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Woody carbon stock estimation in homegarden agroforestry along altitudinal gradients in southwest Ethiopia

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Woody plant species in homegarden agroforestry store a large proportion of carbon stocks. However, there is limited information on the carbon stock potential of homegarden agroforestry along altitudinal gradients in southwest Ethiopia. Therefore, this study aims to estimate aboveground and belowground carbon stocks in homegardens using a non-destructive allometric model. Data were collected from 72 homegardens selected using a random sampling method. Woody plants were measured for diameter at breast height (DBH) of $\geq$ 5 cm and height of $\geq$ 1.5 m. The study revealed that the mean aboveground carbon stock (14.39 $\pm$ 2.95 Mg C ha^{-1}) was significantly (p < 0.05) higher in the middle altitude than (6.12 $\pm$ 0.72 Mg C ha^{-1}) in the low altitude. Carbon stocks were significantly different between middle and low altitudes. The overall mean carbon stock was 11.25 $\pm$ 1.60, with mean aboveground and belowground carbon stocks of 9.39 $\pm$ 1.34 and 1.88 $\pm$ 0.27 Mg C ha^{-1}, respectively. The top 10 woody species contributed to 78.50% of the total carbon stock, of which 56.73% were *Persea americana* and *Cordia africana*. Wealth status and size of homegardens were significantly correlated (r = 0.298 and r = 0.307, respectively) with the carbon stock. The overall woody carbon stock distributions varied primarily due to altitudinal gradients, woody species, and socioeconomic factors. As a result, this study will assist researchers and policymakers in selecting optimal ecological areas and addressing socioeconomic gaps for agroforestry practices that produce biomass and store carbon for long-term climate change mitigation.

KEYWORDS

altitudinal change, carbon stock, socioeconomic, woody biomass, woody plant

1 Background

The practice of agroforestry is acknowledged for its role in climate change mitigation and adaptation because of its positive social and environmental impacts (Mbow et al., 2014; Meragiaw, 2017; Amadu et al., 2020; Jahan et al., 2022). It helps overcome environmental constraints in response to climate change shocks by absorbing atmospheric greenhouse gases and generating a hospitable environment (Verchot et al., 2007; Schoeneberger et al., 2012). In Ethiopia, agroforestry systems provide sustainable ecosystem services, such as climate change mitigation, carbon sequestration, and soil fertility improvement, in addition to livelihood provisions (Negash et al., 2005; Negash, 2013; Meragiaw, 2017). The year-round woody components of the agroforestry systems most frequently contribute to high aboveground biomass production, which is positively correlated with the sequestration and accumulation of biomass carbon (Henry et al., 2009; Alves et al., 2010; Mayele et al., 2020; Yasin et al., 2021). The dense and diverse woody biomass production in agroforestry systems further encourages carbon sequestration, carbon storage potential, and the substitution of fossil fuel products in the climate change mitigation process (Jose and Bardhan, 2012; Liu and Li, 2012).

Trees in agroforestry play a crucial role in mitigating atmospheric greenhouse gas through photosynthesis and accumulation of carbon stocks in aboveground and belowground biomass (Unwin and Kriedemann, 2000; Terakunpisut et al., 2007; Komal et al., 2022). Trees are a dominant carbon pool landscape resource, as 50% of live tree biomass is built from carbon (Tadesse, 2015; Shiferaw et al., 2022). The study in Sri Lanka revealed that trees in homegardens significantly contribute to carbon sequestration and carbon storage processes, while reducing atmospheric greenhouse gas (CO_2) accumulation (Lowe et al., 2022). These findings highlight the potential of agroforestry practices in the global carbon cycle and climate change mitigation based on their extensive biomass production and carbon storage (Nair et al., 2021).

However, woody plant biomass and carbon pool capacity are determined by factors such as tree size, diversity, management, habitat suitability, and altitudinal gradient (Borah et al., 2013; Hagos et al., 2021; Siarudin et al., 2021). Sharma et al. (2023) revealed that biomass production and carbon storage potential vary across different agroforestry systems based on altitudinal gradients. According to Kumar (2023), carbon stocks are negatively correlated with altitudinal gradients and the size of holdings in tropical homegardens of central Kerala, India. Tree diversity, genotype, plantation site, and stand management also influence agroforestry tree biomass and carbon content (Unwin and Kriedemann, 2000; Komal et al., 2022). Previous studies have shown that management systems that are directly or indirectly associated with basal area, abundance, richness, and density also affect the biomass and carbon stock ability of trees (Atsbha et al., 2019; Pokhrel and Sherpa, 2020; Meragiaw et al., 2021; Soazafy et al., 2021). Verma et al. (2024) reported different biomass and carbon distributions for different tree components and agroforestry systems due to varying tree management options, site quality, growth rates, and tree age.

In Ethiopia, studies have investigated the diversification of woody species and their importance for biomass and carbon accumulation in agroforestry practices (Kassa et al., 2022; Tesfay et al., 2022). Gebrewahid and Meressa (2020) revealed tree diversity and carbon stocks of plant communities in parkland agroforestry in Northern Ethiopia. Manaye et al. (2021) repeated a similar assessment to compare different agroforestry systems in Northern Ethiopia. Gebrewahid et al. (2018) and Birhane et al. (2020) reported woody diversity and carbon stocks in scattered trees in farmland and homegarden agroforestry following altitudinal changes in northern and southern Ethiopia, respectively. Other studies have evaluated the same variables in agroforestry and adjacent forests in northern and western Ethiopia (Eyasu et al., 2020; Enkossa et al., 2023).

However, none of these studies have considered biomass carbon stocks from an altitudinal gradient point of view. Therefore, this study aimed to identify the aboveground and belowground carbon stock potential in homegarden agroforestry along altitudinal gradients in southwest Ethiopia. In this study, we hypothesized that aboveground and belowground carbon stocks would vary among altitudinal gradients and woody species in homegarden agroforestry. Furthermore, we hypothesized that aboveground and belowground carbon stocks would positively correlate with household socioeconomic status in southwest Ethiopia.

2 Materials and methods

2.1 Description of the study area

The study was conducted along altitudinal gradients in three districts: Mana and Gomma districts of the Jimma zone and Dhidhessa district of the Buno Bedele zone, Oromia Regional State, Ethiopia. The study areas are located at 7°40'N–8°20'N and 36°20'E–36°40'E, with altitudinal ranges between 1,459 and 2,542 m above sea level (Figure 1). The region received a mean annual rainfall of 1,853 mm, with minimum and maximum temperatures averaging 11.5°C and 24.2°C, respectively, over the past 32 years (WMO, 2022). The midland had the highest area coverage among the three agro-ecological zones (lowland, midland, and highland). The dominant land use systems include cultivated lands, wetlands, settlements, commercial farms, shrublands, grasslands, and forestland, where natural forests serve as shade for coffee cultivation and as a source of various forest products (Tolessa et al., 2019). The farming system in the area is characterized by mixed forest coffee cultivation, cereal production, and livestock rearing. Homegarden agroforestry is one of the dominant farming systems, practiced by more than 85% of local farmers. Homegarden agroforestry in the study area was composed of different indigenous and exotic woody species, including *Cordia africana, Persea americana, Catha edulis, Coffea arabica, Mangifera indica, Psidium guajava, Albizia gummifera, Carica papaya, and Grevillea robusta.*

2.2 Sampling design

A stratified sampling technique was used to collect woody plant data following altitudinal gradients in southwest Ethiopia. The altitude of the study area was classified as low (1459–1750 m), middle (1750–2050 m), and high (2050–2542 m), considering the elevation range and homegarden agroforestry distributions. Elevation data were obtained from the digital elevation model available in Google Earth and accessed for free via EarthExplorer.[1] In addition to altitudinal gradients, household wealth status was stratified into three classes to examine the correlation between socioeconomic variables and woody biomass carbon. Wealth status was classified as rich, medium, and poor with the assistance of developmental agents and local elders. Local criteria, including the number of livestock, size of land, annual crop production, and housing standards, were used for this classification. Then, 72 homegarden agroforestry sites (24 from the mentioned categories) were randomly selected for a complete enumeration of woody plants following Motuma et al. (2008).

2.3 Data collection methods

Data were collected from all live woody plants with a DBH of ≥5 cm and a height of ≥1.5 m, except for coffee, which was measured at 40 cm above the ground. Woody plants below 5 cm in diameter and 1.5 m in height were excluded from data collection because most biomass equations are not valid for smaller stem diameters and heights (MacDicken, 1997). Woody plant diameter and height were measured using a caliper and a Suunto Clinometer, respectively. The

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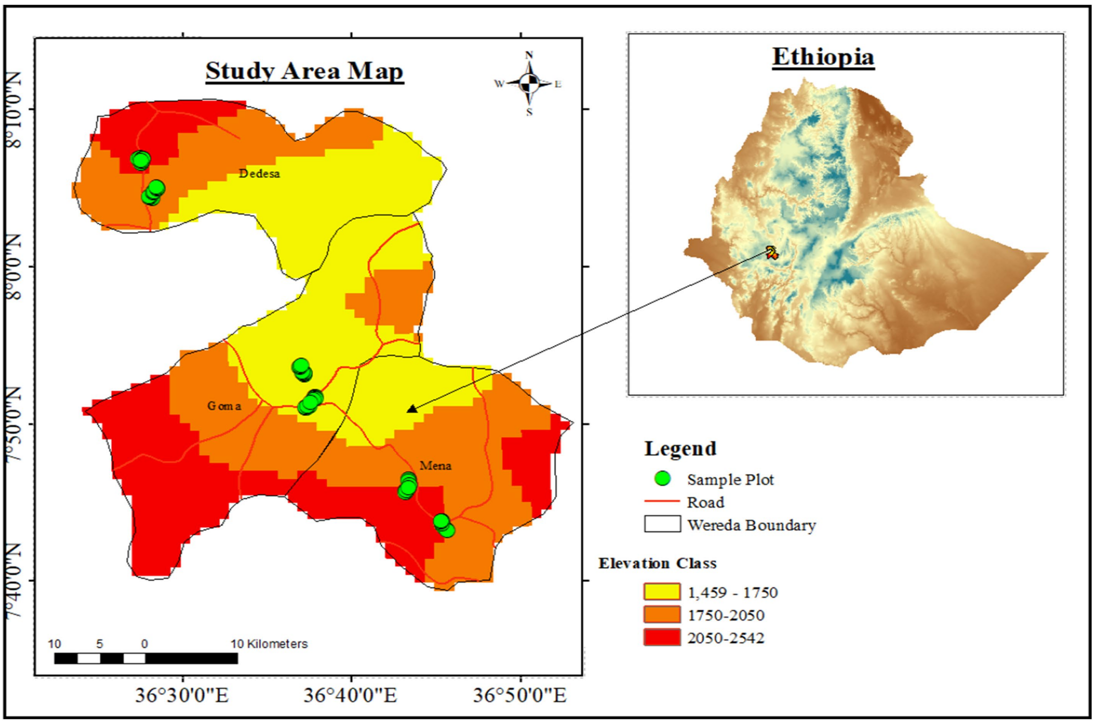

FIGURE 1
Map of the study area.

elevation of each sampled homegarden was measured using a Global Positioning System (GPS Garmin 72). Woody species were identified in the field using voucher specimens. For species not identified in the field, plant samples were collected, coded, pressed, dried, and identified using the *Flora of Ethiopia and Eritrea* (Edwards et al., 1995; Hedberg and Edwards, 1995; Hedberg et al., 2006; Azene et al., 1993).

2.4 Data analysis

The present study used previously published non-destructive allometric models, as farm owners did not permit the destruction of multipurpose woody species in their homegardens. Therefore, biomass and carbon stocks for aboveground and belowground woody plants were estimated using a non-destructive allometric model (Kuyah et al., 2012). Estimation of biomass and carbon stocks in dead wood and litter was not included due to their negligible quantities and their potential for soil surface disturbance in homegarden agroforestry. Woody biomass, except for coffee, was calculated using the allometric equation developed by Kuyah et al. (2012). Coffee biomass was calculated using the allometric model developed by Negash (2013).

Therefore:

Aboveground woody biomass was calculated following the method of Kuyah et al. (2012) as follows:

$$AGB = 0.091 \times dbh^{2.472}$$

where AGB is the aboveground biomass of live trees in kg and dbh is the stem diameter at breast height in cm.

The aboveground biomass of coffee plants was calculated according to Negash (2013) as follows:

$$AGB_{coffee} = 0.147^{*} d_{40}^{\ 2}$$

where AGB_{coffee} is the aboveground biomass of coffee and d_{40} is the stem diameter of coffee at 40 cm.

Aboveground carbon content was calculated as a conversion factor of 0.48 multiplied by AGB, following Kuyah et al. (2012).

Aboveground coffee shrub carbon was calculated using the 43% carbon content of the aboveground biomass, following Negash (2013).

Carbon sequestration from woody species was calculated to estimate the contribution of woody plants to climate change mitigation in homegardens. Aboveground biomass carbon dioxide emissions were estimated using a conversion factor of 3.67, based on the molecular weight ratio of carbon dioxide to carbon ratio, in accordance with the IPCC guidelines (Intergovernmental Panel on Climate Change (IPCC), 2006). Belowground carbon dioxide emissions were calculated following trends similar to those of aboveground carbon dioxide emissions.

Belowground biomass was calculated as a conversion factor of 20% of the AGB following the methods of MacDicken (1997) and Nair (2012). The belowground carbon content of woody species was calculated to be similar to the aboveground biomass, following the method of Kuyah et al. (2012). Total carbon stock was calculated by summing the carbon content of aboveground and belowground carbon (Pearson et al., 2007).

Prior to analysis, the data were checked for normality and analyzed using the Statistical Package for Social Science (SPSS) version 26. Differences between woody carbon stocks and altitudinal gradients were analyzed using a one-way analysis of variance (ANOVA). The least significant difference (LSD) test was used to compare the level of significance ($p < 0.05$) between the variables.

3 Results

3.1 Aboveground and belowground woody carbon

A one-way ANOVA showed that the aboveground and belowground carbon stocks of woody species in homegarden agroforestry varied significantly ($p < 0.05$) among altitudinal gradients. The highest carbon stocks of 14.39 ± 2.95 Mg C ha^{-1} and 2.80 ± 0.60 Mg C ha^{-1} were recorded at the middle altitude in aboveground and belowground stock, respectively. The highest mean carbon stock (16.79 Mg C ha^{-1}) was stored in the middle altitude, followed by 9.62 Mg C ha^{-1} in the high altitude and 8.78 Mg C ha^{-1} in the low altitude. These findings indicate that mean carbon stocks of 63.07 ± 13.01, 33.98 ± 10.54, and 26.95 ± 3.19 Mg C ha^{-1} were sequestered by woody plants at middle, high, and low altitudes, respectively (Table 1). There was a significant difference between the mean carbon stocks at the middle and low altitudes (Table 1). The aboveground and belowground carbon stocks of trees were significantly different ($p < 0.05$) among altitudinal gradients, while coffee did not show such variation. The belowground carbon stock of trees decreased from the middle altitude (2.77 Mg C ha^{-1}) to high (1.59 Mg C ha^{-1}) and low (1.19 Mg C ha^{-1}) altitudes. Hence, trees dominated the total landscape carbon stock distribution in homegarden agroforestry; there was a corresponding change in carbon stock between altitude for trees and total carbon (Supplementary Table 1).

3.2 Total woody carbon stocks

The overall live woody carbon stock potential of woody plants in the homegarden agroforestry is presented in Table 2. The mean carbon stock was 9.39 ± 1.34, 1.88 ± 0.27, and 11.25 ± 1.60 Mg C ha^{-1} in aboveground, belowground, and total carbon stock, respectively. The overall carbon stock within the entire homegarden agroforestry was 810.11 Mg C ha^{-1} (Table 2). Furthermore, the carbon stock and carbon sequestration were calculated for the top 10 woody species and showed a total of 635.95 and 2,333.98 Mg ha^{-1} to carbon stock and carbon sequestration, respectively, per sampled homegarden agroforestry. Among these species, *Persea americana* and *Cordia africana* contributed to 360.79 Mg ha^{-1} carbon stock (Table 3). *Persea americana* and *Cordia africana* alone contributed to 44.54% of the total carbon stock of woody species in homegarden agroforestry in the present study area. The result indicates that agroforestry practices had a significant position in climate change mitigation strategies adopted through farm woody plant diversification for effective biomass production and carbon accumulation.

3.3 Relationship between socioeconomic variables and woody carbon stocks

The Pearson correlation coefficient indicated a positive relationship between the total carbon stocks and socioeconomic factors (wealth status, size, and age of homegardens). The wealth status and size of homegarden holdings by households were significantly correlated with the total carbon stock. The size of the homegardens correlated with the total carbon stock ($r = 0.307$, $p = 0.009$). Wealth status correlated with total carbon stocks ($r = 0.298$, $p = 0.011$). However, there was no significant relationship ($r = 0.187$, $p = 0.116$) between the age of homegarden agroforestry and total carbon stock (Table 4).

4 Discussion

4.1 Woody carbon stocks

Homegarden agroforestry enhances the environmental sustainability of agricultural landscapes by increasing carbon stocks and reducing carbon dioxide (Sharma et al., 2022). It is an effective land-use system for sequestering carbon, as it is composed of structurally complex and biologically diverse woody species (Maryo et al., 2023). The mean aboveground carbon stock recorded (9.39 Mg C ha^{-1}) is lower than the mean aboveground carbon stock (16.74 Mg C ha^{-1}) reported in coffee-based agroforestry in southern Ethiopia (Tesfay et al., 2022). This result is also lower than the mean aboveground biomass carbon of 36.5 Mg C/ha reported in Matale district, Sri Lanka (Lowe et al., 2022), and 23.80 Mg C/ha reported in the Jaffna peninsula, Sri Lanka (Lowe et al., 2024). The stock of belowground biomass carbon (1.91 Mg C ha^{-1}) was lower than that

TABLE 1 Mean (±SE) aboveground and belowground carbon stocks (Mg C ha^{-1}) in woody plants along altitudinal gradients.

Altitude	No of plots	AGC	BGC	TC	TCseq
Low	24	6.12^{b} ± 0.72	1.22^{b} ± 0.14	7.34^{b} ± 0.87	26.95^{b} ± 3.19
Middle	24	14.39^{a} ± 2.95	2.80^{a} ± 0.60	16.79^{a} ± 3.58	63.07^{a} ± 13.01
High	24	7.66^{ab} ± 2.40	1.60^{ab} ± 0.48	9.62^{ab} ± 2.85	33.98^{ab} ± 10.54

AGC, aboveground carbon; BGC, belowground carbon; TC, total carbon; TCseq, total carbon sequestered; different letters on a mean along an altitude indicate a significant difference at a p-value of <0.05.

TABLE 2 Summary of total carbon stock of homegarden agroforestry woody species in southwest Ethiopia.

Categories	AGC	BGC	TC
Mean	9.39 ± 1.34	1.88 ± 0.27	11.25 ± 1.60
Total	675.88	135.02	810.11

AGC, aboveground carbon; BGC, belowground carbon; TC, total carbon.

TABLE 3 Biomass carbon stock and carbon sequestration potential of the top 10 woody species in homegarden agroforestry in southwest Ethiopia.

Species	AGC	AGCseq	BGC	BGCseq	TC	TCseq
Albizia gummifera	29.15	106.99	5.83	21.40	34.98	128.39
Annona senegalensis	6.00	22.03	1.20	4.41	7.20	26.44
Carica papaya	19.79	72.64	3.96	14.53	23.75	87.17
Catha edulis	17.75	65.14	3.55	13.03	21.30	78.17
Citrus sinensis	21.64	79.40	4.33	15.88	25.96	95.29
Cordia africana	144.64	530.84	28.93	106.17	173.57	637.01
Grevillea robusta	60.61	222.43	12.12	44.49	72.73	266.92
Mangifera indica	56.46	207.19	10.89	39.96	67.34	247.15
Persea americana	155.68	571.36	31.54	115.75	187.22	687.11
Psidium guajava	18.24	66.95	3.65	13.39	21.89	80.34
Mean	2.33 ± 0.24	8.57 ± 0.88	0.47 ± 0.05	1.71 ± 0.18	2.80 ± 0.29	10.28 ± 1.05
Total	530.00	1944.94	106.01	388.97	635.95	2333.98

AGC, aboveground carbon; AGCseq, aboveground carbon sequestration; BGC, belowground carbon; BGCseq, belowground carbon sequestration; TC, total carbon; TCseq, total carbon sequestration.

TABLE 4 Relationship between wealth status, size of homegarden, and age of homegarden with total carbon stock in homegarden agroforestry.

Variables	Total carbon stock	Wealth status	Size of homegarden
Wealth status	0.298*	–	
Size of homegarden	0.307**	0.713***	–
Age of homegarden	0.187	0.540***	0.604***

*, **, ***Correlation is significant at 0.05, 0.01, and 0.001 levels, respectively.

reported by Gebrewahid and Meressa (2020), who reported a mean belowground biomass carbon stock of 3.03 Mg C ha^{-1} in northern Ethiopia.

Biomass carbon stocks varied significantly at different altitudes in the present study area. Total biomass carbon stocks (aboveground and belowground) decreased from middle to high altitudes and then to low altitudes. In contrast, previous studies have revealed a linear relationship between total biomass carbon stocks and altitudinal gradients. For instance, Chemeda et al. (2022) reported that decreased biomass carbon stocks with increasing altitudinal gradients in coffee-based agroforestry in Western Ethiopia. Birhane et al. (2020) reported a significant increase in total biomass carbon with increasing altitude in homegarden agroforestry in southern Ethiopia. Asanok et al. (2024) reported that total carbon stock increased with increasing elevation gradients in northern Thailand.

The change in woody carbon stocks along altitudinal gradients is attributed to the decreased number of woody species with large diameter, but not to the increased number of trees per hectare with elevation change (Tsedeke et al., 2021). According to Gebre et al. (2018), species composition and management systems can also cause variations in land use. The mean total carbon of 11.25 Mg C ha^{-1} recorded was comparable with 10.93 Mg C ha^{-1} reported by Gebrewahid et al. (2018) and higher than 7.90 Mg C ha^{-1} reported by Gebrewahid and Meressa (2020). However, it is lower than the carbon stock (13.82 Mg C ha^{-1}) reported by Gebremeskel et al. (2021) for *Rhamnus prinoides*-based agroforestry practices in northern Ethiopia and far lower than the 36.35 Mg C ha^{-1} reported for homestead forests in Bangladesh (Baul et al., 2021).

Tree carbon stock changed along altitudinal gradients, similar to the total carbon stock observed. In contrast, coffee shrub values decreased with increasing altitudinal gradients (Supplementary Table 1). The species-specific contributions of woody carbon stocks and carbon sequestration were calculated for 10 frequently observed species and showed differences among species. The result showed that carbon stock contributions varied between 7.20 and 187.22 Mg C ha^{-1} for *Annona senegalensis* and *Persea americana*, respectively. Similarly, carbon stock variation among tree species (16.20 Mg C ha^{-1} to 57.35 Mg C ha^{-1}) was reported for *Tecomella undulata* and *Hardwickia binata*, respectively, in the agroforestry systems of the arid zones of India (Verma et al., 2024). On the other hand, *Persea americana* and *Cordia africana* contributed to 44.54% of the carbon stock, indicating their great contribution to climate change mitigation among the observed woody species. The result is in line with the study by Lowe et al. (2022), who reported the contribution of coconut and jackfruit to climate change mitigation by providing 55% of carbon accumulation in Sri Lanka.

Previous studies have reported that woody carbon stocks are influenced by species abundance (Manaye et al., 2021). Meragiaw et al. (2021) reported the highest carbon content in areas with a high abundance of large-diameter and tall tree species. Similarly, *Persea americana,* a dominant large-diameter tree, provided the highest carbon stock compared to the less abundant species and trees with small diameters in this study area. Aboveground woody biomass in homegardens plays a vital role in carbon sequestration, thereby helping mitigate climate change conditions (Siyum and Tassew, 2019; Kassa et al., 2022). Similarly, a higher proportion of carbon dioxide was sequestered by aboveground biomass (1944.94 Mg ha^{-1}) than belowground biomass (388.97 Mg ha^{-1}) in climate change mitigation efforts.

4.2 Relationship between socioeconomic variables and woody carbon stocks

Analyzing the effects of socioeconomic factors on woody carbon stocks in homegarden agroforestry is essential for the development of environmental sustainability and community welfare (Maryo et al., 2023). The present study revealed a positive and significant relationship between socioeconomic variables, including wealth status, size of homegardens, and age of homegardens, and total carbon stock. Previous studies have reported the effect of socioeconomic variables on biomass carbon stocks from different land uses (Subba et al., 2017; Contosta et al., 2020). Carbon stored in agroforestry can vary widely, depending on the type, age, and size of agroforestry, the species of trees used, and the management practices used (Nair, 2012; Feliciano et al., 2018). For example, Kumar (2023) reported a weak negative relationship between the size of homegarden and carbon stocks in India. Similarly, Deneke and Negash (2023) reported the effect of wealth status on carbon storage in homegardens, where a significant decrease in carbon stock was observed with decreasing household wealth status in Ethiopia. Kassa et al. (2022) reported differences in biomass carbon between the ages of homegarden agroforests. A review of the literature by Sharma et al. (2022) showed that carbon sequestration by homegarden agroforestry is significantly influenced by age distribution.

5 Conclusion

The aboveground and belowground carbon stock potential of woody species in homegarden agroforestry was assessed along altitudinal gradients. The results indicate that altitudinal change had a significant impact on carbon stocks in homegarden agroforestry. Carbon stocks did not show a parallel change with altitudinal gradients. Woody carbon density was highest at middle, low, and high altitudes, respectively. Stocks also varied for each woody species in homegarden agroforestry. *Persea americana, Cordia africana, Grevillea robusta*, and *Mangifera indica* were the most prominent tree species in the carbon repositories. Socioeconomic variables, including wealth status, size of homegarden holdings, and age of homegardens, are positively and significantly correlated with biomass and carbon stocks. Therefore, altitudinal gradients and household socioeconomic variations had a substantial effect on the development of agroforestry woody carbon stocks for climate change mitigation. However, studies including other ecological factors such as temperature, precipitation, and slope should provide all-inclusive evidence on carbon accumulation and potential climate change mitigation strategies adopted in agroforestry practices of southwest Ethiopia. Furthermore, studies considering litter, dead woody biomass, and soil carbon could be useful in estimating land-use woody carbon stocks.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TJ: Writing – original draft, Investigation, Conceptualization, Formal analysis, Methodology. KH: Conceptualization, Supervision, Writing – review & editing. ZK: Conceptualization, Writing – review & editing, Supervision. AB: Conceptualization, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2025.1512150/full#supplementary-material

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