems in San Ramón, Nicaragua, a notable positive relationship was found between woody species density and C stocks in the present study.
Implication of practicing homegarden agroforestry systems for climate change mitigation and sustainability of agricultural landscapes

Maintenance of tree-based land use systems such as homegarden agroforestry in agriculture can contribute to sustainable systems that meet human needs with a reduced environmental impact [94]. As one of the environmental services, C sequestration provided by sustainable land management systems such as agroforestry gained increasing recognition as it play a substantial role in CO₂ mitigation in the tropics [95].

In the face of a changing and uncertain climate, homegarden agroforestry which is being regarded as more resilient agricultural production system [75]; need to take into account climate change mitigation, including GHG emission reduction, as indicators of sustainable agricultural landscapes [92,96]. As woody plants are key features of agricultural landscapes including homegardens, they represent a globally important carbon stock [97]. Understanding the quantity of C in above- and belowground biomass could help support better scientific decisions and enhance the potential role of homegarden agroforestry in addressing mitigation of climate change, and reducing global warming by absorbing GHGs (CO₂) and their simultaneous effect in sinking global C and further supporting REDD+ (Reduced Emissions from Deforestations and Forest Degradation) projects [4,97,98]. Piloting REDD+ through a landscape approach may make sense and, need to be explored to generate lessons, and open scope for inclusion in and building agroforestry and other agriculture based initiatives into REDD+ [12]. To institutionalize and help strengthen the contribution of agroforestry to REDD+ and emerge as consolidated policy arrangements, quantitative evidence is imperative across the spectrum of local to national levels [99]. On the other hand, lack of acknowledgment of drivers of deforestation and degradation in developing countries by climate convention may impede a threat to the success of any emission reduction strategy [97], which otherwise compelled to raise questions on the implementation of REDD+ objectives that were solely focusing on the forestry sector. Addressing such challenges may help promote the involvement of local practitioners to make global climate initiatives a reality [100].

As a major international policy goal, mitigating climate change through C sequestration appears to be a low-cost environmental benefit of agroforestry [18,95]. The reason why agroforestry systems may have a unique advantage in terms of C sequestration could be due to the long-term C storage potential of all components, and their fast growth and high productivity [95]. As more than half of the assimilated C is eventually transported below ground via root growth and turnover, and litter deposition, and because of these soils are claimed to contain the major C stock in the ecosystem [95].

Furthermore, as it was demonstrated in this study, having a better understanding of the relationship of woody species diversity and C storage would be valuable to maintaining C stocks of agricultural landscapes over the long term while addressing other ecosystem services, namely improvements in soil quality, provision of food production and wood products [4,101]. Although the combined objectives of reducing global warming and biodiversity loss were not addressed by a single project by international organizations [17], the present study did reflect the association of AG woody biomass C and woody species richness, and woody plant density. This may underline the importance of integrating these two aspects for the future sustainable management of agricultural landscapes in the tropics. To achieve global climate goals through added up and combined per country efforts [102], it becomes increasingly clear to address and promote high carbon stock land uses and reduce emissions from all land uses [97]. Whenever agroforestry does support a role in reducing pressure on adjacent natural forests, it will have also an indirect effect on C sequestration [95], implying that agroforestry, including homegarden agroforestry, could offset clearing of remnant forest by providing alternative source of wood, fruits, vegetables and other products from land that has already been cleared [95,103]. Greater agrobiodiversity may thus ensure longer term stability of C storage in fluctuating environments [22], resulting from greater plant productivity at greater diversity which corresponds to strong nutrient use efficiency [104,105]. Namirembe et al. [12] also noted that agroforestry can be included in REDD+ strategies, as ways to reduce drivers of deforestation through a) shifting demand for land (land sparing) as a sustainable intensification (SI) pathway, b) providing alternative sources of products otherwise derived from forest over-exploitation or conversion, and c) as opportunities for profitable labour absorption in a
sustainable intensification pathway. The concept SI is not only limited to increased food production through increasing the flow of environmental services [106, 107], but also considered as an approach that improves food system sustainability through maintaining diverse diets and needs to engage with sustainable development while reducing adverse environmental impacts [106]. SI syntheses highlight food security and socioeconomic betterment fused with environmental sustainability, thus incorporating ecological intensification (EI) goals [108]. And, ecological intensification also entails the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices [109].

**Conclusion**

Enset-based homegarden agroforestry systems are prominent features of the agricultural landscapes in the studied areas of southern and southwestern Ethiopia. As an added ecosystem service, a considerable amount of biomass and biomass C stocks are stored in the present homegardens through carbon sequestration being somewhat comparable to different indigenous multistrata and shaded agroforestry systems including woodlots and some forests in tropical parts of the world. This suggests that integration of these traditionally managed indigenous production systems can be considered as one potential mechanism for sinking C and mitigating climate change as well as the concordance of ecosystem service vis-à-vis conserving biodiversity. It was noted that the woody plant species contribute the largest share to these stocks as compared to that of *enset* and banana plant components. The outcome from this study also reveals that these systems could help enhance the recovery of C stocks years after the establishment of homegardens, especially in the middle age group (> 10 and ≤ 20 years) as compared to the initial one (≤ 10 years), although stagnant stocks were recorded at latter age group (20 years onward) depicting more or less stable production systems. In the present study, positive relationships were noted between AG C stocks in woody biomass and several other attributes such as woody species richness, and woody plant density. Considering the aggregate involvement of large numbers of homegardeners, future improvements and expansion of long rotation tree-based land use systems such as homegarden agroforestry that maintain higher tree densities can enhance the potential to sequester C and thereby mitigate climate change. Besides to setting aside land only for conservation, if harnessed and supported with evidence-based science, practicing agroforestry in subsistence farming systems through increasing the flow of environmental services such as carbon sequestration can help address multiple benefits. Research on the assessment of the dynamics of carbon stocks over time and the existing relationships between biodiversity and soil organic C has to be carried out at a landscape level, including its potential storage as affected by the land use dynamics.

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**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Data availability statement**

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

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Appendix A.

Endemic perennial plant species found in 93 homegarden agroforestry systems surveyed in three sites in Southern and southwestern Ethiopia

| No. | Overall species | Family name | Habit | Native/ Exotic | Endemic (Based on IUCN* Red List) |
|-----|-----------------|-------------|-------|----------------|----------------------------------|
| 1.   | *Erythrina brucei* Schweinf. | Fabaceae | T | N | Least concern (LC) |
| 2.   | *Lippia adoensis* Hochst. ex Walp. | Verbenaceae | S | N | Least concern (LC) |
| 3.   | *Milletia ferruginea* (Hochst.) Bak. | Fabaceae | T | N | Least concern (LC) |
| 4.   | *Prunus africana* (Hook. f.) Kalkm. | Rosaceae | T | N | vulnerable (V) |
| 5.   | *Solanecio gigas* (Vatke) C. Jeffrey | Asteraceae | S | N | Least concern (LC) |
| 6.   | *Vernonia rupeppelli* Sch. Bip. ex Walp. | Asteraceae | S | N | Least concern (LC) |

*Vivero LJ, Kelbessa E, and Demissew S. The red list of endemic trees and shrubs of Ethiopia and Eritrea. Cambridge: United Kingdom: Fauna and Flora International, 2005.