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Soil carbon to go: Agroforestry practices including coffee sequester the highest amounts of soil C in mountainous Southern Ethiopia

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Abstract Agroforestry (AF) systems are considered more sustainable than conventional agriculture because high production and cover enhance carbon sequestration and water and nutrient retention. However, above- and below-ground carbon stocks in different traditional agroforestry systems and in relation to adjacent land use types remain poorly understood, especially in East Africa. This study evaluates the carbon sequestration potential of three agroforestry systems—coffee, enset, and khat—in the Sidama region of southern Ethiopia compared to cropland and eucalyptus woodlots. Ten plots per land use type were selected, and carbon stocks were assessed by estimating woody biomass using allometric equations, and soil organic carbon (SOC) stocks by soil sampling to 60 cm depth. AF systems store significantly higher SOC than cropland and partially woodlots, with coffee-based AF systems sequestering the most carbon. In AF practices, approximately 79% of total carbon stocks were found in the soil, while woody biomass accounted for the remaining 21%. The study highlights a decreasing trend in total carbon stocks from AF-Coffee to cropland, with similar values in woodlots compared to AF practices. The higher SOC levels in these agroforestry plots are attributed to greater plant species diversity and minimal soil disturbance. Our results indicate that AF systems, particularly those based on coffee and enset, are key to enhancing soil carbon storage and promoting sustainable land use practices across the region. The study provides important insights into carbon mapping and climate change mitigation strategies.

Keywords Agroforestry practices · Carbon sequestration · Soil organic carbon · Ethiopian highlands · Coffee · Climate change mitigation

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Introduction

Agriculture constitutes around 50% of Ethiopia's GDP and over 80% of exports, underpinning the economy through smallholder farming (Stellmacher and Kelboro 2019; Zerssa et al. 2021). However, the sector faces growing pressures from population growth, land degradation, and environmental changes (Gebissa 2021). Agriculture occupies a unique position in the climate crisis: it is both highly vulnerable to the impacts of changing climate conditions and a major contributor to climate emergencies. These challenges necessitate the adoption of sustainable agricultural practices to ensure long-term food security, economic stability, and greater equity (Gebrehiwot et al. 2018; Sileshi et al. 2019).

Agroforestry (AF), which integrates trees with crops and/or livestock, is (re) emerging as a promising solution, offering higher yields, production stability, and environmental benefits (Ma et al. 2022), and is particularly suitable for densely populated tropical areas (Foresta 2013; Kurniawan et al. 2021). Globally, AF covers more than 1 billion hectares of land and engages more than 1.2 billion people (Smith et al. 2012). AF systems provide numerous ecosystem services (Wolle et al. 2021), including enhancing food security (Thorlakson and Neufeldt 2012), diversifying income sources, and enhancing biodiversity (Abebe et al. 2013). However, in recent centuries, traditional AF systems have faced significant challenges worldwide, including urbanization, shifts in agricultural policies, changing market dynamics, and climate change (Abebe et al. 2010; Ollinaho and Kröger 2021). Despite these challenges, AF remains widespread in the mountainous regions of Ethiopia (Abebe et al. 2010; Negash and Starr 2015), which has a long history of agroforestry practices, spanning almost 7000 years (Hekstra 2002).

In the Sidama region of southern Ethiopia (Fig. 1), where this study was conducted, AF is the dominant land use system, accounting for 48.7% of the area under cultivation (Tadesse et al. 2021). Diverse AF systems are practiced in the region because of favorable agroclimatic conditions and various socioeconomic factors (Mellisse et al. 2024). The traditional AF systems in southern Ethiopia have been established following two major crops: enset (*Ensete ventricosum*) and coffee (*Coffea arabica*) (Abebe 2005). These systems are characterized by high biodiversity and intensive intercropping (Abebe et al. 2013) and are classified as homegarden, multistrata AF systems (Nair 1991). Common crops grown in these systems include staple crops (enset, maize) and cash crops (coffee, khat (*Catha edulis*), fruits, vegetables, and spices (Abebe 2005). Enset ("false banana") is valued for its carbohydrate-rich pseudostem and corm (Borrell et al. 2020). Coffee is a key cash crop in the region and globally, contributing significantly to household incomes and local economies in Africa (Kassaye et al. 2018), South America, and elsewhere. Coffee is commonly intercropped with enset and other crops in AF systems in Sidama; recent studies have highlighted the potential of AF to partially mitigate the impacts of climate change on coffee production in Brazil (Gomes et al. 2020) and other areas. Khat, a stimulant plant whose leaves are chewed for their mild psychoactive effects, plays an important economic role in the region (Wuletaw 2018). Besides the above-mentioned systems, *Eucalyptus* spp. woodlots have been expanding in the region over the past few decades for firewood and timber (Kebede and Chen 2023). These different AF-based land use types with varying proportions of woody plants are complemented by conventional croplands such as teff and maize, reflecting the farmers strategy to diversify their subsistence and cash needs (Eshetu et al. 2018).

A central concept of AF is its superior capacity to capture resources (Lorenz and Lal 2018). The multilayered canopy structure usually enables greater C capture than monocultural systems, and as the AF systems mature, the soil retains significantly more water and nutrients (Fahad et al. 2022). AF worldwide have therefore been identified as having significant potential for carbon (C) storage, estimated (with large uncertainties) at up to 2.2 Pg C in biomass over the next 50 years (Lorenz and Lal 2014). However, C storage capacity varies widely depending on edaphoclimatic conditions, species, and management practices, underscoring the need for localized assessments. For example, Ma et al. (2022) reported aboveground biomass C from 11 Mg C ha^{-1} in boreal zones to 95 Mg C ha^{-1} in tropical zones. Henry et al. (2009) reported 16 Mg C ha^{-1} in tree-based agricultural landscapes in Kenya. In Ethiopia, there is significant regional variability in C storage across AF systems, particularly in mountainous regions holding unique climate conditions and diverse topography. For instance, Toru and Kibret (2019) documented 28 Mg

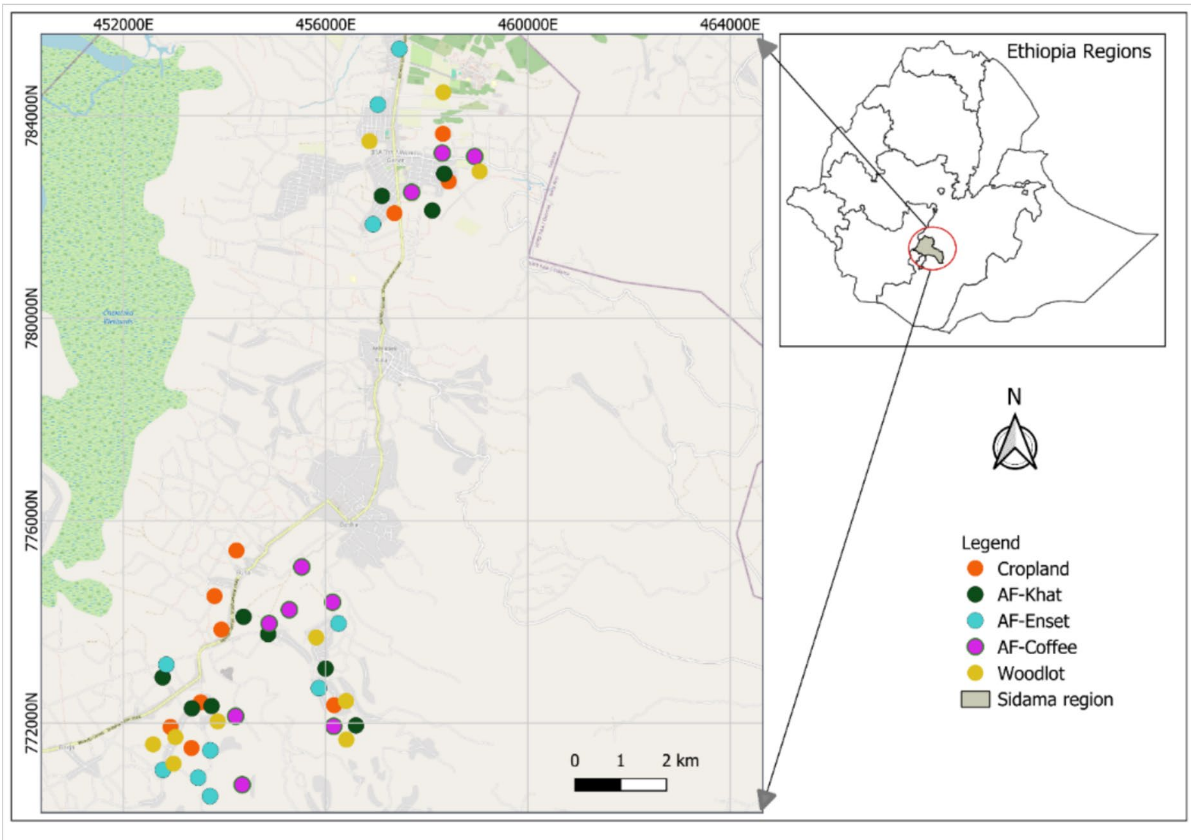

Fig. 1 Study area with individual sample plots per land use type (see legend) in the Wondo Genet district, Sidama region, Ethiopia. AF, agroforestry

C ha^{-1} in coffee-dominated AF systems in eastern Ethiopia, while Negash and Starr (2015) found traditional AF systems in the Gedeo zone, in southeastern Ethiopia, storing up to 67 Mg C ha^{-1}. These differences are believed to be primarily driven by climate, topography, traits of species, and soil management practices. Specifically, management practices such as selective pruning and the integration of fast-growing species have been shown to enhance AF biomass significantly (Henry et al. 2009; Ma et al. 2022). Globally, croplands with scattered woody plants have lower woody biomass C stocks, often < 10 Mg C ha^{-1} (Zomer et al. 2016). Croplands in (southern) Ethiopia hold scattered (fruit) trees and shrubs for shade, erosion control, etc. but their woody C stocks have rarely been quantified.

While woody biomass is an important compartment for C storage, soil organic carbon (SOC) often exceeds aboveground C (Sufardi et al. 2022), particularly in tropical AF systems worldwide (Muthuri et al. 2023). In Ethiopia, for example, Toru and Kibret (2019) reported SOC stocks of approximately 250 Mg C ha^{-1} in the soils of coffee agroforestry systems in eastern Ethiopia, exceeding the aboveground biomass. Similarly, Tesfay et al. (2022) found SOC stocks ranging from 126 to 146 Mg C ha^{-1} in various AF systems within the Gedeo zone. Since woody roots, especially in arid areas, are distributed deeper in soil horizons (Germon et al. 2020), significant effects of AF on subsoil OC contents have been hypothesized. In sum, previous findings underscore the vital role of SOC in overall C sequestration and suggest that soil-focused management practices can significantly enhance C stocks in Ethiopia and elsewhere. However, variability in reported SOC remains high and is underreported compared to biomass/yield data in AF studies. In addition, previous studies have rarely considered a wider range of local land use types (LUTs), such as cropland and woodland, which are often intermixed at the farm level—making comparability of C storage across landscapes and thus up-scaling difficult. For example, Shi et al. (2018) identified globally only 76 papers allowing for a paired comparison between AF and croplands/pastures (i.e. "Controls")–with only 5 originating from eastern Africa–and only 12 studies reporting pairs of (woody) plant biomass and SOC.

Moreover, despite the widely recognized potential of AF systems for C sequestration and other ecosystem services, the specific management practices that maximize ecosystem C stocks remain poorly understood, particularly in mountainous regions and more specifically, in East Africa. Therefore, this study evaluates how different land use practices within traditional farming systems affect C stocks in the Sidama region of southern Ethiopia. Woody biomass and soil C stocks in coffee, enset, and khat AF plots compared to conventional croplands and eucalyptus woodlots and their interrelationships are investigated to better assess above and below-ground C sequestration potentials at the landscape scale. We include subsoils down to 60 cm in our assessment, whereas soil C stocks are often reported only for the topsoil. The results will inform regional monitoring of C stocks and land management strategies.

Materials and methods

Study area

The study was conducted in the Wondo Genet district (also transliterated as "Wendo Genet"; Fig. 1), Sidama Regional State, Ethiopia (7° 06′ N, 38° 37′ E), located at an average altitude of 1850 m above sea level (a.s.l.). The district encompasses an altitude range of 1700–2200 m a.s.l. Wondo Genet experiences a sub-humid tropical climate with a bi-modal rainfall pattern. The long rainy season between July and October contributes over 50% of the total annual rainfall, while the short-rainy season between March and May contributes 28% (Teklay and Malmer 2004). The area receives an average annual rainfall of 1247 mm. The mean maximum and minimum air temperatures are 26.3 °C and 12.4 °C, respectively, with an annual mean of 19.5 °C (Teklay and Malmer 2004). The study area is characterized by Andosol soils with vitric or andic horizons within 25 cm of the surface. These horizons are rich in minerals like allophane and imogolite, which enhance nutrient retention and water-holding capacity (FAO 2015). The region's geology includes volcanic rocks such as ignimbrites, basalts, and tephra, along with volcano-lacustrine sediments from the Plio-Pleistocene age, contributing to its rugged, dissected landscape (Temesgen et al. 2001; Ango and Bewket 2009).

The study area is known for its traditional agroforestry systems, which include coffee, enset, khat, and *Eucalyptus* woodlots. These systems integrate root and tuber crops, vegetables, and annual cereals, and support livestock rearing. We systematically identified and grouped land use types (LUTs) in the study region, following Mellisse et al. (2018). The identified practices were classified into five main LUTs: cropland ("Control"), three homegarden-type agroforestry (AF) practices dominated either by khat (*Catha edulis* (Vahl) Forssk. ex Endl.; "AF-Khat"), enset (*Ensete ventricosum* (Welw.) Cheesman; "AF-Enset") or coffee (*Coffea arabica* L.; "AF-Coffee"), and woodlots of the neophyte *Eucalyptus grandis* W.Hill ex Maiden ("Woodlot"). The selection of *Eucalyptus* woodlots was based on a uniform age (3–5 years old) to ensure relevance to typical regional management practices. Each LUT is managed according to specific strategies (Table 1), as assessed by local questionnaires to farmers. While all LUTs share similar soil types, their configurations vary due to factors such as farm size and farmer preferences. Enset, coffee, and khat plots are typically situated close to homesteads, while cropland and woodlots are more distant. Sampling plots were established where these land uses had been practiced for ≥ 10 years, identified through resident surveys and agricultural office records. Ten plots per LUT (50 plots in total), each ≥ 100 m^2, were randomly selected across two representative sub-sites within Wondo Genet town, ranging in elevation from ~ 1700 to 2200 m a.s.l. (Fig. 1). The sub-sites were selected to better represent the study area; targeted LUTs were present in both sub-sites (15/35 plots on the northern/southern sub-site, respectively; Fig. 1). Plot selection considered exposition and slope.

Soil analysis

Soil samples were collected from each 100 m^2 inventory plot. On each plot, three subplots (located at the

Table 1 Description of five LUTs including management, common in the Wondo Genet district, Sidama region, Ethiopia; modified after Mellisse et al. (2018)

Land use type	Description
Cropland (control)	Land used to grow crops such as corn, haricot beans, sugar cane, and potatoes, with regular crop rotation. Woody plants are a rare component of the land use type (i.e., at plot boundaries). Inorganic fertilizers such as diammonium phosphate (DAP) and urea are commonly used. Tillage is typically used for soil preparation at an average depth of 20 cm, depending on the crop
AF-khat	Agroforestry practice characterized by the cultivation of khat, with > 30% of the agricultural land covered by khat crops, and the rest of the area consisting of other cereals such as maize, haricot beans, and woody crops. Inorganic fertilizers such as DAP and urea are commonly used. Tillage is typically used to prepare the soil at an average depth of 20 cm, depending on the crop
AF-enset	Agroforestry practice with > 35% coverage by enset crops while the rest of the farmland area is occupied by multipurpose trees and some coffee. Enset plots are usually located near the homestead. The addition of animal manure and organic waste is common. No-tillage is usually practiced, which is central to food security and subsistence. The primary focus of these systems is on food security and subsistence farming
AF-coffee	At least 35% of agroforestry plots are planted with coffee, and the rest is often covered with multipurpose trees and enset. Coffee AF is typically located close to the homestead. Minimal tillage is practiced, and the addition of organic waste and animal manure is common. The management practices are primarily focused on maximizing coffee production for economic gain
Woodlots	Areas primarily covered by young *Eucalyptus grandis* trees; sparse ground vegetation does exist. Woodlots are established on formerly cultivated or uncultivated land and serve as a source of poles, timber for construction, and firewood. Leaves are usually collected and burned. Woodlots are harvested constantly but larger pruning occurs in cycles of 3–5 years

AF, agroforestry

left top, center, and bottom right) were selected for soil sampling. Sampling was conducted at two soil depths: 0–30 cm (topsoil) and 30–60 cm (subsoil) using a 5 cm inner diameter auger. Soil samples collected from the three points at the same depth were combined into a composite sample. A total of 100 composite soil samples, with 50 samples at each depth, were collected for chemical analysis. Soil samples for bulk density analysis were taken from a profile wall at both soil depths (0–30 cm, 30–60 cm) within each inventory plot, using a 5 cm diameter and 10 cm long core sampler. Three samples were taken at each soil depth. A total of 100 soil samples were collected, with 50 samples obtained at each soil depth.

Bulk density (BD, g cm^{-3}) values for fine soil were calculated by dividing the dry mass of the soil core obtained by oven drying (105 °C, 48 h) by the volume of the core sample, after subtracting the weight/volume of coarse fractions (> 2 mm; stones, roots, and other non-soil materials) present in the core sample, respectively. The dried soil sample was sieved (2 mm) to remove stones, roots, etc. The removed materials were collected from the sieve, and their combined volume was determined by submerging them in water and measuring the volume of water displaced (Don et al. 2007). This volume accounted for the sample's non-soil space, and its weight was subtracted from the total dry mass. The other collected soil samples were transported to the laboratory and air-dried at room temperature. Plant residues, stones, etc. were meticulously removed, and large aggregates were broken down (FAO 2015). The soil samples were then sieved (2 mm) and homogenized. Soil texture analysis, determining the fractions of sand, silt, and clay, followed by FAO (2020). The pH of topsoil samples was measured in water (pH 3110, WTW, Germany) at a ratio of 1:2.5 (soil:water). Inorganic carbon was removed using hydrochloric acid (HCl) before organic carbon (OC) analysis. OC concentration was then determined by wet digestion (Walkley and Black 1934). In this method, about 60–86% of the OC is oxidized; therefore, a correction factor of 1.32 was used (De Vos et al. 2007). Soil carbon stocks (SOC; Mg C ha^{-1}) were calculated by multiplying the concentration of OC, BD, and soil volume (cm^3) and scaled to hectare (Toru and Kibret 2019) as SOC stock (Mg C ha^{-1}) = OC (mg C g^{-1} soil) × BD (g cm^{-3}) × (1 − Coarse fraction) × Depth (30 cm) × 10^{-1}. SOC was calculated either per soil horizon (0–30 cm; 30–60 cm) or to 60 cm soil depth.

Biomass C stocks

Within each plot, all woody plant individuals with a diameter at breast height (DBH, 130 cm) ≥ 2.5 cm and a total height ≥ 1.5 m (measured vertically from the ground) were recorded. Stem diameter was measured in two perpendicular directions using a caliper (Mantax Blue 800 mm, Haglöf, Sweden) and the average value was used for analysis. For coffee plants, the stem diameter at 40 cm (d_{40}), and for khat and enset plants, basal (pseudo-)stem diameter was measured at 10 cm (d_{10}). For multi-stemmed plants, the equivalent diameter of the plant was calculated (Snowdon et al. 2002); trees forking at a height of ≥ 1.3 m was treated as single individuals. The height of each tree species was measured using a Laser Hypsometer (VL5, Haglöf, Sweden). Trees near the plot boundary were included if ≥ 50% of the stem was within the plot boundary. Generic and species-specific allometric equations were used to estimate woody biomass (Table 2).

Wood density values (oven dry mass per unit of green volume, g cm^{-3}) for each species were obtained from the global wood density database (Donegan et al. 2014). The specific wood density values used are given in Supplementary Table S1. The carbon content percentage (C%) values, originally determined through a loss-on-ignition process involving ignition at 550 °C for 2 h, used were: 43% for coffee and 41% for enset (Negash and Starr 2015); and 48% for fruit and non-fruit trees and shrubs, including khat (Kuyah et al., 2012a). The sum of carbon stocks in the woody biomass of all trees and other perennials was taken as the total standing biomass carbon stocks per plot and extrapolated to a hectare. Ecosystem carbon stocks were calculated by summing up the SOC and woody biomass, excluding the C stored in leaves and fine roots, which are considered minimal contributors to the total ecosystem C pool (De Kauwe et al. 2014). Finally, we determined the ratio and contribution of SOC stocks (0–60 cm; see above) and woody biomass carbon to the total C stocks across LUTs.

Statistical analysis

All statistical analyses were conducted using R v.4.1.2 (R Core Team 2021). Data analysis and visualization were conducted using the following R packages: ‘ggplot2’ for plotting (Wickham 2016), ‘dplyr’ for data manipulation (Wickham et al. 2019), and ‘multcompView’ for post hoc testing (Spencer et al. 2006). Outliers were identified using boxplots based on the interquartile range (IQR), calculated as $Q3 - Q1$. Data points below $Q1 - 1.5 \times IQR$ or above $Q3 + 1.5 \times IQR$ were removed (Barnett and Toby 1994). Normality was evaluated with the Shapiro–Wilk test and homogeneity of variances with Levene’s test. Analysis of variance (ANOVA) was performed to assess the effects of LUTs on soil pH and bulk density, woody biomass C, soil C stocks, etc. For significant ANOVA results, Tukey’s HSD post hoc test was applied to determine pairwise differences among LUTs. A paired t-test was employed to evaluate differences in OC contents between soil depths (0–30 cm and 30–60 cm) within each LUT. Pearson correlation analysis was used to examine the relationships between soil pH, bulk density, SOC concentration, and SOC stocks at different soil depths (0–30 cm, 30–60 cm, and 0–60 cm) and woody biomass C. Finally, a linear regression analysis of SOC stock and woody biomass carbon within LUTs was conducted. The level of significance (*P*-value) used was $\alpha = 0.05$. Descriptive statistics are presented as mean ± standard error (SE).

Table 2 Allometric equations for estimating the aboveground biomass of different woody plant species in the study area

Species	Allometric equation	R^2	Sample size (n)	References
Khat	$AGB_{Khat} = 0.4796 \times d_{10}^{1.5818} \times H_{doh}^{0.1089}$	0.96	31	Getnet and Negash (2021)
Enset	$\ln (AGB_{Enset}) = -6.57 + 2.316\ln(d_{10}) + 0.124 \ln(h)$	0.91	40	Negash et al. (2013a)
Coffee	$AGB_{Coffee} = 0.147 \times d^2_{40}$	0.80	31	Negash et al. (2013b)
Other trees, shrubs	$AGB = 0.225 \times DBH^{2.341} \times \rho^{0.73}$	0.98	72	Kuyah et al. (2012a)

AGB (aboveground biomass; kg d.wt. $plant^{-1}$); DBH (diameter at breast height; cm), d_{40} (stem diameter at 40 cm; cm), d_{10} (stem diameter at 10 cm; cm), ρ (wood density, g cm^{-3}), h (height of individual plant; m), and H_{doh} (dominant height of crop; m)

Results

Soil pH, bulk density, and texture

Soil properties were analyzed across five LUTs, all managed continuously for at least 10 years. Khat plots had the highest pH of 6.89, markedly higher than enset plots, which had the lowest pH of 6.6 (Table 3). Bulk density differed significantly across LUTs and within soil depths. At 0–30 cm soil depth, enset (1.08 g cm^{-3}) and khat (1.10 g cm^{-3}) plots had the lowest bulk density (BD), significantly lower than woodlots, which had the highest (1.37 g cm^{-3}). A similar pattern was found in the subsoil. The BD of the croplands was intermediate between the three AF practices and the woodlots at both depths. Regarding texture classes (0–30 cm), croplands had the significantly greatest percentage of sand (~57%), while khat plots had the significantly highest percentage of clay (~29%). At 30–60 cm depth, woodlots had the significantly lowest/highest percentages of sand (~42%) and clay (~37%), respectively, compared to other LUTs (Table 3).

Soil organic C content and stocks

The results indicate low soil organic carbon (OC) content among the LUTs, with values ranging from 1.59% to 2.53% in the topsoil and 1.0 to 1.72% in the subsoil (Fig. 2). OC (tended to) decreases in the following order: AF-Enset > AF-Coffee > AF-Khat > woodlot > cropland plots at 0–30 cm soil depth. Topsoil OC contents were significantly higher in coffee and enset AF plots (2.33–2.53%) compared to woodlots (1.63%) and cropland (1.59%). In the subsoil, AF-Coffee (1.72%) had significantly greater OC contents than woodlots (1.08%) and croplands (1.0%; Fig. 2). OC at greater depths was more similar between khat and enset, and woodlot and cropland plots, respectively. The OC content differed significantly between soil depths in all LUTs except AF-Khat ($p < 0.1$); greater OC values were recorded in the topsoil (Fig. 2).

Significant differences in soil organic carbon (SOC) stocks were observed among the LUTs. Considering the soil depth to 60 cm, SOC stocks in AF-Coffee (145.76 Mg C ha^{-1}) were significantly higher than in AF-Khat (117.05 Mg C ha^{-1}), woodlots (111.01 Mg C ha^{-1}) and cropland plots (95.16 Mg C ha^{-1}) (Fig. 3). SOC stocks 0–60 cm in AF-Enset (128.78 Mg C ha^{-1}) were significantly higher than those in cropland plots (95.16 Mg C ha^{-1}), while AF-Khat, AF-Enset, and woodlots had similar SOC stocks (Fig. 3). Across all LUTs, SOC stocks tended to decrease with soil depth (Supplementary Fig. S1), driven by the lower OC concentrations in the subsoil (Fig. 2). In the topsoil (0–30 cm), SOC stocks were significantly higher in AF-Coffee (82.28 Mg C ha^{-1}) and AF-Enset (81.10 Mg C ha^{-1}) compared to cropland (58.77 Mg C ha^{-1}; Supplementary Fig. S1). In the subsoil, SOC stocks in AF-Coffee (63.48 Mg C ha^{-1}) were significantly greater than those in woodlots and cropland (42.72 and 36.40 Mg C ha^{-1}, respectively; Supplementary Fig. S1). A Pearson

Table 3 Soil characteristics of five land use types (LUT) and two soil depths in the Wondo Genet district, Sidama region, Ethiopia

Land use type (LUT)	pH (H_2O)	Bulk density (g cm^{-3})	Soil textural classes (%)		
			Sand	Silt	Clay
Soil depth 0–30 cm					
Cropland	6.68 ± 0.01^{ab}	1.24 ± 0.02^{ab}	57.1 ± 0.33^{a}	23.8 ± 0.19^{b}	19.1 ± 0.37^{c}
AF-Khat	6.89 ± 0.02^{a}	1.10 ± 0.01^{b}	50.1 ± 0.33^{b}	20.6 ± 0.19^{c}	29.3 ± 0.40^{a}
AF-Enset	6.60 ± 0.01^{b}	1.08 ± 0.02^{b}	49.3 ± 0.23^{b}	26.3 ± 0.11^{ab}	24.4 ± 0.24^{b}
AF-Coffee	6.64 ± 0.03^{ab}	1.18 ± 0.01^{ab}	51.0 ± 0.48^{b}	26.9 ± 0.39^{a}	22.1 ± 0.33^{bc}
Woodlot	6.76 ± 0.03^{ab}	1.37 ± 0.03^{a}	50.9 ± 0.35^{b}	26.8 ± 0.23^{ab}	22.3 ± 0.20^{bc}
Soil depth 30–60 cm					
Cropland	–	1.21 ± 0.01^{ab}	50.0 ± 0.15^{a}	21.4 ± 0.18^{a}	28.6 ± 0.22^{b}
AF-Khat	–	1.16 ± 0.01^{b}	47.6 ± 0.32^{a}	21.7 ± 0.18^{a}	30.7 ± 0.34^{b}
AF-Enset	–	1.11 ± 0.01^{b}	46.6 ± 0.27^{a}	24.1 ± 0.28^{a}	29.3 ± 0.31^{b}
AF-Coffee	–	1.23 ± 0.01^{ab}	47.2 ± 0.61^{a}	22.8 ± 0.47^{a}	30.0 ± 0.67^{b}
Woodlot	–	1.32 ± 0.01^{a}	41.7 ± 0.27^{b}	21.5 ± 0.24^{a}	36.8 ± 0.22^{a}

Different letters indicate significant differences among LUTs per depth (Tukey test, $p < 0.05$; n = 10; mean ± SE). AF, agroforestry

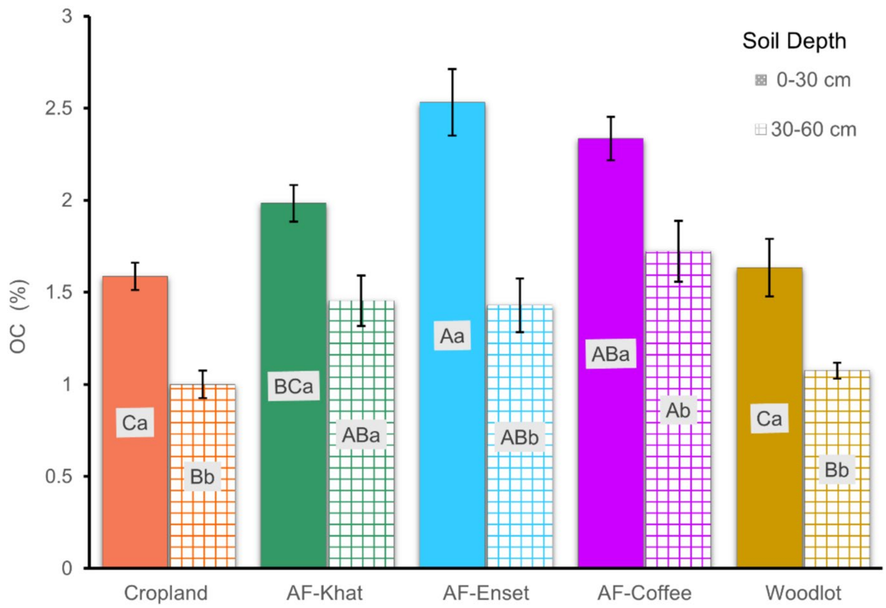

Fig. 2 Organic carbon (OC) contents across five land use types (LUT) and two soil depths (0–30 cm, 30–60 cm) in the Wondo Genet district, Sidama region, Ethiopia. Uppercase letters denote significant differences in OC content among LUTs per depth, lowercase letters indicate significant differences between soil depths per LUT (Tukey test, $p < 0.05$; n = 10; mean ± SE). AF, agroforestry

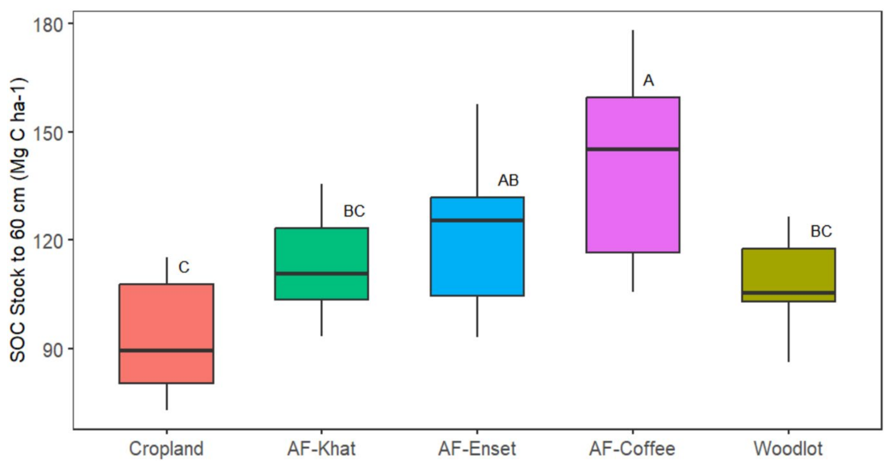

Fig. 3 Soil organic carbon (SOC) stocks (Mg C ha^{-1}) to 60 cm soil depth of five land use types (LUT) in the Wondo Genet district, Sidama region, Ethiopia. Different letters denote significant differences in SOC among LUTs (Tukey test, $p < 0.05$; n = 10). AF, agroforestry

correlation analysis (Supplementary Fig. S2) indicated a significant positive (r = 0.74 to 0.88) correlation between OC and SOC stocks at various depths. In contrast, bulk density showed a significant negative (r = − 0.32 to − 0.40) correlation with OC across soil depths. In the topsoil, pH had a significant negative correlation (r = − 0.29) with SOC stock (Supplementary Fig. S2).

Wood biomass carbon

Not surprisingly, *Eucalyptus* woodlots had the significantly highest woody biomass C with a value of 63.97 Mg C ha^{-1} (Fig. 4). AF practices dominated by khat (35.71 Mg C ha^{-1}), enset (34.88 Mg C ha^{-1}), or coffee (32.29 Mg C ha^{-1}) did not show significant differences in woody biomass C. The AF plots had significantly higher woody biomass C stocks compared to croplands, which contained 13.92 Mg C ha^{-1} (Fig. 4) as scattered trees and hedges. Despite the selection criteria (3–5 years), the variability in woody biomass was markedly highest in woodlots.

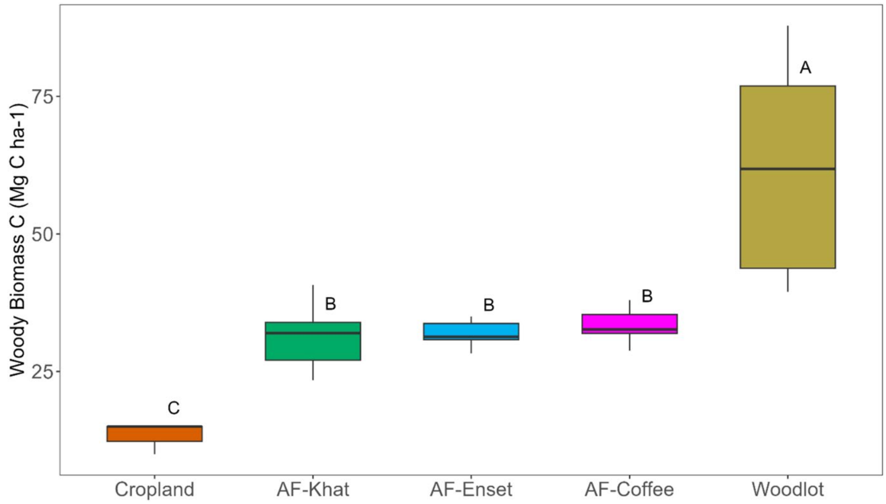

Fig. 4 Woody biomass carbon (Mg C ha^{-1}) across five land use types (LUT) in the Wondo Genet district, Sidama region, Ethiopia. Different letters denote significant differences among LUTs (Tukey test, $p<0.05$; n = 10). AF, agroforestry

Ecosystem carbon stock and the relationship between woody biomass C and soil organic carbon

The agroforestry systems (AF-Coffee, AF-Enset, and AF-Khat) and woodlots exhibited higher total C stocks compared to cropland (109.08 Mg C ha^{-1}). The total "ecosystem" carbon stocks, defined here as SOC (to 60 cm) plus woody biomass C, in these systems, were as follows: AF-Coffee (180.64 Mg C ha^{-1}), woodlot (174.98 Mg C ha^{-1}), AF-Enset (164.49 Mg C ha^{-1}), and AF-Khat (149.34 Mg C ha^{-1}) (Fig. 5). In all LUTs, SOC comprised the largest portion of total C stocks. For example, SOC accounted for ~ 81% of the total C stock in AF-Coffee, and ~ 63% in woodlots, with the remainder contributed by woody biomass. In croplands, SOC contributed 87% of the total carbon stock (Fig. 5). The ratio of SOC to woody biomass C decreases in the order of cropland > AF systems > woodlot, with ~ 6.9 times and 1.8 times more C stored in soil than in woody biomass in croplands and woodlots, respectively.

Discussion

Soil organic carbon stocks

A global meta-analysis showed that soil organic C (SOC) stocks in agroforestry (AF) systems are relatively consistent across climate zones and continents, despite high study-to-study variability (Shi et al. 2018). On a global scale, Shi and colleagues found

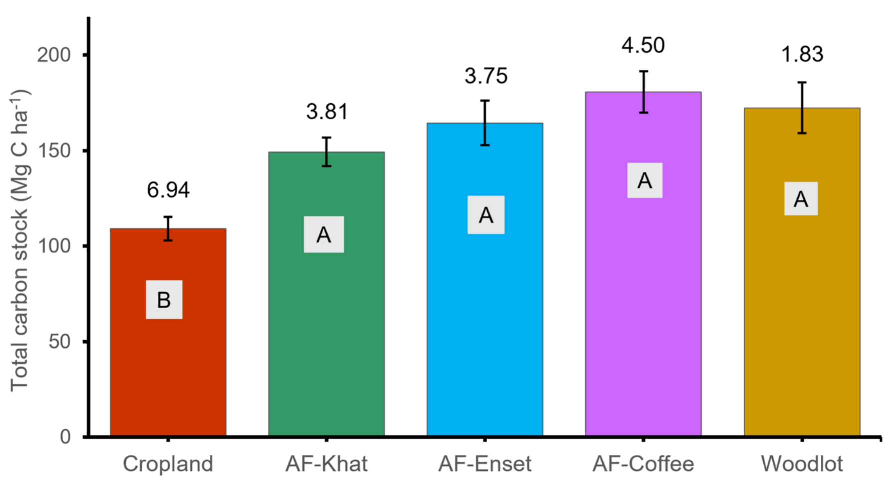

Fig. 5 Total ecosystem carbon stock (Mg C ha^{-1}) across land use types (LUT) in the Wondo Genet district, Sidama region, Ethiopia. The ratio of soil organic C (to 60 cm) to woody biomass C stocks is indicated on top of the bars. Different letters denote significant differences between LUTs (Tukey test, $p<0.05$; n = 10; mean ± SE)

that SOC stocks in the AF types assessed were on average 25% higher than in nearby croplands/pastures, but that homegarden-type AF systems comparable to those studied here had ~ 50% higher soil C stocks than control LUTs. Henry et al. (2009) even reported a 114% increase in SOC stock in western Kenya homegarden AF compared to cropland. In our study, SOC stocks ranked as follows: AF-Coffee > AF-Enset > AF-Khat > woodlot > cropland. AF-Coffee and AF-Enset had 54 to 61% higher SOC stocks than woodlot and cropland (Fig. 3). The absolute SOC stock values in the current study of AF systems (117–146 Mg C ha^{-1}) align with earlier reports from Ethiopia and the larger region. For example, Manaye et al. (2021) reported SOC stocks of ~ 72 to ~ 113 Mg C ha^{-1} in homegarden-type AF in northern Ethiopia, and Tesfay et al. (2022) documented ~ 126 to 146 Mg C ha^{-1} in homegarden AF systems in southeastern Ethiopia. Conversely, OC contents were lower in eucalyptus plantations, grazing lands, and conventional croplands compared to enset and khat-based AF systems in similar ecological settings (Kebebew et al. 2022; Negash et al. 2022). Studies by Schoeneberger (2009) and Larenz and Lal (2014) reported that SOC stocks are strongly influenced by organic carbon (OC) contents, which in turn varies with LUT and management practices. Similarly, our findings suggest that higher OC levels in AF systems, particularly in AF-Coffee and AF-Enset, contribute to greater SOC stocks (Figs. 2, 3; Supplementary Fig. S2). We associate the higher OC/SOC stocks in homegarden-type AF with the high plant/tree density and litter production, which positively correlate with changes in soil C (Abbas et al. 2017). In addition to the amount of leaf litter, the litter quality of tree leaves may differ from the understory of the AF systems. For example, lignified cells within tree litter, branches, and bark contribute significantly to carbon stabilization (Six et al. 2002). While leaf litter is not commonly collected in the three AF practices, leaves are raked for burning in *Eucalyptus* woodlots (Gebremedhin and Negash 2023). We speculate that this may be one reason for the lower SOC accumulation in woodlot soils compared to AF. However, since root litter (quality) and exudates are also key factors in OC sequestration (Assefa et al. 2018; Bateni et al. 2021), we can only hypothesize that the mixed AF plots have a greater amount of (recalcitrant) root biomass and/or higher turnover/exudation rates. Mixed species (tree) stands are frequently found to process higher root biomass than monocultures (Werner et al. 2024). However, the Pearson correlation and linear regression analysis (Supplementary Figs. S2, S3) do not indicate significant relations between (aboveground) woody biomass and SOC stocks across or within LUTs, indicating that other factors like species diversity and identity, but also land use history and management by specific farmers, significantly contribute to the variation in SOC stocks. Finally, different erosion rates may have contributed to the observed differences. Heavy seasonal rainfall and steep slopes cause extensive erosion of agricultural soils worldwide, including in the Ethiopian highlands. Denser canopies in agroforestry (AF) and woodlots reduce topsoil erosion compared to croplands by lessening raindrop impact (Marques et al. 2022).

However, in addition to the OC benefits of AF over cropland and woodlots, AF type significantly affected SOC stocks. AF-Coffee and (to some extent) AF-Enset accumulated more SOC than AF-Khat. While AF-Coffee and AF-Enset are similar in management, featuring limited soil disturbance, AF-Khat differs notably in species composition, with more cereals and beans, and involves mineral fertilizers and tillage to ~ 20 cm depth (Table 1). Previous studies indicate that both tillage and mineral fertilizer reduce C stabilization (Francaviglia et al. 2017; Shi et al. 2018). In sum, however, it remains unknown yet whether higher C inputs or a greater organic matter stabilization led to the superior SOC stocks of AF practices involving coffee. BD was significantly and negatively correlated with OC concentration and stocks across the LUTs—particularly driven by the higher OC content and lower BD in AF practices compared to the cropland. Land use is the main driver for BD variation (Panagos et al. 2024). Changes in soil organic matter content have previously been shown to affect soil physicochemical properties, such as density and porosity, as well as aggregate stability and other soil quality parameters (Lal 2021; Wardak et al. 2022). Similarly, soil textures differed markedly across LUTs; cropland exhibited higher proportions of sand—in line with previous findings (Assefa et al. 2020; Masha et al. 2023). We observed decreasing OC contents across all LUTs with increasing soil depth (Fig. 1), consistent with previous studies (Laganière et al. 2010; Assefa et al., 2017a). Earlier studies identified rooting depth as a key factor differentiating AF systems from adjacent croplands, deeper roots of tree species sequestering C in the subsoil (Shi et al. 2018). This would be especially important for C sequestration considering the long mean residence time of C in deep soil (Agevi et al. 2017). Although AF-Coffee had the most uniform SOC stocks across soil depths (Supplementary Fig. S1), suggesting deeper C placement or leaching, our data do not show a general trend of greater SOC differentiation with depth between tree-dominated LUTs and cropland, which contrasts with global patterns (Shi et al. 2018).

In a previous study of soil C stocks in northern Ethiopia, land conversion from pristine mixed forests led to a ~ 75% reduction in SOC stocks in croplands, and eucalyptus plantations only reached 70% of forest soil C stocks 30–40 years after afforestation (Assefa et al., 2017a). This highlights that although SOC in AF practices surpass that of croplands and monoculture plantations, it remains lower than the potential SOC stocks in forests. Our results are in contrast with Cardinael et al. (2017), who found that young plantations store additional SOC, as it has been suggested that fast-growing tree species such as *Eucalyptus* spp. rapidly increase (root) litter inputs by/after tree pruning (Singh and Gill 2014). However, the system studied here did not support such a mechanism, again highlighting the need to consider the ecosystem-level consequences of introducing new species (Leuzinger and Rewald 2021). While further (mechanistic) studies are needed, we suggest that the “maturity” of a diverse and undisturbed (in terms of soil management) AF system, containing older trees with larger root systems, is particularly conducive to high SOC accumulation.

Woody biomass C and its contribution to ecosystem C stocks

Previous AF research has concentrated on evaluating diversity and aboveground carbon (C) storage, as stems tend to remain stable over extended periods (Muche et al. 2022). Globally, AF systems are reported to hold high aboveground C stocks compared to croplands (Shi et al. 2018). The woody biomass carbon across various LUTs in the Wondo Genet district ranged from 14 to 64 Mg C ha^{-1}, with the lowest woody C in croplands and the highest in woodlots as expected (Fig. 5). Notably, however, the woody biomass of sparse fruit/shade trees and hedgerows adjacent to cropland is higher in the region than the global average Muthuri et al. (2023), suggesting a high cultural and economic value attributed to trees in the Sidama region (Keneni et al. 2021). Nevertheless, woody biomass in AF practices and woodlots was still significantly higher than cropland, and higher in woodlots than AF biomass C stocks—which were surprisingly similar. The study by Negash and Starr (2015) documented woody biomass C content ranging from ~ 35 to ~ 60 Mg C ha^{-1} in traditional AF systems in the Gedeo zone of southern Ethiopia. Our current findings for AF-Coffee (35 Mg C ha^{-1}) and AF-Enset (36 Mg C ha^{-1}) fall at the lower end of this range, possibly due to the warmer and wetter climate of the Gedeo zone (at a similar elevation), which likely supports more robust plant growth and greater biomass accumulation compared to our study area. Compared to similar agroforestry contexts globally, the woody biomass C in the studied region is either higher or lower. For example, Kumar (2011) reported lower mean biomass C of ~ 24 Mg C ha^{-1} in homegardens in central Kerala, India, and Hergoualc’h et al. (2012) reported ~ 25 Mg C ha^{-1} in coffee agroforestry systems in Costa Rica. In contrast, our results are e.g. lower than those reported for coffee AF in Guatemala (~ 89 Mg C ha^{-1}), Panama’s traditional AF systems (145 Mg C ha^{-1}), and semi-forest coffee plantations in Ethiopia (~ 91 Mg C ha^{-1}) (Kirby and Potvin 2007; Laganière et al. 2010; Schmitt-Harsh et al. 2012). In our study, woodlots with a rotation period of 3–5 years exhibited significantly higher woody C stocks compared to other LUTs, due to dense planting, intensive management, and a fast-growing tree species. Similar findings in East Africa show that woodlots have often higher biomass carbon stocks than AF systems. For instance, woodlots on smallholder farms in western Kenya stored between 39 and 123 Mg C ha^{-1} (Henry et al. 2009), while Bajigo et al. (2015) reported that woodlots stored 107 Mg C ha^{-1} in the Gununo watershed in southwest Ethiopia. Given the short rotation cycle and continuous (partial) harvest, this indicates that the aboveground C sequestration rate is much higher in (*Eucalyptus*) woodlots than in AF practices. However, the long-term C-sequestration depends to a larger extent on the use of the harvested biomass, which in the Sidama region is used for construction, but also mainly for firewood.

Thus, it is more sustainable to consider ecosystem carbon budgets rather than focusing solely on carbon accumulation in wood (Kumar and Nair, 2011). Indeed, there is an increasing interest in relating wood biomass to soil and total carbon stocks, although direct comparisons between these two C pools are still rare due to the limited number of studies examining both compartments. Not surprisingly, the total C stocks were significantly higher in AF-Coffee, woodlot, and all AF LUTs compared to cropland (Fig. 5). In all LUTs, soil organic carbon (SOC) stocks (to 60 cm depth) accounted for the majority of total C, contributing to a minimum of 63% in woodlots. On average, SOC stocks in AF systems were 35% to 53% higher than in croplands, while woody biomass C increased by ~ 154% (Fig. 5). Our findings align with other studies underscoring the dominant role of SOC in ecosystem carbon storage. For example, Toru and Kibret (2019) found that ~ 94% of total C was stored in the soil in coffee-based AF systems in eastern Ethiopia. Negash and Starr (2015) indicated that soil C accounted for ~ 84% of total C in enset systems, and about 75% in both enset-coffee and fruit-coffee AF systems in the Rift Valley of Ethiopia. Regionally, Paudel et al. (2023) reported that ~ 97% and ~ 93% of total C was stored in soil across traditional and improved AF systems, respectively, in Nepal's mid-hills. Similarly, Udawatta et al. (2022) was also found that SOC stocks contributed ~ 61% of the total carbon in alley cropping in the United States. These studies highlight the critical role of soil in carbon storage compared to aboveground biomass in diverse agroforestry practices across various regions. However, a higher increase in the aboveground biomass of homegarden AF has also previously been reported for tropic regions (Shi et al. 2018). Specifically, Udawatta et al. (2022), also showed that 80% of the total C stored in silvopasture was in woody biomass, compared to soil C. This suggests that both above- and below-ground C stocks and the persistence of sequestered C need to be assessed to derive a ranking of the most effective LUTs for C sequestration at the landscape scale. In addition, C sequestration is only one ecosystem service, and potential trade-offs with other services, such as food production and habitat provision, need to be considered before developing land management recommendations—especially as mountain environments experience more rapid climate change that threatens the provision of multiple ecosystem services.

Conclusion

In line with global trends, traditional AF practices in the Sidama region of southern Ethiopia show higher C sequestration in both woody biomass and soil compared to conventional croplands and, belowground, woodlots. AF systems dominated by coffee, and to a lesser extent enset, are particularly effective at accumulating substantial amounts of soil organic C, which is essential for sustainable agriculture and makes these systems key for mitigating climate change. While woodlots contribute significantly to aboveground C storage, their short management cycle and litter removal seem to limit soil carbon sequestration. Importantly, soil carbon dominates total C storage within AF systems (78–80%)—highlighting the need to assess C storage across spheres. Furthermore, significant amounts of SOC in the subsoil illustrate the importance of not constraining sampling to the topsoil. The correlation between reduced soil bulk density and higher soil carbon concentrations emphasizes the importance of added soil organic matter in enhancing soil structure and reducing compaction. The deviation of C stock values from global averages and other Ethiopian AF ecosystems underscores the need for site-specific data to inform regional land management strategies. Future research should aim to better understand the mechanisms of soil C accumulation and to quantify C quality and accumulation rates in AF systems in East Africa and elsewhere. This, together with better data on the spatial extent of AF systems, will allow the development of comprehensive C budgets and their sensitivity to changes in management practices and climate.

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Data availability The data will be made available on request from the first/corresponding author.

Declarations

Competing interests The authors state that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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