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Original Research

Biomass and soil carbon stocks under different coffee agroforestry systems in Hurumu District, southwest Ethiopia

Getahun Legesse[1] & Solomon Tadesse[2*]

[1]Ministry of Agriculture, Sustainable Land Management Program, Addis Ababa, Ethiopia
[2]Geography and Environmental Education Unit, Addis Ababa University, Addis Ababa, Ethiopia

Abstract

Understanding the carbon storage capacity of coffee agroforestry systems is essential for promoting sustainable land use and addressing climate change. However, there is a lack of scientific data on biomass and soil carbon stocks in Ethiopia's coffee-growing regions. This study estimated biomass and soil carbon stocks in garden, semi-forest, and forest coffee production systems in Hurumu District, southwestern Ethiopia. Data were collected from 24 plots measuring 20 m × 20 m, with soil samples (0–30 cm) analyzed for organic carbon and biomass carbon estimated using allometric equations. One-way ANOVA was used to compare the mean carbon stocks among the systems. The results showed that the forest coffee system had the highest mean total carbon stock (635.12 ton/ha), followed by the semi-forest (450.87 ton/ha), and the garden system (294.39 ton/ha). These variations were statistically significant at the 5% level (p < 0.05). The study identified the key shade tree species that contribute to carbon storage in each system: Podocarpus falcatus in the forest (45.73 ton/ha), Cordia africana in the semi-forest (35.74 ton/ha), and Prunus africana in the garden system (29.98 ton/ha). The results suggest that promoting these species enhances carbon storage and supports climate resilience.

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*Corresponding Author:
Solomon Tadesse

E-mail:
solomon.gtadesse@aau.edu.et

INTRODUCTION

Agroforestry systems are gaining recognition as potentially cost-effective strategies for mitigating climate change due to their important role in storing and sequestering carbon (IPCC, 2014). One of the key ecosystem services they provide is carbon storage, which occurs in both the living vegetation and the soil (Nair, 2012). Agroforestry systems hold significant potential for carbon sequestration due to the presence of trees and shrubs, while also supporting food and nutritional security (Betemariyam et al., 2020). However, the total carbon storage capacity of such systems differs across regions and is influenced by the - species and growth patterns of the trees involved (Tesfaye et al., 2019). In African coffee farming systems, the aboveground carbon biomass potential is estimated to range from 1.0 to 18.0 Mg C ha^{-1} (Nair, 2012). Various trees used for shading coffee plants have significant potential for storing and sequestering carbon in soil and biomass (Negash & Starr, 2015). However, increasing the intensity of the coffee farming system lowers the capacity to store carbon due to a reduction in shade tree diversity and density (Seta & Demissew, 2014).

In Ethiopia, various coffee production systems, including forest, semi-forest, garden, and plantation methods, are employed across diverse and intricate landscapes (Denu et al., 2016). Among these, forest and semi-forest coffee systems have the most significant tree canopy, suggesting that they offer the highest potential for global benefits, particularly carbon storage (Getachew et al., 2014). Agroforestry is recognized as a vital component of Ethiopia's climate-resilient green economy strategy (Betemariyam et al., 2020), with coffee farming systems being especially common in southwestern Ethiopia, the region where this study was conducted. According to Tesfaye et al. (2022), climate change is one of the most pressing global challenges, and sustainable land use practices such as agroforestry are increasingly being promoted as effective solutions for sequestering carbon both above and below ground, including enhancing soil carbon storage. Similarly, Betemariyam et al. (2020) found that shade trees used in coffee-based agroforestry systems are ideal for REDD+ initiatives, which focus on reducing emissions from deforestation and forest degradation, as well as enhancing carbon sequestration through sustainable forest management, conservation, afforestation, and reforestation efforts.

Despite the growing recognition of coffee-based agroforestry systems as effective strategies for mitigating climate change and managing land sustainably, there is still limited empirical data quantifying biomass and soil carbon stocks in these agroforestry systems (Betemariyam et al., 2020). Moreover, to effectively implement international initiatives like REDD+ (IPCC, 2014), science-backed information across all land-use types is essential. Yet, there's a present shortage of scientific data on carbon stocks specifically for coffee-based land-use systems in southwest Ethiopia. So, this lack of information led the researchers to study how much carbon coffee-based agroforestry systems can store in the Hurumu district of the Illubabor zone in the southwest highlands.

Statement of the problem

Coffee-based agroforestry systems play an important role in mitigating climate change, primarily by enhancing carbon sequestration. The diverse trees integrated with coffee, such as shade trees, actively absorb atmospheric CO_2 and store it in their above-ground and below-ground biomass and soil organic carbon, transforming agricultural landscapes into effective carbon sinks (Betemariyam et al., 2020). While the importance of a coffee-based agroforestry system for carbon sequestration in southwest Ethiopia is increasingly recognized, a specific spatial knowledge gap exists regarding the current carbon stock variations within the remaining native forest patches of the study area. Although several empirical studies (Seta & Demissew, 2014; Tadesse, 2015; Negash & Starr, 2015; Betemariyam et al., 2020) have reported on carbon storage in Ethiopian agroforestry systems, there is still a lack of comprehensive empirical data specifically focused on the role of coffee shade tree-dominated systems in reducing emissions and enhancing carbon sinks in agricultural landscapes.

This information gap hinders our understanding of the actual carbon sequestration potential of coffee-based agroforestry systems, thereby hampering policymakers and land managers in their efforts to optimize climate mitigation strategies. Furthermore, to our knowledge, there is a limited amount of data showing the precise locations of carbon stocks within this specific study area. Therefore, the general objective of this study is to estimate the carbon stock potential of coffee-based agroforestry systems and their contribution to climate change mitigation in the Hurumu district of the Illubabor zone in southwestern Ethiopia. Empirical findings from this study substantiate the role these distinct coffee-based agroforestry systems have in climate change mitigation.

Research questions

This study sought to answer the following research questions:

1. What is the amount of biomass carbon stock in three coffee farming systems?
2. What is the amount of soil carbon content in three coffee farming systems?
3. Is there a significant difference in the mean carbon stock amount among the three coffee farming systems?

MATERIALS AND METHODS

Study Area

This study was undertaken in the Hurumu district of the Illubabor administrative zone in southwestern Ethiopia (Figure 1), focusing on three coffee-based agroforestry systems: garden coffee, semi-forest coffee, and forest coffee. Geographically, the study area lies between 8°19'59" N latitude and 35°40'59" E longitude. The study area has a diverse topography, with elevations ranging from 799 to 2,583 m.a.s.l. According to CSA (2013), the study district had a total population of 105,265, with females accounting for 50.22% and males comprising 49.78%. The dominant native tree species in the district vary depending on the type of coffee farming system. *Croton macrostachyus, Acacia abyssinica*, and *Albizia gummifera* are the most common in garden coffee systems. *Croton macrostachyus*, *Sapium ellipticum*, and *Ficus sur* are the most prevalent in semi-forest coffee systems, and *Albizia gummifera*, *Millettia ferruginea*, and *Croton macrostachyus* are typical of forest coffee systems.

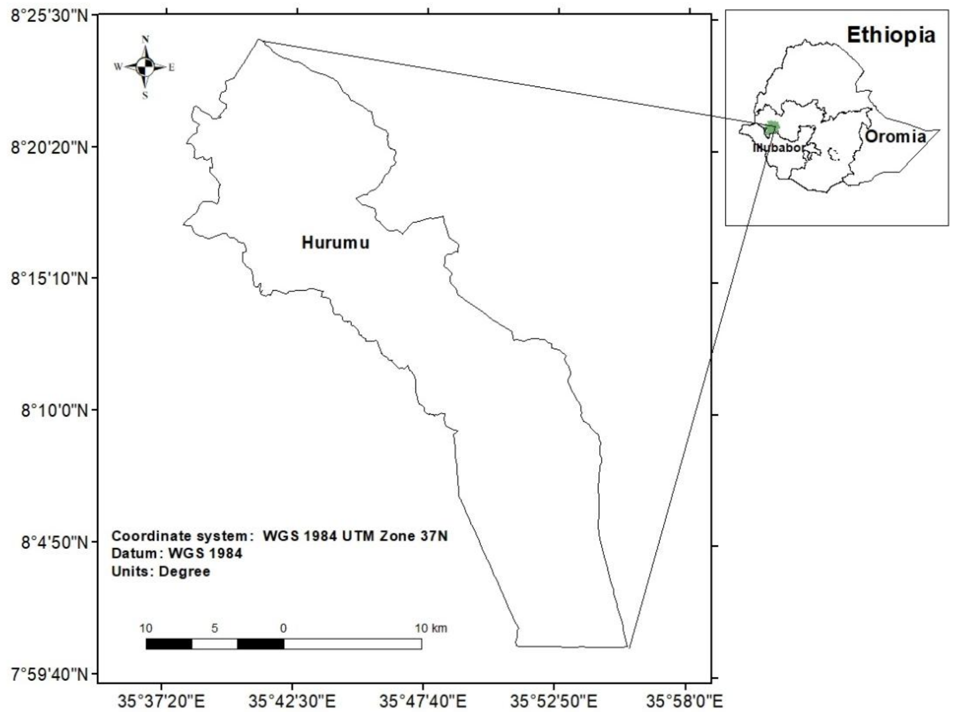

Figure 1. *Location of the study area*

In this district, dystric nitisols are the dominant soil type, with other frequently occurring soils including dystric gleysols, calcic xerosols, orthic acrisols, orthic solonchaks, and leptosols. The study area has a tropical highland humid climate, with a distinct rainy season from June to August, which is influenced by oceanic winds. It receives an average annual rainfall of 2000 mm and has a mean temperature of 20°C, as reported by Gemeda et al. (2021). Local livelihoods primarily depend on rainfed agriculture, coffee agroforestry, and livestock. Coffee-based agroforestry systems cover most of the district land, with forest and semi-forest types being the most extensive, although the cultivation of garden coffee is increasing.

Shade tree inventory

A preliminary investigation was carried out in the district in collaboration with agricultural experts to better understand the biophysical features within the coffee agroforestry systems. A total of 24 plots (8 from each coffee agroforestry system), measuring 20 m x 20 m, were randomly established to conduct an inventory. The biomass carbon stock potential was assessed by measuring the DBH (1.3 m) of all living trees in each plot. Local informants helped to identify species by common names, which were then confirmed using the Flora of Ethiopia and Eritrea. To avoid bias associated with the study's focus on woody plants, coffee shrub diameters were not measured.

Soil sampling

Soil samples were collected from the top 0–30 cm layer within 1 m x 1 m plots across the three coffee agroforestry systems, yielding a total of 24 samples, 8 from each system. A soil auger was used for general sampling, while a core sampler was employed specifically for bulk density analysis. For laboratory preparation, the composite soils were air-dried, thoroughly homogenized, and passed through a 2 mm sieve. From each processed set, a 1 kg composite sample of soil was sent to the Bedelle Agricultural Soil Testing Center, where the soils were oven-dried at 105°C for 12 hours and analyzed using the Walkley-Black method (Walkley & Black, 1934).

Biomass and carbon stock estimation

The researchers used the general model developed by Brown et al. (1989) to estimate the aboveground biomass of individual shade trees due to a lack of species-specific allometric equations for all shade tree species in the study area. This model was deemed suitable as the area's vegetation is classified as tropical moist Afromontane Forest, aligning with the model's intended application. The biomass was calculated using the following formula:

$$AGB = 38.4908 - 11.7883*DBH + 1.1926*DBH^2 \quad (1)$$

Where AGB represents the aboveground biomass in kilograms, and DBH denotes the tree diameter at breast height in centimeters. To estimate the carbon content, the aboveground biomass was multiplied by 0.47, following the approach outlined by Pearson et al. (2005).

$$AGC = AGB*0.47 \quad (2)$$

AGC refers to aboveground carbon, while AGB stands for aboveground biomass. Due to the high cost and time requirements of directly measuring belowground biomass, it is estimated using the AGB (shoot-to-root ratio). A standard methodology for estimating belowground biomass, cited by MacDicken (1997), is the assumption that it represents 20% of the aboveground tree biomass, yielding a 1:5 root-to-shoot ratio employed for this study. The following equation was used:

$$BGB = AGB * 0.2 \quad (3)$$

Where BGB represents belowground biomass (20% of AGB) and AGB is the aboveground biomass. The estimation for belowground carbon stock was obtained by multiplying the belowground biomass by 0.47 to determine the belowground carbon content.

$$BGC = BGB*0.47 \quad (4)$$

BGC stands for belowground carbon, and BGB for belowground biomass.

Soil carbon stock estimation

To calculate the carbon stock per unit area, the researchers used the soil's organic carbon content, which was obtained through laboratory analysis. Then, they applied the formula by Pearson et al. (2005) to determine the soil volume, bulk density, and soil organic carbon content.

$$V = h\,\pi r^2 \quad (5)$$

In this formula, h denotes the height of the core sampler in cm for each partition, r is the radius of the core sampler in cm, and V is the soil volume in cm³.

$$\text{Bulk density} = \frac{Oven\ dry\ Wt.(g/cm2}{Soil\ Volume} \quad (6)$$

The researchers estimated the soil carbon stock with this formula (Pearson et al. 2005).

$$SOC = BD * d * \%\,C \quad (7)$$

In this formula, SOC represents soil organic carbon stocks per unit area (ton/ha); BD is the soil's bulk density (g/cm²); d signifies the total depth from which samples were taken (30 cm); and % C indicates the carbon concentration measured in the laboratory.

Total carbon stock

Researchers calculated the total carbon stock per hectare by combining the carbon stocks of the AGC, BGC, and SOC pools, based on the formula provided by Pearson et al. (2005).

$$TCS = AGC + BGC + SOC \quad (8)$$

The total carbon stock (TCS, in ton/ha) combines aboveground carbon (AGC, ton/ha), belowground carbon (BGC, ton/ha), and soil organic carbon (SOC, ton/ha). This TCS value is then converted into tons of CO_2 equivalent by using a multiplier of 3.67 (or 44/12). This multiplier is the ratio of the molecular weight of CO_2 to that of O_2 (Pearson et al., 2007).

Statistical data analysis

The collected data were analyzed using descriptive statistics, such as minimum, maximum, mean, and standard deviation, to summarize the data. Inferential statistics were also used for a more detailed analysis. Specifically, a one-way ANOVA was conducted to assess whether there were statistically significant differences ($p < 0.05$) in the mean carbon pools across the three coffee farming systems. All statistical analyses were carried out using SPSS version 25.

RESULTS AND DISCUSSIONS

Results

Woody species composition

The study identified a total of 53 tree species belonging to 41 families within the coffee agroforestry systems, indicating a high overall diversity. Species richness was increased from garden coffee (37 species) to semi-forest (41 species) and was highest in forest coffee (49 species). The dominant families varied: Euphorbiaceae, Fabaceae, and Boraginaceae were most abundant in garden coffee; Euphorbiaceae dominated in the semi-forest; and Fabaceae was the leading family in forest coffee systems.

Biomass and carbon stock

Table 1 shows the estimated biomass and carbon storage values for the different coffee farming systems. The results showed significant variation in carbon storage among the three agroforestry systems studied. Significant variation was observed in biomass and carbon stocks among the three coffee-based agroforest systems studied. Based on the generic Brown et al. (1989) allometric equation estimation, the mean AGB of trees was estimated to be 247.60 ton/ha for garden coffee, 457.20 ton/ha for semi-forest coffee, and 684.26 ton/ha for forest coffee. Similar estimates were made for the mean root biomass in the garden, semi-forest, and forest coffee farming systems, which were 49.52, 91.44, and 136.85 ton/ha, respectively. The coffee forest was found to have significantly higher ($p < 0.05$) AGB and BGB compared with the two types of coffee-based agroforestry systems. AGC varied from 62.91 ton/ha in garden coffee to 473.86 ton/ha in forest coffee across the three coffee-based agroforestry systems. Compared to semi-forest coffee (214.89 ton/ha) and garden coffee (116.38 ton/ha), forest coffee had a higher mean of AGC (321.60 tons/ha). The results showed statistically significant ($p < 0.05$) variations in AGC carbon storage among the three coffee farming systems. Likewise, the value of BGC ranges from 12.58 ton/ha for garden coffee to 94.77 ton/ha for forest coffee. Garden coffee, semi-forest coffee, and forest coffee were found to have mean BGC stock values of 23.27, 42.98, and 64.32 ton/ha, respectively. There was a substantial ($p < 0.05$) variation in the mean value of BGC among the three coffee-based farming systems (Table 1). In these systems, AGC accounted for 83.33% of the biomass carbon stock, while BGC accounted for the remaining 16.67%.

Table 1

Average carbon stocks for each coffee farming system

Coffee farming types	Biomass and carbon stocks in different coffee farming systems (ton/ha)					TCS	TCO_2 eq
	AGB	AGC	BGB	BGC	SOC		
Garden coffee	247.60	116.38	49.52	23.27	154.75	294.39	1080.41
Semi-forest coffee	457.20	214.89	91.44	42.98	193.01	450.87	1654.69
Forest coffee	684.26	321.60	136.85	64.32	249.20	635.12	2330.89
p-value	0.001*	0.001*	0.001*	0.001*	0.000*	0.000*	0.000*

*Note: * indicates significance at $p < 0.05$ probability level*

Tree species contribution to biomass carbon stock

Table 2 shows the contribution of each shade tree species to the biomass carbon storage. The results revealed that *Podocarpus falcatus, Pouteriaadolfi-friederici,* and *Prunus africana* stored the largest proportions, which were 45.73, 28.56, and 26.65 ton/ha, respectively, in the forest coffee. In the semi-forest coffee, *Cordia Africana, Albizia gummifera,* and *Sapium ellipticum* stored 35.74, 22.31, and 21.96 ton/ha, respectively. *Prunus africana, Cordia africana,* and *Ficus sur* stored 29.98, 12.67, and 8.36 ton/ha, respectively, in the garden coffee. These results suggest that the forest coffee system has the highest levels of carbon storage among the tree species in the study area. The highest BG carbon stock in forest coffee is estimated to be 9.15 ton/ha for the *Podocarpus falcatus* and 5.71 ton/ha for the *Pouteriaadolfi-friederici* (Table 2). The highest belowground carbon concentration (7.15ton/ha) was found for *Cordia Africana* under semi-forest coffee, and 6 ton/ha for *Prunus africana* in the garden coffee system.

Soil organic carbon stock

SOC stocks varied considerably ($p < 0.05$) among the coffee farming systems, ranging from 116.87 to 299.38 t/ha (Table 1). The mean SOC was highest in forest coffee (249.20 t/ha), followed by semi-forest (193.01 t/ha) and garden coffee (154.75 t/ha). These results highlight forest coffee's greater SOC potential, with reductions of 56.19 and 94.45 t/ha observed in semi-forest and garden systems, respectively.

Table 2

Distribution of biomass and carbon stocks by shade tree species

Coffee farming systems	Species	Biomass and carbon stocks (ton/ha)			
		AGB	AGC	BGB	BGC
Garden coffee	*Prunus africana*	63.80	29.98	12.76	6.00
	Cordia africana	26.96	12.67	5.39	2.53
	Ficus sur Forssk	17.78	8.36	3.56	1.67
	Albizia gummifera	14.73	6.92	2.95	1.38
	Croton macrostachyus	6.96	3.27	1.39	0.65
	Sapium ellipticum	6.27	2.95	1.25	0.59
	Acacia abyssinica	5.24	2.46	1.05	0.49
	Ehertia cymosa	4.38	2.06	0.88	0.41
	Bersama abyssinica	2.12	1.00	0.42	0.20

	Vernonia amygdalina	1.66	0.78	0.33	0.16

***Table 2* continues.**

Semi-forest coffee	*Cordia africana*	76.04	35.74	15.21	7.15
	Albizia gummifera	47.48	22.31	9.50	4.46
	Sapium ellipticum	46.73	21.96	9.35	4.39
	Trichilia dregeana	26.92	12.65	5.38	2.53
	Macaranga capensis	24.01	11.29	4.80	2.26
	Schefflera abyssinica	18.43	8.66	3.69	1.73
	Ficus sur Forssk	16.86	7.92	3.37	1.58
	Croton macrostachyus	11.46	5.39	2.29	1.08
	Ficus vasta Forssk.	8.60	4.04	1.72	0.81
	Acacia abyssinica	5.68	2.67	1.14	0.53
Forest coffee	*Podocarpus falcatus*	97.30	45.73	19.46	9.15
	Pouteriaadolfi-friederici	60.76	28.56	12.15	5.71
	Prunus africana	56.70	26.65	11.34	5.33
	Ficus vasta Forssk	52.58	24.71	10.52	4.94
	Ficus sur Forssk	46.41	21.81	9.28	4.36
	Cordia africana	38.85	18.26	7.77	3.65
	Syzygium guineense	33.05	15.54	6.61	3.11
	Albizia gummifera	29.58	13.90	5.92	2.78
	Olea welwitschii	17.49	8.22	3.50	1.64
	Allophylus abyssinicus	15.67	7.36	3.13	1.47

Total carbon stock

Total carbon stocks increased significantly in all systems, from 294.39 t/ha in the garden and 450.87 ton/ha in the semi-forest to a high of 635.12 t/ha under forest coffee. This difference, with forest coffee storing significantly more carbon than the other two systems ($p < 0.05$; Table 1), is visually shown in Figure 2. Of the measured carbon pools, -biomass above the ground accounted for the largest share of the total carbon (47.30%), closely followed by soil organic carbon (43.25%), while belowground biomass contributed the least (9.46%). On average, these three coffee agroforestry systems sequestered an estimated 1688.66 ton/ha of carbon dioxide equivalent.

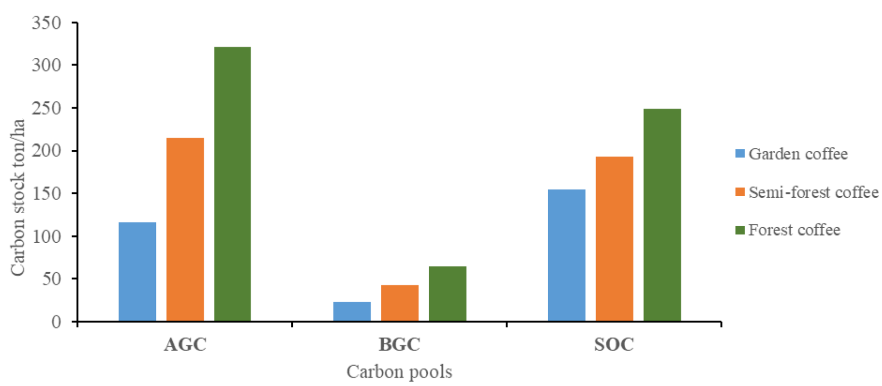

Figure 2. *Distribution of average carbon stock across various carbon pools*

Discussion

Biomass carbon stock

Quantifying these stocks is essential to understanding the importance of agroforestry in the worldwide carbon cycle and to developing sustainable production and carbon trading strategies (Tesfaye et al., 2019). Total biomass carbon storage under the coffee farming systems studied ranged from 139.64 to 385.92 ton/ha. Notably, a forest coffee system contained significantly more aboveground biomass carbon than a semi-forest system, by 106.72 ton/ha, and garden coffee systems by 205.32 ton/ha. This trend of higher stocks in forest coffee extended to the belowground carbon pool (Table 1). The higher AG and BG carbon storage found in forest coffee systems is attributed to their greater species diversity, higher tree density, and the prevalence of larger diameter trees. Conversely, the lower carbon content in garden coffee is likely due to management practices such as the targeted removal of shade trees to help coffee grow, resulting in the dominance of smaller trees. This observation is consistent with findings by Schmitt and Grote (2006), who documented farmers reducing canopy cover in semi-forest systems in southwestern Ethiopia to reduce vegetation competition and increase coffee density and yield.

Previous research supports the finding that tree density affects carbon stocks in coffee agroforestry systems. For instance, a study by Senbeta and Denich (2006) discovered the reduction of tree density in semi-natural coffee forests in southwestern Ethiopia to increase coffee production. Similarly, Hager (2012) linked differences in aboveground carbon stocks to varying tree densities within different coffee systems. Tesfaye et al. (2019) established the general principle that lower vegetation densities typically reduce total aboveground biomass carbon. Tesfaye et al. (2022) further support this finding by showing significant variation in mean total aboveground carbon (AGC) and belowground carbon (BGC) across coffee systems in southern Ethiopia. The current study highlights the importance of specific trees in dense systems. In this study, the contribution of aboveground biomass to the total carbon stock was 47.30%. This figure is lower than the findings of a recent study by Ararsa and Endalamaw (2024) on coffee-based agroforestry systems in the Nono Sale Forest in southwestern Ethiopia. Their study reported that, on average, 75% of the carbon was stored in tree biomass (both above and belowground), representing the largest carbon pool in the study area. The difference in biomass carbon stocks may be due to various factors, including the inclusion of coffee plants in carbon accounting, differences in allometric equations, and site-specific conditions such as management practices and climate. Furthermore, a recent empirical study by Pramulya et al. (2025) revealed the significant potential of coffee cultivation in agroforestry systems to reduce CO_2 concentrations by storing above-ground biomass. This result supports the conclusion that shade-grown coffee systems are effective strategies for afforestation and reforestation, enhancing carbon sequestration and contributing to the mitigation of climate change (Niguse et al., 2022). The result also found that only four species, such as *Podocarpus falcatus*, *Pouteria adolfi-friederici*, *Prunus africana*, and *Ficus vasta,* contributed over 125 ton/ha of biomass carbon stock within the forest coffee system (Table 2). This result aligns with Niguse et al. (2022) findings, who reported that the net carbon sequestered by coffee plants in agroforestry systems ranges from 18.8 tons per hectare in the Syzygium-shaded coffee stratum to 48.5 tons per hectare in the Albizia-shaded coffee stratum in southwestern Ethiopia. The results of the present study indicate that, on average, the three coffee agroforestry systems sequestered an estimated 1,688.66 tons per hectare of carbon dioxide equivalent. Comparable findings were reported by Niguse et al. (2022) in southwestern Ethiopia and Tesfay et al. (2022) in the Moist Mid-Highlands of Southern Ethiopia.

Soil carbon stock

SOC plays an important role in global carbon storage and cycling (Betemariyam et al., 2020). The study found statistically significant differences ($p < 0.05$) in SOC stocks between the coffee agroforestry systems studied. Garden coffee had the lowest SOC (154.75 ton/ha), possibly due to practices such as repeated planting and removal or burning of crop residues during land preparation. This is consistent with the findings of Betemariyam et al. (2020), who attributed lower SOC in home garden systems to intensive management practices such as cleaning, weeding, and biomass removal. Overall SOC stocks in the three systems were comparable to the ranges reported in other Ethiopian agroforestry studies (Gebeyehu et al., 2017), the mean SOC in forest coffee (249.20 ton/ha) significantly exceeding the values reported by Tesfaye et al. (2022) for southern Ethiopia. The finding of relatively lower SOC in garden coffee compared to other coffee systems is supported by other research, such as Albrecht and Kanji (2003), who observed significantly higher SOC under coffee forests. This result supports the findings of Niguse et al. (2022), who reported higher SOC stocks in forest coffee agroforestry systems than in other coffee agroforestry systems. This difference is likely due to the presence of diverse plant species with varying decomposition rates. Tesfaye et al. (2022) reported lower mean SOC values, which are inconsistent with the findings of this study. The higher mean SOC observed in this study may be attributed to the high diversity of plant species in coffee agroforestry systems. This diversity helps prevent soil erosion and contributes to maintaining SOC stocks.

Total carbon stock density

The amount of carbon stored in the vegetation (biomass) of the Ethiopian coffee agroforestry systems studied was like global estimates, which are 12-228 Mg ha^{-1} (Tadesse, 2015). However, when considering the carbon stored in the vegetation and the carbon stored in the soil, these Ethiopian systems stored significantly more carbon overall than was documented for shade-grown coffee in Indonesia, 82 MgC ha^{-1} (Van, 2002). The total carbon storage also varied considerably at $p < 0.05$ among garden, semi-forest, and forest coffee systems within Ethiopia. A similar finding was reported by Ararsa and Endalamaw (2024) in coffee-based agroforestry systems in the Nono Sale Forest in southwestern Ethiopia.

CONCLUSIONS

This study assessed the potential of carbon stocks under three coffee-based agroforestry systems in the Hurumu district of the Illubabor zone in southwestern Ethiopia. Significant differences were found, with forest coffee systems storing the largest proportion of carbon (46.01%), followed by semi-forest systems (32.66%) and garden systems (21.33%). Researchers attributed the higher storage in forest coffee to its greater species richness, denser tree population, and prevalence of larger trees. Carbon amounts also varied significantly within different carbon storage pools (above- and below-ground biomass and soil). In conclusion, these coffee-based agroforestry systems, particularly forest coffee, store considerable amounts of carbon, suggesting their valuable role in mitigating climate change.

Recommendations

To maintain and increase carbon storage in coffee-based agroforestry systems, the district agricultural office must actively combat deforestation, forest degradation, and illegal logging in these areas. This will play a significant role in carbon sequestration and climate change mitigation.

There is a need to implement programs and provide support to encourage coffee farmers to plant and maintain a diverse range of naturally regenerating shade trees on their farms, representing the structure of high-carbon forest coffee systems.

It is important to explore mechanisms and advocate for the inclusion of Ethiopian coffee-based agroforestry systems in national and international carbon offset programs, such as REDD+, in order to provide financial incentives for carbon sequestration.

Conservation efforts should prioritize the maintenance and protection of existing forest coffee systems, given their significantly higher carbon storage capacity compared to semi-forest and garden coffee systems.

Further studies are needed to quantify carbon stocks in other important carbon pools within these agroforestry systems, such as leaf litter and dead wood, to better understand their full capacity for storing carbon.

CRediT authorship contribution statement

Getahun Legesse: Conceptualization, methodology development, data collection, and formal analysis. **Solomon Tadesse**: Writing, reviewing, and editing of the manuscript.

Data availability

The data used in this research is available upon request.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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