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Soil organic carbon changes under selected agroforestry cocoa systems in Ghana

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ABSTRACT

Given the pressing issue of climate change, there is a clear need for long-term and reliable soil organic carbon (SOC) data. This data should be complemented by insights into agricultural management practices, with a particular emphasis on agroforestry systems. Unfortunately, such comprehensive data remains in short supply. We report SOC and bulk density changes in the soil ($\leq$ 60 cm depth) of Ghanaian agroforestry cocoa systems sampled along a chronosequence of farm fields established 3, 15, 18, 30 and 45 years after forest conversion. Additionally, we assessed changes in SOC and bulk density from agroforestry cocoa systems fifteen years after similar data was collected from the same fields. The 45-year-old plot significantly had higher ($p < 0.05$) SOC concentration, comparable to the pre-conversion forest. Cocoa trees aged 18 and above had higher SOC concentrations than the forest at the 20–60 cm depth. The SOC stocks initially declined by 18% (12 Mg ha^{-1}) after forest conversion in the three-year-old cocoa farm but increased considerably thereafter to 121 Mg C ha^{-1} after 45 years of cocoa production. The 45-year-old cocoa plantation had more than twice the SOC stocks observed in the forest at the 20–60 cm depth. A 15-year period comparison of agroforestry cocoa systems revealed proportional increases in SOC stocks, with the exception of minor declines observed within specific age groups at the 0–10 cm depth. Mean bulk densities did not exceed the critical value of 1.6 g cm^{-3} above soil conditions considered unsuitable for plant growth. Soil bulk densities generally increased with depth, and agroforestry cocoa systems had significantly ($p < 0.05$) denser soils compared to the forest. Our study provides compelling long-term empirical evidence emphasizing the importance of agroforestry cocoa systems on SOC storage and reinforces their role as a sustainable and climate-smart approach to agriculture.

1. Introduction

Cocoa (*Theobroma cacao*) contributes about 25% to Ghana's GDP, employs about 60% of farmers, and provides over 700,000 jobs in the Southern part of the country(Kolavalli and Vigneri, 2011). Though very important to the economy of Ghana, cocoa cultivation is a driver of deforestation (Asare et al., 2018) with 1.45 million hectares, representing 26% of forests cleared since the 1980s (Mohammed et al., 2016). Cocoa cultivation through the conversion of natural to agricultural ecosystems has resulted in the loss of biodiversity and has diminished soil organic carbon stocks. Considering that Ghana is pursuing a low greenhouse gas emissions strategy (GoG, 2011) and is committed to reducing emissions from deforestation and forest degradation, policymakers and practitioners are promoting climate-smart cocoa production systems.

The majority of agroforestry cocoa systems' carbon (C) stock is stored in soils as SOC (Mohammed et al., 2016). Soil organic carbon is the largest terrestrial C pool in the tropics (Lal, 2004), and is the key component of soil that affects its physical, chemical, and biological properties. Since SOC plays a crucial role for many soil functions and ecosystem services (Lal, 2004; FAO, 2017), it is imperative to understand long-term changes in carbon fluxes in the soils under agroforestry cocoa systems to determine whether soils act as net sources or sinks for carbon. Studies in the tropics have shown significant changes in SOC

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following deforestation and subsequent cultivation, and these changes have been shown to affect soil fertility (Tiessen et al., 1994; Neill et al., 1997; Dominy et al., 2002). Losses of SOC due to forest clearing and conversion to arable land have been observed and may result from several processes including decreased input of organic matter, changes in composition of plant litter, increased rates of soil organic matter decomposition and soil erosion (Lugo and Brown, 1993; Feller and Beare, 1997). On the other hand, forest conversion to agroforestry systems is reputed to accumulate both above and belowground carbon (Nair et al., 2010; Lorenz and Lal, 2014), and agroforestry systems have been recommended as climate smart agricultural approaches that need to be widely adopted, especially, in small scale low external input tropical farming systems (Dawoe, 2009). Increased nutrient inputs, reduction in nutrient losses, and improved soil physical properties are all characteristics of agroforestry systems as compared to sole cropping systems (Young, 1989; Nair, 1993). However, the recovery of SOC in agroforestry cocoa systems and the accumulation of important nutrients, such as nitrogen, are not well understood. Both the scope and duration of nutrient instability after forest conversion, and over prolonged agroforest rotations, requires further study.

Conflicting and inconclusive evidence remains as to the long-term quantity of soil nutrients and SOC in agroforestry cocoa systems (Schroth et al., 2001). Available short-term data are often used to make predictions on SOC and nutrient cycling over the long-term (Kelty, 2000). This type of extrapolation requires further investigation to confirm predictions about changes in SOC stocks in the productivity of agroforestry cocoa systems. In Ghanaian and tropical agroecosystems in general, research on long-term system level carbon and nutrient sustainability and the maintenance of nutrient cycles, specifically in traditional multistrata agroforestry systems like shade cocoa are inadequate. This study addresses a critical research gap by providing insights into the changes in SOC and bulk density over an extended period in agroforestry cocoa systems. By conducting a long-term study spanning several decades, this research offers a unique perspective on the temporal dynamics of SOC and bulk density in these systems, filling a significant knowledge gap in the literature.

We assessed the changes in SOC stocks, as well as soil bulk density changes from agroforestry cocoa systems established 18, 30 and 45 years after forest conversion. SOC and bulk density values recorded from the mentioned age groups were compared to values from the same fields obtained 15 years earlier when the agroforestry cocoa system were 3, 15 and 30 years after forest conversion. Data obtained from this chronosequence (3, 15, 18, and 45 years) after forest conversion were compared to forest values as standard reference or control (that is, agroforestry cocoa at zero year) to contribute to our understanding of long-term dynamics of SOC fluxes in shade cocoa systems in the Ashanti Region of Ghana.

2. Materials and methods

2.1. Description the study sites

The study was conducted in the Ashanti Region of Ghana. The site lies approximately between latitude 6^{o} 32′ N and 6^{o}75′ N and between longitude 1^{o} 36 and 2^{o} 00′ West (Fig. 1). It is situated in the western part of the Ashanti region and covers an estimated area of 184 km^2. The region is characterized by wet semi-equatorial climatic conditions with a double maximum rainfall (from mid-March to July and from September to November) with an annual rainfall from 1700 mm to 1850 mm. Temperature range from 27 °C (August) to 31 °C (March) (Atwima Nwabiagya Municipality, 2018). The vegetation is predominantly a semi-deciduous forest type (Celtis-Triplochiton Association) and has largely been influenced by human activities. Some of the trees in the upper and middle layers shed their leaves in the dry season (Hall and Swaine, 1981).

The agroforestry cocoa systems in the region consist of mixed stands of cocoa with shade trees including *Terminalia superba* Engl. & Diels, *Triplochiton scleroxylon* K. Schum., *Alstonia boonei* de Wild and *Ceiba pentandra* (L.) Gaertn. The Cocoa Research Institute of Ghana recommends the application of cocoa fertilizer (Asare wura) composed of N, P, K, CaCO, S and MgO at a ratio of 0:22:18:9:7:5 and applied at a rate of 375 kg ha^{-1} (Snoeck et al., 2010). The majority of farmers however, do not apply any fertilizers due to costs considerations.

The geology of the area, according to Atwima Nwabiagya Municipality (2018), comprised Cape Coast granites, Birimian phyllites, greywacks, schist, and gneisses. Soils are classified as Ferric Lixisols or Leptosols/Regosols (CSIR-SRI, 1990; FAO/UNESCO/WRB, 1990). According to the Ministry of Food and Agriculture (MoFA, 2000), most of these soils are deep, moderately well drained with a silty loam texture and a medium to high humus content. We classified soils of our study sites as Ferric Lixisol using the IUSS Working Group WRB (2015). The soils had clay accumulation (argic) in the subsurface horizon characterized by low-activity clays and high base saturation. The Ferric Lixisols show special morphology of redoximorphic features as a result of (active or relict) redox processes in forms of large Fe (or Fe and Mn) mottles or discrete concretions or nodules surrounded by Fe (and Mn) depleted soil matrix in the subsoil. The similar soil type, soil properties, and management history forming the basis for comparisons among sites (Tables 1 and 2).

2.2. Selection of sites study design and soil sampling

Nine cocoa systems from three different age groups (established 18, 30, and 45 years after forest conversion) were selected based on earlier research (Dawoe, 2009) in the Ashanti Region, Ghana. These selected agroforestry cocoa systems correspond, respectively, to farms which were 3, 15 and 30 years in the study by Dawoe (2009). Farms are located at Kobeng, Apaakrom, Nkutin, Amankyea and Seidi communities (Fig. 1). The natural forest (6° 36′ N, 1° 52′ W) located within the communities were used as a standard reference representing the initial state of the agroforestry cocoa systems following the clearance of certain areas for cocoa cultivation (that is, cocoa at zero year). The goal was to evaluate changes in SOC stocks in agroforestry cocoa systems over a 45-year period and compare them to a previous study conducted in the same farms/sites 15 years ago.

Sampling plots (40 × 50 m to 60 × 80 m) depending on the agroforestry cocoa system size were established in 2009. From each age group, soil samples from twelve points corresponding to three points per replicate along an S-shaped transect (Fig. 2) were taken by auguring to depths of 0–10, 10–20 and 20–60 cm. This yielded 36 samples per site and a total of 108 samples for three soil depth for each site. The selected sampling depths reflect the typical plough depth for crop production (0–20 cm) and were separated into 0–10 cm and 10–20 cm intervals to capture influences from litterfall, organic matter inputs, microbial activity, and management practices. The wider interval in the lower horizon (20–60 cm) was chosen due to practical considerations as it is less affected by biological activities and management practices. The role of roots in this zone is crucial for soil bulk density and carbon storage dynamics. The collected soil samples were bagged for laboratory analysis in duplicates. Undisturbed core samples (288) were collected from mini profiles (0–10, 10–20 and 20–60 cm soil depths) for bulk density estimation. Plot layout and sampling procedure adopted (i.e., sites/plots, depths and replicates) for this study are similar to that in the study by Dawoe (2009).

2.3. Soil analysis

The collected soil samples were air-dried, passed through a 2 mm sieve, ground to a size fraction of <0.5 mm, and prepared for further analysis. The SOC content was determined by the Modified Walkley-Black method (van Reeuwijk, 2002). Soil bulk density at (0–10, 10–20 and 20–60 cm) was determined for each age group in duplicates for soil

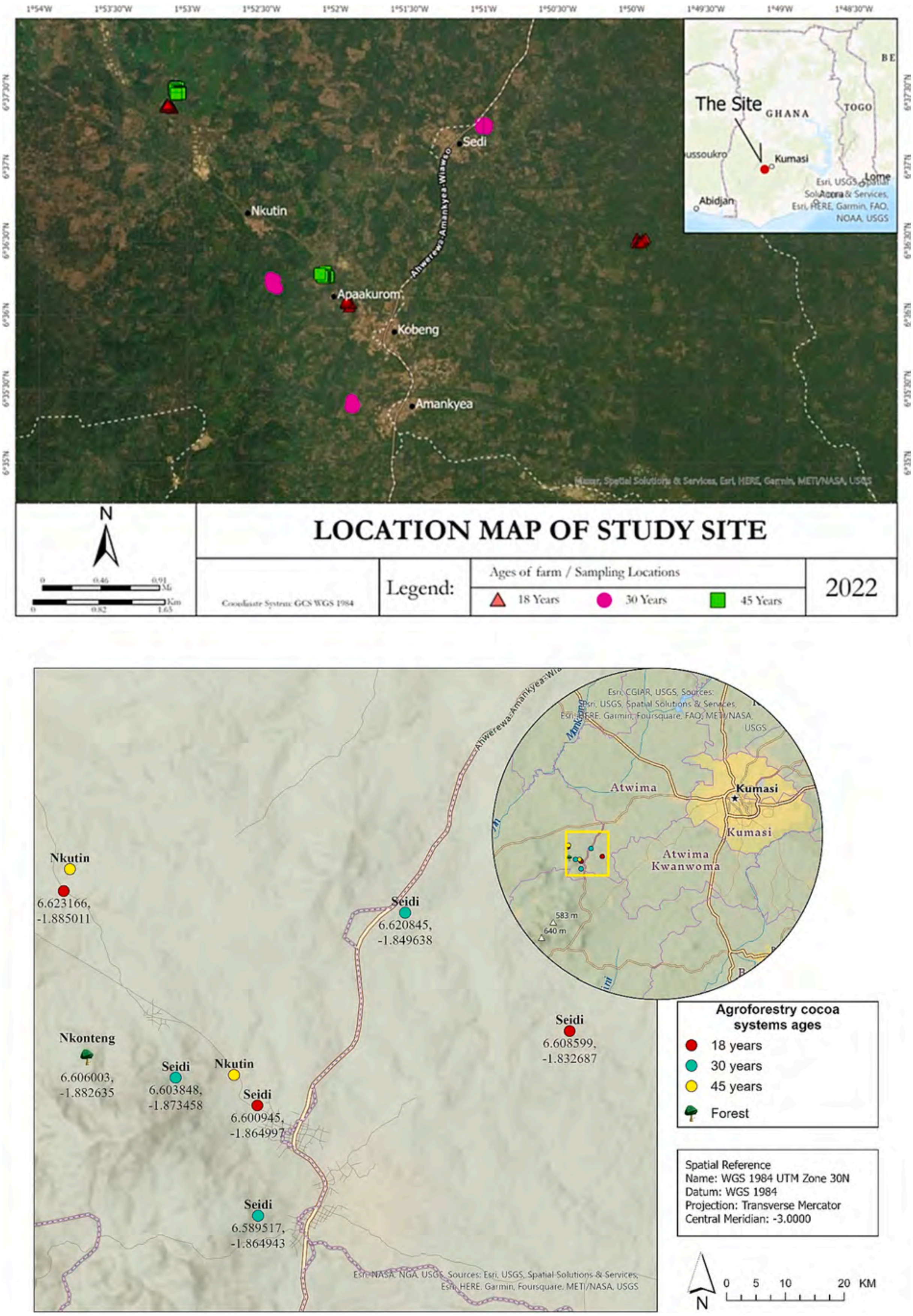

Fig. 1. Aerial view of the location of the selected agroforestry cocoa systems in the Ashanti Region of Ghana.

Table 1
Soil chemical characteristics of the agroforestry cocoa systems, at various depths, across all sites (mean value) in the Ashanti region of Ghana. Adapted from Dawoe (2009).

Soil Depth (cm)	pH	Organic matter %	Total N %	Avail. Bray's P ppm	Exch. K^+ meq/100 g	Exch. Ca^{2+} meq/100 g	Exch. Mg^{2+} meq/100 g	Exch. Na^+ meq/100 g	CEC meq/ 100 g	Base Saturation %	Exch. Al^{3+}
0–10	5.9 ± 0.2	4.40 ± 0.2	0.2 ± 0.01	2.0 ± 0.4	0.5 ± 0.1	9.4 ± 0.8	5.3 ± 0.7	0.2 ± 0.0	15.7 ± 1.2	98.8 ± 0.3	0.2 ± 0.1
10–20	5.4 ± 0.2	1.43 ± 0.2	0.1 ± 0.01	1.3 ± 0.2	0.3 ± 0.0	4.9 ± 0.7	2.1 ± 0.5	0.2 ± 0.0	7.8 ± 1.2	95.6 ± 1.5	0.3 ± 0.1
20–60	5.3 ± 0.3	0.73 ± 0.0	0.1 ± 0.12	0.7 ± 0.20	0.2 ± 0.0	3.9 ± 0.4	1.7 ± 0.3	0.2 ± 0.0	6.4 ± 0.5	94.4 ± 1.4	0.4 ± 0.1
0–60	5.5 ± 0.2	2.18 ± 1.1	0.1 ± 0.03	1.3 ± 0.4	0.4 ± 0.1	6.1 ± 1.7	3.03 ± 1.1	0.20 ± 0.0	9.9 ± 2.9	96.2 ± 1.3	0.3 ± 0.1

Table 2
Mean particle size distribution and their standard error at a 0–60 cm depth in the forest (control) and the 3-, 15- and 30-year-old agroforestry cocoa systems in the Ashanti region of Ghana. All four sites had the same soil type (Ferric Lixisol) and soil texture (silty loam). Adapted from Dawoe (2009).

Parameters	Land use			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Sand %	20.2 ± 0.82a	28.5 ± 1.98a	19.6 ± 1.36a	24.1 ± 1.14a
Silt%	61.9 ± 2.26a	57.5 ± 3.48a	61.4 ± 2.43a	50.9 ± 4.43a
Clay%	17.9 ± 2.28a	14.0 ± 1.88a	19.0 ± 2.05a	24.93 ± 3.73a
Soil type	Ferric Lixisol	Ferric Lixisol	Ferric Lixisol	Ferric Lixisol
Textural class	Silty Loam	Silty Loam	Silty Loam	Silty Loam

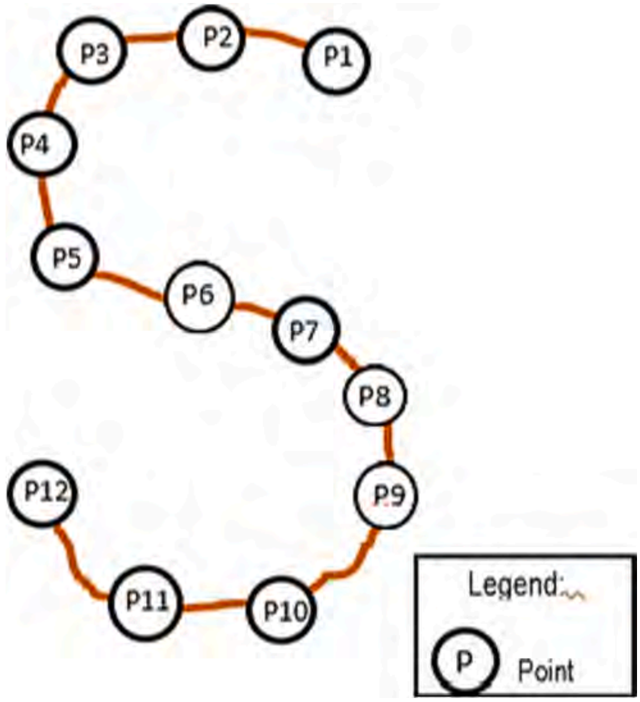

Fig. 2. An S-shape sampling design used for soil sampling in the forest (control) and the agroforestry cocoa sites in the Ashanti region of Ghana.

samples using Blake and Hartge (1986) method. Soil pH was measured with an electrometric pH meter (VWR Phenomenal 1100 L) in soil: water suspension of ratio of 1:2.5 according to the method described by Carter and Gregorich (2008). Analyses were done in three and four replicates for SOC and pH, respectively. Since pH was confirmed to be between the normal and moderately acidic (HCl test on selected samples) range, it was assumed that soil did not contain inorganic carbon. Total C was therefore considered as SOC.

2.4. Soil organic carbon (SOC) stock calculation

SOC stock for each sampled depth was calculated from SOC concentration (SOC %), soil layer thickness (z meters) and bulk density (BD) of the samples following the equation from Solomon et al. (2002):

$$\text{SOC}\left(\text{Mg ha}^{-1}\right) = \text{SOC}\ (\%)\ \text{X BD}\left(\text{Mg m}^{-3}\right)\ \text{X z (meters) X } 10,000\ \text{m}^2$$

Where z represented the sampled soil depth.

To compare SOC stocks from this study with stocks from the earlier study, SOC stocks for the different depths in Dawoe (2009) (earlier study) were recalculated using the above equation. For each age group, SOC stocks in each layer (0–10, 10–20, 20–60 cm depths) were summed up to get the SOC stock.

2.5. Data analysis

We acknowledged that the similarity in soil type (Ferric Lixisol), soil properties, and management history among sites allowed for meaningful comparisons. However, it is important to acknowledge that the presence of pseudoreplication in our data may limit the generalizability of our findings. To analyze the effects of age (3, 15, 18, 30 and 45 years after forest conversion) on SOC stocks and soil bulk densities, data from this study (i.e., cocoa farms established 18, 30 and 45 years after forest conversion) was combined with data from Dawoe (2009) (i.e., cocoa farms established 3, 15, and 30 years after forest conversion). Shapiro-Wilk test was used for testing the normality of our data, with a significance threshold of >0.05 for identifying normality. A one-way analysis of variance (ANOVA) using generalized linear model was performed. Prior to conducting further statistical analysis, we applied a square root transformation exclusively to data that did not meet the assumptions of ANOVA. Multiple comparisons of means using Tukey HSD test at 95% confidence interval was used to determine significant differences among farms. We also analyzed using *t*-test over a 15 fifteen-year period the trends and changes in SOC stocks from 3, 15 and 30-year-old plots to corresponding plots at 18-, 30- and 45-year after forest conversion, respectively. That is, increases from 3 to 18 years, 15 to 30 years, and 30 to 45 years after forest conversion. To explain and predict changes in SOC stocks in the different depths (0–10, 10–20,20–40 and 0–60 cm), we subjected data to a polynomial regression analysis and fitted models. All statistical analyses were performed using the GenStat 12 edition and Statistix 7.0 software package.

3. Results

3.1. Temporal changes in soil organic carbon and density in agroforestry cocoa systems along a chronosequence

We evaluated changes in SOC concentrations, bulk densities and SOC stocks over a 45-year period following forest conversion to agroforestry cocoa land use (Fig. 3; Tables 3 and 4). The SOC concentrations were generally consistently highest in the 0–10 cm depth and lowest in the 3-year-old cocoa farms across all soil depths (Fig. 3). The 45-year-old agroforestry cocoa system had significantly higher SOC concentration with values similar to those of the forest before the conversion and was even greater than that of the forest at the 20–60 cm depth (Fig. 3). At the 10–20 and 20–60 cm depths, SOC content in the 18- and 45-years old plantations were greater ($p < 0.05$) than in the 3-, 15- and 30-years old plantations (Fig. 3). The influence of the cocoa trees on SOC storage were more prominent in the 20–60 cm depth where cocoa trees of age 18 and above contained more SOC concentration than in the forest (Fig. 3). The SOC in the aggregated 0–60 cm depth were not significantly different among the different agroforestry cocoa systems although a pattern of increasing SOC across the chronosequence was observed in the cocoa farms.

Depth wise, soil bulk densities in the different aged cocoa systems generally increased with increasing depths (Table 3). Mean bulk densities at the 0–60 cm ranged from 1.25 to 1.42 Mg m^{-3} in the forest and cocoa systems, respectively and did not differ significantly ($p > 0.05$) along the chronosequence. After 45 years of cocoa cultivation, bulk density was similar compared to that of the 30-year-old cocoa system but lower bulk density than all other years at the 10–20 cm. Bulk density values of the 45-year-old agroforestry cocoa were similar to those of the forest at 20–60 cm depth. Generally, more dense soils were observed in the cocoa systems than in the forest but bulk density decreased with age of the agroforestry cocoa system.

SOC stock changes at the different depths varied from 25 to 30, 10 to 22, 20 to 69 and 55 to 121 Mg C ha^{-1}, at the 0–10, 10–20, 20–60 and 0–60 cm, respectively (Table 4). Soil carbon stocks decline in the first 3 years after the forest was converted to Agroforestry cocoa except for the-20-60 cm depth. However, there was a steady increase in SOC stock with age after forest conversion. Soil carbon stocks in the 45-year-old cocoa plantation was more than twice, and 80% higher, than that observed in the forest at the 20–60 and 0–60 cm depths, respectively. At depths >10 cm, decline in SOC stocks was consistently observed in the 30-year-old cocoa farm.

Table 3
Bulk Density (Mg m^{-3} ± SEM), at the different depths of the soil profile in forest and cocoa land use systems in the Ashanti Region, Ghana.

Depth (cm)	Land use					
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 18 years	Cocoa 30 years	Cocoa 45 years
0–10	1.01 ± 0.02b	1.19 ± 0.04a	1.26 ± 0.04a	1.19 ± 0.20a	1.31 ± 0.02a	1.22 ± 0.24a
10–20	1.4 ± 0.42a	1.45 ± 0.05a	1.40 ± 0.09a	1.43 ± 0.12a	1.44 ± 0.02a	1.32 ± 0.14b
20–60	1.34 ± 0.08b	1.63 ± 0.04a	1.59 ± 0.06a	1.50 ± 0.10a	1.63 ± 0.05a	1.46 ± 0.14ab
0–60	1.25 ± 0.07a	1.42 ± 0.07a	1.42 ± 0.06a	1.37 ± 0.09a	1.46 ± 0.05a	1.33 ± 0.09a

Bulk Density values in the same row followed by the same superscript for different land uses are not statistically different at α = 0.05 level using Tukey's HSD range test.

Using years after forest conversion as explanatory variables and SOC as response variable, we fitted polynomial regressions models to explain and predict the changes in SOC stocks of the agroforestry cocoa systems with soil depths (Fig. 4). The SOC stocks increased significantly along the chronosequence at 0–10 cm ($R^2 = 0.39$, $p = 0.00$), 10–20 cm ($R^2 = 0.75$, $p = 0.03$) and 0–60 cm ($R^2 = 0.62$, $p = 0.02$). The pattern found in the 20–60 cm depth was not consistent.

3.2. *Changes in SOC stocks and bulk densities over 15 years*

While there were gains in SOC stocks (5.13–179%) at nearly all the depths, there were only marginal declines of - 2.23% and − 9.05% at the 0–10 cm in the 15–30- and 30–45-year-old sites, respectively (Table 5). After the 15-year time span, there were no significant differences ($p > 0.978$) in bulk densities in the 3 and 18, 15 and 30, and 30- and 45-year-old agroforestry cocoa systems at all depths (Fig. 5). A general pattern of less dense soils was found 15 years after data collection from all soil

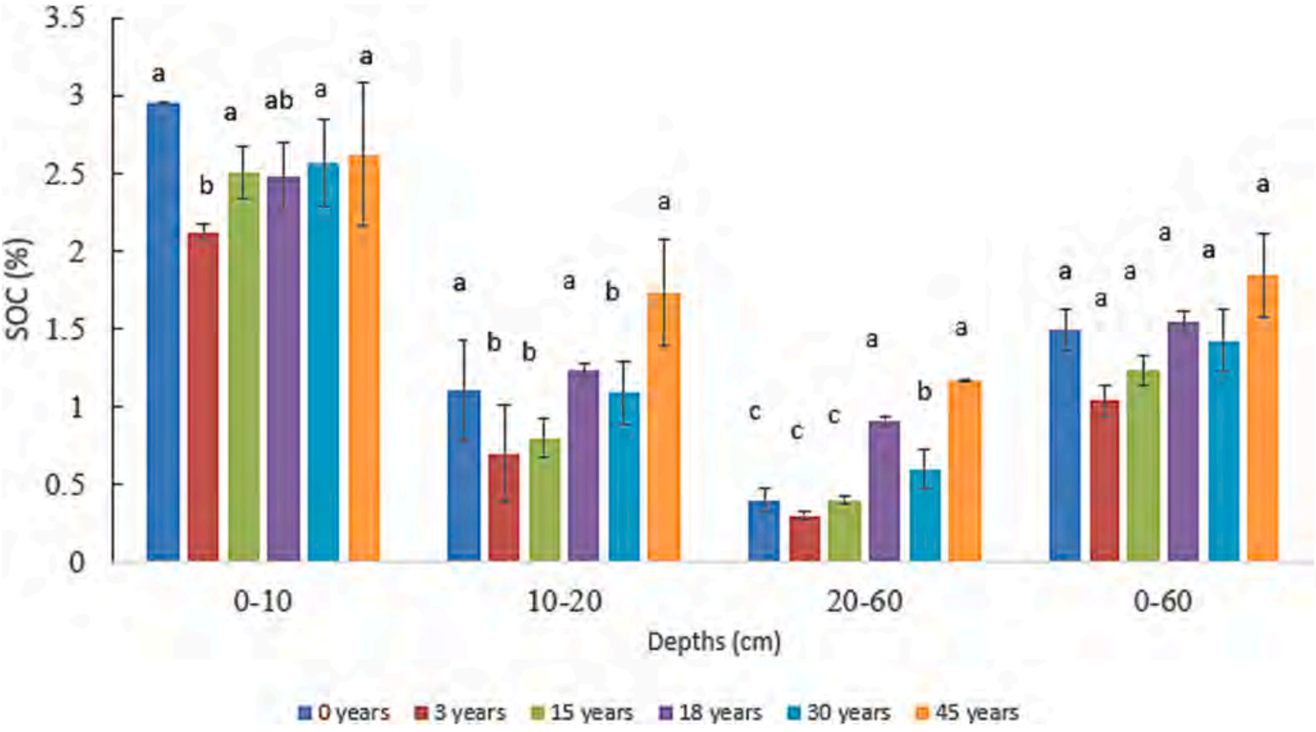

Fig. 3. SOC concentration (%) at various soil depths in the cocoa land use systems of different ages in the Ashanti Region, Ghana. Values with the same lower-case letter are not significantly different at $p > 0.05$.

Table 4
Quantities of carbon (Mg ha^{-1} ± SEM), at the different depths in forest and cocoa land use systems in the Ashanti Region, Ghana.

Depth (cm)	Land use					
	Forest Mg C ha^{-1}	Cocoa 3 years Mg C ha^{-1}	Cocoa 15 years Mg C ha^{-1}	Cocoa 18 years Mg C ha^{-1}	Cocoa 30 years Mg C ha^{-1}	Cocoa 45 years Mg C ha^{-1}
0–10	29.8 ± 0.4a	25.3 ± 1.3b	31.4 ± 1.1a	26.6 ± 2.9ab	30.7 ± 3.8a	30.4 ± 0.3a
10–20	15.8 ± 5.1a	10.4 ± 4.8b	11.0 ± 1.0b	17.6 ± 1.7a	14.8 ± 2.7b	22.1 ± 2.1a
20–60	21.8 ± 5.0c	19.5 ± 1.5c	25.4 ± 2.1c	54.4 ± 4.6a	35.9 ± 3.1b	68.5 ± 6.6a
0–60	67.4 ± 10.1c	55.2 ± 4.5d	67.8 ± 0.1c	98.6 ± 7.8ab	81.4 ± 4.3b	121.0 ± 4.7a

Carbon stocks values in the same row followed by the same superscript for different land uses are not statistically different at α = 0.05 level using Tukey's HSD range test.

depths, except for the 18 year old system.

4. Discussion

4.1. Impact of time since forest conversion on soil bulk density

The conversion of forest to agroforestry cocoa systems represents the beginning of a controlled forest fallow where cocoa trees become the main layer (Dawoe et al., 2014). This change in land use has the potential to alter soil physical and chemical properties over the long-term. Bessah et al. (2016) and Mulat et al. (2018) showed that bulk density increases with soil depth in agroforestry systems which corroborates the findings of this study. Bulk densities ranging from 1 to 1.6 Mg m^{-3} have been observed for silt loam topsoils above which roots penetration hindrance may occur (Landon, 2014). With reference to bulk density ranges reported by Landon (2014), majority of the soil bulk densities in all the agroforestry cocoa systems studied were below the critical value (≤ 1.6), denoting no extreme soil compaction. Practices such as pruning shade and cocoa trees, weeding, harvesting of cocoa pods and other management operations seem to have a strong influence on bulk density (Adiyah et al., 2022), especially, especially in the top soil (0–20 cm) which was also observed in this study. Bulk density in the lowest depth were probably much more influenced by root extension and growth which are characteristic of agroforestry systems (Dawoe et al., 2014; Adiyah et al., 2022). Bulk density is controlled by factors related to organic matter input, including root litter, exudates, above-ground litter, and organic amendments (Rasse et al., 2005; Kutsch et al., 2009). Cultivation practices probably influenced bulk density levels in the agroforestry cocoa systems as all the cocoa soils were denser than the forest. The impact was more visible in the top 0–10 cm layer which is more sensitive to cultivation practices and human traffic associated with these plantation management operations. This study also showed that mean bulk densities among the agroforestry cocoa systems tended to generally decrease in soil depths ≥10 cm with age which we link mostly to increasing SOC build up. The observed trend may be attributed to the progressive development and expansion of root systems over time, characterized by increased horizontal and vertical

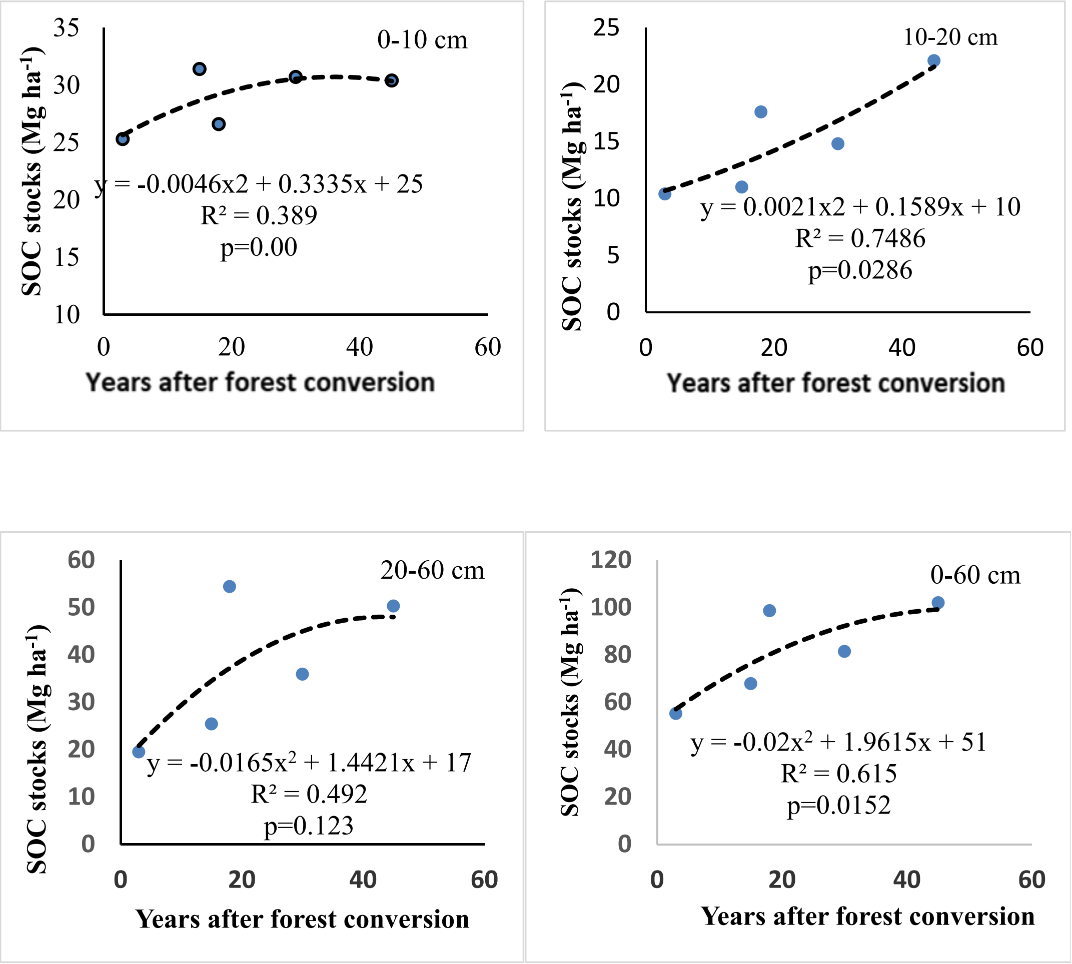

Fig. 4. Regressions of SOC stocks at 0–10, 10–20, 20–60 and 0–60 cm depths along a chronosequence of agroforestry cocoa systems in the Ashanti Region, Ghana.

Table 5
Mean and standard errors of SOC stocks (Mg ha^{-1}) in the agroforestry cocoa fields at 15-year intervals in the Ashanti Region, Ghana.

Depth (cm)	SOC Stocks (Mg ha^{-1})	SOC Stocks (Mg ha^{-1})	ΔSOC Stocks	Gain/ Loss	% Change	p-value
	3 years after forest conversion (2004)	18 years after forest conversion (2019)	Mg ha^{-1}	Mg ha^{-1}		
0–10	25.3 ± 1.32	26.6 ± 2.88	1.3 ± 3.17	Gain	5.13	0.696
10–20	10.4 ± 4.82	17.6 ± 1.72	7.2 ± 5.12	Gain	69.2	0.23
20–60	19.5 ± 1.46	54.4 ± 4.57	34.9 ± 4.7	Gain	179	0.002
0–60	55.2 ± 4.51	98.6 ± 7.8	43.4 ± 9.0	Gain	78.6	0.008
	15 years after forest conversion (2004)	*30 years after forest conversion (2019)				
0–10	31.4 ± 1.08	30.7 ± 3.82	−0.7 ± 10.9	Loss	−2.23	0.961
10–20	11.0 ± 0.96	14.8 ± 2.65	3.8 ± 2.59	Gain	34.5	0.219
20–60	25.4 ± 2.11	35.9 ± 3.11	10.5 ± 7.56	Gain	41.3	0.237
0–60	67.7 ± 0.07	81.4 ± 4.3	13.7 ± 20.44	Gain	20.2	0.573
	30 years after forest conversion (2004)	45 years after forest conversion (2019)				
0–10	33.47 ± 3.79	30.4 ± 0.29	−3.03 ± 4.90	Loss	−9.05	0.581
10–20	12.46 ± 2.77	22.1 ± 2.12	9.63 ± 3.91	Gain	77.2	0.091
20–60	28.16 ± 5.92	68.5 ± 6.57	40.32 ± 9.08	Gain	143.2	0.021
0–60	74.09 ± 12.4	121.0 ± 4.74	46.92 ± 16.4	Gain	63.3	0.065

[*] 30 years after conversion: Agroforestry cocoa system was 15 years after forest conversion in Dawoe (2009).

growth. This process leads to higher accumulation of root biomass and enhanced turnover of fine roots, contributing to the SOC pool. The lowest bulk density observed in the 45-year-old cocoa farm at the 10–20 cm depth together with its similar bulk density values as that of the forest showed a propensity towards less dense soils as cocoa farms age. Although better illustrated in the next section, we posit that soil carbon inputs from incessant supply of plant roots and litter from growing cocoa and shade trees may be influencing the low bulk density observed in the 45-year-old cocoa farm.

These findings provide insights into the long-term effects of agroforestry cocoa systems on soil bulk density. Overall, our study showed soil bulk densities in agroforestry cocoa systems were generally below the critical value, indicating no extreme soil compaction and increased with soil depths. Cocoa soils are denser than forest soils due to cultivation practices although older cocoa farms exhibit lower bulk density, resembling the forest. We generally highlighted the complex relationship between agroforestry cocoa systems, cultivation practices, and soil bulk density dynamics.

4.2. *Soil organic carbon dynamics*

Soil organic carbon concentrations were higher in surface than deeper layers across all the studied agroforestry cocoa systems confirming research findings of several authors (Saiz et al., 2012; Dawoe et al., 2014; Adiyah et al., 2022). The critical factor driving SOC turnover and subsequent changes is the continuous influx of carbon through various sources, such as root litter and exudates, above-ground litter inputs, and organic amendments (Rasse et al., 2005; Kutsch et al., 2009). In agroforestry systems, the build-up of SOC primarily occurs through the deposition of above-ground litterfall and the decomposition of fine roots, with a significant concentration in the topsoil (Dawoe et al., 2014: Adiyah et al., 2022). However, it's important to recognize that SOC turnover is influenced by a multitude of interacting factors, including moisture, temperature, clay content, soil porosity, and the composition of microbial communities (Six et al., 2002; Aguilera et al., 2013; Don et al., 2017). Due to the higher concentration of these organic matter inputs in the surface soil layers of our agroforestry cocoa systems, SOC tended to accumulate more prominently in the topsoil compared to deeper soil depths. This higher input of organic matter near the surface probably enhanced microbial activity in the topsoil, resulting in higher

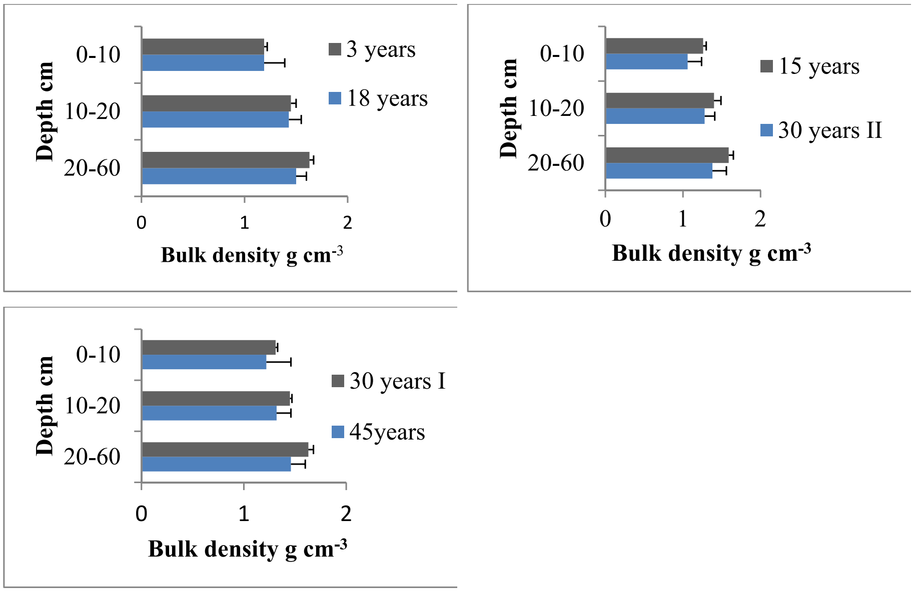

Fig. 5. Changes in bulk density with depths (a) changes between 3 and 18-year-old farms (b) 15 and 30-year-old farms, and (c) 30 and 45-year-old farms. The "*Cocoa 30 II years" represents a 30 year old cocoa farm sampled in this current study whilst "Cocoa 30 years" represents a cocoa farm sampled in 2004 by Dawoe (2009).

SOC levels in this layer within agroforestry systems.

Soil erosion and depositional processes also play essential roles in SOC accumulation (Doetterl et al., 2016). Cultivation practices before and few years after cocoa tree establishment exposed soil surfaces to erosion, and may account for the low SOC observed in the 3-year cocoa farm. Exposed soil surfaces increase the susceptibility of the finer earth fractions, particularly silt to erosion (Wu et al., 2020).

Agroforestry provides many benefits over traditional agricultural systems (Jose, 2009; Tscharntke et al., 2011) with the potential of increasing SOC storage and permanence (Dawoe et al., 2014; Adiyah et al., 2022). The presence of tree biomass increases soil organic matter and provide favorable environment for soil biota to break down biomass for nutrient release to plants. Soil organic carbon increases after the third year of cultivation reinforces the impact cocoa and shade trees have on carbon sequestration. Similar observation was made by Dawoe et al. (2014) and Ledo et al. (2018).

In Ghana, a severe drought occurred in 1982, followed by a country-wide wildfires in 1983. This affected natural vegetation and agro-ecosystems that led to severe losses of trees, crops and human lives. These events can have long-lasting effects on soil characteristics and SOC dynamics influencing patterns and magnitudes of SOC accretion, especially that along a chronosequence. For example, Saiz et al. (2012) reported lower SOC concentrations in savannas affected by wildfires compared to unaffected areas in West African ecosystems. However, over time, the ecosystem can gradually recover, and SOC stocks can increase through the reestablishment of vegetation and the resumption of organic matter inputs.

Comparing agroforestry cocoa systems 15 years after they were last studied by Dawoe et al. (2014), provided valuable insights into the potential of using perennial systems like agroforestry cocoa to sequester SOC. Mohammed et al. (2016) in their study of Ghanaian cocoa ecosystems reported SOC stock values of 61.7–137.8 Mg ha^{-1} for the 0–60 cm depth which was similar to SOC stocks (55.2–121 Mg ha^{-1}) observed in our study for the same depth. Ledo et al. (2020) evaluated the dynamics of SOC under perennial crops across the globe and observed that the most important factor affecting SOC changes was stand age, or time after perennial establishment, with SOC stocks increasing at an average of 0.05 Mg ha^{-1} year^{-1} over 20 years. In the present study i.e., over the 42-year period between the 3-year-old and 45-year-old cocoa farms, SOC stocks in our cocoa systems increased at an average rate of 1.57 Mg ha^{-1} year^{-1}, higher than that reported by Ledo et al. (2020). The general trend of increasing SOC stocks with cocoa age observed in our study is at variance with some studies. This trend could be influence by several factors including land use, vegetation and shade tree type, soil type and management practices of the study area (Ledo et al., 2020). Agroforestry cocoa systems, characterized by the presence of shade trees, hold promise for carbon sequestration (Nair et al., 2010; Dawoe et al., 2014; Mohammed et al., 2016). Tree roots are key contributors to SOC in the 20–60 cm depth range (Kell, 2012), with deeper SOC enrichment near trees (Nair et al., 2010). The presence of nitrogen-fixing shade/upper canopy trees may enhance higher biomass production and, thus SOC sequestration. Effective management practices like pruning, mulching with tree residues, reduced cultivation intensity, and organic residue incorporation raise SOC stocks, aligning with previous research (Nair et al., 2010; Ledo et al., 2018). Mature cocoa trees shield soil, reducing SOC loss through oxidation and leaching (Montagnini and Nair, 2004; Utomo et al., 2016; Dawoe et al., 2014). Cocoa agroforestry's potential to offset deforestation necessitates efficient tree integration and management. This practice has potential of increasing carbon sequestration, aiding climate change mitigation and sustaining rural food security (Soto-Pinto et al., 2010).

This study shows that over a 45-year period, cocoa agroforestry systems consistently increased SOC stocks in the 0–60 cm depth range, surpassing the pre-conversion levels of the reference forest. This trend aligns with similar findings in Dawoe (2009) research on a younger secondary forest. The overall positive correlation between SOC stocks and the age of agroforestry cocoa systems highlights their capacity for long-term carbon sequestration. Our SOC stock calculations did not account for soil bulk density variations, which can affect results, although some studies suggest these discrepancies have limited influence (Saiz et al., 2012). Wendt and Hauser (2013) found that calculating SOC stocks by multiplying soil bulk density, depth, and organic carbon concentrations at fixed depths tends to overestimate SOC stocks when comparing different soil masses due to bulk density variations. The study showed that there is considerable potential for agroforestry cocoa systems to serve as significant carbon sinks to help mitigate climate change in Ghana. Understanding agroforestry cocoa SOC dynamics will inform sustainable land management and climate mitigation strategies.

The fitted polynomial regression models provided valuable insights into the changes in SOC stocks within agroforestry cocoa systems at different ages (3, 15, 18, 30 and 45 years) and soil depths (0–10, 0–20, 20–60, and 0–60 cm The polynomial regression models determined that agroforestry cocoa systems have the potential to sequester SOC in surface soil horizons. We suggest that the increase in SOC stocks is attributed to the continuous supply of plant roots and litter from cocoa and shade trees, as well as other management practices such like mulching, pruning, organic residue incorporation, and reduced cultivation intensity that promote organic matter input to the soil. Further investigation is needed to understand the underlying causes and develop strategies to maintain or enhance SOC stocks in mature agroforestry cocoa systems. The studied agroforestry cocoa systems will be maintained for long term experimentation with the focus of overcoming generalizability of our findings as a result of limitations imposed by pseudoreplication.

5. Conclusion

Our long-term study provides compelling evidence of a consistent buildup of SOC concentration and stocks in agroforestry cocoa systems over time. The findings highlight the capacity of agroforestry cocoa systems to rival natural secondary forests in accumulating significant amounts of SOC, with the potential for even greater storage. The results reveal a substantial increase in soil carbon stocks, with a remarkable 119% rise from 55 Mg C ha^{-1} in the 3-year cocoa farm to 121 Mg C ha^{-1} in the 45-year-old cocoa farm. The cocoa soils were overall denser than forest soils yet showcased a propensity towards lower bulk density as the cocoa farms age in the lower depths ($\geq$ 10 cm). These findings underscore the remarkable carbon sequestration potential of agroforestry cocoa systems and emphasize their value as a sustainable land-use practice in promoting soil carbon accumulation in the era of climate change.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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