HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

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THESIS OF THE DOCTORAL (PHD) DISSERTATION

DEPTH DISTRIBUTION OF SOIL ORGANIC CARBON IN DIFFERENT LAND-USE AND SOIL TYPES IN GHANA: A CASE STUDY IN THE ASHANTI REGION

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1 INTRODUCTION AND OBJECTIVES

1.1 Background

Generally, Ghana's agricultural productivity is low, and this has been attributed to low soil organic carbon (SOC) and soil fertility degradation by recent studies (Buri et al., 2004, 2009; MOFA 2009; Issaka 2010; Whalen, 2012; Omari et al., 2018). Continuous cultivation of a piece of land without (organic and inorganic) fertilization results in SOC reduction and nutrient mining that negatively influences annual and perennial cropping yield. For a better-informed decision to be made by policymakers and farmers' there is the need for a better understanding of the dynamics of SOC and its importance on soil fertility and climate change.

From the 1980s till now, there has been a high rate of deforestation for the establishment of cocoa plantations in Ghana in response to efforts aimed at reviving the nearly collapsed sector (Kolavalli & Vigneri, 2011). Deforestation is expected to have a significant impact on SOC decline, thus affecting related soil properties and productivity and causing global warming in general (Minasny et al., 2017). The influence of SOC on soil buffering capacity, nutrient adsorption, good water holding capacity, structure formation, chelation, and carbon sequestration highlights the need for sustainability and evaluation of soils under these cocoa systems. The importance of SOC for soil fertility maintenance and also as a sink and a source for carbon in the atmosphere make it crucial for understanding its dynamics in cocoa systems.

Furthermore, The cocoa sector's inclusion into the nation's carbon emission budgetary plans call for further and in-depth research into factors affecting the country's carbon balance equation, thus the need to understand better the carbon stock dynamics in the soils of cocoa agroforest is well established and supported in this study.

Against the background of the importance of SOC to ecosystem services and its influence on climate change, the objectives of this study are:

- Determine soil characteristics and classify soils of the study site.
- Determine the effects of landuse on SOC dynamics and physico-chemical characteristics of selected shaded-cocoa and connected forest soils.

- Determine the effects of topography (hillslope position) on SOC dynamics and physico-chemical characteristics of selected shaded-cocoa and connected forest soils.
- Evaluate the changes of SOC stocks in selected shaded-cocoa systems over a 15-year period.
- Assess cocoa farmers’ local knowledge of SOC and its effects on fertility and management practices.

2 MATERIALS AND METHODS

2.1. Description of the Study Area

The study area is found in the Atwima Nwabiagya Municipality (ANM) of Ghana (Figure 3.1) and is one of the forty-three (43) Administrative Districts in the Ashanti Region. Formerly known as the Atwima Nwabiagya District; it was upgraded to Municipality status by a Legislative Instrument (LI 2298) in 2018. The Municipality is situated in the western part of the region and lies approximately on latitude 6^0 32' N and 6^0 75' N, and between longitudes 1^0 36' and 2^0 00 W.

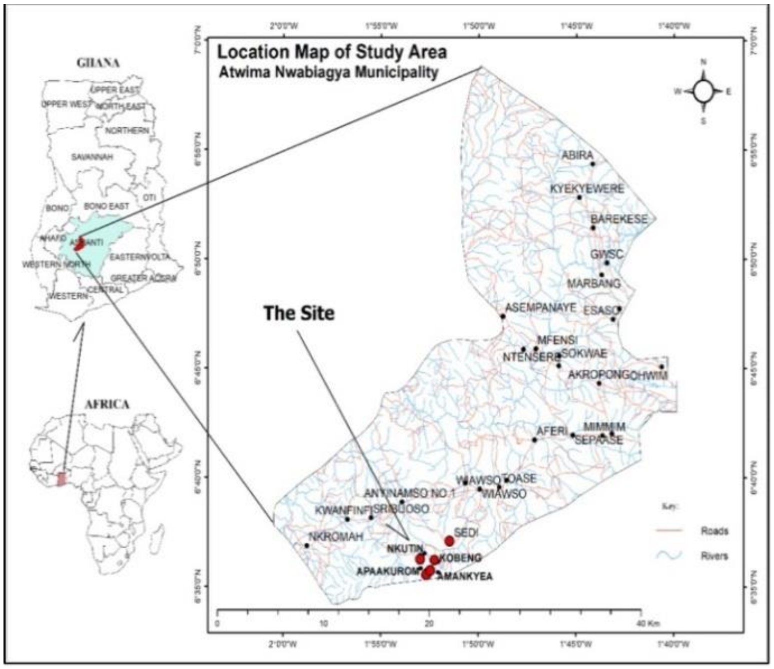


Figure 1 *Map of the study site*

2.2. Soil sampling design

Based on the defined research aims (Chapter 1.3), different soil sampling designs were applied.In order to determine the effects of topography (slope position) on the depth distribution of SOC content and SOC stocks (research objective 2), the *catena method of sampling* was selected, while to determine the effects of landuse and time (research objective 1 and 3) on the depth distribution of SOC content, quality and SOC stocks, the *pattern-based random soil sampling* design was applied.

2.2.1 Catena method of sampling

For the characterization and description of soils and to study the effect of topography on SOC and other selected soil parameters, samples were collected using the concept of soil catena or topo-sequence method (Fig. 3.3). Catena 1 and catena 2 were dug in shaded-cocoa landuse systems in Kobeng community, while Catena 3 was situated in a secondary forest in Nkutin community (Fig. 3.2). Three profiles were opened in each catena, described based on international standards (FAO, 2006) and classified according to the WRB soil classification system (IUSS Working Group WRB, 2015). Thus a total of nine (9) soil profiles were opened and described using FAO guidelines (FAO, 2006). The profiles were sampled to a depth of 145 cm in each catena at three different hillslope positions (upper, middle and lower hillslope positions, respectively) for SOC and BD determinations. From 0-5, 5-15, 15-30, 30-60, 60-100 and 100-145 cm soil depths, undisturbed core samples, (3 catenas x 3 hillslope positions/catena x 6 depths x 3 replicates = 162 soil samples) were collected from pits for bulk density estimation. At depths of 0-5, 5-15, 15-30 and 30-60 cm, 108 (i.e. 3 catenas x 3 hillslope positions/catena x 4 depths x 3 replicates) soil samples were also collected by augering for SOC determination. Samples for SOC determination were complemented by additional 54 samples (3 catenas x 3 hillslope positions/catena x 2 depths x 3 replicates) collected from pits at 60-100 and 100-145 cm depths which could not be augured due to rocky nature at these lower depths. Thus, in all a total of 324 soil samples were placed in labelled zip-lock bags and sent to the laboratory for analysis. GPS coordinates data was recorded for all sampling points at all locations. Figure 3.4 shows the topography and positions of the sampled catenas.

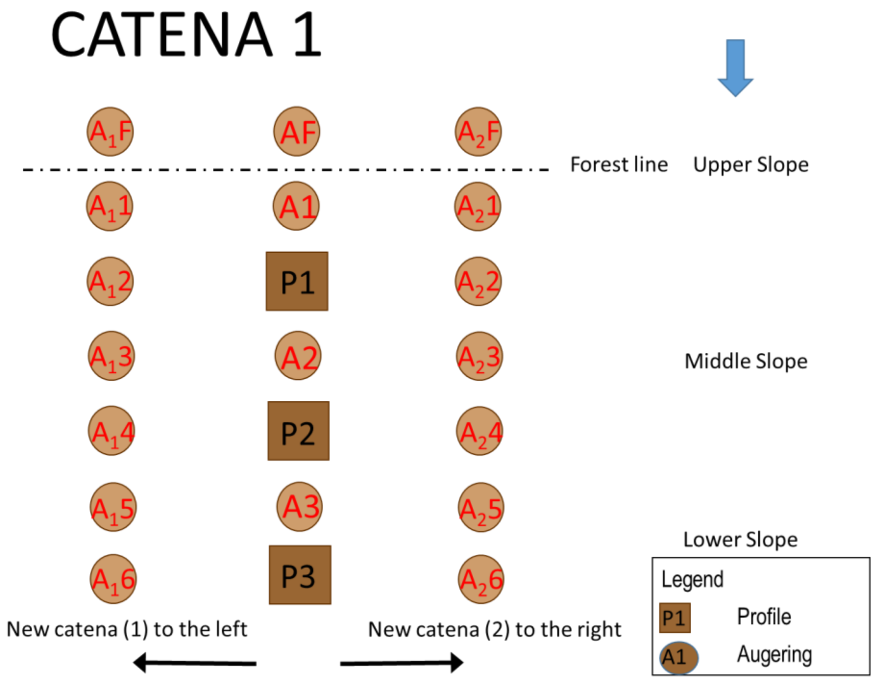


Figure 2 ***The catena sampling design for both cocoa and forest land-use***

2.2.2. Pattern-based random soil sampling

With a goal of evaluating changes in SOC over time (chronosequence) under cocoa agroforestry systems, the selection of cocoa farms was based on earlier studies (Dawoe, 2009). Shaded-cocoa farms from 3 different age groups, 18, 30 and 45 years after forest conversion, corresponding to farms which were 3, 15 and 30 years after forest conversion in Dawoe's study (2009) were selected. Forest represented in the chronosequence study was sampled by Dawoe (2009) and described as time zero (0).

The selected farms were the following: Kobeng (18 years), Apaakrom (30 and 45 years), Nkutin (18 and 45 years), Amankyea (30 years) and Seidi (18 and 30 years) (Figure 3.5).

Sampling plots (40×50m to 60×80m) based on the farm size were established. In each age group, soil samples from twelve points corresponding to three points per replicate (along an S-shaped transect starting from one of the diagonals) (Figure 3.6) were taken by auguring to a depth of 0-10, 10-20 and 20-60 cm giving 36 samples per farm and a total of 288 samples. Samples were bagged for laboratory analysis. Further 288 undisturbed core samples were collected from small soil profiles using fixed depth intervals of 0-10, 10-20 and 20-60 cm depth respectively, for bulk density calculation estimation.

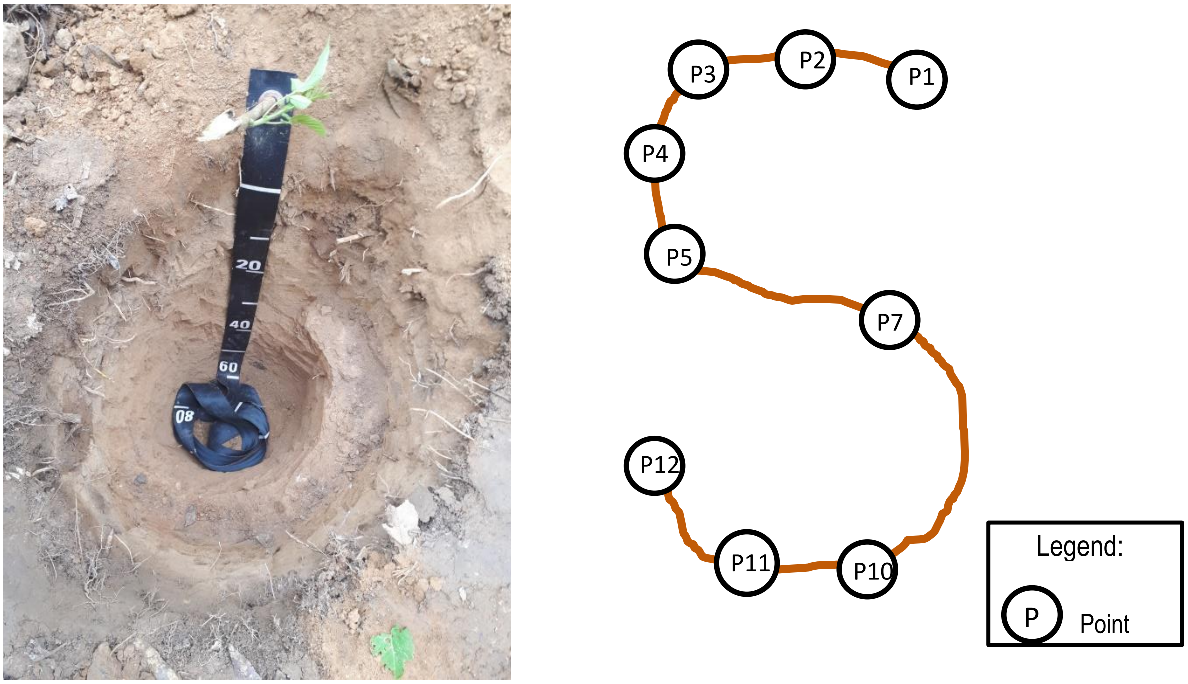


Figure 3. The S-shape sampling design and a small soil profile

2.3 Laboratory Analysis of soil samples

The Munsell colour chart was used in the determination of soil colour.Soil organic carbon was determined following the Walkley-Black procedure (van Reeuwijk, 2002). Humic substances were determined following E4:E6 ratio determination (Chen et al., 1977). Soil CEC and base saturation were determined following the $BaCl_2$ Compulsive Exchange Method (Gillman & Sumpter, 1986; Ross & Ketterings, 2011). Some of the advantages of this procedure include high repeatability, precision, and direct measure of the soil's CEC. Exchangeable cations (K, Ca, Mg, and Na) were determined following Mehlich 3 extraction method (Mehlich, 1984). Soil pH in H_2O was potentiometrically measured in the supernatant suspension of a 1:2.5 soil: extractant mixture (Carter & Gregorich, 2008). Soil N was determined using the C:N ratio using the C–N analyzer (vario MAX CN; Germany), using sulphur (50 mg; N – 9.7 %; C – 34.0 %) to aid in the calibration of the equipment and a standard soil sample (1 g; N – 1.2 %; C – 1.4 %). Soil available K and P were determined using 40 ammonium lactate acetate solution method (Egnér et al., 1960). The distribution of clay, silt and sand particles was determined by mechanical analysis using the pipette method (Haluschak, 2006). Coarse fragment was determined using the sieving method (Zhang et al., 2019). The core method was used to determine soil bulk density (g/cm3) (Blake & Hartge, 1986).

2.4. Soil Organic Carbon (SOC) Stock calculation

The following equations were used in calculating for Soil carbon stocks. Equation (4) was used to calculate stocks for soil samples from the catena.

Soil organic carbon stocks for each sampled depth were calculated from SOC concentration, depth thickness, bulk density and coarse fragment following the equation of Bautista et al. (2014). Calculation is shown in equation (4)

$$SOC = \sum_{i=n}^{i=1} \left([(BDi * (THi * 0.01) * [1 - \frac{CRi}{100}]) * Ci] * 100 \right) \qquad (4)$$

Where: SOC [Mg ha^{-1}]: organic carbon full profile; n: total number of horizons full profile; BD[g mL^{-1}]: bulk density of the horizon i; TH i[cm]: thickness of the horizon i in cm; Cri i[vol.%]: volume of coarse fragments by horizon i; Ci [%]: percentage of organic carbon horizon i.

Soil organic C stocks in (Mg ha^{-1}) in the soils of the 8 cocoa farms in relation to time was calculated using equation (5)

$$\text{SOC stocks (Mg ha}^{-1}) = SOC\% \ X \ BD \ Mg \ m^{-3} \ X \ z \ meters \ X \ 10,000 \ m^{2} \qquad (5)$$

Where:

% SOC concentration, soil layer thickness (z meters), and bulk density (BD) of the samples by the following equation from Solomon et al (2002):

The carbon stocks in each layer (0-10, 10-20, 20-60 cm depths) were summed up for total SOC stock in the 0-60 cm layer.

2.4.1. Nutrient Stocks

The N, P and K stocks in each soil depth were calculated by following the same equation used in calculating SOC stocks. Overall, nutrient stock was estimated by summing stocks of the various depths.

2.5. Methods of Data Analysis

This section describes how data obtained from both laboratory analysis and interview was subjected to various analytical techniques.

2.5.1 Characterization of soils, landuse and topography effects on SOC of the study area

Data from laboratory measurements were keyed into Excel sheet and imported to R (R Core Team, 2016) and Statistix 7.0 software (Analytical Software, 2000) for statistical analysis.

The data were analyzed using Linear Mixed-Effect Models. The lmer() package was used, allowing residual plots to use standardized/normalized residuals rather than raw residuals, and supports more complex combination of random effects. Random intercept (model 1):

Model 1 <- lmer (SOC ~ Land_use + (1|Catena) + (1|Slope))

and random slopes (Models 2 and 3):

Model 2 <- lmer (SOC ~ Land_use + (Land_use|Catena))

Model 3 <- lmer (SOC ~ Land._use + (Land_use|Slope))

were used to account for the effect of soil catena and slope on the distribution of the soil parameters measured. Landuse was fixed factor while catena and slope were considered as random factors. Mean separations were performed on the random intercept model using Tukey's post hoc HSD test at $\alpha = 0.05$. Pearson correlations were used to examine relationships among soil properties and land uses. The data were analyzed using the R statistical and Statistix 7.0 software packages.

2.5.2. Analyzing soil organic carbon changes along a 45-year old chronosequence

To analyze the effects of age (duration after forest conversion to cocoa agroforestry system) on SOC and soil bulk density sampled at depth 0-10, 10-20 and 20-60 cm, data from this study (cocoa farms established 18, 30 and 45 years after forest conversion) was combined with data from Dawoe (2009) (cocoa farms established 3, 15, and 30 years after forest conversion), and a one-way analysis of variance (ANOVA) using generalized linear model was performed to establish significant effects of age on SOC stocks and bulk density. Sampling depths for the fourth objective (0-10, 10-20 and 20-60 cm) which is related to the above statement is different from the second and third objectives (0-5, 5-15, 15-30, 30-60 60-100 and 100-145) Multiple comparisons of means using post hoc Tukey HSD test was used to determine significant differences among farms. All data were expressed as mean ± standard error. We also analyzed overall, the trends and changes in SOC stocks from 3 to 45 years after forest conversion and compared specifically stock increases over the 15-year period from 3, 15 and 30-year-old plots to the same plots at 18-, 30- and 45-year-old after forest conversion respectively, i.e., increases from 3 to 18 years, 15 to 30 years, and 30 to 45 years after forest conversion. To visualize the progression of stock increases after forest conversion, we subjected data to a polynomial regression analysis as this gave the best fit. Pearson correlations were also used to examine relationships between soil properties and land-uses. All statistical analyses were performed using the Statistix 7.0 software package (Analytical Software, 2000).

2.6. Social data collection

2.6.1 Interview design

Qualitative social data with respect to cocoa farmers' local knowledge about soil organic carbon and their management practices was obtained through the administration of semi-structured interview guide (Patton, 2002) to 33 cocoa farmers from three communities, namely, Seidi, Kobeng, and Amanchia, in July and August 2018. Interview questions (Appendix A) were framed to elicit and understand farmers' activities, access to training, perception about soil, SOC/SOM knowledge, farm management practices, and perceived changes in the soil fertility on their farms following cultivation. Farmers were purposively selected with the assistance the zonal agricultural extension officer from the Ministry of Food and Agriculture responsible for the communities. Subsequently, farmers were met in groups for introduction, familiarity, and to highlight the purpose and importance of the research. Interviews were subsequently scheduled based on their free days in the period of July and August, 2018 in their homes and community and church centers, lasting from 45 min to 1 hour. During the interviews, notes were taken, and ten interviews were recorded. A summary of each interview was prepared based on the notes and recordings.

The interviews were conducted following the fundamental ethical principles of social research sharing the research's main aim, securing voluntary participation, confidentiality, and anonymity, asking permission for recording and causing no harm to participants (Patton, 2002; SRA, 2003). The fieldwork was approved by the Ad Hoc Ethical Committee of the Doctoral School of Environmental Sciences of Hungarian University of Agriculture and Life Sciences, Hungary, in accordance with the Code on Research Ethics of the Hungarian Academy of Sciences, and the European Code of Conduct for Scientific Integrity.

2.6.2. Qualitative content analysis of interviews to assess farmers' local knowledge of SOC

A summary for each interview was prepared based on the notes and recordings with Microsoft word. Summaries were analyzed with the qualitative content analysis using emergent codes and assisted by the QCAmap software (Mayring, 2014). Quotes were used as illustrations, and numbers were assigned to each quote for identification purposes. Quotes include a number assigned to the farmer and the community from which they live. Example S2_4 means (S) is the Seidi which is the name of the community, (2) is the second in numbering the community and (4) is farmer number four (4).

3 RESULTS AND DISCUSSION

3.1. Soil physical parameters in the studied land-uses

Table 1. Shows the physical properties of the studied soils with the texture being silty loam for both cocoa and forest landuses. Between the forest and cocoa systems, sand, silt and clay fractions were similar ($p > 0.05$) at all corresponding depths (Table 1). However, the overall mean silt and clay contents (0-145 cm) differed significantly ($p < 0.05$) between forest and cocoa systems. Coarse fragments significantly ($p < 0.05$) differed between the two landuses in the topsoil (0-5, 5-15 and 15-30 cm depths) and for the entire profile depth (0-145 cm) being higher in the cocoa plantation than in the forest. The bulk density ranged from 1.13±0.11 to 1.58±0.07 g/cm^3 in the forest and cocoa systems at all depths. Comparatively, lower bulk densities were observed in the forest system. Bulk density in the forest and cocoa systems at the 0-5 and 15-30 cm depths were similar ($p > 0.05$), but marked differences were found in the 5-15, 30-60, and 60-100 cm. Bulk density values were generally observed to increase with increasing depth in both landuse systems (Table 1).

Table 1. Differences in soil physical parameters between forest and cocoa land- uses

Soil physical Parameters	Depths (cm)	Landuse	
		Forest	Cocoa
Sand (%)	0-5	16.19±1.18^{a}	22.34±2.66^{a}
	5-15	18.12±2.13^{a}	23.06±2.40^{a}
	15-30	18.17±2.88^{a}	21.07±2.56^{a}
	30-60	20.83±3.14^{a}	18.26±3.32^{a}
	60-100	17.60±1.17^{a}	11.79±1.11^{a}
	100-145	17.88±7.68^{a}	16.81±2.55^{a}
	Mean± SEM	**18.13±1.33^{a}**	**18.89±1.15^{a}**
Silt (%)	0-5	63.46±2.81^{a}	58.10±2.30^{a}
	5-15	54.56±1.78^{a}	52.58±2.86^{a}
	15-30	48.66±1.44^{a}	50.61±2.77^{a}
	30-60	40.93±1.82^{a}	47.12±1.57^{a}
	60-100	38.02±3.44^{a}	49.89±2.82^{a}
	100-145	41.79±8.02^{a}	52.84±2.39^{a}
	Mean± SEM	**47.90±2.54^{b}**	**51.86±1.10^{a}**
Clay%	0-5	20.35±1.93^{a}	19.56±1.61^{a}
	5-15	27.33±3.49^{a}	24.37±1.99^{a}
	15-30	33.17±3.41^{a}	28.32±2.84^{a}
	30-60	38.24±4.93^{a}	34.63±3.18^{a}
	60-100	44.38±4.61^{a}	38.32±2.78^{a}

	100-145	40.33±14.62^{a}	30.34±2.60^{a}
	Mean±SEM	**33.97±3.08^{a}**	**29.27±1.43^{b}**
Coarse fragment	0-5	22.33±2.60^{b}	36.83±4.15^{a}
	5-15	18.67±3.48^{b}	43.50±5.41^{a}
	15-30	30.00±4.04^{b}	47.50±3.78^{a}
	30-60	44.00±7.23^{a}	50.17±2.17^{a}
	60-100	50.67±4.37^{a}	49.67±3.13^{a}
	100-145	34.67±5.67^{a}	43.17±6.37^{a}
	Mean±SEM	**33.39±3.19^{b}**	**45.14±1.83^{a}**
Bulk density(g/cm^{-3})	0-5	1.13±0.11^{a}	1.20±0.19^{a}
	5-15	1.27±0.02^{b}	1.38±0.10^{a}
	15-30	1.42±0.03^{a}	1.45±0.07^{a}
	30-60	1.32±0.15^{b}	1.58±0.07^{a}
	60-100	1.38±0.13^{b}	1.57±0.10^{a}
	100-145	1.42±0.09^{b}	1.56±0.09^{a}
Texture	0-5	Silt Loam	Silt Loam
	5-15	Silt Loam	Silty clay loam
	15-30	Clay loam	Silty clay loam
	30-60	Silty clay loam	Clay loam
	60-100	Sitly clay loam	Clay
	100-145	Silty clay loam	Silty clay
		Silt Loam	**Silt Loam**

Values in the same row followed by the same superscript for different landuses are not significantly different at α = 0.05 using Tukey's HSD test. Mean values SEM (in bold) are means for the entire studied depth 0-145 cm soil depth.

The finding of this study accords with Dawoe et al. (2014) who reported significantly higher bulk densities in cocoa compared to secondary forest soils. The differences in the topsoil are more likely due to natural variations in the two landscapes as land preparation for cocoa establishment, planting of cocoa seedlings and subsequent management activities are likely to cause disturbances that would lead to the redistribution of coarse fragments in the profiles.

3.2. Effects of land-use changes on SOC concentrations and stocks

Soil organic carbon stocks in the 0-30 cm aggregated depth represented about 71 to 76 % of the total stocks in the 0-60 cm depth (Figure 4).

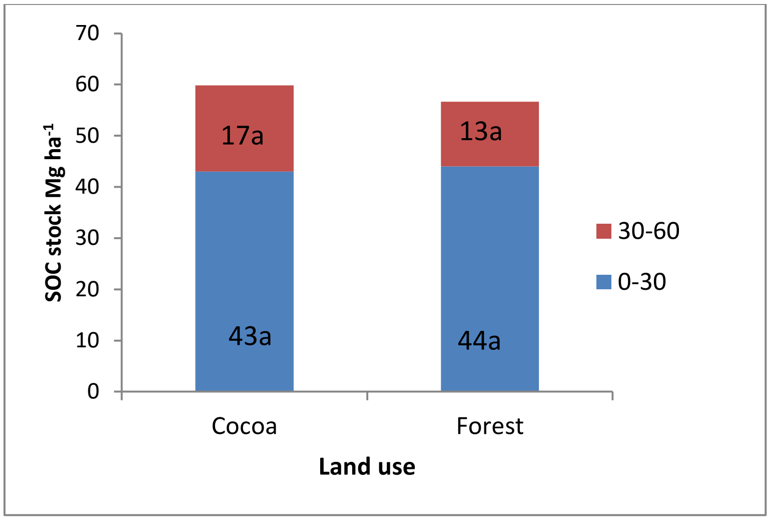
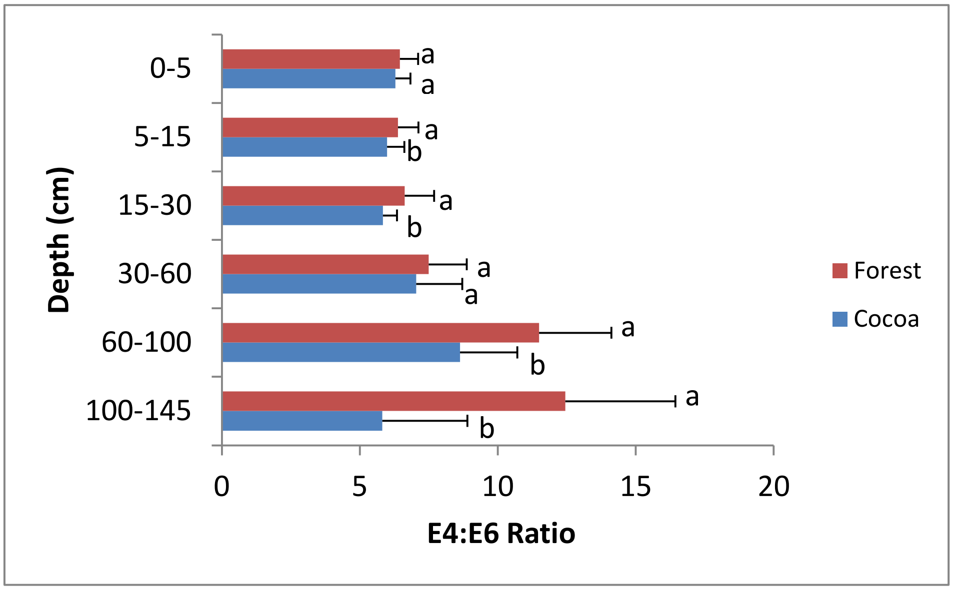


Figure 4 Effect of landuse on SOC stocks at 0–30 and 30–60 cm aggregated depths in soil profiles in forest and cocoa agroforestry systems.

The report of Dawoe (2009) in the same study area did not observe significant differences in total SOC stocks between forest and different aged cocoa systems where mean SOC stocks ranged from 49.0 to 67.4 Mg ha^{-1} (0-60cm) for a 3-year-old cocoa farm and secondary forest system respectively. For that same depth (0-60cm), the carbon stocks in this study were similar and varied from 58 Mg ha^{-1} and 60 Mg ha^{-1} in secondary forest and cocoa plantation, respectively. It appears that as tree-based cropping systems age, carbon stocks approach pre-conversion levels (Don et al., 2011; Guo and Gifford 2002). The findings of this study show carbon stock differences between older cocoa and forest systems were small.

3.2.1 Quality of SOC in the studied land uses



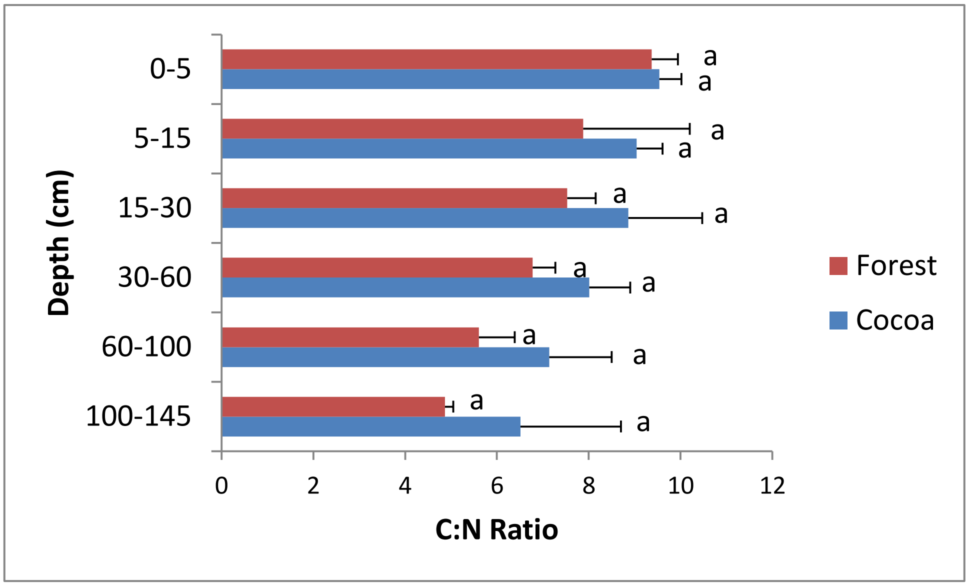


Figure 5 Variations in E4:E6 (a), and C:N ratios (b) with changes in soil depths in cocoa agroforestry and forest systems. Error bars represent standard deviations of means.

Largely, the C:N ratio of the two landuses were similar in all depths. Kunlanit et al. (2019) also reported similar C:N ratios in their study that assessed the effect of landuse change from forest to cassava and rice paddy in which no significant differences were observed in their studied landuses. The E4:E6 ratios observed in this study showed that fulvic acid (FA) was the most abundant fraction of the extractable organic matter. Generally, the ratios were above 6.0 suggesting a low molecular weight and less polymerization of humic substances (Stevenson, 1994). The results in this study concord with Reddy et al. (2014) who observed higher FA ratios in tree-based forest and coffee systems. The cocoa system was observed to have more biomass materials with higher humification rate as evidenced by lower E4:E6 ratio compared to that of the forest. Thus, the most labile, more soluble and readily available organic molecules are under forest systems whereas higher proportion of stabilized, less available organic molecules (lower E4:E6 ratio) are in cocoa soils in the form of humic acids.

The relationship between E4:E6 and depth was strong for the forest system, but weak for the cocoa system. Soil C:N ratio on the other hand correlated negatively with depth in both forest and cocoa systems (Figure 6).

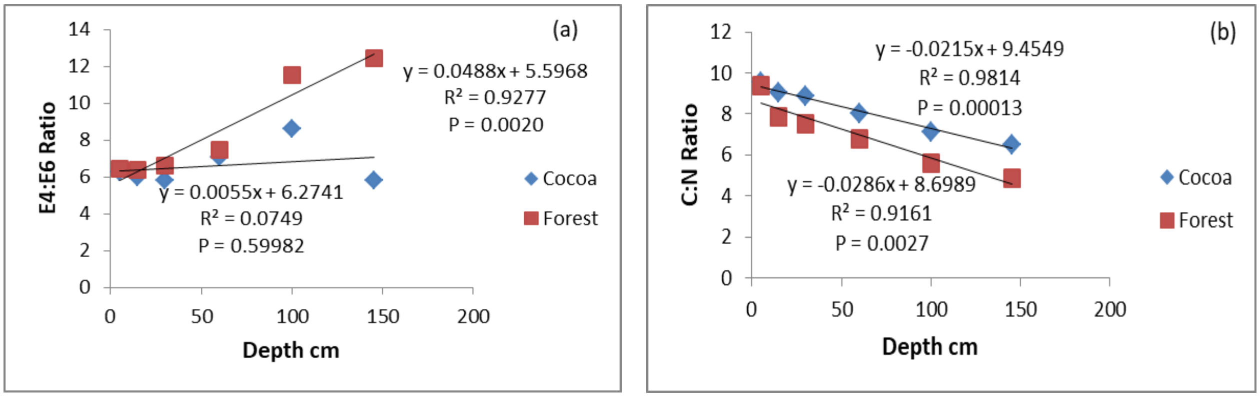


Figure 6 Linear regression analysis between (a) Humic substances (E4:E6 ratios) and soil depth, (b) C:N ratio and soil depth, cocoa agroforestry and forest systems in the Atwima Nwabiagya Municipality of the Ashanti Region, Ghana.

With respect to the relationship between E4:E6 and pH, the regressions revealed a weak and non-significant relationship in cocoa systems (Figure 7a) while a stronger and highly significant ($p < 0.001$) relationship was observed in the forest system (Figure 7b). The E4:E6 ratios were generally higher at lower pH values in both forest and cocoa soils, that is, the ratios decreased (ie., improved soil quality) with increasing pH values. The change in E4:E6 ratios with changing pH indicates that rate of improvement in soil quality in the forest system was faster (gradient − 2.89) than the rate of change (gradient − 0.469) in the cocoa system.

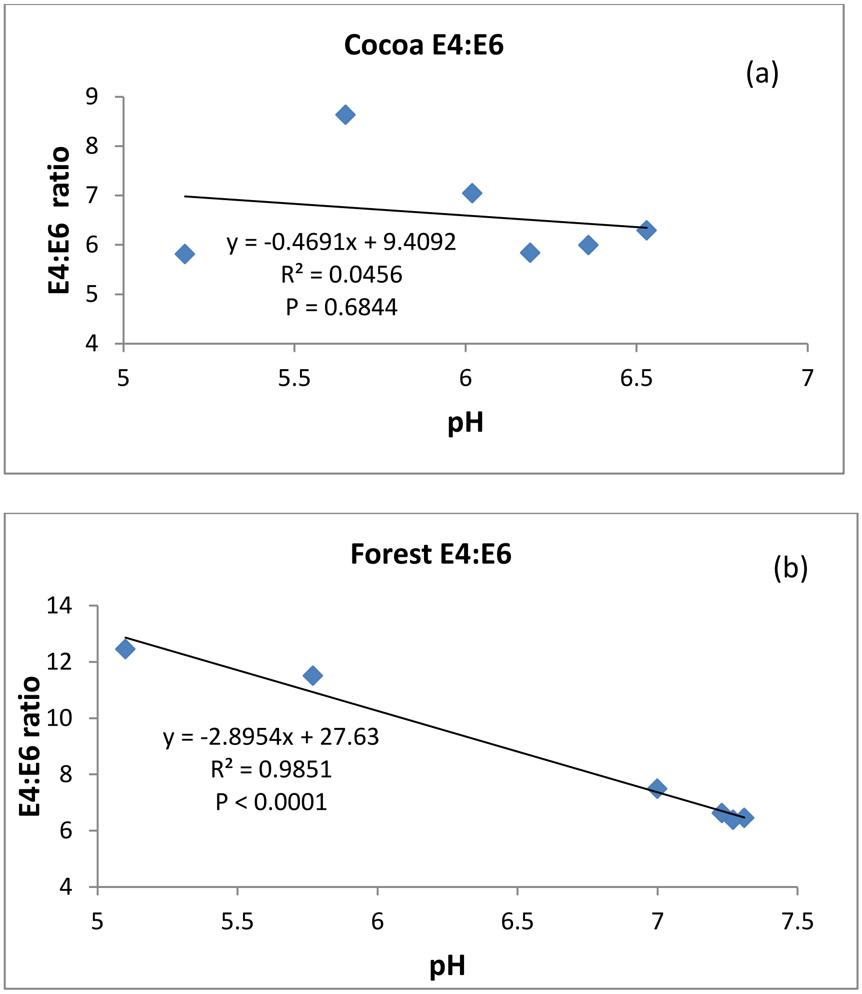


Figure 7 Regressions of E4:E6 and pH

Changes in carbon quality in terms of changes in molecular size of humic substances was found in the cocoa system making carbon more stabilized possibly as a result of higher pH thus lower rate of mineralization following landuse change to cocoa.

3.2.2 Relationships between SOC and selected soil physical and chemical properties in the studied land-uses

The correlation coefficients are shown in Table 4.5. SOC stocks significantly negatively correlated with E4:E6 ratio and clay content but significantly positively correlated with silt. Furthermore, SOC% positively correlated with SOC stocks and silt significantly but the relationship with clay content was negative. Silt negatively correlated significantly with bulk density and E4:E6 ratio and sand had a significantly strong negative association with E4:E6. The

E4:E6 ratio increased significantly with increasing clay content while the SOC and clay content correlated negatively significantly.

Table 2 Pearson correlations among selected chemical and physical properties of soils under land use types in the Ashanti region, Ghana (0-30 cm)

	CN	pH	BD	SOC stocks	E4:E6	Sand	Silt	Clay
SOC%	-0.12	0.20	-0.40**	-	-0.36**	0.03	0.49***	-0.42***
CN		-0.06	0.05	-0.18	-0.58	0.39	0.14	-0.53
pH			-0.60***	0.14	0.18	-0.19	0.02	0.15
BD				-0.09	-0.14	0.17	-0.39**	0.16
SOC stocks					-0.42***	0.16	0.26*	-0.34**
E4E6						-0.37**	-0.35**	0.59***
Sand							-0.26*	-0.65***
Silt								-0.56***

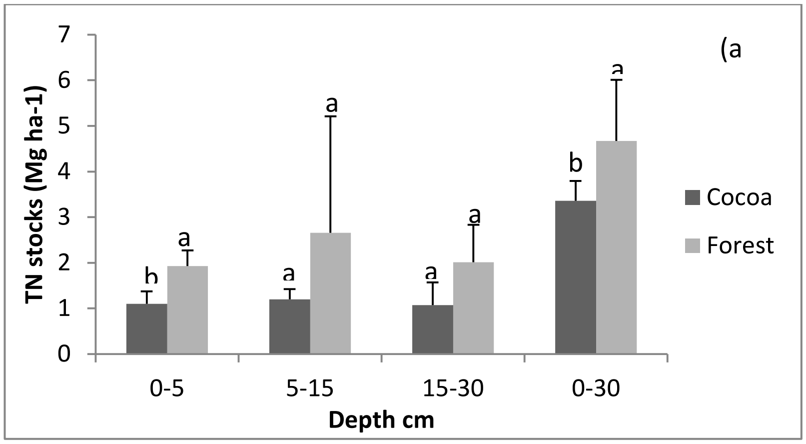
Asterisks indicate significant levels. *p < 0.05, **p <0.01 and ***p <0.001

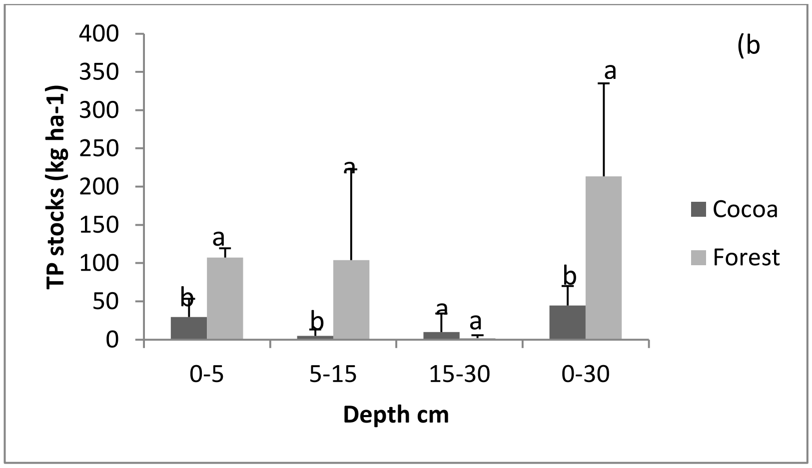
The silt acted as an indicator of SOC ($r = 0.49$, $p < 0.001$). Initial cultivation practices of cocoa trees disturb the soils (Dawoe, 2009) and exposes soil surfaces to erosion increasing the susceptibility of the more prone silt particles to erosion (Wu et al., 2020). Worth mentioning also is the strongly negative and statistically significant correlation between SOC and clay. Given that higher clay contents of forest soils are usually associated with higher SOC stocks, the results are surprising. Piccolo & Mbagwu (1990) observed that aggregate stability of micro aggregates revealed significant correlation with humic substances content (humic plus fulvic acids). This explains the significantly positive correlation observed between E4:E6 ratio and clay content in our study.

3.2.2 TN, TP and TP stocks under the studied land-uses

Total nitrogen (TN), total phosphorus (TP) and total potassium (TK) stocks were significantly affected by land-use and soil depth (Figs. 8 a, b, and c). For each nutrient, stocks varied in the individual layers (0-5, 5-15 and 15-30 cm), and ranged from 1.07 to 2.66 Mg ha^{-1}, 2.09 to 107.09 and 597.12 to 1971.52 kg ha^{-1} for TN, TP and TK respectively. TN stocks in forest soils was significantly higher than stocks in cocoa soils in 0-5 cm and the 0-30 cm depths (Fig. 8a). TP stocks in forest soils were significantly higher in 0-5 and 5-15 cm compared to cocoa soil (Fig

8b). A similar trend was observed for TK stocks, with stocks in 0-5 cm soil depth being significantly higher in the forest compared to cocoa soils (Fig 8c). Thus, for all three nutrients, stocks were significantly higher in forests compared to cocoa plots at 0-30 cm aggregated depth.





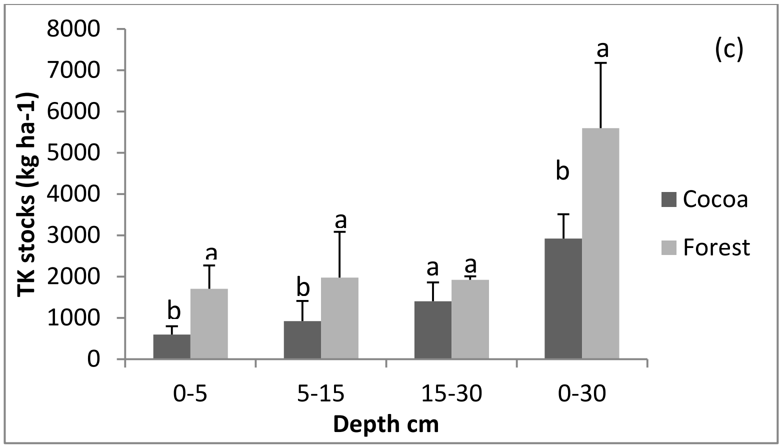


Figure 8 Landuse effect on nutrient stocks in the topsoil of soil profiles(a) total nitrogen (b) total phosphorus, and (c) total potassium stocks at 0-5, 5-15, and 15-30 cm individual depths, and at 0-30 cm aggregated depth. Error bars represent standard deviation of the mean.

This difference could be attributed to the removal of nutrient through yield (beans and husks). Various studies have reported varying amounts of nutrient exports (losses) through cocoa beans harvests. For instance, Wessel (1985) recorded a loss of 22.8, 4.0 and 8.4 kg of N, P and K, respectively from a 1000 kg of dry cocoa beans in Nigerian soils, while Snoeck & Jadin (1992), recorded losses of 22.1, 3.0 and 7.5 kg of N, P and K, respectively from 1000 kg of dry cocoa beans in Ivory Coast. Again, low amount of fertilizer applied by cocoa farmers could explain the difference between the two landuse systems. The low nutrient in the soil is further mined by the cocoa crop.

3.3. Effects of topography (slope position) on soil organic carbon concentration and stocks

Carbon stocks generally decreased from the highest to the lowest topographic positions at the 0-30 and 0-60 cm layers (Figure 9). On other hand, carbon stock differences between the cocoa and forest ecosystems on the lower, middle and upper hillslope positions at the various soil depths were not significant but the cocoa carbon stock was higher than that of the forest in the lower slopes at the 30-60, 60-100 and 100-145 cm depths. Results are in accordance with the findings of other studies (Leifeld et al., 2005; Fernández-Romero et al., 2014; Rezaei et al., 2015; Che et al., 2021). Again, vegetation was denser at the upper slope positions and it is very likely that litterfall and other plants cover from this denser vegetation contributed to protecting the surface soil from exposure to weather elements, decomposition and erosion, thus preventing the breakdown of carbon in the soil (Duran-Zuazo et al., 2013). Litter cover on both land uses possibly reduces raindrop detachment of soil particle consequently limiting the impact of soil erosion on the fields. Result also suggests minimal erosion, sedimentation and leaching of organic carbon at the study site. There is also the absence of decadal movement of soil from the higher to lower slope positions across both landuse systems in the study site.

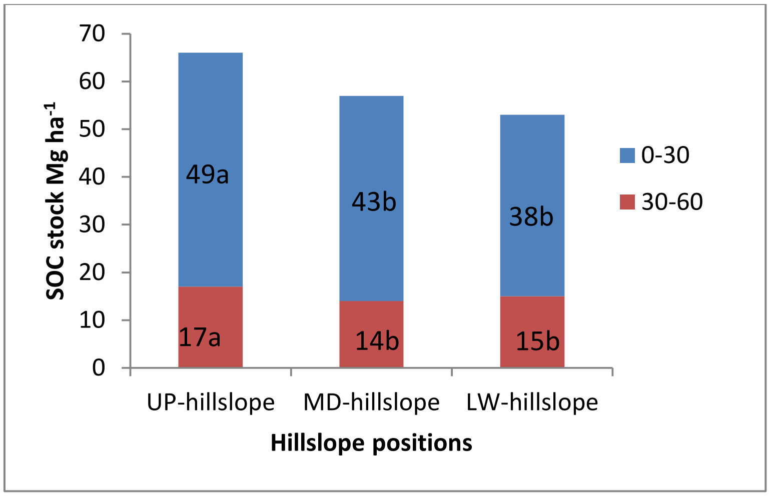


Figure 9 Soil carbon stocks along varying topographic positions.

3.3.1 Effect of topography (hillslope position) on the quality of soil organic carbon in soils

Table 2 Mean E4:E6 ratios in the different hillslope positions at varying depths between the cocoa and forest land uses

Depth	**Slope**	**E4:E6 ratio**	
		Cocoa	**Forest**
0-5	Upper	6.01 ± 0.11^{a}	6.10 ± 0.43^{a}
	Middle	6.55 ± 0.33^{a}	6.51 ± 0.21^{a}
	Lower	**6.58 ± 0.17^{b}**	**7.02 ± 0.07^{a}**
5-15	Upper	5.68 ± 0.15^{a}	5.45 ± 0.08^{a}
	Middle	6.09 ± 0.18^{a}	6.46 ± 0.15^{a}
	Lower	**6.17 ± 0.16^{b}**	**7.20 ± 0.08^{a}**
15-30	Upper	5.67 ± 0.13^{a}	5.41 ± 0.21^{a}
	Middle	5.95 ± 0.11^{b}	6.66 ± 0.11^{a}
	Lower	**5.81 ± 0.21^{b}**	**7.88 ± 0.13^{a}**
30-60	Upper	7.23 ± 0.50^{a}	5.65 ± 0.47^{a}

	Middle	7.18±0.38^a	7.67±0.23^a
	Lower	**6.68±0.55^b**	**8.72±0.33^a**
60-100	Upper	8.42±0.58^a	8.53±0.81^a
	Middle	9.64±0.26^a	7.63±2.71^a
	Lower	**7.73±0.84^b**	**10.53±2.82^a**

Figures in the same row followed by the same superscript for different land uses are not significantly different at $p < 0.05$ level using Tukey's HSD range test.

Table 3. Mean values of C:N ratios in the forest and cocoa land uses at depth 0-145 cm.

Slope position	C:N Ratio	
	Cocoa	Forest
Upper	8.39±0.53^a	7.43±0.68^a
Middle	7.77±0.50^a	6.21±0.65^a
Lower	8.39±0.40^a	7.37±0.84^a

Values in the same row followed by the same superscript for different land uses are not significantly different at $P < 0.05$ level using Tukey's HSD range test.

The C:N ratios along the slopes were not significantly ($p > 0.05$) different between the studied landuses. Slope positioning, however, significantly affected E4:E6 ratio in the topsoil with narrower ratios in the upper slope positions showing a higher degree of humification comparatively. The finding of this study agrees with the observations made by Galioto (1985). The author found higher E4:E6 ratios at lower slopes comparatively in the south slope, Santa Catalina Mountains, Pima County, Arizona. Carbon is more stabilized in the upper slope positions which could play a major role in conditioning the soil by reducing nutrient loss, regulate pH values, increase soil aggregation, and increase buffering properties.

3.3.2 Slope effects on nutrient content and stocks in soils

The TN stocks were significantly ($p < 0.05$) different between cocoa and forest systems in the upper and lower slope positions. TK stocks were also significantly ($p < 0.05$) different between landuses in all the slope positions. TP stocks significantly ($p < 0.05$) differed between landuses at the middle slope position (Table 4).

Table 4. Effect of slope positions on nutrient stocks (±SEM) at 0-30 cm depth in cocoa and forest soils

Nutrient	Slope position	Land-use

		Cocoa	Forest
TN stocks (kg ha^{-1})	Upper	3.72±0.57^{b}	10.46±0.05^{a}
	Middle	3.97±0.12^{a}	3.73±0.00^{a}
	Lower	3.11±0.55^{b}	5.63±0.00^{a}
	Mean	3.60±0.27^{b}	6.61±1.27^{a}
TP stocks(kg ha^{-1})	Upper	60.20±26.96^{a}	141.01±7.89^{a}
	Middle	52.45±14.64^{b}	241.94±68.12^{a}
	Lower	34.07±9.60^{a}	101.13±46.32^{a}
	Mean	48.91±10.24^{b}	161.36±34.04^{a}
TK stocks(kg ha^{-1})	Upper	3841.1±433.65^{b}	7436.3±91.38^{a}
	Middle	2872.7±101.22^{b}	4598.0±101.26^{a}
	Lower	2668.8±68.19^{b}	4767.8±57.10^{a}
	Mean	3127.5±205.48^{b}	5600.7±582.53^{a}

Values in the same row followed by the same superscript for the different slope positions are not significantly different at $P < 0.05$ according to Tukey's HSD test.

3.4. Temporal changes in SOC concentration, bulk density, and stocks along a chronosequence in cocoa agroforestry systems

The changes on SOC concentrations, bulk densities and SOC stocks over a 45-year period following forest conversion to shaded cocoa landuse was evaluated in 8 farms from 3 different age groups and compared with those of Dawoe (2009) covering a time span of 15 years. In Tables 3.5, 3.6 and 3.7, the study shows how SOC concentration, stock and bulk density varies with time. Therefore, the results on the forest, and 3, 15 and 30 years cocoa farms sampled by Dawoe (2009) in (2004) was combined with results from the same farms sampled after 15 years (2019) ie. 3 years now 18 years, 15 years now 30 years and 30 years now 45 years old farms to see how the soil properties mention above varies from time 0 (forest as time zero) to 45 years onward. SOC concentrations were generally consistently highest in the 0-10 cm depth across all the ages. Concentrations at the 10-20 and 20-60 cm depths did not follow any consistent trend though at both depths, the 45-year-old plot apparently recorded significantly higher values (Table 3.5). SOC changes in the 0-60 cm depth were not significantly different between the different plot ages.

Table 5 Carbon concentration (OC% ± SEM), at the different depths of the soil profile in forest and cocoa land-use systems in the Atwima Nwabiagya District, Ashanti Region, Ghana.

Landuse

Depth (cm)	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 18 years	Cocoa 30 years	*Cocoa 30 years	Cocoa 45 years
0-10	2.95±0.005a	2.12±0.051c	2.5±0.174b	2.48±0.278b	2.55±0.250ab	2.59±0.342ab	2.62±0.455ab
10-20	1.11 ± 0.322b	0.70±0.306c	0.8±0.125c	1.23±1.72b	0.867±0.200c	1.31±0.227ab	1.73±0.34a
20-60	0.4 ±0.392c	0.3±0.025c	0.397±0.019c	0.909±0.026b	0.437±0.099a	0.764±0.164b	1.17±0.01a
(MEAN) 0-60	1.49±0.392a	1.04±0.290a	1.23±0.328a	1.54±0.253a	1.28±0.336a	1.55±0.299a	1.84±0.304a

Carbon concentration (OC %) 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. The "*Cocoa 30 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).

Some marked difference in SOC content was observed in the top 0-10 cm across with the 3 year cocoa farm having the lowest SOC content. Cocoa at the 15 and 18 years of cultivation had lower SOC content than in the forest (zero year). Concentrations were generally highest in the top layers.

Changes in bulk density at 0-60 cm soil depth over time from 3 to 45 years after forest conversion are also shown in Table 3.6. Mean bulk densities (0-60 cm) did not differ significantly ($p>0.05$) along the chronosequence ranging from 1.24±0.095 to 1.46±0.049 g cm-^{3}. However, comparing similar depths (0-10, 10-20 and 20-60 cm depths) between the age groups, differences were significant for the 15-years' time span covering 15-30 years (Table 3.6).

Table 6 Bulk Density (g cm-3 ± SEM), at the different depths of the soil profile in forest and cocoa land-use systems in the Atwima Nwabiagya District, Ashanti Region, Ghana

Depth (cm)	Landuse						
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 18 years	Cocoa 30 years	*Cocoa 30 years	Cocoa 45 years
0-10	1.01±0.015c	1.19±0.035a	1.26±0.044a	1.19±0.197a	1.31±0.023a	1.06±0.180c	1.22±0.239a
10-20	1.4 ±0.42a	1.45±0.053a	1.40±0.087a	1.43±0.121a	1.45±0.020a	1.28±0.132b	1.32±0.14ab
20-60	1.34 ±0.08b	1.63±0.04a	1.59±0.061a	1.50±0.099a	1.63±0.047a	1.38±0.178b	1.46±0.14ab

(MEAN) 0-60	1.25±0.066a	1.42±0.067a	1.42±0.059a	1.37±0.087a	1.46±0.049a	1.24±0.095a	1.33±0.091a

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. The "*Cocoa 30 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).

Changes in SOC stocks at the studied depths, as well as the mean SOC stocks at 0-60 cm soil depth are shown in Table 3.7. Overall, mean SOC stocks generally increased along the chronosequence. While total mean stocks were lowest in the younger systems (3 and 15 years), stock accumulation over the fifteen-year period (3-18 years) was 2.89 Mg C ha^{-1} -year) the rate for the period 30-45 years was 3.12 Mg C ha^{-1} -year.

SOC stock accumulation was significantly higher in the earlier years following forest conversion, thereafter stocks accumulated at a decreasing rate and increased again as the system ages.

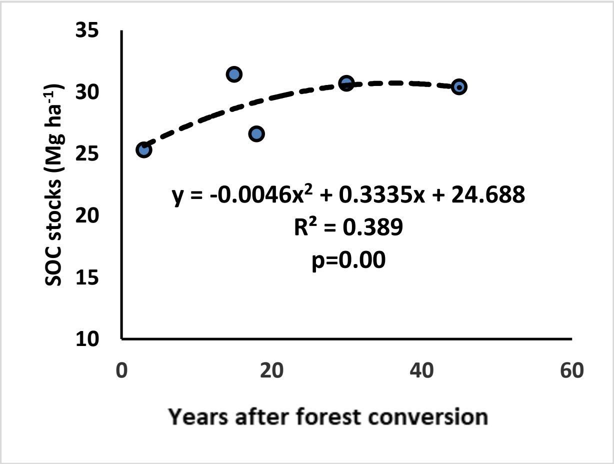
Table 7 Quantities of carbon (Mg ha-1 ± SEM), at the different depths in forest and cocoa land-use systems in the Atwima Nwabiagya District, Ashanti Region, Ghana

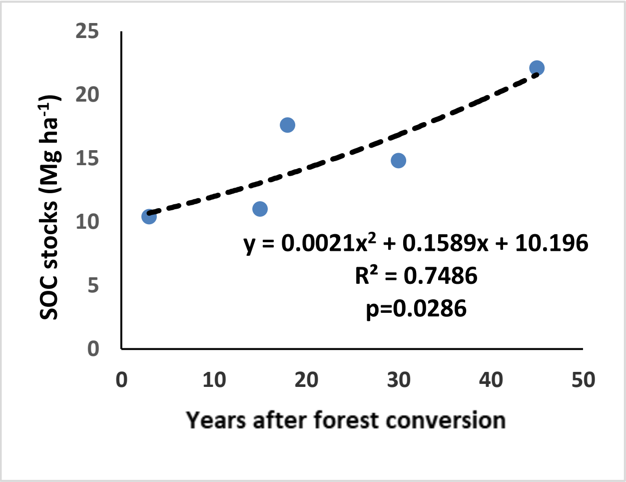
Depth (cm)	Land-use						
	Forest Mg C ha^{-1}	Cocoa 3 years Mg C ha^{-1}	Cocoa 15 years Mg C ha^{-1}	Cocoa 18 years Mg C ha^{-1}	Cocoa 30 years Mg C ha^{-1}	*Cocoa 30 years Mg C ha^{-1}	Cocoa 45 years Mg C ha^{-1}
0-10	29.8 ±0.40a	25.3±1.32b	31.4±1.08a	26.6±2.88b	33.5±3.79a	27.9±8.01a	30.4±0.29a
10-20	15.8 ±5.10c	10.4±4.82c	11.0±0.96c	17.6±1.72a	12.5±2.77c	17.0±4.64a	22.1±2.12a
20-60	21.8 ±5.02c	19.5±1.46c	25.4±2.1c	54.4±4.57a	28.2±5.92b	43.6±14.9a	68.5±6.57a
0-60	67.4±10.1c	55.2±4.5d	67.8±0.07c	98.6±7.8a	74.2±5.4b	88.5±1.8b	121.0±4.74a

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. The "*Cocoa 30 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).

While there was only a marginal decrease (-11.1 and -9.25%) in the 0-10 cm layer in the 15-30 and 30-45 years old groups, respectively, total SOC stocks in the 0-60 cm profile depth recorded increases in the range of 31% to 79% across the chronosequence in the 15-year period since the last study and gives an indication of the potential to use perennial systems like cocoa to sequester organic carbon. Mohammed et al. (2016) recorded SOC stock values of 61.7 – 137.8 Mg/ha for the 0-60 cm depth which was similar to SOC stocks (55.15-121 Mg ha^{-1}) recorded in the study for the same depth. Ledo et al. (2020) observed that the most important factor identified to affect SOC changes was stand age, or time after perennial establishment, with SOC stock increased over 20 years at an average of 0.05 Mg ha^{-1} year^{-1}. In the present study i.e., over the 42-year period between 3-year-old and 45-year-old cocoa plots, SOC stocks in our cocoa systems increased at an average rate of 1.56 Mg ha^{-1} year^{-1}, higher than SOC stocks reported by Ledo et al. (2020).

To visualize SOC accumulation over time and to estimate optimum SOC accumulation point, regressions were performed to show SOC stocks against cocoa systems at different ages at the various depths with the polynomial regressions found to give the best fits (Figures 4.10 a, b, c and d) for the 0-10, 0-20, 20-60 and 0-60cm soil depths, respectively. Hence, subsequent relationships observed between chronosequence and SOC presented in the study were done using second order polynomial regressions. Whereas the regression was weak for the 0-10 cm soil depth, it was moderately strong (r^2) ranging from 0.615 to 0.7486 for 0-60 and 10-20 cm soil depths respectively. SOC stock increase in the top 0-10 cm depth was low. In the 10-20, 20-60 and 0-60 cm depths, stocks increase were slow in the early years but with time stocks increased at an increasing rate and continued to show an increasing trend even after 40 years of forest conversion.





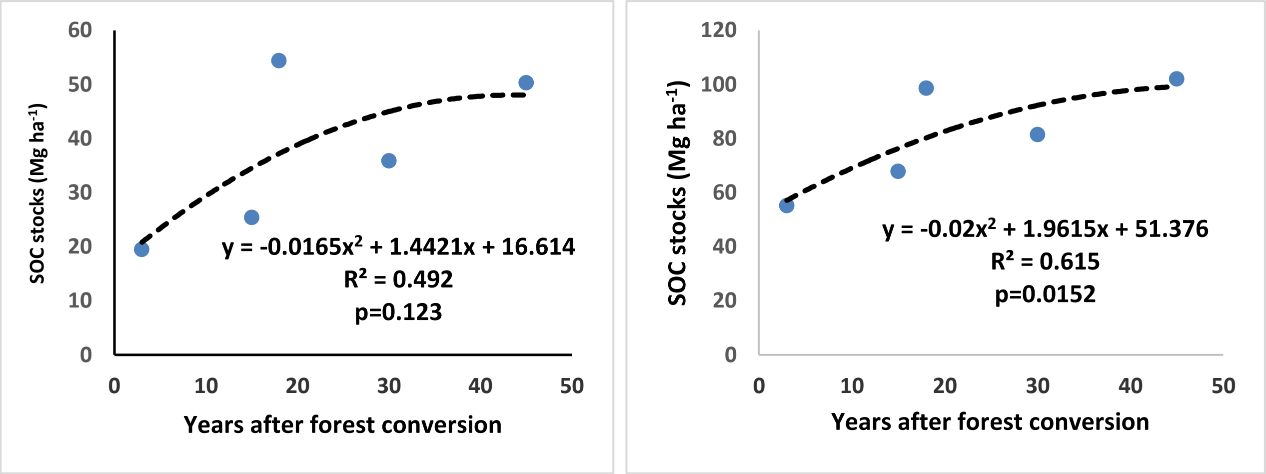


Figure 10 Regressions of SOC stocks at 0-10, 10-20, 20-60 and 0-60 cm depths along a chronosequence of cocoa farms in the Atwima Nwabiagya District of the Ashanti Region, Ghana

4.5.2 Farm management strategies and their relation to SOC

The majority of farmers practiced cocoa agroforestry while only a few practiced full sun (non-shaded system). "Shading is essential for cocoa seedlings after transplanting as well as when they mature into trees. That is, the reason for leaving trees on my farm" (Cocoa farmer K1_6). The ten types of shade trees used in their agroforestry systems are shown in Table 8. The most used tree species were the *Terminalia ivorensis* (Emire) and *Spathodia campanulata* (Akuokuo nosuo). According to farmers, a maximum of nine trees is ideal for a 0.8 hectare (2 acres) cocoa farm.

Table 8 Tree species mentioned as being used on cocoa farms as shade in the Ashanti region, Ghana.

Local Name	Botanical Name
Emire	*Terminalia ivorensis*
Odum	*Chlorophora excelsa*
Mango	*Mangifera indica*
Sesemasa	*Newbouldia laevis*
Nyame dua	*Alstonia boonei*
Mahogany	*Khaya ivorensis*
Wawa	*Triplochiton scleroxylon*
Oduma	*Musanga cecropioides*
Framo	*Terminalia superba*

Akuokuo nosuo	*Spathodia campanulata*
Nwama	*Ricinodendronheudelotii*
Nyankyrene	*Ficus exasperata*
Papia	-
Atowa	-
Adugene	-

Table 9 shows management practices that are perceived by farmers to increase and/or decrease soil fertility. Farmers perceived practices such as planting of shade trees, mixed cropping, mulching, and fertilizer application as practices that increase fertility while burning of weeds, excessive use of agrochemicals, and non-pruning of cocoa and shade trees were perceived as practices that decrease fertility. Farmers apply practices such as weeding, mulching, pruning, mixed cropping, fertilizer application, manure, and compost application on farms to increase SOM/SOC

.

Table 9 Farmers' responses to management practices that increase or decrease soil fertility in cocoa plantations in the Ashanti region, Ghana.

Increase fertility	Decrease fertility
Mulching	Burning of weeds on the farm
Weeding/ no-burning	Excessive use of chemicals (weedicides and pesticides)
Fertilizer application	Tillage
Shade to protect soil and crops	no-pruning
Turning up of soil surfaces	
No-till	
Litterfall	
Mixed cropping	

4.5.5 Farmers Perception about Soil and SOC

None of the farmers knew of the presence of organic carbon in the soil and, indeed, had not even heard about the term, but organic matter was not new to them. Table 10 shows farmers' perception of factors that influence crop yield, indicators of good soil, organic matter, and effects of organic matter on climate, vegetation, and biological activities on organic matter and how organic matter influences soil properties.

Table 10 Summary of farmers' perception on soil and soil organic matter.

Soil related characteristics	Factors and indicators mentioned by farmers
Factors that influence crop yield	• Management practices • Organic matter • Soil type • Climate • Soil organisms
Importance of soil	• Plant growth • Habitat for microorganisms
Indicators of good soil	• Colour • Texture • Vegetation • Presence of microorganism • Age • Organic matter
Indicators of organic matter	• Presence of microorganism • Smell • Vegetation • Colour • Thickness • Moisture content • Texture
Climate effects on organic matter	• Rainfall (wet season) • Sunshine (dry season)
Vegetation effect on organic matter	• Litter fall • Husk of cocoa pods
Biological activity on organic matter	• Breaking down of leaves or litter • Soil mixing and turning • Burrowing • Water movement through soil
The impact of organic matter on soil properties	• Improve soil structure • Improve soil colour • Improve soil texture

- Improve soil moisture

4.5.6 Perceived Changes in SOC and Fertility Status of Farms since Cultivation

A few farmers mentioned that there had been changes in either organic matter content or fertility levels of their farms. They assumed possible changes in SOM and soil fertility because of an increase in their crop yield. They also associated poor growth and low yield with declining soil fertility. One farmer said he thinks the organic matter is low on the part of his farm saying, "part of my land looks very dry therefore cocoa trees in that part of the land is not healthy at all, so I think the soil is tired and has low organic matter." (Cocoa farmer A3_4). A good majority were not sure if there were any changes. Most were, however, optimistic that within the next 10-20 years, organic matter content and fertility status of soils on their farms would increase due to litterfall and improved management practices, leading to increased cocoa beans yields. A few, however, said that their farms would lose 'strength' or 'die' because of their age and money constraint. One farmer said, "Looking at how old I am now, I might not be alive and if there is no one to take proper care of it as I do, then the farm would not be in good shape or might even die."(Cocoa farmer A3_3) A few were not sure of what will happen in the future; they said it would depend on the availability of help they get in terms of money to hire labour to work on the farm and buy fertilizers to improve soil nutrient leading to higher crop yield. "Weeding is the most difficult thing for me, but I also do not have the means to hire labourers to weed throughout the year."(Cocoa farmer K1_2)

4.5.7 Farmers' perception of climate change and its' relationship with SOC

According to farmers, climate change is known to them as *"Ewiem Nsesaye"* in the twi language, which literally means "Changes in the atmosphere." To them, climate change is mainly about sunshine and rainfall; therefore, soil and cocoa yield is affected by extremes of these climatic factors. They also said excessive sunshine and prolonged dry weather affect soil organisms that aid in SOM formation. On the other hand, some said that heavy rains remove the topsoil that contains most of SOM and also kills some soil organisms and cocoa trees when soils are waterlogged for long periods. They also observed that the effects of organic matter breakdown on climate include worsening drought due to increased evaporation, rains with thunderstorms, and rising temperatures. Farmers reported that litterfall from cocoa trees influences organic matter formation. Most of them also mentioned cocoa pod husks as a source of organic matter formation. Even though farmers knew the sources of SOM, how they form on their cocoa farms and the effects of rainfall and sunshine (climate) on SOM, they had no idea how SOM influenced climate change.

4 KEY SCIENTIFIC FINDINGS

1. Landuse change from secondary forest to matured cocoa agroforestry (above 15 years) did not significantly affect soil organic carbon as similar quantities were observed between the two landuses. This research found that the level of soil organic carbon stocks in the shade cocoa systems, in old cocoa systems were significantly higher than in secondary forests This demonstrate the need for sustainable management systems and the inclusion of trees in cocoa systems, which presumably could be an important contributing factor to high and comparative carbon stocks after the change of landuse from forest ecosystems to shaded-cocoa landuses.
2. The effects of topography on carbon stocks in this research cannot be ignored. The upper slope positions recorded 5.11 % and 7.39 % of more SOC stocks than the middle and lower slope positions respectively in the total profile. On the other hand, slope influence on the topsoil was statistically not significant between landuses This suggests the need to consciously adopt land/farm management practices that do not expose soils, especially, in the lower hillslope positions to minimize the disturbance and exposure of these soils and subsequent breakdown of carbon stored in them.

3. For the first time, the use of E4:E6 ratio to assess humic substances (carbon quality) in Ghanaian cocoa systems was studied. It was confirmed that:

- Landuse change influenced carbon quality increasing carbon stability in the cocoa system than in the forest. Based on the results, it is posited that more stable organic molecules (lower E4:E6 ratio) are found under cocoa systems whereas higher proportion of less stabilized, more soluble organic molecules (higher E4:E6 ratio) are found in forest soils.
- Depth wise, carbon in the forest system was more stabilized in the upper horizons which is likely to prevente the leaching and mineralization of SOC and nutrients in the soil.
- Carbon quality in the upper hillslope positions were more stabilized as lower E4:E6 ratios were recorded. More stabilized carbon was also observed in the upper hillslope position for the forest system showing better soil conditioning. The higher rate of fulvic acid at lower, backslope and toeslope positions may be the result of leaching. Fulvic acids are more soluble and can move with percolating water movements along the slope at low pH.

These are new and significant findings which contribute and adds to the stock of existing knowledge about organic carbon dynamics and carbon quality in shaded cocoa systems following landuse change from forest to cocoa agroforestry in the Ashanti region of Ghana.

4. SOC stocks increased significantly in total profile between the 3 years to 45 years study period showing that SOC stocks increase with time in cocoa agroforestry systems. While knowledge on increasing carbon stocks with duration after forest conversion is known, this study established that SOC stocks in cocoa systems can exceed preconversion levels, especially, if cocoa systems are established after the conversion of secondary forests
4. The research identified that knowledge of soil organic carbon and its impact on climate change and soil properties was nonexistent among farmers in the study area. though they had a rich knowledge about soil organic matter and its influence on soil fertility.

5 CONCLUSION

The conclusion for the first objective is based on aggregated soil properties of both the cocoa and forest soils sampled from the catena study. The general physico-chemical characteristics of soils (0-60 cm soil depth) of the sites depict soils with neutral pH (6.74), and mean parameters ranging from low (exchangeable cations, available P, extractable K, base saturation and C:N ratio), moderate (CEC, Mg^{2+}) to medium (N and OC) levels typical of soils found in the study area. Fertilization of soils using both organic and inorganic fertility resources could improve soil characteristics. The soils were classified as Acrisols according to the WRB soil classification system, and the Nzema and Bekwai series according to the Interim Ghana soil classification system. The Interim Ghana Classification system is a hierarchical taxonomy with fuzzy borders between the classes and more qualitative while the WRB uses strict limits to key out a soil name and provides more information about the major characteristics of soils. The two classification systems should go hand in hand to help farmers, policy makers and researchers understand the soils of Ghana better.

In the second objective it was observed that soil organic carbon (SOC) concentrations between forest and cocoa systems were similar for all studied depth, more probably because of their similarities as tree-based landuse systems. Mean SOC concentrations in both forest and cocoa systems for the different depths ranged from 0.22 % to 2.78 % across all sites, and in the topsoil were higher than the critical level of 1.1% below which serious decline in soil quality may occur in agricultural soils. Based on our findings, it can be concluded that good land management decisions such as agroforestry, mulching, minimum tillage etc protect soils from SOC decrease after landuse change.

Conversion of forest to cocoa agroforestry influenced carbon quality except for the 0–5 and 30–60 cm depths. Generally, the forest contained significantly higher E4:E6 ratios than the shaded-cocoa soils. Thus, we can conclude that more stable organic molecules (lower E4:E6 ratio) are found under cocoa systems whereas higher proportion of less stabilized, more soluble organic molecules (higher E4:E6 ratio) are found in forest soils. Depth wise, carbon in the forest system was more stabilized in the upper horizons. Soil C:N ratio was generally lower than 10 suggesting favourable mineralization of SOM in both cocoa and forest soils.

SOC stocks were similar in forest and cocoa systems with no significant ($p > 0.05$) differences observed at most individual depths (0–5, 5–15, 60–100 and 100–145 cm). SOC stocks were higher in cocoa than in forest soils at the 15–30 and 30–60 cm depths being at least 21%, greater in cocoa compared to the secondary forests. Based on the results, we concluded that differences between SOC stocks of the studied old cocoa and forest systems are generally small.

Generally, topography affected SOC concentration significantly only at 5-15 cm depth. SOC concentration also differed significantly between forest and cocoa systems only at the lower hillslope position for the 0-5 cm depth. For all other hillslope positions, concentrations were similar.

It was observed that E4:E6 ratios were also signifcantly ($p < 0.001$) affected by slope positions, especially, in the topsoil layers (0–5, 5–15, 15–30 cm). Slope positions did not affect the ratios at lower soil depths, and C:N ratios were not affected by slope position at all depths. More stabilized carbon was also observed in the upper hillslope position for the forest system showing better soil conditioning while increasing clay content seems to promote the release of humic substances.

Hillslope positions' impact on SOC distribution in both the cocoa and forest soils was generally similar and statistically not significant. The slope influence on the topsoil was statistically not significant between the landuses. However, cumulatively, the upper slope significantly had higher SOC (stocks) at the 0-30 cm and 0-60 cm depths than in the other slope positions. The upper slope positions contained about 5 % and 7 % more SOC stocks than the middle and lower hillslope positions, respectively, in the total profile. It can generally be concluded that topography influences SOC storage and permanence.

The fourth objective of the study clearly show a steady buildup of SOC stocks along the chronosequence of shaded- cocoa farms with SOC stocks increasing with increasing cocoa plantation age. SOC stocks in shaded-cocoa systems are comparable to natural secondary forests in accumulating high amounts of SOC. The SOC stocks increased significantly in the studied 0-60 cm depth between the 3 and 45 years old cocoa plantations. The steady increase in SOC stocks with increasing cocoa plantation age highlights the importance of the application of good management practices and the maintenance of matured cocoa agroforestry systems.

Soil carbon stocks were generally high over the 45-year chronosequence exceeding the stocks observed by Dawoe (2009) in forest systems. It can be concluded that less soil disturbance and mechanical interventions in shade cocoa systems may not only reduce SOC losses but may also contribute more to C inputs through incorporation of organic residues.

The study showed that farmers have a rich knowledge about their soils. Their knowledge and perceptions regarding their soil management practices, the role of soil organic matter and their effect on soil fertility have developed over time and, is based on their experiences and information acquired from their forefathers, fellow farmers, and formal training. Farmers perceived that there was a relationship between organic matter and soil fertility. Even though they did not have a scientific understanding about the relationship between soil organic matter and soil fertility, they knew that soils would not be fertile and would be less productive without organic matter. On the contrary, their knowledge of soil organic carbon and its impact on climate change and soil properties was nonexistent. Most importantly, their current farm management practices have been influenced by knowledge gained through their involvement in the training given to them through extension officers from the MoFA and NGOs. The inclusion of farmers' rich local knowledge would be important for the development of sustainable farm management practices. The scaling up of extension activities in the study area is required to enable farmers to be informed about the role of SOC and soil management practices required to mitigate the effects of climate change and increase soil fertility.

6 REFERENCES

Bautista, F., García, E., & Gallegos, A. (2016). The App SOC plus a tool to estimate and calculate organic carbon in the soil profles. J. Appl. Res. Technol. 14, 135–139. https://doi.org/10.1016/j.jart.2016.03.002.

Blake, G.R., & Hartge, K.H. (1986). Bulk density. In: Klute A, editor. Methods of soil analysis. Part 1, physical and mineralogical methods. 2nd ed., Agronomy Monograph No. 9. Madison, WI: *Soil Science Society of America*, p. 363–375.

Buri, M. M., Iassaka, R. N., Fujii , H., & Wakatsuki, T. (2009). Comparison of Soil Nutrient status of some Rice growing Environments in the major Agro-ecological zones of Ghana. *International Journal of Food, Agriculture & Environment,* 8 (1), 384- 388.

Carter, M. R., & Gregorich, E. G. (2008). Soil Sampling and Methods of Analysis Second Edition Edited by. In E. G. Carter, M.R., Gregorich (Ed.), *Canadian Society of Soil Science*, CRC Press.

Chen, Z.S., Hsieh, C.F., Jiang, F.Y., Hsieh, T.H., & Sun, I.F. (1997). Relationships of soil properties to topography and vegetation in a subtropical rain forest in southern Taiwan. *Plant Ecol*, 132, 229– 241.

Che, M., Gong, Y., Xu, M., Kang, C., Lv, C., He, S., & Zheng, J. (2021). Effects of elevation and slope aspect on the distribution ofthe soil organic carbon associated with Al and Fe mineral phases in alpine shrub– meadow soil. *Science of the Total Environment*, 753, 141933. 10.1016/j.scitotenv.2020.141933

Dawoe, E. (2009). Conversion of natural forest to cocoa agroforest in lowland humid Ghana: impact on plant biomass production, organic carbon and nutrient dynamics. *Ph.D. Thesis, Kwame Nkrumah University of Science and Technology* (pp. 279).

Dawoe, E. K., Quashie-sam, J. S., & Oppong, S. K. (2014). Effect of land-use conversion from forest to cocoa agroforest on soil characteristics and quality of a Ferric Lixisol in lowland humid Ghana. *Agroforestry Systems*, 88, 87-99. doi: 10.1007/s10457-013-9658-1.

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Global change Biol*, 17,1658-1670.

Durán-Zuazo, V.H., Francia-Martínez, J.R., García-Tejero, I., & Cuadros-Tavira, S. (2013). Implications of land-cover types for soil erosion on semiarid mountain slopes: towards sustainable landuse in problematic landscapes. *Acta Ecol. Sin*, 33, 272– 281.

Egnér, H., Riehm, H., & Domingo, W. R. (1960). Untersuchungen uber die chemische Bodenanalyse als Grundlage fur die Beurteilung des Nährstoffzustandes der Böden. II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. Kungliga Lantbrukshögskolans Annaler, 26, 199–215.

FAO. (2006). Guidelines for soil description. 4th edition, Food and Agriculture Organization of the United Nations, Rome, 2006.

Fernández-Romero, M. L., Lozano-García, B., & Parras-Alcántara, L. (2014). Topography and land use change effects on the soil organic carbon stock of forest soils in Mediterranean natural areas. *Agriculture, Ecosystems & Environment*, 195, 1–9. doi: https://doi.org/10.1016/j.agee.2014.05.015.

Galioto, Thomas Robert (1985). The influence of elevation on the humic-fulvic acid ratio in soils of the Santa Catalina Mountains, Pima County, Arizona. Publisher: University of Arizona. http://hdl.handle.net/10150/191859

Gillman, G. P., & Sumpter, E. A. (1986). Modification to the compulsive exchange method for measuring exchange characteristics of soils. *Aust. J. Soil Res*., 24, 61–66.

Gou,L. B., & Gifford, R.M. (2002). Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345–360.

Haluschak, P. (2006). Laboratory Methods Of Soil Analysis Canada-Manitoba Soil Survey.

Issaka, R. N., Buri, M. M., Adjei, O. E., & Ababio, F. O. (2010). Characterization of indigenous resources in Ghana: Locally available soil amendments and fertilizers for improving and sustaining rice production. CSIR-SRI/CR/RNI/2010/01.

IUSS Working Group WRB. (2015). *World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps*. (World Soil Resources Reports No. 106. FAO, Rome).

Kolavalli, S., & Vigneri, M. (2011). Cocoa in Ghana : Shaping the Success of an Economy. *Yes Africa Can*, pp. 201–217. doi: 10.1596/978-0-8213-8745-0.

Ledo, A., Sith, P., Zerihun, A., Whitaker, J., Luis Vicente-Vicente, J., Qin, Z., McNamara, P. N., Zinn, L. Y., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., & Hillier, J. (2020). Changes in soil organic carbon under perennial crops. *Global Change Biology*, 26(7), 4158–4168. doi: 10.1111/gcb.15120.

Mehlich, A. (1984). Mehlich-3 soil test extractant: a modification of Mehlich-2 extractant. *Communications in Soil Science and Plant Analysis*. https://doi.org/ht10.1080/00103628409367568.

Minasny, B., McBratney, A.B., Malone, B.P., & Wheeler, I. (2013). Digital mapping of soil carbon. In: Sparks, D.L. (Ed.), *Advances in Agronomy*. vol. 118. Elsevier Academic Press Inc, San Diego, pp. 1–47.

MOFA. (2009). Agriculture in Ghana. Facts and Figures. SRID, Ministry of Food and Agriculture.

Mohammed, A. M., Robinson, J. S., Midmore, D., & Verhoef, A. (2016). Carbon storage in Ghanaian cocoa ecosystems. *Carbon balance and management*. Springer International Publishing, 11(1), 6. doi: 10.1186/s13021-016-0045-x.

Leifeld, J., Bassin, S., & Fuhrer, L. (2005). Carbon stocks in Swiss agricultural soils predicted by landuse, soil characteristics, and altitude. *Agric. Ecosyst. Environ*., 105, 255-266.

Omari, A. R., Bellingrath-kimura, D. S., Addo, S. E., Oikawa, Y., & Fujii, Y. (2018). Exploring Farmers' Indigenous Knowledge of SoilQuality and Fertility Management Practices in Selected Farming Communities of the Guinea Savannah Agro-Ecological Zone of Ghana. Sustainability 2018, 10, 1034.

Patton, M. Q. (2002). Qualitative research and evaluation methods (3rd ed.). Thousand Oaks, CA: Sage Publications.

Piccolo, A., & Mbagwu, J.S.C. (1990). Effects of different organic waste amendments on soil microaggregates stability and molecular sizes of humic substances. *Plant and Soil*,123 (1), 27-37.

R Core Team (2016). R: A Language and Environment for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/.

Reddy, H., Nagaraja, M.S., Punith Raj, T.S., Police Patil, A.S., & Dhumgond, P. (2014). Elemental analysis, E4/E6 ratio and total acidity of soil humic and fulvic acids from different landuse systems. *Ann. Plant Soil Res*., 16, 89–92.

Rezaei, H., Jafarzadeh, A., Alijanpour, A., Shahbazi, A. F., & Kamran, K. V. (2015). Effect of Slope Position on Soil Properties and Types Along an Elevation Gradient of Arasbaran Forest, Iran. *International journal on Advance science engineering information technology*, 5 (6), 449-456. DOI: 10.18517/ijaseit.5.6.589

Ross, D. S., & Ketterings, Q. (2011). Recommended Methods for Determining Soil CationExchange Capacity. In A. Wolf & J. McGrath (Eds.), ” *Recommended Soil Testing Procedures for the Northeastern United States (3rd ed.).*

Social Research Association (SRA) (2003). Ethical Guidelines. Available at: https://the-sra.org.uk/SRA/Resources/Goodpractice/SRA/Resources/GoodPractice.aspx?hkey=ccb6430d-24a0- 4229-8074-637d54e97a5d, (assessed, December 2019).

Solomon D, Fritzsche F, Tekalign M, Lehmann, Zech W (2002) Soil organic matter dynamics in the sub-humid agro-eco- systems of the Ethiopian highlands: evidence from natural 13C abundance and particle-size fractionation. Soil Sci Soc of Am J 66:969–978

Snoeck, J., & Jadin, P. (1992). Cacao. In “IFA World Fertilizer Use Manual”, pp. 520–531. IFA, Paris.

Statistix 7.0 for Windows (2000). Analytical Software, Tallahassee, FL, USA.

Stevenson, F. J. (1994). Humus Chemistry: Genesis, Composition and Reactions. John Wiley and Sons Publications, New York. pp. 496.

van Reeuwijk, L. (2002). Procedures for soil analysis (L. van Reeuwijk (ed.); 6th ed.). *International Soil Reference and Information Centre (ISRIC)*.

Whalen J.K. (ed.) (2012). Soil Fertility Improvement and Integrated Nutrient Management - A Global Perspective. 318 pages, Publisher: InTech, Chapters published under CC BY 3.0 license.

Wu, G. L., Liu, Y. F., Cui, Z., Liu, Y., Shi, Z. H., Yin, R., & Kardol, P. (2020). Trade-off between vegetation type, soil erosion control and surface water in global semi-arid regions: A meta-analysis. Journal of Applied Ecology, 57(5), 875-885.

Zhang, Z.C., Hou, G., Liu, M., Wei, T.X., & Sun, J. (2019). Degradation induces changes in the soil C:N:P stoichiometry of alpine steppe on the Tibetan Plateau. *J. Mt. Sci*., 16, 2348–2360.

LIST OF PUBLICATION AND CONFERENCES

Adiyah, F, Micheli, E., Csorba, A., Weldmichael , T. G., Gyuricza, PhD C., Melenya, O. C., Dawoe, E.,*, Owusu, S., & Fuchs, M. (2022). Effects of land use changes and topography on the quantity and distribution of soil organic carbon stocks on Acrisol catenas in tropical small-scale shade cocoa systems of the Ashanti region of Ghana. https://doi.org/10.1016/j.catena.2022.106366

Awoonor, J. K., **Adiyah, F.,** & Dogbey, B.F. (2022). Land-Use Change on Soil C and N Stocks in theHumid Savannah Agro-Ecological Zone of Ghana. Journal of Environmental Protection, 13, 32-68. https://doi.org/10.4236/jep.2022.131003

Adiyah, F., Fuchs, M., Micheli, E., Dawoe, E. & Kovacs, E. (2021). Cocoa farmers' perceptions of Soil Organic Carbon effects on fertility, management and climate change in the Ashanti region of Ghana. Afr. J. Agric. Res. Vol. 17(5), pp. 714-725, May, 2021. DOI: 10.5897/AJAR2020.15320 http://dx.doi.org/10.5897/AJAR2020.15320

Awoonor, J.K.,Yeboah, E., Dogbey, B.F. & **Adiyah, F.** (2021) Sustainability Assessment of Small-holder Farms in the Savannah TransitionAgro-Ecological Zone of Ghana. Agricultural Sciences, 12, 1185-1214 https://doi.org/10.4236/as.2021.1211076

Weldmichael, T. G., Márton, D., Simon, B., Michéli, E., Reda, G. T., **Adiyah, F.,** & Cserháti, M. (2021). Bacterial Community Characterization and Microbial Respiration of Selected Arable Soils of Ethiopia. Eurasian Soil Science, 2021, Vol. 54, No. 12, pp. 1921–1934. https://doi.org/10.1134/S1064229321120140

Adiyah, F., Duah A. S., & Fuchs, M.(2018). Evaluation of some selected soil parameters influencing water management of different types of soils in Ghana: A case study in Ashanti region. In G. habil Jakab, A. Tóth, & E. Csengeri (Eds.), International Conference on Water Sciences, Szent Istvan University, Szarvas, Hungary, March 22, 2018 (pp. 211–217). Szent Istvan University. http://intelszak.szarvas.szie.hu/sites/default/files/uploads/444_compressed.pdf