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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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DEDICATION

This work is dedicated to:

My husband, Dr. Reagan Kaaiemabong Daplah, for encouraging me to pursue a PhD degree. I am happy to share with him the joy of celebrating the Doctor of Philosophy degree achieved.

My daughter, Elsa Daplah, you have endured my absence when you needed the presence of a mother in growing up. It was not easy for you but you held on to the end and I say thank you for your sacrifice.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
BS	Base saturation
CEC	Cation Exchange Capacity
cmol kg^{-1}	Centimole per kilogram
C:N	Carbon to nitrogen ratio
FAO	Food and Agriculture Organization
g cm^{-3}	Gram per centimeter cube
HSD Test	Honestly Significant Difference Test
mg kg^{-1}	Milligram per kilogram
Mg	Mega-gram (ton)
pb	Bulk density (dry)
Pg	Petagram
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
MoFA	Ministry of Food and Agriculture
RMP	Recommended management practices
SEM	Standard error of mean
SD	Standard deviation
SRI	Soil Research Institute
mg	milligram
USDA	United State Department of Agriculture
WRB	World reference base for soil resources

1.0 INTRODUCTION

This chapter introduces the study, presents its importance and the research problem to be investigated. It is further organized under the following sub-headings: the background, problem statement, research objectives and research questions. The background provides information about the agriculture sector of Ghana, traditional soil management systems and soil organic carbon (SOC) under shaded-cocoa systems. The problem statement highlights the gaps that justify the need for further research and intervention. Research objectives state the individual purpose of this research and finally, the research questions which are questions presented to achieve the objectives of the research.

1.1 Background

1.1.1 The Agriculture Sector in Ghana

Agriculture is the primary occupation of the economically active group of the country both directly and indirectly, therefore, the country's economy is dominated by the agricultural sector with 54% in terms of its share of Gross Domestic Product (GDP), employment and 40% foreign exchange earnings. Although food crops contribute most to agricultural output, cocoa production continues to dominate as an individual export crop as Ghana produced about 0.835 million Mg (18.2% of global production) in 2014 (FAOSTAT 2016). Ghana and Côte d'Ivoire produce almost half of the world's cocoa beans. The sector consists of smallholder farmers with an average holding of less than one hectare accounting for 80% of the agricultural production.

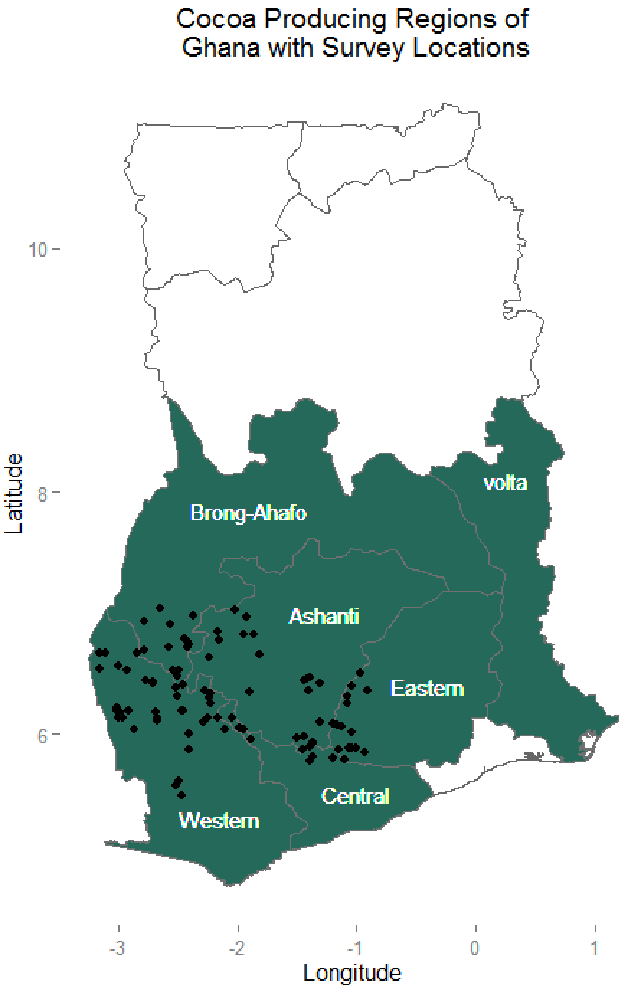


Figure 1.1 Cocoa producing regions of Ghana (Source: McKinley et. al., 2016)

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). Cocoa's contribution to agricultural growth from 2006 to 2016 has been 10%, which remains a concern because yields were well below potential levels and not rising fast in its competitiveness (FAOSTAT, 2018). Averagely, the national cocoa yield in Ghana from 2015-2019 was 525 kg ha^{-1} (FAOSTAT, 2020) which was below the potential of 1889 kg ha^{-1} estimated by Aneani & Ofori-Frimpong (2013). According to Bymolt (2018) cocoa yield for 2015-2016 was 360 kg/ha for the Ashanti region of Ghana. The Brong Ahafo, Central, Eastern and Western regions of Ghana recorded 367, 538, 390 and 468 kg/ha of cocoa yields, respectively (Bymolt, 2018). Poor cocoa yields could be due to many factors such as varieties grown, soil fertility, pest and diseases, and management and agronomic practices (Acheampong, 2014). 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. The majority of farmers attribute the low productivity of their soils to the high cost of maintaining soil fertility on their farms. 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.

The aim of this research was to explore the effects of topography, time and landuse change from forest to cocoa agroforestry on the quantity, quality, and depth distribution of SOC stocks, and provide qualitative information about farmers' understanding of their soils.

1.1.2 Traditional soil management systems in Ghana

Traditionally, land preparation involves slashing and burning of trees and the removal of unwanted plants and weeds to make the land bear. This process results in the volatilization of carbon (C) and nitrogen (N) into the atmosphere, which influences global warming and affects SOC stocks. Ash from burned biomass incorporated into the soil increases phosphorus (P) and other cations, increasing soil fertility (Nye & Greenland, 1960; Giardina et al., 2000). Farms are abandoned after three years when yields begin to decline for new fields to be cleared. This is a strategy meant to restore SOC and soil fertility on the abandoned farms through fallowing. However, land scarcity and the need to increase food production due to population pressure have led to short and, in some areas, the non-existence of fallow periods (Dawoe, 2009).

1.1.3 Soil organic matter dynamics under shaded-cocoa systems in Ghana

Cocoa cultivation is typically done on cleared forest land or grown on forest soils (Vervuurt et al., 2022), which are relatively higher in SOC stocks, especially under the virgin forest. In the perennial tree cropping systems, SOC stocks and soil fertility is preserved through a closed recycling system. Soils are productive and environmentally sustainable for up to 30-50 years; hence may not require fertilization within these periods (MoFA, 1998; Dugumah et al., 2001). However, in recent years, dwindling forest areas in the Ashanti Region have made secondary forest fallow the most common landuse prior to cocoa cultivation (Atwima Nwabiagya Municipality, 2018).

The SOC stocks of soils under cocoa agroforestry systems can be sustained for a long time due to the ability of cocoa to recycle organic carbon back into the soil through litterfall and litter decomposition (Ledo et al., 2018). Organic matter from this biomass sustains productivity as SOC stocks increase but with continuous harvesting of beans over a while, nutrient diminishes.

1.2 Problem Statement and justification.

1.2.1 Cocoa systems as potential source and sink of soil organic carbon

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. Most soils in Ghana are old and highly weathered, having low organic matter content (about 1.5% in the A horizon) (Adu, 1992). These soils have been leached over a long period making them acidic and dominated by low activity clays, low cation exchange capacity (CEC), and low base saturation (Adu, 1992). Dominant soils are Acrisols and Lixisols (IUSS Working Group WRB, 2015) ("Ochrosols" in the interim Ghana soil classification system) and these are found in the moist Semi-deciduous forest zone. Their characteristics affect their nutrient reserves which are falling, and this continues to cause a significant decline in the yields of food and cash crops on smallholder farms. 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.

1.2.2 Potential carbon in the subsoil

Global soil survey indicates that the soil can store about 1500-1600 Pg of C in the 1 m depth (Batjes, 2014). It has been recognized that SOC is mostly found in the topsoil of 30 cm depth. Evidence also exists to suggest that deeper soils similarly can sequester high amounts of SOC (Congreves et al., 2014; Jobbágy & Jackson, 2000; Lorenz & Lal, 2005) mainly as a result of soil organic matter stability with increasing soil depth (Sollins et al., 1996). Recalcitrant chemical compounds such as lignins, tannins, and suberins in deeper soil layers serve as potential sinks for C sequestration (Lorenz & Lal, 2005). Few studies such as Dawoe (2009); Mohammed et al. (2016) have assessed the potential of subsoil in cocoa agroforestry systems to sequester carbon in Ghana, but related SOC data is limited. Information on SOC in deeper layers is critical to help deal with climate change.

1.2.3 National carbon emission budget of Ghana

The need for environmentally viable agro-production systems has necessitated identifying strategies for mitigating the negative effects of global warming, therefore introducing a national carbon emission budget for every country to play its part (Chagas et al., 2010; Acheampong et al., 2014). Ghana seeks to reduce carbon emissions by promoting climate-smart cocoa production which will help secure the future of Ghana's forests while enhancing income and livelihood opportunities for farmers (Chagas et al., 2010). Farms are created in the forest through the cutting down of trees; this results in significant emissions. Therefore, climate-smart cocoa production is a more sustainable option that is supposed to help to avoid the expansion of cocoa farms into forest lands. Incomes of farmers are continuously being improved by increasing cocoa prices and increasing access to financial services, which are supposed to positively influence soil management. The cocoa sector's inclusion into the nation's carbon emission budgetary plans calls 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 agroforests is well established and supported in our study.

1.3 Research Objectives

Against the background of the importance of SOC to ecosystem services and its influence on climate change, the overall purpose of this study is to provide quantitative information on the effects of forest conversion to shaded-cocoa systems on the depth distribution of SOC stocks and provide qualitative information about farmers' understanding of their soils. The study may contribute to the development of environmentally sustainable management practices as well as developing principles and management strategies to enhance SOC stocks in shaded-cocoa systems. The following objectives were defined to achieve this aim:

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

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

1.4 Research questions

The questions that guided the study were:

1. Objective one

- i. What are the defining characteristics of soils under the studied cocoa and forest systems?
- ii. What are the major WRB reference soil groups (RSGs) under the studied cocoa and forest systems?
- iii. What are the major soils observed using the Ghana soil classification system?

2. Objective two

- i. What are the effects of landuse change on selected soil physical and chemical properties (bulk density , texture, pH, SOC, C:N ratio, E4:E6 ratio, CEC, Ca^{2+}, Mg^{2+}, K^{+}, Na^{2+}, and macro-nutrient (N, P and K) stocks) under the studied cocoa and forest systems?
- ii. What are the effects of landuse change on SOC quality and depth distribution under the studied cocoa and forest systems?
- iii. What are the effects of landuse change on the soils' macro-nutrient content and depth distribution under the studied cocoa and forest systems?

3. Objective three

- i. What are the effects of slope position on SOC quantity and depth distribution under the studied cocoa and forest systems?

ii. What are the effects of slope position on the SOC quality and depth distribution under the studied cocoa and forest systems?

iii. What are the effects of slope position on soil macro-nutrient content and distribution under the studied cocoa and forest systems?

4. Objective four

i. Does SOC change with time in the studied cocoa systems, and which depths are most affected?

5. Objective five

i. What are farmers' perceptions on SOM and SOC?

ii. What are the perceptions of farmers on management practices adopted on cocoa farms that affect soil organic carbon?

iii. What are farmers' perception of climate change, the effects of climate change on SOM/SOC and the effects of SOM/SOC on mitigating the impacts of climate change?

1.5 Hypotheses

The study hypothesized that:

a) Soil characteristics of the forest and cocoa landuse are similar.
b) Landuse will affect SOC dynamics and physico-chemical properties.
c) SOC dynamics and physico-chemical properties is affected by top-sequence/ hillslope positions.
d) SOC stocks and bulk density will change significantly with time (15 years).
e) Cocoa farmers' local knowledge of soils affect the management practices they adopt.

1.6 Justification for study municipality

Firstly, the Atwima Nwabiagya municipality was chosen because of previous research on SOC accumulation conducted here between 2005 and 2008 (Dawoe, 2009). The study assessed the impact of forest conversion on plant biomass production, on organic carbon and nutrient dynamics, and therefore provided a compelling basis for a follow-up study fifteen years later. Secondly, the municipality has a meaningful framework with which data collection and analysis and recommendations can be implemented sustainably. Lastly, the municipality provides opportunities for understanding the nature of cocoa production. It is one of the oldest cocoa growing districts in the Ashanti region through historical factors and research, therefore, allowing a comprehensive and holistic approach with the possibility of scaling-up to other areas.

2.0 LITERATURE REVIEW

This section presents a review of existing literature relevant for this thesis. The major soils of Ghana and the characteristics of soils in the Ashanti region are presented. Secondly, SOC and its dynamics in the tropical forest and cocoa agro-ecosystem are discussed. The nutrient cycling under these systems are also presented. Thirdly, effects of land-use change, management practices, topography and time on SOC are discussed. Methods for measuring and sampling SOC are discussed, and SOC stock calculation is introduced. Lastly, indigenous knowledge contribution to soil is presented in this section.

2.1 Major soils of Ghana

Accurate soil information is essential for sustainable agriculture (Viscarra-Rossel, 2008) and climate change mitigation (Bajtes, 1996) - thus knowledge of soils and its major characteristics in the studied region has high importance.

The African continent is characterized by great soil diversity having Arenosols (22%), Leptosols (17%), Cambisols (11%) and Ferrasols (10%) as the major soil types according to the WRB international soil correlation system (Jones, et al., 2013). The main soil types of Ghana are Acrisols, Alisols, Lixisols and Plinthosols (European Commission, 2013). The characteristics of these soils are influenced by local climate and vegetation, as well as other organisms acting on the various geological materials and modified by topography over time (Brammer, 1962).

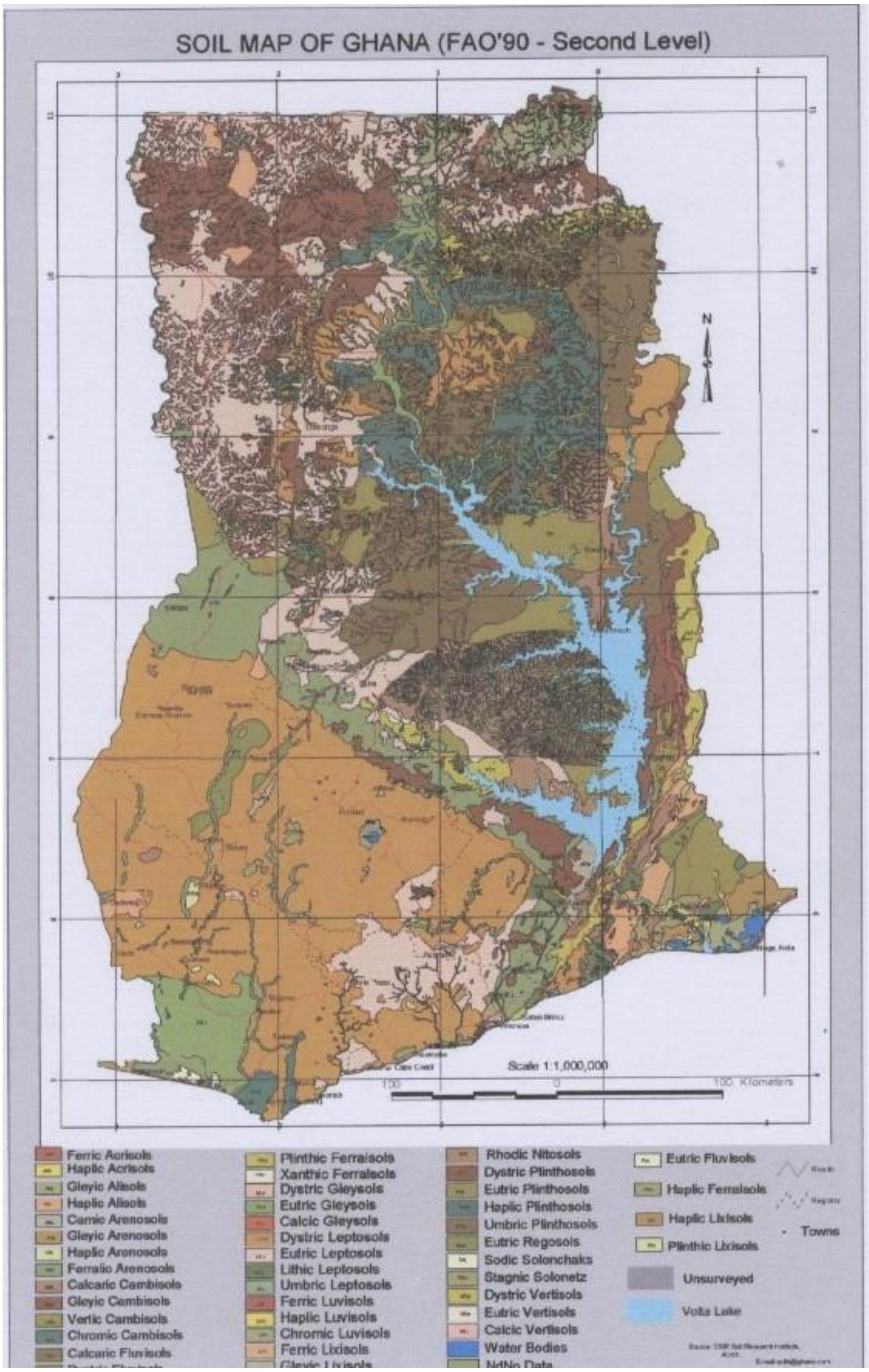


Figure 2. 1 Classification of Ghana soils according to the FAO soil classification system (Source: CSIR- Soil Research Institute)

2.1.1 Characteristics of major soils in the Ashanti Region

Soil information in the Ashanti region is mainly found in MEMOIRs written by the Soil Research Institute (Council for Scientific and Industrial Research). Adu (1992), in the MEMOIR No. 8 titled Soils of the Kumasi Region, Ashanti Region, Ghana discussed extensively the soil formation processes, soil classification and soil suitability of the region. This MEMOIR is highly dependent on soil information by researchers (Afrifa et al., 2009; Dawoe et al., 2014).

Soil mapping, classification and evaluation began in Ghana in 1946. The experiences collected about soils during the 1940-60s period resulted in the formulation of the so-called "Interim Ghana Soil Classification System" (Brammer, 1962). The System, which is multi-categorical, has been an important tool in the mapping and classification of soils in the whole country (Adjei-Gyapong & Asiamah, 2002).

In Ghana, the usual soil mapping unit used is the soil series according to the Interim Ghana Soil Classification System, and these are defined as soils with similar profile morphology derived from similar conditions of climate, vegetation, relief, and drainage. For a survey for larger areas, soil series are combined into larger assemblages known as soil associations. In the Ashanti region soils are usually developed on Lower Birimian Phyllites, Greywackes, Schists and Gneisses, and are classified as the following: the Bekwai-Nzima/Oda Compound Association, Akumadan-Bekwai/Oda Compound Association, Bekwai-Zongo/Oda Complex Association, Mim/Oda Compound Association, Kobeda-Amuni-Bekwai simple and Association Asikuma-Atiwa-Ansum/Oda compound Association (Crossbie, 1954, 1955; Adu & Mensah-Ansah, 1971; Adu, 1992).

According to Adu (1992), the majority of soils in the Ashanti region are mainly Acrisols with some Nitisols, Alisols, Leptosols, Gleysols, and Fluvisols according to the Soil Map of the World Revised Legend (FAO, 1988). Acrisols have clay accumulation ("argic") horizon characterized by low-activity clays (mostly kaolinite) in the argic horizon and a low base saturation in the 50–100 cm depth. Acrisols are generally developed on weathering products of parent materials such as phyllites, schists, granites, sandstones, peneplain drifts, and can be found on terraces and on gently undulating to strongly rolling topography. The texture of soils is related to the nature of the parent material, and these include soils being more sandy, having iron-pan, bauxite, or more ironstone concretions in the subsoil, having gravels, and stones to varying degrees. Originally, Acrisols are good for tree crops and forestry. Despite their challenges, Acrisols are suitable for both trees (cocoa, coffee, citrus and oil palm) and arable crops (maize, cassava, yams, cocoyam, plantain and banana (Adu, 1992; Adiyah et al., 2021). But Adu (1992) recommends hand cultivation rather than intensive mechanical cultivation of these soils.

Nitisols are deep, well-drained, red tropical soils with diffuse horizon boundaries and a subsurface horizon with at least 30 percent clay and moderate to strong angular blocky structure breaking into polyhedral or flat-edged or nut-shaped elements with, in moist state, shiny aggregate faces. Weathering is relatively advanced but Nitisols are far more productive than most other red tropical soils.

Alisols have a clay accumulation (“argic”) horizon characterized by high-activity clays throughout the argic horizon and a low base saturation in the 50–100 cm depth. Leptosols comprise very thin soils over continuous rock and soils that are extremely rich in coarse fragments, and are particularly common in mountainous regions. Gleysols comprise soils saturated with groundwater for long enough periods to develop reducing conditions resulting in gleyic properties, including underwater and tidal soils. Fluvisols accommodate genetically young soils in fluvial, lacustrine, or marine deposits.

2.2 Soil organic carbon cycling in tropical forest and cocoa agro-ecosystems

SOC remains in soil after partial decomposition of living organisms. It is a key element in carbon cycling through the atmosphere, vegetation, and soil (Von Lützow et al., 2006; Paul, 2014). The importance of SOC as a key supporter of soil functions such as soil structure stabilization, retention and release of plant nutrients, water infiltration and storage cannot be ignored. It is therefore essential to ensure soil health, fertility and food production. The loss of SOC indicates a degree of soil degradation and exacerbates climate change (FAO & ITPS, 2015).

SOC is a useful indicator of soil health in the study area, which controls the soil structure development, nutrient turnover stability, regulation of carbon emission, moisture retention and susceptibility to land degradation (Mu et al., 2014; Lorenz & Lal, 2016; FAO, 2017a). Thus, a reliable assessment of SOC is essential for farmers, scientists and policy makers in contributing to sustainable agriculture while reducing the negative effects of climate change. Furthermore, a quantitative estimate of SOC in different land-use systems and soils is necessary for SOC monitoring (Owusu et al., 2020). The Ashanti region falls under the Semi-Deciduous Forest (SDF) of the Agro-Ecological Zones (AEZs) in Ghana that has a mean SOC concentration of 11.2 g kg^{-1} and SOC stocks of 24.8 Mg C ha^{-1} (ISRIC SoilGrids (ftp://ftp.isric.org); Owusu et al., 2020). On a wider scale, SOC content of soils in Africa is poor and can be attributed to carbon releases from land-use conversion from forest to agriculture. Appropriate land-use management could contribute to soil carbon sequestration (FAO, 2015).

According to FAO (2017), soils under forest ecosystems could serve as a hot spot for SOC sequestration. SOC in these systems is heterogeneous and can be found in different SOC pools. The SOC pool is mainly humus, which is a mixture of plant and animal residues at various stages of decomposition and microbial by-products (Lal, 2004a). Pools consist of the particulate organic carbon (fresh plant residue), slow pool (humus which is the product of decomposition), dissolved organic carbon, microbial biomass (micro and mesofauna) inert and passive or resistant C (complex organic carbon, char, and phytoliths), having different turnover times (<10 years, 10-200 years, and > 100 years) respectively (Gregorich & Monreal, 1994; Allen et al., 2010).

Carbon dynamics in the forest is mainly through the assimilation of CO_2 through photosynthesis, plant respiration, transfer of carbon into the soil through leaf, wood and root litter, exudation of organic compounds into deeper depths and then the release of soil carbon back to the atmosphere through decomposition and respiration of microbes and heterotrophs (Malhi & Grace, 2000; Owusu-Bennoah et al., 2000). Therefore, the net C budget of a tropical forest is the balance between net production and heterotrophic respiration (Malhi & Grace, 2000). Tropical forest is characterized by high temperatures which generally favor microbial activity throughout the year. Usually, there is low storage of carbon with high amount of litter decomposition. Although rising temperatures may increase production, which eventually increase carbon inputs to the soil, microbial decomposition of SOC tend to increase (Keestrea et al., 2016).

Cocoa (*Theobroma cacao* L.) is usually cultivated in agroforestry systems and is credited for storing significant amounts of carbon (Dixon, 1995: Oke & Olatiilu, 2011; Dawoe et al., 2014; Mohammed et al., 2016). The carbon dynamics in matured cocoa agroforestry systems is not different from that of the forest as it captures atmospheric carbon dioxide and stores carbon in shade and cocoa trees and soils (Dawoe et al., 2014; Dawoe et al., 2016).

2.2.1 Depth distribution of Soil Organic Carbon

The storage of SOC in the soil is determined by the additions and losses of C which depend on the abundance of plant species (faunal and microbial), and also on environmental factors such as temperature, moisture and soil texture (Lorenz & Lal, 2005). However, Batjes (1996) mentions vegetation and landuse change as the main factors that influence SOC variations in soils. Jobbágy & Jackson, (2000) confirms that vertical SOC distribution is affected by vegetation types The importance of roots for soil carbon sequestration is backed by their potential to be stabilized in soil. Global SOC pool to 2 m is lower in tropical regions compared to all other regions (Batjes, 1996). Regardless of their low carbon (C) content, most subsoil horizons contribute to more than half of the total soil carbon stock (Rumpel & Kögel-Knabner, 2011). Organic carbon finds its way into subsoil in the form of dissolved organic carbon (DOC) through the pathway flow as aboveground or root litter and exudates along root channels and or through bioturbation (Hobley and Wilgoose, 2010; (Rumpel & Kögel-Knabner, 2011). According to Batjes (1996), higher concentrations of SOC can be found in top layers of soils but a large amount can also be stored between 1-and 2- m and large amount of SOC can also be found below 1 m e.g. in Acrisols. Sub-humid forest has shallow SOC concentration (Jobbágy & Jackson, 2000). Jobbagy & Jackson (2000) have estimated soil profiles of 3 m depth related to natural vegetation. Sommer et al. (2000) also did a study on carbon storage up to 6-m depth in different land-use systems in the Eastern Amazon region of Brazil, and observed that even though carbon concentrations of the deeper layers (>1 m depth) were low they still contributed about 50% to the total carbon content of the soil under extensive root vegetation.

Jobbágy & Jackson (2000) have observed that climate and vegetation are two factors that highly influence the relative vertical distribution of SOC. However, when it comes to determining the absolute amounts of SOC, climate and clay contents are the most important factors. Clay content becomes a dominant factor in increasing depth (Bakhshandeh et al., 2014), therefore soils rich in clay under high rainfall require sampling to the bedrock which is necessary to accurately assess SOC stocks (Hobley & Wilson, 2016). There is also the translocation of organic matter through pedogenic processes (Chabbi et al., 2009). Sampling depths therefore become essential for accurately accounting for SOC stocks explaining the rationale behind the 1 m depth suggested by Lorenz & Lal (2005) as sufficient.

2.2.2 Soil Organic Matter (SOM) dynamics

Soil organic matter (SOM) is defined as a continuum of organic resources from fresh plant residues to stabilized organic matter (OM) or humus (Stevenson, 1994). SOM plays very important role in the absorption and stability of nutrients, soil water holding capacity, erosion, cation exchange capacity and in general improves the environment for plant growth. It serves as the main carbon source which balances the entire soil ecosystem. SOM is extremely important to the potential of carbon sequestration management. Decomposing organic matter releases nutrients like N, P, S and K that are important for plant and microbial growth. It determines cation exchange capacity of some coarse textured and low activity clay soils including Ferrasols and Acrisols, which are dominant soil types in the tropics. SOM is controlled by environmental factors such as moisture, soil temperature, oxygen supply (drainage), soil acidity, soil nutrient supply, clay content and mineralogy (Batjes & Sombroek, 1997). The chemical composition, amount and spatial distribution of fresh organic residues have a varying effect on the content and composition of organic matter in the soil. According to Wattel-Koekkoek et al. (2003), koalinite-associated SOM had a fast turnover (360 yr on average).

2.2.3 Humic fractions and quality of soil organic matter

Organic carbon accounts for almost 62 percent of global soil carbon, with at least half of this carbon classified as the chemically resistant portion known as humic substances (Swift, 1989; Orlov, 1990; Lal, 2004b). These fractions influence soil fertility by regulating most of its processes (Stevenson, 1994; Huang, 2004). Humic substances regulate the solubility and availability of plant nutrients, and are a source of carbon and energy for soil biota. It also regulates the thermal characteristics of soil and water retention capacity (Kunlanit et al., 2019). They are found in three forms and differentiated based on their reactions in alkali-acid solutions. The HA (humic acid) fraction coagulates when alkaline extract is acidified, FA (fulvic acid) fraction: soluble in both acid and alkali; and Humin fractions are insoluble in both acid and alkali conditions (Reddy et al., 2014). However, the status and composition of humic substances are dependent on factors such as climate, biota, topography and management (Feller, 1997).

2.2.3.1 Quality of SOM (E4:E6 ratio)

The humification and stabilization of SOM/SOC are studied by determining the E4:E6 ratio of humic substances (the ratio of absorbance at 465 nm (E4) and at 665 nm (E6) (Chen et al., 1977; Aranda et al., 2011). The E4:E6 ratios determine the degree of aliphaticity or aromaticity of humic substances to the degree of humification. Some studies compared E4:E6 ratios between humic acids and fulvic acids of different landuses (Reddy et al., 2014), while others compared E4:E6 ratios between topsoils and subsoils in cultivated and forest soils (Kunlanit et al., 2019).

2.2.3.2 C:N ratio

The composition of the reactivity of humic substances also includes the carbon-to-nitrogen (C/ N) ratio. The C/N ratio is sometimes used as a determinant for the health of a soil (Xu et al., 2016). Soil microorganisms (fungi, bacteria, protozoa, nematodes, etc.) are directly affected by the C/N ratio. Microbial growth is dependent on nitrogen therefore a higher C/N ratio results in lower decomposition activities by soil microorganisms (Brady & Weil, 2002; Xu et al., 2016). Generally, C/N ratios in cultivated soils are lower than that of the forest due to lower C/N ratios of crop residue inputs and microbial decomposers (Murty et al., 2002). Reddy et al. (2014) recorded wider C/N ratios of HA and slightly wider ratios of FA in forest and coffee plantations than in agricultural soils and these were attributed to N supplementation and the complexity of SOM in agricultural soils. The vertical pattern of C/N ratio along a profile varies with ecosystems and landuse. C/N ratio declines with soil depth in general as subsoils do not have active supplies of SOM and shallow root systems to penetrate (Brady & Weil, 2002). Yang et al. (2010) observed no significant change in C/N ratio along an alpine grassland profile, Lawrence et al. (2015) reported decreasing C/N ratios in shallow soils in southwestern Washington. Therefore the composition of humic substances will be influenced by the nature of OM that is added to soils, as well as its decomposition under varied climates and land-use management (Feller, 1997; Reddy et al., 2014). There is a more intensive humification of humic materials in semi-arid tropical climates than in transitional high rainfall climates as observed by Reddy et al. (2014).

2.3 Nutrient Cycling in Tropical Forest and agro-ecosystems

The nutrient pools in the forest ecosystem are found both above-ground in tree, woody and shrub biomass and below-ground in plant residues, soil fauna, soil organic matter and also in nutrient available soil solution (Isaac et al., 2005; Dawoe, 2009). The major pathway of nutrients consists of stores and flows as well as gains and losses. Nutrient cycling in forest ecosystems is mainly controlled by climate, site, abiotic properties and biotic communities (Foster, 2015). Nutrients are added or lost through natural (e.g., erosion, fire and leaching) and human activities (e.g., management practices) (Lal, 2004). Its availability is strongly influenced by the quantity and quality of litterfall produced in forest (Owusu-Sekyere et al., 2006). Nutrients in tropical forest systems are mainly dependent on the transfer from vegetation to soil through litter production. Soils of the tropics are generally deficient in nutrients due to the fact that they are highly weathered and leached (Jobbágy & Jackson, 2000; Gibbs et al., 2007). Owusu-Sekyere et al. (2006) reported that mean annual litter produced by both primary and secondary semi-deciduous forests was 7.9 Mg ha^{-1}. Hartemink (2005) in a review on nutrient cycling in cocoa systems established that average annual litter-fall in shaded-cocoa across all ages was 10 Mg ha^{-1} yr $^{-1}$. Nutrient cycling in cocoa systems are not very different from that of the forest (Dawoe, 2009). Parent materials on which they develop could not be expected to produce soils rich in plant nutrients (Adu, 1992) if the parent materials are inherently low in nutrients. Also, due to the climatic conditions (erratic) nature of rainfall in the tropics, plant nutrients have been severely and highly leached and eroded. This has been exacerbated by the continuous cultivation of these soils over a long time without any external nutrient inputs. Therefore, the nutrient status of these soils is dependent on the topsoil organic matter mainly. It serves as a medium for feeding plant roots, especially where fertilization is absent or minimal because of the poor economic background of farmers (Dawoe et al., 2014).

2.3.1 Macro nutrients and SOM in cocoa systems

In cocoa systems, soil organic matter serves as a reservoir of nutrients for crops. The decomposition of SOM further releases mineral nutrients such as Phosphorus (P), Nitrogen (N), Potassium (K), Calcium (Ca) and Magnesium (Mg) which are made available for plant growth (Van der Wal & de Boer, 2017).

Phosphorus is one of the very important macro nutrients needed for plant growth. Adu (1992) observed that most of the soils in the Ashanti region are deficient in phosphorus. He explained that this may partly be due to the very small amount of apatite, the source of soil phosphorus originally present in the soil parent material. Dawoe et al. (2014) further explained that its amount available to plants is reduced with high acidity. , The major source of available phosphorus in these soils is organic phosphorus found in the upper thin organic layers (Adu, 1992).

According to Adu (1992), nitrogen is even more closely connected to organic matter than phosphorus. Studies have shown that most soils under secondary forest and thicket vegetation are fairly supplied with nitrogen and this is available to crops for at most the first two years of cultivation of cocoa. Therefore, areas that have been cultivated for long without incorporation of extra nitrogen in the form of fertilizers are very low in nitrogen levels.

Elements such as calcium and magnesium are also sourced from organic matter on the topsoil in general since nutrients readily available to plants are leached through percolating water and washed away through erosion. Levels are therefore low under these systems with continuous cultivation. Dry deposition from the atmosphere may also act as a nutrient source for plants. This is enhanced by the frequent biomass burning that releases a large part of the nutrients stored in aboveground biomass to the atmosphere (Pivello & Coutinho, 1992; Kauffman et al., 1998).

2.3.2 Nutrient exchange

Generally, humus accounts for 50 to 90% of the cation-adsorbing power of mineral surface soils (Brady & Weil, 2008). Humus colloids hold nutrient cations in easily exchangeable forms where they can be used by plants and not readily leached out by percolating waters. Through its cation exchange capacity (CEC) and acid and base functional groups, organic matter provides much of the pH buffering capacity in soils. SOM has a very high CEC ranging from 250 to 400 meq/100g (Moore, 1998), but this CEC strongly depends on the pH of the surrounding solution. Increasing pH increases the amount of pH variable charge, and therefore also increases CEC, while on the other hand, decreasing pH results in decreasing CEC (Brady& Weil, 1999). Thus, in strongly leached and acidic tropical soils, the CEC is generally low.

A decline in CEC with soil depth along with a decline in SOM but unchanged clay content and composition was observed by Oades et al. (1989). Oades et al. (1989) observed that a 1% increase in SOC leads to 1 unit ($\mathrm{cmol}_{(+)}\ \mathrm{kg}^{-1}$) increase in CEC in variable charge soils. Furthermore, SOM’s importance on CEC increases as soils weather and change from aluminosilicates to kaolinite which is mostly associated with SOM (Duxbury et al., 1989). Thus maintaining high SOM is very important in tropical soils.

In addition, nitrogen, phosphorus and micro-nutrients are stored as constituents of soil organic matter, from which they are slowly released by mineralization. Organic matter breaks down mainly into minerals, water and carbon dioxide, and these minerals serve as nutrients for crops (Brady & Weil, 2008). Again, soil organic matter influences the composition of soil organisms like nitrogen fixing bacteria which can change the elemental nitrogen of the air into chemical compounds that plants can use (Calvo, 2014). They are important for nitrogen (N) transformations in the soil since they store nitrogen in their bodies. Small animals including mites and earthworms transform plant and animal waste into rich-humus which improves nutrient cycling.

2.4 Effect of land-use changes on SOM and nutrient content in the tropics

The IPCC in its report attributed about 12-20 % of the human induced greenhouse gas emissions to land-use change and this remains the second largest source (IPCC, 2007). As reported by the FAO (2006) the dominant type of landuse change is the conversion of forests to agricultural systems accounting for about 13 million ha being deforested per year. The destruction of primary forest causes a rapid biomass loss which results in C loss from above and under soils (Dawoe, 2009, Dawoe et al., 2014). In the tropical areas, about 36-60% of C is stored in the soils of the forest (Malhi et al., 1999; FAO, 2006). SOC change is mainly controlled by the decomposition and alteration in the quantity and quality of C cycled through the ecosystem. The landuse and land management may decrease SOC stocks in agricultural systems more than that of the forest through erosion and this is true for soils in the tropics. Low inputs of nutrient and C into nutrient-poor and highly weathered soils of the tropics increases the susceptibility of SOC stocks to erosion (Trumbore, 1993). According to Dixon et al. (1994), C in tropical forests is partitioned more or less equally between the vegetation and soil encouraging rapid decomposition of soil organic matter and recycling of nutrients into vegetation growth.

2.4.1 Conversion of Forest to Agriculture land-use

Studies have shown that forest conversion to agricultural landuse significantly impacts soil's physical and chemical properties and can influence ecological processes depending on the new landuse and the management practices adopted after conversion (Sharma et al., 2004; Goma-Tchimbakala et al., 2008; Dawoe, 2009; Dawoe et al., 2014). SOC and nutrient stocks can be improved by perennial crops through the provision of litter and shading to the soil most especially in the maturity phase. Thus while some studies (Duguma et al., 2001; Wall & Hyto¨nen, 2005) have reported improvements in soil organic carbon and soil fertility under various tree crops and forest plantations, others (Adejuwon & Ekanada, 1988; Ekanade et al., 1991; Ogunkunle & Eghaghara 1992; Duah-Yentumi et al., 1998) have reported declines in fertility following forest conversion to plantations. Contrary to these findings, other reports (Kotto-Same et al., 1997; Kauffman et al., 1998; Smiley & Kroschel, 2008) have also emphasized that soil carbon pools remain approximately constant during most land conversion practices in the tropics. Dawoe et al. (2014) reported that there was a significant reduction of SOC concentrations in the 0-10 and 10-20 cm depth in the early phase after forest conversion to cocoa in the Ashanti region. This change could be due to the decomposition and mineralization of SOM during the first 2-3 years of land disturbance, thus change in SOC concentration is also dependent on soil depth. These and other reports of soil organic matter dynamics following forest conversion illustrate the difficulty in generalizations about the direction of soil organic matter change. Koto-Same et al. (1997) have aptly posited that the magnitude and direction of change of SOC and other nutrients are likely to be a function of several factors including the soil type, initial C content, the history of land-use, the new land-use system and the sampled depth.

2.5 Management, Topography and Time as a function of soil organic carbon

2.5.1 Effect of management practices on SOC

Soil management is potentially an important tool for minimizing global warming through carbon sequestration. Soil fertility and improved physical and biological properties of soil (reduced bulk density, increased water-holding capacity, improved soil structure and increased microbial activity) are all benefits that accrue to soils when SOC is increased (FAO, 2017). Agricultural soils lose organic carbon through mechanisms such as oxidation/mineralization, leaching and erosion hence there is a need for measures that can slow down these processes. Measures such as crop rotation, organic amendment and minimum tillage or no tillage can reverse or slow down the loss of organic carbon (Batjes & Sombroek, 1997; Söderström et al., 2014).

2.5.1.1 The potential of land management in soil C sequestration

Various land management practices have been identified as having great potential to increase C concentration in croplands. Practices such as reducing tillage intensity and frequency, efficient fertilizer application, better crop management and adopting agroforestry practices have been identified as having high potential for soil C sequestration on croplands. Lal (2004) supports these mentioned management practices and coined the term recommended management practices (RMP) for SOC improvement on croplands. The RMPs also included integrated pest management, integrated nutrient management, mulch farming and precision farming. These practices have been argued to reduce soil disturbances, erosion losses and increase quantities of biomass both below and above ground. According to Hutchinson et al. (2007), the benefits from these management practices may depend on geographical region, climatic conditions, soil texture and antecedent level of SOC. However, most land users combine the use of some of these practices. These RMPs aid in moisture conservation and improves biodiversity influencing SOC dynamics. However, it is also argued that improved soil moisture also leads to rapid soil C decomposition thereby reducing SOC content, but with the right management practice and favourable climatic conditions (temperature), soil C decomposition may be less. The relevance of soil biodiversity on SOC and its dynamics cannot be ignored therefore soil biota including earthworms, termites, ants, some insect larvae and some larger animals have strong influence on soil structure, porosity, aeration, water infiltration, nutrient cycling and organic matter pool fluxes. As a consequence, soil management practices contribute to favorable environment for soil biota are favourable for increasing soil C sequestration as well.

2.5.1.2 Agroforestry and soil C sequestration

2.5.1.2.1 Definition and Concept

Agroforestry is a land-use system involving the combination of trees with crops (Duguma et al., 2001) and/or animals on the same land management unit (Bene et al., 1977). It has been an age-old practice where farmers have grown food crops, trees and animals together for producing multiple ranges of products. Bene et al. (1977) defined agroforestry as a sustainable management system for land that increases overall production, combines agricultural crops, forest plants and tree crops and/or animals simultaneously or sequentially, and applies management practices that are compatible with cultural patterns of a local population.

In all agroforestry land management, the idea is to conserve and improve a close system improving nutrient cycling. Therefore there is an optimum combined production of trees, agricultural crops and animals. Mostly agroforestry can improve productivity through output of tree products, improved yields of associated crops, reduction of cropping systems and labour efficiency. It also improves sustainability by conserving the production potential of the resource base mainly through the benefits woody perennials give to soil, therefore, maintain SOC and fertility goals.

2.5.1.2.2 Benefits of Agroforestry

Agroforestry has been shown to provide many benefits over traditional agricultural systems (Jose, 2009; Tscharntke et al., 2011). Literature has shown that soil degradation in the tropics can be reversed through agroforestry (Dawoe et al., 2014). The trees and shrubs improve the physical properties of soil in particular soil aggregation which enhances water infiltration and water holding capacity reducing surface run-off and soil erosion. Trees and shrubs also reduce the impact of drought and this is very important for agriculture in the tropics. The trees' biomass also increases soil organic matter and provides favorable environment for soil biota in breaking down the biomass for nutrient release to plants. Biodiversity conservation is not excluded from the benefits of agroforestry. Trees provide protection within and alongside fields creating secondary habitat for species.

In agroforestry systems water conservation is paramount. There is an improvement of soil moisture retention in rain-fed croplands. Stream flow, flood hazards and water supply through reduction of run-off and improvement of interception and storage in infiltration are all regulated. Also, drainage is improved in waterlogged or saline soils by trees with high water requirements.

Agroforestry has been proven to affect carbon sequestration services and its influence on climate change. Through sequestration, carbon is stored in above ground biomass (Gockowski & Sonwa, 2011; Obeng & Aguilar, 2015) and below ground biomass in soil (Ofori-Frimpong et al., 2007). The role of trees in the capture and storage of atmospheric CO_2 in vegetation, biomass products and soils has been accepted as a GHG- mitigating strategy under the Kyoto Protocol (Nair et al., 2009). The potential of C sequestration under agroforestry is estimated by combining the above ground values and the soil carbon values which is influenced by factors such as climate, soil type and depth, previous and current land-use, selection of species, level of soil disturbances and the initial size of SOC stock. Nevertheless, Blaser et al. (2017) found no evidence of positive improved effects of agroforestry on either carbon sequestration or soil fertility.

2.5.1.3 Soil organic carbon under cocoa land-use

According to Hartemink (2005), most cocoa tap roots are restricted to the depth of 30 cm, hence most of its nutrient is in the topsoil and these cocoa trees remain in their position for many years in which changes in SOC could be dependent on the soil, climate and management practices. Toxopeus (1986) also reported that matured cocoa trees could have tap roots up to 120-200 cm long hence there is the possibility of organic carbon formation in deeper soil layers of cocoa plantations. Most studies have considered soil organic carbon in cocoa systems based on their age, management practices and climate, cocoa density, etc (Isaac et al., 2005; Dawoe et al., 2014; Ajami et al., 2016). They all measured SOC changes ranging from depths of 0-60 cm. Dawoe et al. (2014) used the chronosequence method of studying soil organic carbon under cocoa farms in the Ashanti region of Ghana West Africa and found out significant differences in carbon quantities between 3-year-old and 15-30 years old farms' soils.

2.5.1.3.1 Shaded-cocoa systems and Carbon Sequestration

The concept of carbon sequestration under shaded systems is still yet to be well understood due to the conflicting results of various studies done (Ofori-Frimpong et al., 2007; Gockowski & Sonwa, 2011; Jacobi et al., 2014; Mohammed et al., 2016). However, the Cocoa Research Institute of Ghana (CRIG) recommends to farmers to maintain 16 -18 forest trees on each hectare of cocoa farm with the cocoa trees spaced at 3.0 m apart (Manu & Tetteh, 1987). Afrifa & Acquaye (2010) found out that irrespective of shading, the net gains of carbon in the soils were higher in farms with less plant density, hence, cocoa under shade stores more carbon per unit area of soil than equivalent area of cocoa planted at higher density without shade. Dawoe (2009) also saw a significant decrease in soil carbon stocks in 3 years old cocoa farms which could possibly be as a result of the loss of forest canopy which serves as shade compared to 15- and 30-years old farms that had canopies. However, Gockowski and Sonwa (2011) and Mohammed et al. (2016) observed no effects of shade trees on soil organic carbon. Shade regulates temperature by minimizing maximum temperatures and maximizing minimum temperatures (Hardy, 1960). Hurd and Cunningham, (1961) observed in a shade experiment in Ghana a 2-3 ^{o}F temperature difference was noted in the canopies of shaded and unshaded cocoa. Water loss through transpiration is reduced with reduced temperature (Alvim 1959). Cocoa systems can act as a sink or source depending on the kind of land-use they replace, in that a land that has been degraded will have the potential to serve as a sink for atmospheric carbon dioxide (Mohammed et al., 2016). Likewise a land which has not been degraded could be a source of increase in atmospheric carbon regarding its management practices. According to Afrifa & Acquaye (2010), crop management has a positive impact on carbon stocks in soils under cocoa.

2.5.1.4 Cocoa in Ghana

Cocoa a major cash crop contributes a lot to the growth of the Ghanaian economy, no wonder the forest ecosystem has been substituted for its extensive growth in the past decade (Mohammed et al., 2016). Cocoa production is mainly undertaken by smallholder farmers whose farms range from 0.5 to 2 acres (Dawoe et al., 2014). Challenges like decline in soil fertility, diseases and pest infestation, low yielding cocoa varieties, limited access to credit facilities and access to land affect cocoa production. Nevertheless, these farmers try their best to produce despite these challenges. Cocoa grows well in areas with rainfall ranging between 1150 mm to 2500 mm (Wilson, 1999) and under temperatures between 18 to 23 degree Celsius and pH of 5 - 7.5 is suitable for its growth. In terms of soil, a mixture of sand and clay helps in the better penetration of cocoa roots for stability

Previously land for cocoa cultivation was weeded and burnt (Amoah, 1995) but in recent times with the help of extension services through education on sustainability of soil fertility measures farmers either use weedicides or weed fields and use weed residues as mulch to protect the soil surface from direct sunshine (Isaac et al., 2005; Dawoe et al., 2014; Adiyah et al., 2021). With forest conversion to cocoa farms, trees are cut down which serves as fire-wood for domestic purposes. Food crops such as plantain, cassava, cocoyam etc. are planted before or hand in hand with cocoa seedlings which serve as shade for cocoa seedlings to prevent direct sun rays which can kill seedlings. Under the shaded cocoa system, shaded trees of about 16-18 in number are found within a hectare of land at spacing intervals of 2.4 m x 2.4 m to 3.6 m x 3.6 m with tree densities of 900-1300 (Afrifa & Acquaye, 2010). Fruit trees like mango and orange are examples of shade trees used. Cocoa trees have heights of about 4-8 m tall with lateral shoots originating at heights of 1-1.5 m. Fruiting begins at 3-5 years. Cocoa growth largely depends on management practices like weeding as it matures. Its common disease is the black pod disease which strongly affects tree growth. With good management practices, cocoa can have a life span up to 50 years.

2.5.1.5 SOC depletion and balances in agro-ecosystems

2.5.1.5.1 SOC budgets and balances

The distribution and cycling of SOC in agro- ecosystems are mainly in two forms, inputs and outputs. The main sources of inputs are from plants and microbial materials while outputs are by means of solution losses (leaching), volatilization, erosion (wind and water) and harvesting of plant parts (Baldock & Skjemstad, 1999). According to Allen et al. (2010), the amount of organic matter in soil at any given time reflects the long-term balance between input and loss rate. The rates and processes are controlled by soil formation which includes climate, topography, parent material, potential biota, time and human activity (Baldock & Skjemstad, 1999). Variations in climate may also drive inputs and losses of soil carbon to and from the soil system and can be calculated using variations in mean average temperature and mean average precipitation. The soil organic carbon balances are calculated at different scales, the farm, regional and the global levels.

2.5.1.6 Spatial variability of SOC and SOC pools

2.5.1.6.1 Plant/pedon scale

In this regard, vegetation and plant dynamics are the main contributors to spatial SOC variability according to Allen et al. (2010). Plant materials like litter fall, the production of root exudates, and root mortality are the main source of SOC (Bird et al., 2001). The carbon input in an area is dependent on the size, morphology and the spatial distribution of plants (trees, grass and scrubs). In addition, SOC variability is also dependent on the movement of organic materials across the landscape by wind and water through erosion (Ludwig & Tongway, 1995). Bird et al. (2001) reports that patterns of plant growth also affect the location of other sources of SOC. Microbial biomass and soil fauna tend to gather around areas already high in organic C content contributing to SOC heterogeneity (Bird et al., 2001). Soil mixing or bioturbation by soil macro and micro-fauna also increase SOC heterogeneity (VandenBygaart, 2006).

2.5.1.6.2 Community scale

The spatial variability of SOC at the community scale level includes the role of soil type and management practices. Soil types higher in clay content are generally able to hold more nutrients and moisture, therefore, influencing plant or biomass growth (Jobbágy & Jackson, 2000). In addition, the ability of clay to adsorb SOC in isolation provides physical protection within stable macro and micro aggregates; this can reduce SOC susceptibility to decomposition (VandenBygaart & Kay 2004; Don et al., 2007). Consequently, coarse textured and poorly structured soils have been observed to be poor in SOC availability (Harms & Dalal, 2003). Again, SOC variability is also affected by land management (management practices) at the community level. In the tropics where soils are inherently low in soil fertility management practices such as fertilizer use, lime application or the use of more productive species can increase SOC (Schnabel et al., 2001). Slash and burn and natural bushfires over a period of time affect the distribution of SOC. Coetsee et al. (2010) found that frequent fires in savannas over a 50-year period changed the distribution of SOC.

2.5.1.6.3 Regional and landscape scale

Topography and climate are the main factors responsible for SOC variability in terms of regional or landscape scale (Allen et al., 2010). Topography influences soil moisture and depth and hence biomass production and C input into soils. Steeper slopes have been found to have lower SOC and down-slope position higher in SOC due to erosion (Jia & Akiyama, 2005; Liu et al., 2006). The moisture content turns to be higher in downslope positions through runoff hence increasing biomass production contributing to higher SOC concentrations and stocks (VandenBygaart, 2006). In addition, wind erosion can also be a source of SOC variability considering the movement of soil and their associated organic C around the landscape (Zuo et al., 2008). Climate cannot be ignored in and describing SOC variability, especially, on regional scale level. Plant biomass production and soil respiration are influenced by temperature and rainfall. Therefore, SOC tends to be higher in cold and wet climates and lower in warm and dry climates (Amundson, 2001). When temperatures increase biomass and soil respiration rate also increase. However, adequate moisture will balance biomass production and decomposition rates, while excessive moisture content will decrease decomposition rates and increase SOC storage due to the effect of anaerobic conditions within the soil (Amundson, 2001).

2.5.2 Effect of topography on SOC

According to Zhu et al. (2018) soils in the mountainous regions are characterized by high organic carbon stocks having a strong topography-induced heterogeneity, thus causing uncertainties in regional SOC storage estimations. Therefore, elevation, slope aspect, and slope position are considered in the spatial variability of SOC (Gregorict et al., 1998; Rawls et al., 2003; Chen et al., 2016; Shi et al., 2019). In general, temperature is likely to get lower as the elevation increases contributing to increasing SOC trend; this could be attributed to limited decomposition at higher elevations (Parras-Alcantára et al., 2015). However, an increase in elevation to a certain height may cause a decrease in SOC as a result of reduction in precipitation. Chen et al. (2016) observed an increase in SOC density at an elevation of

2650 m but above 3400 m there was a decreasing trend in the Qilian Mountains with regards to vegetation. Thus, the slope aspect contributes to regulating solar radiation on hill slopes.

Increasing soil erosion with increasing effective slope results in an increase in the clay content, OC and elements in the lower slope position and these are important factors for soil fertility (Bakhshandeh et al., 2014). Bakhshandeh et al. (2014) concluded that the upper slopes of both granite and phyllite parent materials were more prone to erosion. Soils on this landscape occur in a sequence called a catena which shows properties that reflect the effect of topography on water movement and drainage. Steep slopes generally influence rapid soil loss by erosion and allow less rainfall into the soil before running off (Gregorict et al., 1998). This also affects vegetation cover influencing SOC stocks (Jobbágy & Jackson, 2000).

Soil organic carbon stocks generally differ in soils on a catena (Fernández-Romero et al., 2014; Zhang et al., 2018). In the semi deciduous forest zones, trees are normally dense in depressions than on highlands mostly because depressions are wetter than highland positions (Adu, 1992). Consequently, SOC turns to be higher in the initial than in the latter. Fernández-Romero et al. (2014) reported that soil quality was higher in lower topographical positions for both natural forest and olive grove in the Mediterranean areas and SOC increased along the hillside with the toeslope recording the highest in olive grove. Shi et al. (2019) made similar observation that slope position was an important topographic factor governing the SOC distribution in artificial forest, grassland and sloping cropland. Ahukaemere et al. (2019) also observed that carbon sequestration varied depending on the landscape position and the footslope sequestered significantly higher carbon. In a given landscape, the absorbance of solar energy is also dependent on topography. During the dry season when temperatures are much warmer the upper and middle slopes are more exposed to the sun rays lowering moisture content which tends to be lower in SOC.

2.5.3 Effect of time on SOC

In the study of Dawoe (2009) on plant biomass production, organic carbon and nutrient dynamics along a chronosequence of farm fields in the Ashanti region of Ghana, SOC stocks did not differ significantly between forest and cocoa land use over time. SOC stocks decreased significantly in the top 0-10 cm soil depth but were similar for the 0-60 cm depths for both forest (67.4 Mg) and cocoa systems (49.0, 57.3 and 63.6 Mg) for 3, 15 and 30 years respectively. SOC concentration was similar at the 0-10 cm in the 3, 15 and 30 years cocoa farms but significantly different from the forest system. It was also observed that SOC was similar between the forest and the 15 and 30 years cocoa systems at depths of 10 – 20 cm and 20-60 cm but significantly different from the 3 years farm fields. Dawoe's study showed that as cocoa system matures it appears carbon stocks approach pre-conversion levels with the result that differences between old cocoa and forest systems are small which is also supported by Don et al. (2011) and Guo & Gifford (2002). Duguma et al. (2001) observed under shaded cocoa systems in Cameroon that soils remained productive and sustainable for up to 50 years at levels comparable to long-term fallows or primary forests. Contrary to the above statement, Mohammed at al. (2016) observed a general decline of SOC stocks as time progressed in the cocoa system (7-28) in their study titled carbon storage in Ghanaian cocoa ecosystems.

2.6 Methodologies for studying long-term agro-ecosystem dynamics

Two approaches are often used in studying ecosystem dynamics. The most ideal approach is 'temporal monitoring', where the dynamics of ecosystem components e.g., changes in aboveground vegetation, roots, and soil characteristics are examined over a long period at a single site. This is feasible where long-term research sites have been established and data are available and changes in ecosystem components over time can be directly measured. Unfortunately, such long-term sites and data are rarely available in tropical countries (Sanchez et al., 1985) like Ghana. Even where available, such data usually come from on-station experiments that do not reflect the environment and management conditions of farmers' fields. Bhojvaid & Timmer, 1998 and McDonagh et al., 2001 have observed that it is rarely possible to follow this approach especially in poorly resourced tropical countries and under on-farm situations.

The other alternative is to use the spatial analogue and chronosequence methods (Young, 1991; Bhojvaid & Timmer, 1998). The spatial analogue method involves spatially sampling sites that are subject to different land uses but operating within a similar environment and on similar soil types (Dawoe 2009). The chronosequence method is a synchronized spatial sampling from neighbouring sites of different ages managed on similar soils, under similar climatic conditions and management practices (Young, 1991; Hartemink, 1998). A chrono-sequence itself is a series of sites that differ in age but otherwise occur on similar soil types and environmental conditions within the same climatic zone. Using chrono-sequences, long-term effects of global climate change (Tate, 1992), changes in soil productivity (Martin et al., 1990), soil carbon dynamics due to landuse change (Dominy et al., 2002), soil nutrient dynamics and carbon storage changes (Garten, 2002) as well as effects of deforestation and subsequent cultivation on soils (Sanchez et al., 1985; McDonagh et al., 2001) have all been evaluated.

Though chrono-sequence and spatial analogue methods have the danger of confounding time with possible spatial variability and assume that all measured differences reflect the effects of time or management and not inherent spatial variability, they nevertheless have been and still are widely used in studying different aspects of ecosystem dynamics and nonetheless, can provide very useful information about soil dynamics and they have greatly advanced our understanding of short- to long-term landscape and soil processes (Marques & Ranger, 1997; Bhojvaid & Timmer, 1998; McDonagh et al., 2001)

The major advantage of the spatial analogue and chronosequence techniques is that they provide data on long-term changes in soil, plant or other ecosystem components within a reasonable time. In situations where data on long-term studies are very rare, the chronosequence and spatial sampling approaches are valuable alternatives to studying ecosystem dynamics in a temporal perspective. A necessary assumption in using the chronosequence approach to studying soil dynamics is that soil conditions or other parameters of interest for all the sites studied should be similar before changes in the landuse have been introduced. This is because observed differences in present soil conditions or other parameters can be interpreted as being caused by the present land-use practices only if the conditions were assumed comparable prior to the introduction of the new land management. Similarity in particle size distributions in the sub-surface (those parts of the soils that are little affected by the changing land management) particularly the clay fraction at all depths supports the assumption that soil conditions prior to the shifts in land management were more or less similar (Sanchez et al., 1985; Lilienfein et al., 2000).

Thus, the study of chrono-sequences has a long tradition, and both ecologists and soil scientists use the concept of substituting space for time to understand ecosystem and soil dynamic processes.

2.7 Methods for measuring Soil Organic Carbon

To ensure regular monitoring of SOC several methods have been used. However, there is no standardized approach to measure SOC since it is not evenly distributed over large scale areas, landscape positions, soil type and depth (Laurenz & Lal, 2016). The dry combustion using the automated analyzer and the wet chemical oxidation (Walkley & Black) methods are the most widely used methods for measuring and studying SOC content. Most studies suggest that when it comes to accuracy the dry combustion method is the best but it is very expensive in acquiring the analyzer (Lettens et al., 2007; Wang et al., 2012; Bragança et al., 2015). Also, organic matter may be destroyed in soils and instruments may also be eroded when pretreatment is done to remove $CaCO_3$ by acids in calcareous soils. The Walkley and Black method compared to the dry combustion is less expensive and a standard procedure for measuring SOC worldwide. This is said to give accuracy of 60 to 86% with a mean recovery being 76% (Walkley & Black, 1934; Nelson & Sommers, 1996). According to Wang et al. (2012), the use of dichromate in this method can cause Cr hazard and variability in SOC recovery. In recent times, innovative methods that rapidly and inexpensively characterize SOC, like visible and near-infrared (Vis-NIR) and mid-infrared (MIR) reflectance spectroscopy has been used (Ellerbrock et al., 1999; Janik et al., 2007; Viscarra Rossel et al., 2006; Miltz & Don, 2012). These methods are fast, inexpensive, non-destructive, and requiring little to no sample pre-treatment. However, there is the challenge of calibrations of data sets which often affects accuracy. The measuring of SOC in situ is possible through IRS analysis and has been successfully used by (Stevens et al. (2008), thus helping to resolve the problem of inadequate data resolution.

2.8 Sampling designs suggested for farm scale SOC studies

As previously introduced, SOC content is influenced by several factors like vegetation, climate, parent material, topography, soil type and site management, and as a result, SOC stock is highly variable on both spatial and temporal scales creating a challenge for efficient sampling. Sampling methods are predominantly based on design-based (classical) statistical techniques, crucial to which is a randomised sampling pattern that negates bias. Alternatively, a model-based (geostatistical) analysis can be used, which does not require randomization (Allen et al., 2010).

For small (farm) scale studies design based samplings are more suitable. Lawrence et al. (2020) recommend design-based sampling in most situations for its simplicity, cost, and objectivity.

In the following, the applied soil sampling methods of this study are discussed.

2.8.1 Catena method of sampling

The catena concept is a means of describing the variability of soils in space (Sommer & Schlicting, 1997). Schaetzl & Anderson (2005) refers to the term catena as a toposequence of soils derived from a similar parent material and climatic conditions but have different characteristics due to variations in relief and other related processes like drainage, transport, material deposition, leaching, etc. (Hall & Olson, 1991). These soils that form on a toposequence vary in morphological, physical and chemical properties. Soils on these landscapes are found in the upper, middle and lower slopes (Eze, 2015). Soils developed on different positions along a slope are likely to form a catena due to the possible difference in drainage characteristics and its subsequent influence on soil organic carbon variations along the different slope positions. Thus, the function of topography in SOC distribution cannot be ignored. Soil erosion and depositional processes play an essential role in the accumulation and stability of soil organic carbon (Doetterl et al., 2016). Novak & Bertsch (1991) observed that topography influence the formation of the various humic fractions. Porder et al. (2004) quantified variation in plant nutrient concentrations and provenance along a catena in landscapes of three different ages (0.15, 1.4, and 4.1 ma) in the Hawaiian Islands. Eze (2015) sampled soils along a catena that runs from the Legon hill, Ghana, in order to study the spatial variability and differences in soil classification occurred. Igwe (2005) also used the catena sampling method in the work titled "Soil physical properties under different management systems and organic matter effects on soil moisture". It has been observed that eroding positions typically have lower SOC and nutrient content with thin thickness compared to depositional positions (Berhe et al., 2008). Other studies (e.g. Smith et al., 2001; Fontaine et al., 2007) emphasize the need for interventions that protect SOC from further decomposition at depositional positions. Therefore, variations in SOC distribution along hillslope are important in adapting sampling stratification that considers landscape features. In addition, modifications of the catena by anthropogenic activities (i.e. deforestation and management practices) can also contribute to its variability within a relatively short period (Barrios et al., 2015). Catena sampling provides quantitative information on the spatial heterogeneity of soil properties, on which sustainable, and site-specific soil management decisions can be based (McBratney et al., 2014).

2.8.2 Pattern-based random soil sampling

The most commonly used sampling design for many field studies is the design based, systematic sampling using either transects or grids. In random sampling individual samples are collected from locations that are randomly distributed across the representative portion of the field. The common design-based sampling protocol prescribes collection of individual cores in a zig-zag, "Z", "S", or "W" pattern that are combined to produce a composite sample. The sampler should avoid sampling atypical areas such as eroded knolls, depressions, saline areas, fence lines, old roadways and yards, water channels, manure piles, and field edges. Typically, all samples are combined and a composite sample is taken and submitted for laboratory analysis. Composite sampling is comparatively inexpensive since only one sample from each field or subsection of a field is sent for laboratory analysis. However, this design provides no assessment of field variability and relies on the ability of the soil expert to identify portions of the field that may have inherently different soil characteristics (Carter & Gregorich, 2006).

2.8.3 Sampling of soil profiles by genetic horizons, vertical transect and fixed-depth intervals

The accurate estimation of SOC stocks has become essential for climate change mitigation (Minasny et al., 2013). From a soil, profile soils can be sampled by horizons or by fixed intervals (Allen et al., 2010). Bulk samples are collected at the center of each horizon and horizons are described on the field in the middle of the profile. Zhang & Hartemink (2017) divided soil profile walls into 10 vertical transects (10 cm width) and soil properties of each horizon were represented by soil properties over 10 cm depth interval at which horizon centers were located. Also, according to Marinho et al. (2017) samples can be collected from a single vertical transect in a soil pit at depth intervals. Others have also compared fixed-depth sampling and horizon-based sampling and found out that SOC was higher in the surface (0-20 cm) and 30-40 % higher in the whole profile (0-80 cm). Grüneberg et al. (2010) reported that sampling by depth interval is ideal for regional SOC estimation while sampling by horizon is good for pedo-genesis studies. The benefits of sampling at fixed-intervals include easy budget and implementation and its practicality. It been observed that vertical sampling design does not capture the horizontal variations of soil (Hole, 1953). The soil profile is divided into layers with depth intervals. Samples are then randomly taken from each layer (Webster & Lark, 2012).

2.9 SOC Stock Calculation

Accurately quantifying soil organic carbon (SOC) is considered fundamental to studying soil quality, modeling the global carbon cycle, and assessing global climate change. In order to reach this goal, SOC stock calculations are performed, by using the following soil data: SOC content, bulk density, rock fragment content and depth of a respective soil layer.

SOC stock is an important issue in the context of climate change and soil degradation (FAO, 2017). The complex interaction between variables involved in SOC stocks (i.e. SOC concentration, bulk density, sampling depth and rock fragment content) has made it difficult to accurately identify and quantify SOC stocks (Goidts et al., 2009). A precise estimation of SOC stocks is very important in linking atmospheric and territorial carbon. According to Poeplau et al. (2017), estimation of SOC stocks are based on soil inventories from regional to continental scale taking into consideration soil bulk density (BD, open dry mass of soil per unit volume) and various depths of soil layers (Twongyirwe et al., 2013). Usually, an aliquot sample of fine soil that passes through a 2 mm sieve is used in determining carbon in soils (Twongyirwe et al., 2013; Muhati et. al., 2018). Other studies include coarse fragments or rock fragments (> 2 mm) in the estimation of SOC stock. According to IPCC 2003 stoniness results in a lot of uncertainty in SOC stock estimates.

2.9.1 Key elements and problems to consider in SOC stock calculation

Bulk density is essential for the calculation of SOC stocks, and converting soil organic carbon percentage by weight and by volume content but it varies with the mineralogy, water content and compaction (Brown & Wherrett, 2014; Han et al., 2016; Walter et al., 2016). However, it is mostly underestimated at the field level and most times information on the method and number of replicates is lacking. This according to Walter et al. (2016) imposes large uncertainty errors on SOC stock estimates and SOC stock changes. In most times, bulk density is determined by the core sampling method (volumetric cylinder method) and is comparable to the clod method. However, measurements for extremely gravelly to gravelly soils are difficult to compare since results vary significantly with sample volume (Batjes et al., 1996). The core method is time consuming and difficult to use for sampling multiple soil depths, therefore if the core cylinder is used, sampling depth, operator experience and soil moisture content affect results accuracy (Al-Shammary et al., 2018). According to Batjes (1996), bulk density values for Acrisols, Ferrasols, Fluvisols and Gleysols globally have mean averages of 1.41, 1.40, 1.26 and 1.38 Mg m^{-3} respectively. Also, its accuracy decreases with sampling depth (Al-Shammary et al., 2018).

In their estimation, the mass and volume of oven-dried soil samples are measured. The volume of a soil sample can be obtained by measuring the size of the sampling cylinder or the quantity of the soil (Campbell, 1994). More studies have reported that these methods depend on measurements of the volume and mass of the soil sample because the mass of a dry soil sample is obtained by weighting, whereas the total volume of the soil, including air and moisture, is observed by indirect measurement (Ferreira et al., 2015). The dry soil BD (bulk density) can be calculated using the formula:

$BD = M_s/V_s$

Where BD is in Mg m^{-3}, M_s is the weight of the dry soil sample in Mg, and V_s is the volume of the dry soil sample in m^3 (Han et al., 2016).

2.10 Indigenous Knowledge on soils

With increasing use of participatory research approaches, it is becoming relevant that farmers' knowledge and perceptions of their soils are important resources for the development of technologies and management interventions (Asiamah et al., 1997; Dawoe et al., 2012). Osunade (1992) emphasizes that the integration of all experiences rather than the reliance on one tradition at the expense of the other is key for sustainable agriculture. Thus, the literature discusses farmers' perception on soils by using different indicators in assessing SOM and fertility.

Indigenous knowledge also known as local knowledge, folk knowledge, people's knowledge, traditional wisdom or science is transferred by communities over time and helps them in coping with their agro-ecological and socio-economic environments (Fernandez, 1994). It is knowledge rooted in a particular place and set of experiences, and generated by people living in those places (Haverkort & de Zeeuw, 1992). It is usually orally-transmitted, imitated and demonstrated. In general, it is empirical rather than theoretical knowledge. Indigenous knowledge systems have a broad perspective of ecosystems and of sustainable ways of using natural resources. However, colonial educational system has influenced the academic ways of learning today with western ideas (Senanayake, 2006).

Indigenous soil knowledge or ethnopedology has recently been highlighted as important in creating a sustainable soil ecosystem (Dawoe et al., 2012; Awoonor et al., 2021). Ethnopedology is a combination of natural and social sciences disciplines to fully understand the management of soil sustainability (Dawoe et al., 2012; Wawire et al., 2020). Studies on soil taxonomy, soil management, climate change effects on soil, and soil organic matter have involved the indigenous knowledge of farmers. Their perceptions about how and why they use certain techniques influence their involvement with soil. Dawoe et al. (2012) reported on how farmers in the Ashanti region of Ghana understand their soils and soil fertility processes under cocoa systems. Farmers' perception on land degradation in northern Ethiopia was reported by Tesfahunegn (2019), farmers' perception and adaptation to climate; a case study in Ghana by Fosu-Mensah (2010), integrating scientific and farmers' evaluation of soil quality indicators in Central Kenya by Mairura et al. (2007), farmers' knowledge and use of soil fauna in agriculture: a worldwide review by Pauli et al. (2016).

2.10.1 Farmers' perception of soil fertility

While laboratory analysis proves to be a useful procedure in helping to recognize the physical and chemical variations between soils, an appreciation of 'ethnopedology' reflects an acknowledgment of the important contributions that alternative epistemologies can make. Soil fertility by scientists is mainly determined through laboratory experiments determining nutrient levels aside from the physical characteristics. Therefore the nutrient level determines whether a soil is fertile or not bringing out appropriate amendments in correcting nutrient deficiency. In central Kenya farmers' criteria for distinguishing fertile soil from non-fertile soils included crop yield and performance, soil colour, texture and tilth, the presence of soil micro fauna and the abundance and diversity of weed species (Mairura, 2007). Elsewhere in Cameroon farmers generally perceived good soil tilth as a factor of soil fertility a condition in which the soil is easy to till such that it does not require any other tillage to enhance plant growth (Kome et al., 2018). According to Machonachie (2012), farmers in Kano Nigeria revealed that a soil that is white and sandy is generally considered to be the least fertile, and requires large application of amendments to become productive. Dawoe et al. (2012) identified that farmers in the Ashanti region of Ghana mentioned water holding capacity as a characteristic indicator of fertile or infertile soil. Soils with high moisture content are dependent on the soil texture and SOC content, and this influences the characteristics of the soil as a whole. Plant growth is maximum when soil is easy to till.

2.10.2 Methodologies for assessing farmers' ethnopedological knowledge

In the studies of Barrera-Bassols & Zinck (1998); WinklerPrins (1999) they identified ethnographic, comparative and integrated approaches as the main sources of ethno-pedological information. In the ethnographic approach, the objective to recognize farmers' environmental rationality from a cultural perspective therefore, it involves field data analysis (Conklin, 1957). Ethno-pedological information is not compared with scientific soil information. The comparative approach identifies the similarities and differences between local knowledge and scientific information (Sillitoe, 1998). The integrated approach promotes an interdisciplinary perspective of balancing the relationship between cultural and scientific information on natural resource management (Dawoe et al., 2012).

The qualitative research focuses on getting data through open-ended and conversational communication which allows for deeper understanding of responses (Buxton et al., 2018). The interviewee's motivation and feelings is also taken into consideration by researchers or the interviewer. Data collection instruments used in a qualitative research are semi-structured methods such as in-depth interviews, focus groups, and participant observation (Patton, 2002). Process of observation uses subjective methodologies to gather systematic information or data. Thus, the five sensory organs and their functions- sight, smell, touch, taste and hearing uses characteristics instead of measurements and numbers (Omoshola, 2015). During data collection, one or more of these; handwritten notes, audio and video are recorded as well as text documents. Images are also considered as a source of data since inferences are drawn from them. Recordings are transcribed for data analysis.

3 MATERIALS AND METHODS

The section describes the study area considering the location of the site, its climatic conditions, vegetation and soil characteristics, and justifies the reasons why the site was selected. The methodology used in soil sampling, soil description and classification is described. Laboratory analysis protocols, statistical and qualitative analyses used are discussed. Finally, the method of determining and collecting the social data was presented.

3.1. 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.

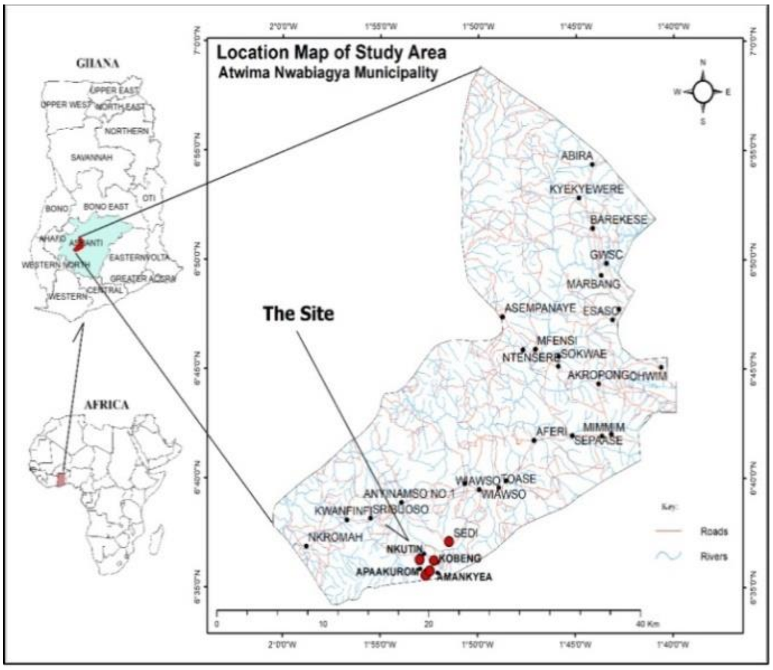


Figure 3.1 Map of the study site

It has about 64 settlements with Nkawie as the administrative capital with about 35.3 % being urban and 64.7 % being rural. It covers an estimated area of 184 sq km (Atwima Nwabiagya Municipality Assembly, 2018). According to the 2010 population and housing census, the total population of Atwima Nwabiagya District was 149,025, with an annual growth rate of 2.6%. However, carving out the Atwima Nwabiagya Municipality has given the municipality a population of 103,698. The Municipality is predominantly rural, with about 68.5 percent living in the rural areas, and only 31.5% of the population lives in urban areas. The upland and slope soils are suitable for the tree and arable crops such as cocoa, citrus, oil palm, mangoes, guava, avocado, maize, cassava, yams, cocoyam, plantain, pawpaw, groundnuts, pineapple and ginger. The valley bottoms are good for the cultivation of rice, sugarcane, and vegetables (Atwima Nwabiagya Municipality Assembly, 2018).

3.1.1 Site selection

Study sites were selected based on a research conducted in five farming communities in the district between 2004-2008 by Dawoe (2009). A follow-up was made to these communities namely Seidi, Kobeng, Apaakrom, Nkutin and Amanchia in 2019. Eleven (11) sampling sites were chosen from these 5 communities based on the vegetation type, landuse, management practices (Table 3.2), undulating topography and the time factor to compare with the previous study conducted by Dawoe (2009). Sites with different landuses of forest reserve and cocoa agroforestry were selected. Ten cocoa farms and one forest reserve (Jimira forest) were selected eventually. Farms were established after conversion of the natural forest (Figure 3.2a), its' sizes ranged between 3 and 6 acres with farm ages ranging from 12 to 45 years. The Jimira forest reserve is a rejuvenating secondary forest previously logged forty years ago (Figure 3.2b), but thereafter designated as a protected area or reserved forest. Farming is not permitted in the reserve, it is managed by the forest commission in the Municipality.

Sites selected under objective one (1) were selected from Kobeng and Nkuntin communities, sampling from two shaded cocoa- farms and the Jimira forest reserve respectively.

Sites for objective two (2), were selected for this research based on the landuse type, and management practices of these landuses. Two shaded-cocoa farms were selected at Kobeng and a forest reserve at Nkutin community for soil sampling as same for the first objective.

For objective three (3), sites chosen for the study were based on the topography of the area. Soil samples from the same sites for objective two were used i.e., two shaded-cocoa farms at Kobeng and the forest reserve at Nkutin communities.

The time factor was considered as the main bases for site selection under the fourth (4) objective in order to compare with the previous study of Dawoe (2009). The eight (8) cocoa farms were located in the Apaakrom, Kobeng, Seidi, Nkutin and Amanchia communities. Study sites had similar soil types and management histories and formed the basis for comparisons between sites. Stand and mean particle size distribution density of the study sites are shown in Table 3.1 respectively.

Table 3.1 Stand characteristics and mean particle size distribution% of 0-60 cm soil depth in of the study sites.

Parameters	Land-use			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Stand density (trees ha^{-1})				
Cocoa canopy	-	1,500	1,100	900
Upper storey canopy	900	16	35	26
Sand %	20.2	28.5	19.6	24.1
Range	(15.96-23.59)	(24.34-40.12)	(14.7-25.18)	(19.02-28.4)
Silt%	61.9	57.5	61.4	55.6
Range	(49.43-72.02)	(39.31-65.15)	(48.21-72.27)	(30.47-71.0)
Clay%	17.9	14.0	19.0	20.4
Range	(8.03-30.39)	(10.13-26.07)	(10.2-26.61)	(8.0-42.47)
Soil type	Ferric Lixisol	Ferric Lixisol	Ferric Lixisol	Ferric Lixisol
Textural class	Silty Loam	Silty Loam	Silty Loam	Silty Loam

Source: Dawoe (2009)

Lastly, sites for the social study of this research which is the last objective were selected from all the five (5) communities namely Apaakrom, Kobeng, Seidi, Nkutin and Amanchia. These communities were selected based on the management practices of the farmers, landuse type, farm sizes (0.8 to 6 hectares) and farm ages (1-33) years.

Table 3.1 Agricultural (cocoa) and forest landuse characteristics of study site

Sampling sites	**Landuse type**	**Vegetation type**	**Management practices**
Cocoa farm 1 and 2	Agriculture	a. Cocoa trees b. Food crops: Plantain, Cocoa-yam, Cassava c. Trees: Terminalia *ivorensis*, *Terminalia superba*, *Celtis milbraedii*.	a. Agroforestry b. Litter cover/mulching c. Application of organic and inorganic fertilizers d. Pruning and weeding
Forest	Forest	a. Trees: *Terminalia ivorensis*, *Terminalia superba*, *Ceiba pentandra*, *Triplochiton scleroxylon* b. Shrubs, woody climbers, coppice shoots, young trees, soft-stemmed leafy herbs: *Chromolaena odorata*, *Trema guineensis*, *Aspilia latifolia*.	

Figure 3.2 Cocoa Land use (a) and secondary forest (b)

3.1.2 Climate, vegetation, geology and geomorphology of the Atwima Nwabiagya Municipality

The Municipality lies within the wet semi-equatorial zone, having a double maxima rainfall distribution pattern with annual rainfall ranging between 170 cm and 185 cm. Mid-March to July marks the major rainfall season, while September to mid-November marks the minor rainfall season. Temperature is fairly uniform ranging between 27 ˚C in August and 31 °C in March. It has a mean relative humidity of about 87 to 91 % experiencing the lowest 83-87 % in the morning and 48-67 % in the afternoon in February/April (Atwima Nwabiagya Municipality Assembly, 2018).

The municipality is characterized by a semi-deciduous type of vegetation s largely disturbed by human activities. Trees are mainly of the *Celtis triplochiton* Floristic, which shed their leaves usually in the dry season. Species include *Triplochiton scleroxylon*, *Celtis milbraedii, Baphia nitida*, and *Groffornia simplicifolia*. Dawoe et al. (2014) highlighted two species of Sterculia: *S. rhinipelata* and *S. Oblongata* as the other common forest type tree species. Tree heights usually exceed 50 m and 60 m. The Jimira forest reserve is the only reserve found in the municipality.

The geology in the study area is underlain by the Lower Birimian rocks (figure 3.3), which consist of phyllites, greywacks, and gneiss, and the Cape Coast Granite all bearing gold deposits (Atwima Nwabiagya Municipality, 2018). The weathered phyllite is soft and easily broken while granites are well foliated (Adu, 1992). The granite contains quartz, orthoclase and microcline, plagioclase, muscovite, biotite and chlorite (Junner, 1940).

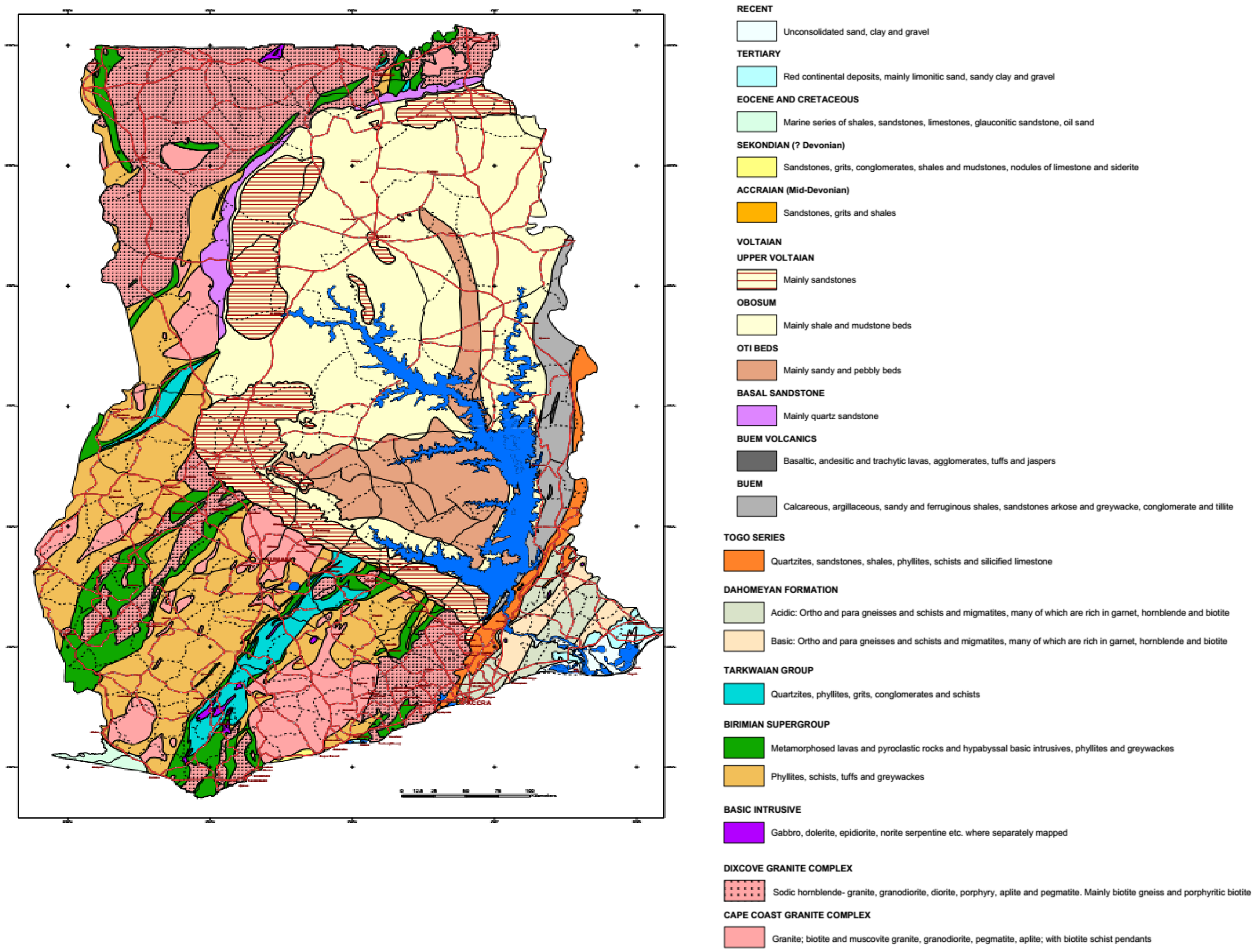


Figure 3.3 Geological map of Ghana **(Source: Ghana Geological Services)**

Geomorphologically, the region forms part of a dissected peneplain with the rise of inselbergs or mountain ranges occasionally, preserving older remnants on their summits (Adu, 1992). The topography is steep to undulating. The highest surfaces are at altitudes of approximately 610 meters (Crosbie, 1956; Brash, 1962).

3.1.3. Major soil types of the Atwima Nwabiagya Municipality

The predominant soil in the municipality is the Kumasi-Asuansi/Nta-Ofin Compound Association and the Bekwai-Nzema/Oda Complex Associations according to the Interim Ghana Soil Classification System (Adu, 1992). The Kumasi-Asuansi Compound Association is generally medium to coarse-textured, has good structure, and moderately gravelly. Bekwai-Nzema/Oda Complex Association is developed over Birimian Phyllites, Greywacks, Schist, and Gneisses and are deep, red, well-drained, and brown (Adu, 1992)

According to Adu (1992), due to the nature of the parent materials underlying soils of the Ashanti region, their topsoils are mainly sandy loam and silt loam which are moderately fine granular in structure and friable in consistency. The texture of subsoil is highly variable having sandy clay loam, silty clay loam, sandy clay or silty clay with common to many (10-40%) quartz gravels and stones and hard iron and manganese dioxide concretions. The soils are moderate to strong medium sub angular blocky to angular blocky structured with firm to very firm consistency. These soils have good moisture-holding capacity, although surface layers are prone to dry season drought (Adu, 1992). They are easily leached of nutrients due to high rainfall regime experienced in the moist semi-deciduous forest zone. There is high base saturation, generally about 60 to 80%, pH is between 5-6, and total exchangeable bases (TEB) are below 10 meq 100^{-1} g soil. Cation exchange capacity (CEC) is low, usually above 16 cmol (+)/ kg clay but less than 24 cmol (+)/kg clay. Fertility status is generally low to medium, with most nutrients concentrated on the topsoil. Soils are good for agriculture and are suitable for tree and arable crops such as cocoa, citrus, oil palm, mangoes, guava, avocado, maize, cassava, yams, cocoyam, plantain, pawpaw, groundnuts, pineapple, and ginger. Soils found at the bottom of the valley are suitable for the cultivation of rice, sugarcane, and vegetables.

According to the international soil correlation system, the World Reference Base for Soil Resources (WRB), the major soils of the study area include Acrisols, Lixisols and Leptosols. Acrisols and Lixisols are developed over highly weathered phyllites (Adu, 1992). Acrisols have a clay accumulation (argic) horizon which has a CEC of less than 24 $\mathrm{cmol}_{(+)}$ / kg starting within 100 cm from the soil surface, and having an effective base saturation of less than 50% at a defined depth. They are acidic soils and are dominated by low activity clays (kaolinite) in the clay accumulation horizon. They also have a low nutrient holding capacity, thus they require fertilizer application for sustainable production (Infonet, 2019). Lixisols also have clay-enriched subsoil (argic horizon) dominated by low activity clays and low nutrient capacity but comparatively, they have high base status. They are prone to erosion with high intensity rainfall. Leptosols have continuous rock at or very close to the surface or are extremely gravelly, and mainly occur in the mountainous region of the area exhibiting weak soil structure as a result of their limited pedogenic development (IUSS WRB Working Group, 2015).

3.2 Field work and soil data collection

This section gives detailed descriptions of the approaches used for soil sampling in this study. Soil sampling was conducted to aid in the characterization of soils and accurate determination of soil organic carbon stocks. It also highlights the design used for the collection of social data obtained on farmer's decisions on management strategies influencing soil fertility.

3.2.1 Soil description and classification

The Interim soil classification of Ghana was developed in 1950s (Adjei-Gyapong & Asiamah, 2002). The focus of the classification is mainly based on natural soils and soils deeply transformed as a result of agriculture. The classification system is based on two approaches: one, a soil series empirical classification and the other, a general geographical and environmental approach to grouping of soil. The series is the last level of the soil taxonomy which uses general characteristics in classifying soils of Ghana. Diagnostics are mainly keyed out depending on chemical (supplementary use of simple laboratory analyses) and morphological characteristics while localities' names are used in the terminologies in the soil classification of Ghana (Krasilnikov et al 2009). For this study, the last level of soil taxonomy (soil series) was adopted.

The WRB soil classification system is based on soil properties defined in terms of diagnostic horizons, properties and materials which should be measurable and observable in the field. The soil forming processes contributes to the better characterization of soils but are not used as a differentiating criterion in the WRB classification system. Possibly at a higher level of generalization, diagnostic features that are of significance for soil management are selected

(IUSS Working Group WRB, 2015). The WRB classification is based on two levels: the first has 32 RSG, and the second level consists of the RSG combined with the principal and supplementary qualifiers (IUSS Working Group WRB, 2015).

The field work was carried out on 3rd and 4th February 2019. Soil profiles were described and characterized according to FAO Guidelines (2006) and classified based on IUSS Working Group WRB (2015). Nine (9) profiles were described on three catenas and classified under the reference soil group (RSG) as Acrisols. These profiles were sited in the Nkutin and Kobeng communities. Tools like shovels, tape measure, Global Positioning System (GPS), Munsel colour charts, bucket, pH meter, 10% HCl acid, spraying bottles, distilled water, FAO Soil Description and WRB guidelines were used for the exercise.

3.2.2 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.

3.2.2.1 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. 3.4). 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 (impermeable layer limiting) 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 3.5 shows the topography and positions of the sampled catenas.

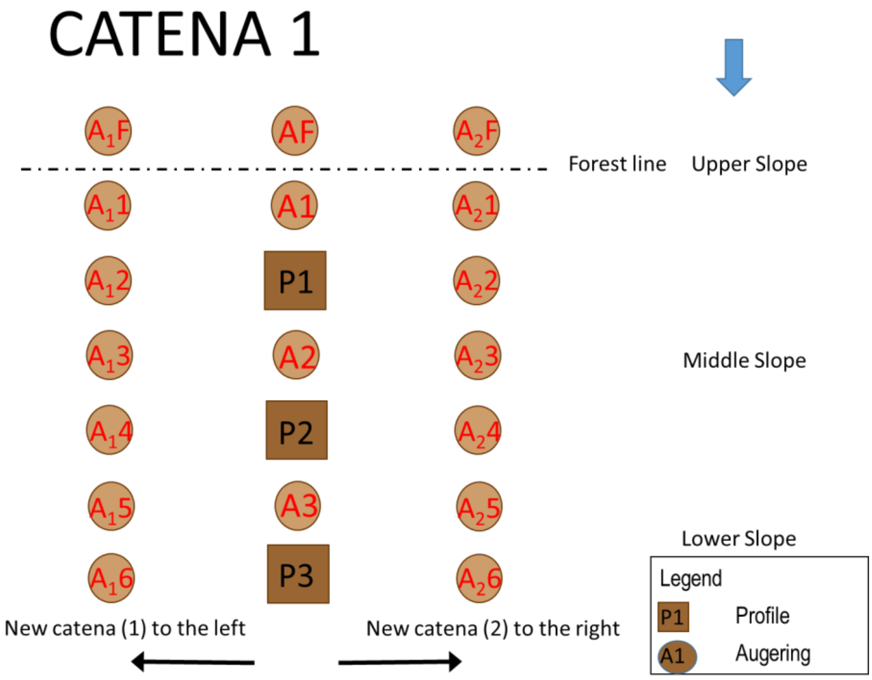
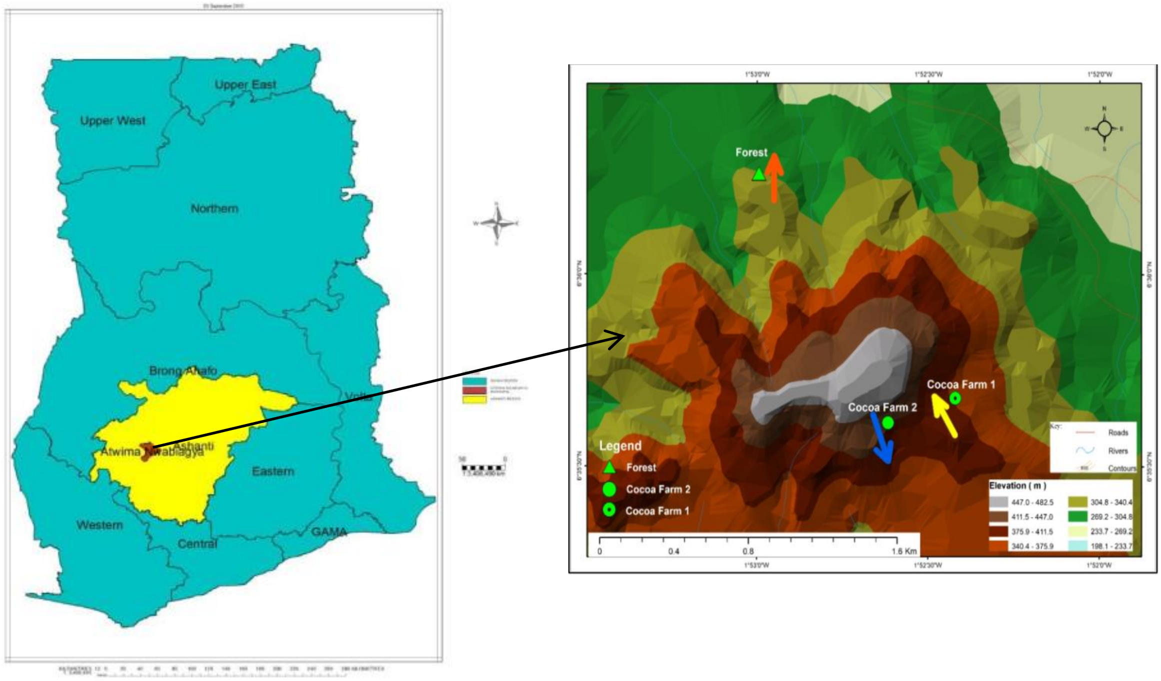


Figure 3.4 The catena sampling design for both cocoa and forest land-use



Source: Spatial planning department (2017)

Figure 3.5 Topography and positions of 3 catenas in the Atwima Nwabiagya Municipality in the national context.

(Yellow, blue and orange arrows show direction of sampling from upper to lower slopes)

3.2.2.2 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 3.6).

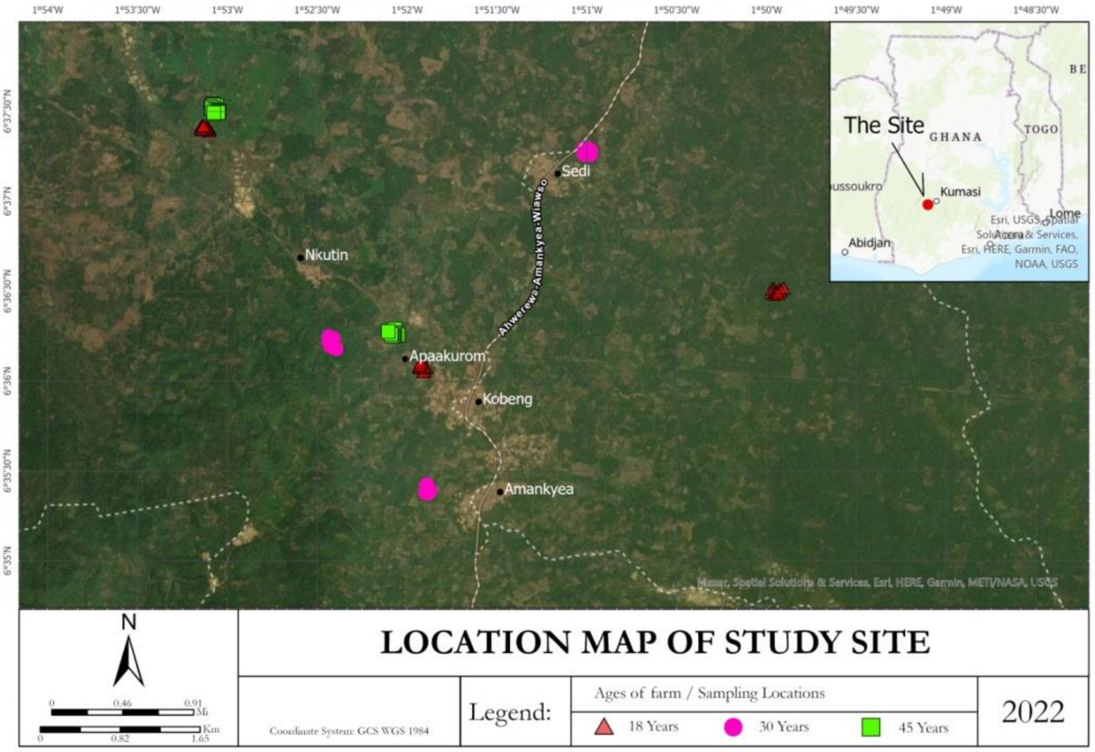


Figure 3.6 Map of farms selected for the chronosequence study in the Atwima Nwabiagya Municipality, Ashanti Region, Ghana

Sampling plots (40×50 m to 60×80 m) 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 3.7) 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.

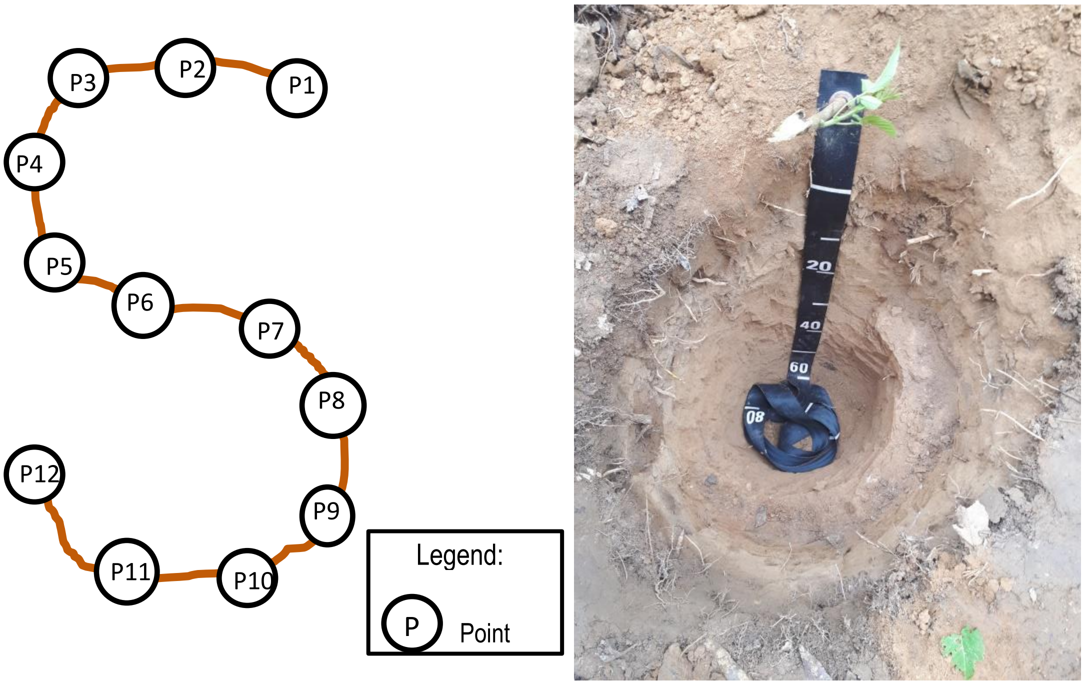


Figure 3.7 The S-shape sampling design and a small soil profile

To facilitate faster drying, large clods of soil were broken up. Visible plant residues were removed and samples were air-dried for 48 hours. Soil colour was determined at the laboratory for both dry and wet samples using the Munsell colour chart. The samples were crushed using a pestle and mortar and sieved with a 2 mm mesh for further laboratory procedures.

3.3. Laboratory Analysis of soil samples

This section describes laboratory protocols used in analyzing the various soil properties. These include soil organic carbon (SOC), humic substances (E4:E6 ratio), pH, cation exchange capacity (CEC), exchangeable cations (Ca, K, Mg, Na), particle size distribution (clay, silt, sand), coarse fragment and bulk density. Measurements obtained from analyses also include texture and base saturation, and available nutrients such as Nitrogen (TN) phosphorus (P) and potassium (K) were determined. The Munsell colour chart was used in the determination of soil colour.

The bulk density, coarse fragment and soil colour analyses were carried out in the Kumasi Soil Research Institute (SRI) laboratory, Kwadaso Ghana. All other measurements were done in Hungarian University of Agriculture and Life Science laboratories in Gödöllő.

Soil organic carbon was determined following a modifiedWalkley-Black procedure (van Reeuwijk, 2002). The procedure involves wet combustion of organic matter with acidified potassium dichromate which is titrated back into a dark brown colour with 1 M of ferrous sulphate using diphenylamine as indicator. 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).

SOC, E4:E6 ratio, pH and coarse fragment were measured for all samples.

Out of 324 soil samples for the 1st, 2nd and 3rd objectives, forty-four (44), 54 and 27 representative soil samples were subjected to CEC and exchangeable cations, particle size and nutrient laboratory analyses protocols, respectively. The 44 and 27 representative samples were selected from the 324 samples subjected to the Mid Infrared Spectra (MIR) analysis of SOC. The selected samples were determined using the K- means clustering method based on the MIR, this technique can be used on both organic and inorganic materials and allows for qualitative analysis of large samples ranging from biological samples to clay minerals. The selected soil samples were determined based on multivariate calibration techniques (chemometrics). Partial Least Squares Regression (PLSR) with leave-one-out cross validation was used to calibrate the bruker. MIR is considered a powerful tool for soil analysis because of a combination of interpretation of spectra and development of calibrations (Robertson & Pérez-Fernández, 2017).

3.4. Calculation of bulk density and coarse fragment and carbon stocks

3.4.1 Calculation of bulk density

The bulk density of soils were calculated with the equation (1)

$$BD = (W_1 - W_2) \times V^{-1} \quad (1)$$

Where: W_2 = Weight of core cylinder + oven – dried/grams, W_1 = Weight of empty core cylinder/grams, V = Volume of core cylinder ($\pi r^2 h$), cubic centimeters where: $\pi = 3.142$, r = radius of the core cylinder and h = height of the core cylinder. The bulk density is expressed in g cm^{-3}.

The mass of the soil and coarse fragment were weighed. The coarse fragment by weight was calculated following the equation of Zhang et al. (2019): Calculation coarse fragment is shown in equation (2)

$$Coarse\ fragment = \frac{\text{Weight of coarse fragment}}{\text{Total weight}} \quad (2)$$

Base saturation

Base saturation: Base saturation (BS %) was calculated by dividing the sum of the base forming cations by CEC of the soil multiplied by 100.

3.4.2 Carbon concentration calculation

SOC percentage was calculated for soils of each land-use type in various depth layers following the method: Calculation of SOC concentration is shown in equation (3)

$$\%\ \text{organic C in soil} = 10 / s * (1 - V_1 / V_2) * 0.39 * 1.724 \quad (3)$$

Where:

S = weight of air-dried sample in gram

V_1 = ml ferrous sulphate solution required for titrating sample

V_2 = ml ferrous sulphate solution required for titrating a blank

0.39 = 3*0.001*100% * 1.3 (3 = equivalent weight of C)

1.3 = a compensation factor for the in complete combustion of the organic matter

3.4.3 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)

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

3.4.4 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.

3.5 Methods of Data Analysis

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

3.5.1 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.

3.5.2 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).

3.6 Digital soil maps

The Geographic Positioning System (GPS) was used to record coordinates of sampling locations. These locations were plotted and maps produced showing their spatial distribution using the ArcGIS Pro Sortware version 2.8.6. https://pro.arcgis.com/en/pro-app/2.8/get-started/get-started.htm.

3.7 Social data collection

3.7.1 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 (figure 3.8). A summary of each interview was prepared based on the notes and recordings.

Figure 3.8 Field semi structured interview with farmers

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.

3.7.2 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).

4 RESULTS AND DISCUSSION

This chapter is organized/divided into different sub-sections based on the objectives of the study. Each sub-section is assigned to an objective. Results are presented along with discussions.

4.1 Soil characteristics and classification of the study site.

This chapter presents the results and discussions related to achieving objective one:

1. Determine soil characteristics and classify soils of the study site.

4.1.1 Physico-chemical characteristics of soils of the study site

The mean physico-chemical properties (±SE) of soils at the study site computed from aggregated values from both forest and cocoa sites at 0-30 cm and 0-60 cm depths are presented in Table 4.1. Appendix F shows the mean physico-chemical properties of the cocoa and forest soils.

Table 4. 1 Mean physico-chemical properties of the study site at 0-30 and 0-60 cm depths

Property	Mean ± SE (0-30)	Mean ± SE (30-60)	Mean ± SE (0-60)
pH (1:2.5,-H_2O)	6.82 ±0.061	6.51±0.49	6.74 ±0.087
CEC (cmol$_{(+)}$kg)	14.02 ±1.90	9.95±0.55	13.00 ±1.68
SOC (%)	1.81 ±0.527	0.58±0.01	1.50 ±0.484
BS (%)	34.52 ±3.49	25.35±10.3	32.23 ±3.37
N (%)	0.23 ±0.076	-	0.18 ±0.484
AL-P_2O5 (mg kg^{-1})	7.59 ±4.727	-	5.69 ±3.844
AL-K_2O (mg kg^{-1})	186.58±49.18	-	139.94±58.18
K^+ (cmol$_{(+)}$ kg^{-1})	0.19 ±0.044		0.17 ±0.038
Ca^{2+} (cmol$_{(+)}$ kg^{-1})	3.52 ±1.002	1.36±0.38	2.98 ±0.891
Mg^{2+} (cmol$_{(+)}$ kg^{-1})	1.08 ±0.216	0.98±0.48	1.06 ±0.155
Na^+ (cmol$_{(+)}$ kg^{-1})	0.00 ±0.000	0.015±0.01	5.000E-03±5.000E-03
C/N ratio	8.71±0.384		8.30 ±0.49
E4:E6 ratio	6.24±0.107		6.48 ±0.25
Sand (%)	19.83±0.394	19.55±1.29	19.76±0.29
Silt (%)	54.66±3.262	44.03±3.10	52.01±3.52
Clay (%)	25.52±3.119	36.44±1.81	28.25±3.51
BD (g cm^3)	1.47 ±0.094	1.45±0.13	1.47 ±0.07
Coarse Fragments (%)	33.14±2.839	47.09±3.09	36.63±4.02

Abbreviations: bulk density (BD), soil organic carbon (SOC), cation exchange capacity (CEC), base saturation (BS).

The slightly acidic and neutral pH (6.51-6.92) based on the ratings of Bruce & Rayment (1982) observed in soils across the study area, are atypical and could be related to the relatively high mean soil organic carbon content of 1.5 %. The pH is at a range where most essential plant nutrients are available and is suitable for the production of most commercial crops. Landon (1991) reported a neutral pH range of 6.3 to 7.5 in a 1:2.5 soil:water suspension. Soils of the study sites are mostly lower characterized by strong weathering and leaching (Kawaguchi & Kyuma, 1977) which is influenced by the chemical nature of phyllite; the parent material (Adu, 1992). Soil pH is the main component that regulates plant nutrient availability, hence levels found are conducive for the vegetation (forest), tree crop (cocoa) and food (plantain, maize etc.) production practiced by farmers at the site. This pH range is within the stated values (5.5 -7.0) reported as the optimal pH range conducive for the cultivation of most food and tree crops (Adu, 1992; Dawoe et al., 2014). CEC values ranged from 9.95±0.55-17.60±0.60 cmol/kg with ratings based on Metson (1961) interpretations varying from low to moderate across the study sites. Rating for the 0-60 cm depth 13.00±1.68 $cmol_{(+)}$/kg) was moderate similar to the observation made by Dawoe et al. (2014). Soil CEC levels of soils in that agroecological zone (semi-deciduous) are mostly low due to leaching (which are influenced by high rainfall) (Adu, 1992). Adu (1992) indicated that exchangeable bases are low because of incomplete weathering of primary minerals under prevailing tropical environments, low activity clays and leaching implying; more basic cations could be made available after further weathering of parent materials. The currently moderate CEC level observed could be attributed to SOC level of 1.5 % even at the 0-60 cm depth. The CEC gives an indication of soils ability to hold basic cations and influences soil nutrient holding capacity. Lower values of 0.18 % for nitrogen, 5.69 for available phosphorous, 139.94 mg/kg for extractable potassium were found at the 0-60 cm depth. At that same depth, values of 2.98, 1.06, 0.17 and 0.00 cmol/kg for exchangeable calcium, magnesium, potassium and sodium, respectively were observed. Soils of the study area were very low for Na^+, and low for K^+ and Ca^{2+}. However, moderate levels of Mg^{2+} were found in soils based on the limits given by Metson (1961). Mean nitrogen level was medium with values in all soils ranging from low to high based on the ratings of Bruce & Rayment (1982).

Clay content ranged between 19.96 and 36.44 % while silt varied from 44 to 60.78 %. Using Hazelton & Murphy (2007) ratings, bulk density levels were moderate varying between 1.33 and 1.65 g cm^{-3} with about 29.6 to 47 % made up of coarse fragments. In the 0-60 cm depth, mean values recorded for sand, silt, clay, coarse fragment and bulk density were 19.76, 52, 28, 36.63 % and 1.47 g cm^{-3}, respectively. Generally, soils had a textural grade of silty loam for the 0-60 cm depth having about 25 % of clay and more than 25% of silt (McDonald et al., 1994). Soils were moderately compacted for the study area comparing to values (1.4 to 1.6 g cm^{-3}) suggested as compaction by Blake & Hartge (1986). SOC ranged from 0.58 to 2.77 % showing that levels were generally very low to very high when considering soil health or soil condition (Hazelton & Murphy 2007). Generally, BS ranged between 25 % and 41.5 % showing a low to moderate levels across sites (Metson, 1961), with a mean of 32 % for 0-60 cm. According to Metson (1961), BS is used as an indication of the intensity of leaching of exchangeable bases hence, values observed in the study site could indicate strongly to moderately leached soils.

Mean values for C:N ratio at 0-30 and 0-60 cm (8.71±0.38 and 8.30±0.49) showed that decomposition could be at a maximum rate possible under environmental conditions (Hazelton & Murphy 2007). Nevertheless, according to Hazelton & Murphy (2007) the rate of decomposition is also dependent on the availability of resistant materials (eg. lignin, cellulose, charcoal like materials, etc) irrespective of the soils C:N ratio.

In this study, mean E4:E6 ratios were all above 6 for both 0-30 and 0-60 cm depths and these according to the ratings of Chen et al. (1997), Reddy et al. (2014) and Kunlanit et al. (2019), shows less stabilized and more soluble organic moleclues in the form of fulvic acids in the studied soils.

4.1.2 Soil description of profiles of the catena study

4.1.2.1 Soil description

Figure 4.1 show images of 9 sampled hillslope positions and their respective genetic horizons on three catenas in the cocoa and forest systems.

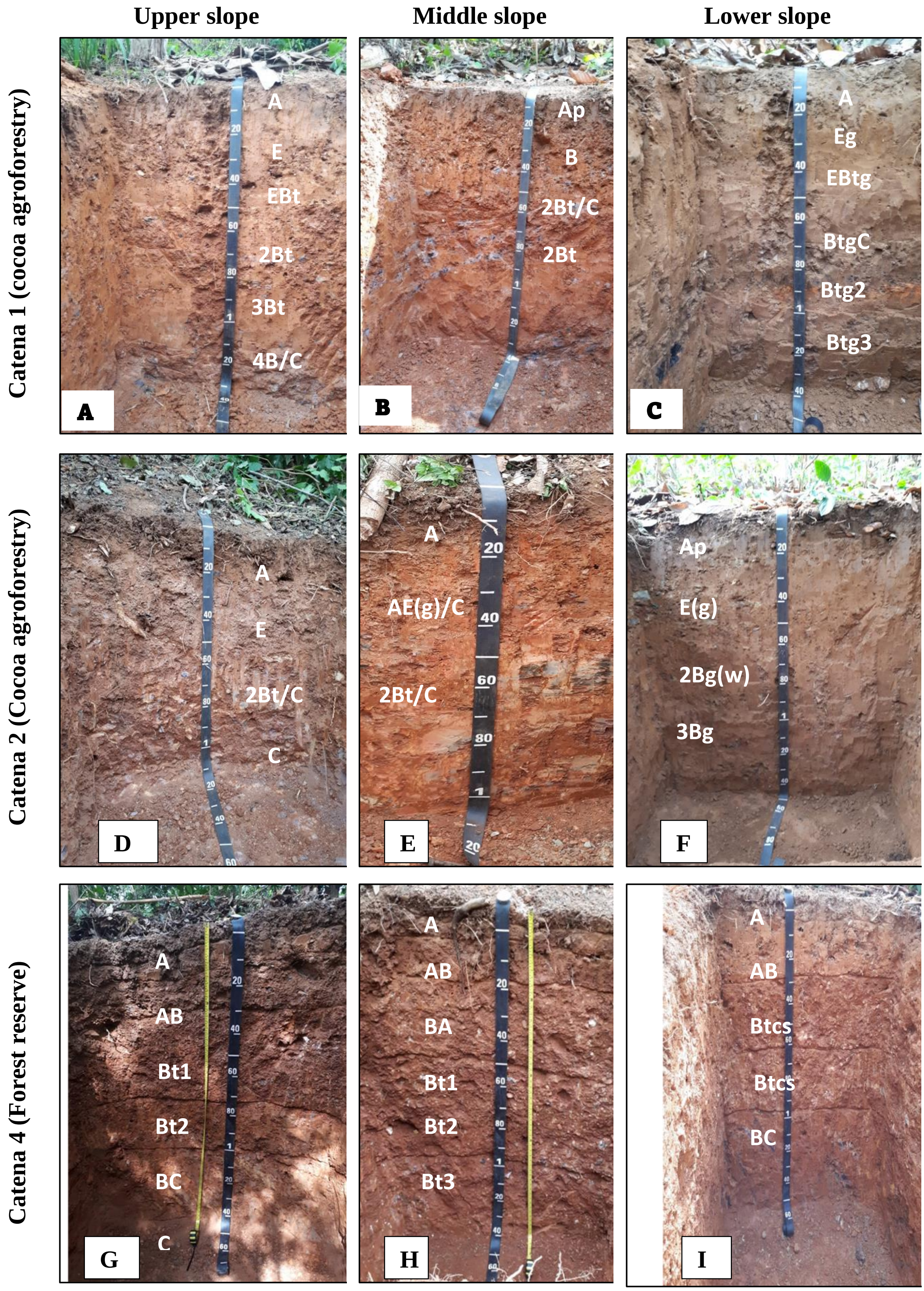


Figure 4.1 Soil profiles and its genetic horizons of the 3 sampled catenas

(Rows represent the 3 different catenas, while columns represent the different hillsope positions – where A, D and G profiles are situated in the upper; B, E and H profiles in the middle; and C, F and I profiles in the lower hillslope positions, respectively)

Profiles in the study sites had A horizons showing a darker surface with some organic matter accumulation. Some A horizons were ploughed (Ap). Leached E horizons were also observed in profiles showing loss of clay, iron, aluminum or a combination of all which has resulted in a lighter colour compared to the A and B horizons. Transitional (AB, EB, BC, B/C) horizons, vertical subdivisions (Bt1, Bt2, Bt3) as well as discontinuties (2B, 3B, 4B) were also observed in profiles. Other subordinate distinctions (c, g, p, s and w) indicate the presence of concretions or nodules, stagnic conditions, ploughed surface and development of structure, respectively within the master horizons were also observed (FAO, 2006).

The studied soils were characterized by the presence of clay accumulation ("Bt") horizon in the subsoil. In the current study clay, enrichment in Bt horizons were observed in the form of clay skins or cutans on horizontal and vertical peds, clay bridging sand grains, clay lining pores and an increase in clay from an overlying eluvial horizon. Furthermore, parent material (phyllite) may be a critical factor influencing clay illuviation (Shaw et al., 2004). Soils with abundant coarse fragment content often have deeper argic horizons (Gile & Grossman, 1968). This could be explained by the water movement within these profiles, as water containing suspended silicate clay is readily able to move downward more easily. Moreover, movement of clay is highly dependent on the amount of water available (Bockheim & Hartemink, 2013) explaining the formation of argic horizons under these well-drained soil in the study area. Furthermore, predominant pedogenetic formation of clay from the parent material in our study area could also explain clay in the subsoil. Some studies have established that argic horizons are more strongly developed on backslopes than on active eroding shoulders (Olson et al., 2005; Wilson et al., 2010). This was observed in the lower slopes in the current study having deeper argic horizons than of the middle slopes. There were variations relating to topographical positions and drainage status of soils along the catena (Adu 1992; Owusu-Bennoah et al., 2000; Eze, 2015). It was observed that profiles at the lower positions have stagnation properties (Figure 4.1) (see Appendix B). The deeper depth of solum in the lower part of the catena could be attributed to the deposition of materials at the lower slopes by water or wind (Tsui et al., 2004; Rezaei et al., 2015) in early years of soil formation in the area of study and also by excess water that may go deeper in the profile. Some profiles showed the presence of iron and magnesium (as mottles and/or concretions) which may also be attributed to the parent material (Breuning-Madsen et al., 2007) and temporally reducing conditions due to water stagnation. Worm casts and roots were also found in profiles, therefore, the presence of clay in subsoils could also be as a result of biological activities. The

C horizon was also observed for almost all the profiles which were less affected by pedogenetic processes.

4.1.3 Classification of soils of the catena study sites based on WRB and the interim Ghana classification system

Soil classification was done employing the International soil classification system for naming soils, the World reference base for soil resources (WRB) (IUSS Working Group WRB, 2015) and the interim Ghana soil classification system (Adu, 1992).

4.1.3.1 WRB Diagnostic Horizons and Properties

According to the WRB system the diagnostic horizons, properties and materials were determined prior to classification. The results are presented in Table 4.2.

Table 4.2. shows that all the 9 profiles had an ”argic” (clay-accumulation) horizon as the major diagnostic horizon, with either clay increase or clay coatings or both in the sub horizons, especially, at the 0-60 cm depth. Profiles had light to bright colours at the lower horizons with darker coloured upper soils. Qualifiers such as albic and chromic were assigned in this regard. There were mottlings found in some of the profiles which showed stagnic properties, especially in the lower slopes of the catena. The cutanic qualifier was assigned to show the presence of clay coatings while the differentic qualifier showed clay increase in the profiles (IUSS Working Group WRB, 2015).

The laboratory analyses confirm low CEC clay in the argic horizon and a low base saturation for all the profiles from 0-100 cm. The classification qualifiers (principal and supplementary) associated with the Reference soil group in the study site showed variability of the soil types.

Information on laboratory analyses on soil profiles can be referred to in Table A1, A2 and A3 in appendix B.

4.1.3.2 WRB Reference soil groups of the study area

Based on the classification key, as argic horizon starting ≤ 100 cm from the soil surface was described in all profiles, and the presence of low activity clays in the argic horizon (CEC of < 24 cmolc kg^{-1} clay) and low base status (in half or more of the part between 50 and 100 cm from the mineral soil surface) was confirmed by laboratory analyses, all the 9 soil profiles were classified as Acrisols according to the WRB (IUSS Working Group WRB, 2015). Furthermore, despite soils being classified as Acrisols, differences over catenas were observed (Table 4.2). Pre and suffixes for profiles keyed soils as Haplic Chromic Acrisol (loamic, aric, colluvic, cutanic, differentic, ochic, ruptic), Epyskeletic Chromic Acrisol (loamic, aric, colluvic, cutanic, differentic, profondic, ruptic), Ferric Amphistagnic Acrisol (loamic, colluvic, cutanic, differentic, ochric, magnesic, profondic), Endoskeletic Albic Acrisol (clayic, aric, colluvic, cutanic, differentic), Epystagnic Acrisol (clayic, aric, colluvic, cutanic, differentic), and Amphistagnic Acrisol (clayic, aric, colluvic, cutanic, differentic) for profiles in the cocoa systems. Profiles in the forest system were keyed as Amphiskeletic Chromic Acrisol (loamic, colluvic, cutanic, differentic, profondic), and Amphiskeletic Ferric Albic Acrisol (clayic, colluvic, cutanic, differentic, profondic).

Full WRB classification of the profiles is provided in Table 4.2.

4.1.3.3 The Interim Ghana Soil Classification System

According to Adu (1992), soils in the Ashanti region have similar profile morphology derived from similar conditions of climate, vegetation, relief, and drainage. Topographically, Bekwai series are generally found on the summit, upper and middle slopes with slope gradients of 3-12%. However, Nzima series is an associate of Bekwai series and they are also found at the upper to middle slopes (5-12%) (Adu, 1992; Owusu-Bennoah et al., 2000). Sometimes they can occur in isolation over summit sites. In the present study, soils were differentiated based on their colours, depth and drainage, and compared to descriptions provided in Adu (1992). Bekwai series are red with Munsell colors of dark brown or dusky red (A horizon) to reddish-brown to red in B and C horizons. Similar colors are found in the A horizon of the Nzima series as that of the Bekwai series, but their subsoil has brown colors to yellowish-red instead of red. Bekwai series were deep and well-drained, while Nzima series were deep and moderately drained. The Bekwai and Nzima series also show slity clay loam topsoil (A horizons) and a firm blocky silty clay subsoil (B horizon) and frequent ironstone concretions. They also have a C horizon weathered substratum consisting of red mottled yellow silty clay for Nzima and a red mottled yellow silty clay loam for Bekwai both exibiting patches of decomposing phylite.

Table 4.2 Results of soil classification according to the Interim Ghana and the WRB soil classification systems

Profile code	Ghana classification	Principal and Supplementary qualifiers	WRB-RSG
C1-P1	*Nzima series*	Haplic Chromic Acrisol (loamic, aric, colluvic, cutanic, differentic, ochic, ruptic)	Acrisol
C1-P2	*Nzima series*	Epyskeletic Chromic Acrisol (loamic, aric, colluvic, cutanic, differentic, profondic, ruptic)	Acrisol
C1-P3	*Nzima series*	Ferric Amphistagnic Acrisol (loamic, colluvic, cutanic, differentic, ochric, magnesic, profondic)	Acrisol
C2-P1	*Nzima series*	Endoskeletic Albic Acrisol (clayic, aric, colluvic, cutanic, differentic)	Acrisol
C2-P2	*Nzima series*	Epystagnic Acrisol (clayic, aric, colluvic, cutanic, differentic)	Acrisol
C2-P3	*Nzima series*	Amphistagnic Acrisol (clayic, aric, colluvic, cutanic, differentic)	Acrisol
C3-P1	*Bekwai series*	Amphiskeletic Chromic Acrisol (loamic, colluvic, cutanic, differentic, profondic)	Acrisol
C3-P2	*Bekwai series*	Amphiskeletic Chromic Acrisol (clayic, colluvic, cutanic, differentic, profondic)	Acrisol
C3-P3	*Nzima series*	Amphiskeletic Ferric Albic Acrisol (clayic, colluvic, cutanic, differentic, profondic)	Acrisol

In comparing the Interim Ghana Classification system and the WRB it is observed that the former depends more on qualitative characteristics while the latter uses strict limits in keying out soil names. It can be said that the WRB provides more information about the major characteristics of soil as compared to the Interim Ghana classification system.

4.2 Effects of land use and land management practices on the depth distribution of SOC content, quality, stock, macro-nutrients in selected shaded-cocoa and forest soils

This chapter presents the results and discussions related to objective two:

2. Determine the effects of landuse and land management practices on the depth distribution of SOC content, quality and SOC stocks in selected shaded-cocoa and connected forest soils

4.2.1 Soil physical parameters in the studied land-uses

Table 4.3 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 4.4). 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 4.3).

Table 4. 3 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.

Cocoa systems are perennial cropping systems with cocoa trees being the main tree layer. Human influence in managing cocoa farms such as harvesting activities, weeding and pruning seem to have a strong influence on bulk density in the cocoa systems hence the generally significantly higher bulk densities recorded in cocoa compared to secondary forest soils (Dawoe et al., 2014). 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. There were no significant differences in percentage sand, silt and clay under the studied land-uses, thus corroborating the textural homogeneity between cocoa and forest systems. Similar textural composition of soils in cocoa and forest systems also suggests similar parent materials and climatic conditions (Dawoe et al., 2014).

4.2.2 Effects of land-use changes on SOC concentrations and stocks

The soil organic carbon concentrations (SOC) for the different depths ranged from 0.22 to 2.78 % across all sites (Table 4.4). Generally, SOC concentrations decreased down the profile with the forest and cocoa systems having similar concentrations at all corresponding depths (Table 4.4).

Table 4. 4 SOC concentrations in the two studied landuses at all sampled depths (0-145 cm)

Depths	Cocoa	Forest	P
0-5	2.78 ± 0.81^a	2.76 ± 0.62^a	0.981
5-15	1.65 ± 0.47^a	1.76 ± 0.64^a	0.822
15-30	0.96 ± 0.38^a	0.93 ± 0.48^a	0.886
30-60	0.57 ± 0.23^a	0.58 ± 0.29^a	0.837
60-100	0.41 ± 0.17^a	0.40 ± 0.20^a	0.879
100-145	0.37 ± 0.23^a	0.22 ± 0.11^a	0.656

Values in the same row followed by the same superscript for different landuses are not significantly different at $\alpha = 0.05$ using Tukey's post hoc HSD test.

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 4.2).

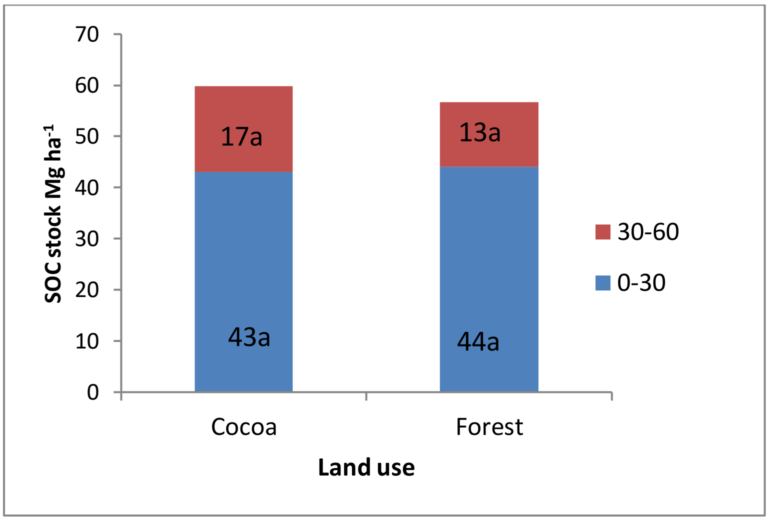


Figure 4.2 **Effect of landuse on SOC stocks at 0–30 and 30–60 cm aggregated depths in soil profiles in forest and cocoa agroforestry systems.**

As expected, SOC concentrations were higher in the topsoils than in the subsoils possibly resulting from the effect of continuous addition of organic materials to topsoil through litterfall, fine roots turnover and woody materials addition and subsequent decomposition (Emiru & Gebrekidan, 2013; Kunlanit et al., 2019). Topsoil SOC concentrations in both the cocoa (15 to 20-year-old) plantation and forest systems were comparable but higher than the critical level of 1.1% below which serious decline in soil quality may occur in agricultural soils (Aune & Lal 1997). Dawoe et al. (2014) working in the same municipality reported significantly lower SOC concentrations in younger (3 and 15-year-old) plantations compared to secondary forests. The similar SOC concentrations in the two landuses in the present study might be related to their similarities, as tree-based landuse systems recycling nutrients taken up from soils developed from similar parent material and returns same through litterfall to the forest floor. It might also be related to the fact that the cocoa system in the present study is older (15-20 years) compared to the younger systems in Dawoe et al. 2014, and soil samples in the present study were collected in the dry season while in the former, samples were collected in the wet season.

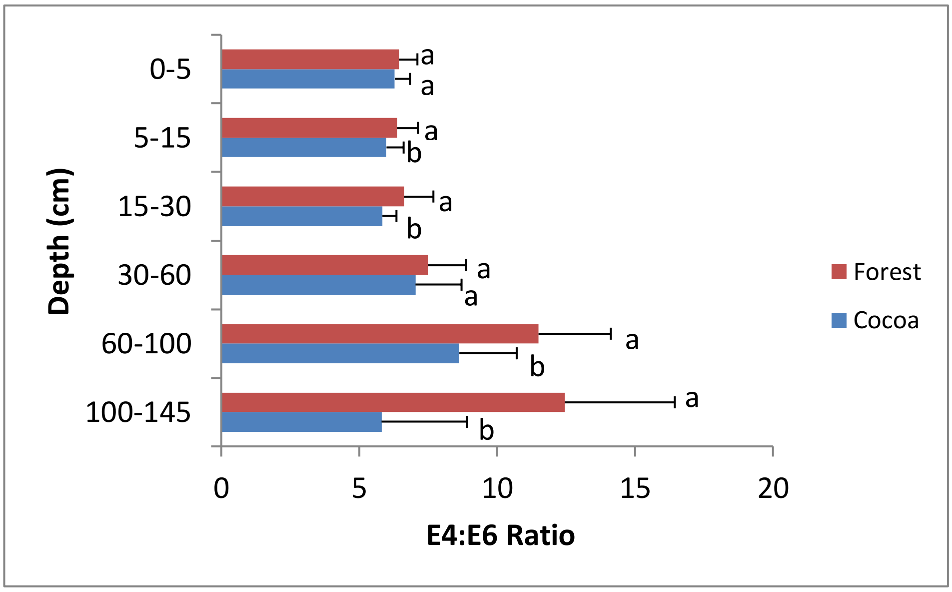
While this study did not measure litterfall, Dawoe et al. (2009) observed that litterfall production showed a significant increase over time after forest conversion and ranged from 5.0 to 10.4 Mg DM ha^{-1} yr^{-1} on the same sites. A number of studies (eg. Owusu-Sekyere et al., 2006; Opakunle, 1989; Isaac et al., 2005 and Hartemink, 2005) have all observed that litterfall contributes significantly to nutrient cycling in forests and tree-based cropping systems like shade cocoa 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 & Gifford 2002). The findings of this study show carbon stock differences between older cocoa and forest systems were small.

The results also showed that whereas carbon stocks in the 0-60 cm soil depths were similar in forest and cocoa systems, stocks in the 15-30 and 30-60 cm depths of cocoa plantation (15-20 years) was at least 20 % greater than in the secondary forest even though it was not statistically significant.. This observed difference is more likely due to higher bulk density under cocoa landuse compared to the forest system. It is important to emphasize here that, we did not correct for bulk density in our determination of SOC stocks. Mass correction of SOC stock estimates is crucial in order to estimate land-use change effects since land-use change is always accompanied by bulk density changes, a situation which calls for the need to compare SOC stocks in equivalent soil mass. The comparison of SOC stocks based on different soil mass deeply confounds estimates of SOC changes. Wendt & Hauser (2013) have observed that quantifying SOC stocks at fixed depths as a product of soil bulk density, depth and organic carbon concentrations systematically overestimates SOC stocks as different masses of soil are compared due to bulk density differences. This is likely to be the case in this study and SOC estimates in this study may be more accurate if they were based on the quantification of equivalent soil masses. Moreover, perennial crops develop larger roots that penetrate and develop fine roots deeper in soil. Thus, agroforestry systems store more C in deeper layers near trees than away from trees (Nair et al., 2010) and this might be the case in cocoa agroforestry system in this study.

4.2.3 Quality of SOC in the studied land uses

The E4:E6 ratio of humic and fulvic acids, and C:N ratio which relates the chemical composition of SOC in the shaded-cocoa and forest soils in this study are presented in Figures 4.3 a and b. The E4:E6 ratios in cocoa and forest soils ranged from 5.81 to 12.45. Ratios increased with increasing depth in the forest soils while ratios of the cocoa soils did not follow any consistent depth-wise trend. With the exception of the 0-5 and 30-60 cm depths, significant ($p < 0.05$) differences in E4:E6 ratios were found between shaded-cocoa and forest soils with the forest soils generally having higher ratios. Soil C:N ratio decreased with increasing depth in both cocoa and forest soils with the ratios generally higher in the former than in the latter. The cocoa soils had significantly ($p < 0.01$) higher C/N ratio than the forest soils at 30-60 cm depth.



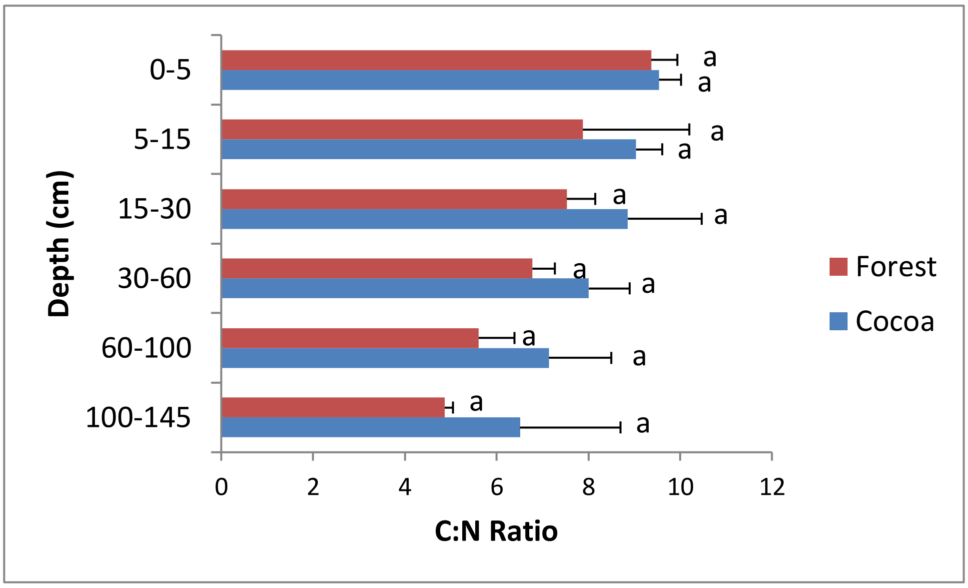


Figure 4. 3 Variations in E4:E6 (a), and C:N ratios (b) with changes in soil depths in cocoa agroforestry and forest systems. Error bars represent standard deviations of means.

The C:N ratio is a good indicator of the degree of decomposition and quality of organic matter in soil (Batjes et al., 1996) and its balance affects carbon and nitrogen cycles. C:N ratios of the cocoa and secondary ecosystems were similar with all ratios lower than 20 suggesting the quality of organic materials in the soils are high. Swangjang (2015) reported C:N ratio ≤ 20 is preferred for agriculture soils for better mineralization of organic matter. Soil C:N ratio decreased with increasing depth reflecting the general decrease in litter amount and microbial population with soil depths. Both SOC and nitrogen contents are primarily dependent on decomposition rate which is driven by microorganisms. Lower C:N ratios found in the deeper profile may also reflect a greater degree of breakdown and older age of humus stored in the lower parts of the profile (Batjes et al., 1996). 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. Similar C:N ratios between the cocoa and forest ecosystems in the profiles could be explained by the management and vegetation of both systems retaining higher organic matter content as well as having greater nutrient absorption by plant roots (Lal, 2002). Other researchers reported higher C:N ratios in forest than in cultivated soils contrary to our findings (e.g. Murty et al., 2002). Higher accumulation of soil carbon in the cocoa plantation at the 30-60 cm may account for its higher C:N ratio compared to the secondary forest. Murty et al. (2002) noted crop residues N content are low in agriculture soils. Aranibar et al. (2004) attributed low C/N ratio in soils of some Sahelian ecosystems to lower litter amounts and vice versa.

The humic substances were also affected by landuse change and soil depth. As pointed out, E4:E6 ratio used as a key indicator of SOM quality. The E4:E6 ratios differed significantly at all depths (except for the 0-5 and 30-60 cm depths) with the forest generally having higher ratios than the cocoa system. Higher E4:E6 ratios suggest the presence of aliphatic compounds in the form of fulvic acids. Lower values, on the other hand, are indicative of the presence of organic molecules with higher humification rates in the form of humic acids (HA), which are more stable and less soluble in soils. 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. Furthermore, contrary to the findings of Gondar et al. (2005) and Kunlanit et al. (2019), it was observed that lower values were found in upper compared to lower horizons in the forest but the pattern in the cocoa plantation with respect to the different horizons was not consistent. Even though frequent biomass additions were observed in all landuses, soil organic carbon status was still in a varied state of humification as evidenced by the wide variations in E4:E6 ratio values in the two landuse 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.

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. Thus, SOC persistence is higher (lower E4:E6 ratios) in cocoa compared to forest systems. 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 4.5a and b). Furthermore, with the apparent changes in carbon quality, the availability of readily available SOC could be reduced for plant uptake in the forest system compared to that of the cocoa. Depth wise, carbon quality in the forest system was more stabilized in the upper horizons. Stabilized carbon prevents leaching and mineralization of SOC and nutrients in the soil.

Regressions of E4:E6 and C:N ratios against depth and SOC stocks are shown in Figure 4.4. Relationships established showed that while depth significantly affected E4:E6 ratios only in forest soils (Figure 4.4a), it significantly influenced C:N ratios in both land uses (Figure 4.4b).

A number of authors (Young et al., 2010; Lawrence et al., 2015; Chandler, 2016; Marty et al., 2017) have all observed that C:N ratios generally vary with ecosystems and landuse. Aranibar et al. (2004) explained that declining C:N ratio with depths is as a consequence of carbon content decreasing down the soil profile. Also, Diekow et al. (2005); Ouédraogo et al. (2006) and Yamashita et al. (2006) attributed decreasing C:N ratio with increasing depth to clay increase and this could be the case in this study. The relationship 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. The E4:E6 and C:N ratios showed very low linear correlations with SOC stocks (Figures 4.5 and 4.6). Correlations between E4:E6 and C:N ratios against SOC stocks were generally weak. For E4:E6 against SOC stocks, R^2 ranged from 8E to 05 to 0.25 for 0–5 and 60–100 cm depths respectively, while in the case of C:N ratios against SOC stocks, R^2 ranged from 0.002 to 0.193 for the 30–60 and 0–5 cm soil depths respectively.

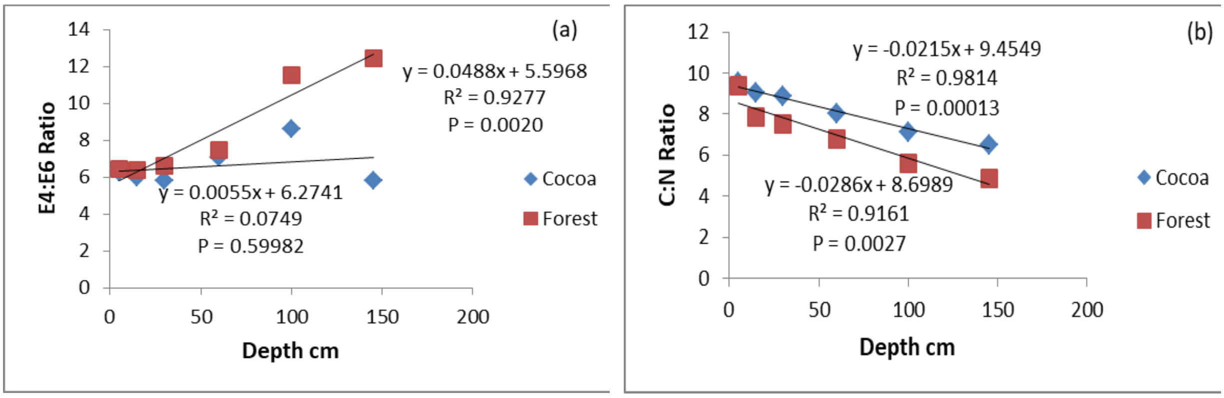


Figure 4.4 Linear regression analysis between (a) Humic substances (E4:E6 ratios) and soil depth, (b) C:N ratio and soil depth, cocoa agroforestry and forest systems in the Atwima Nwabiagya Municipality of the Ashanti Region, Ghana.

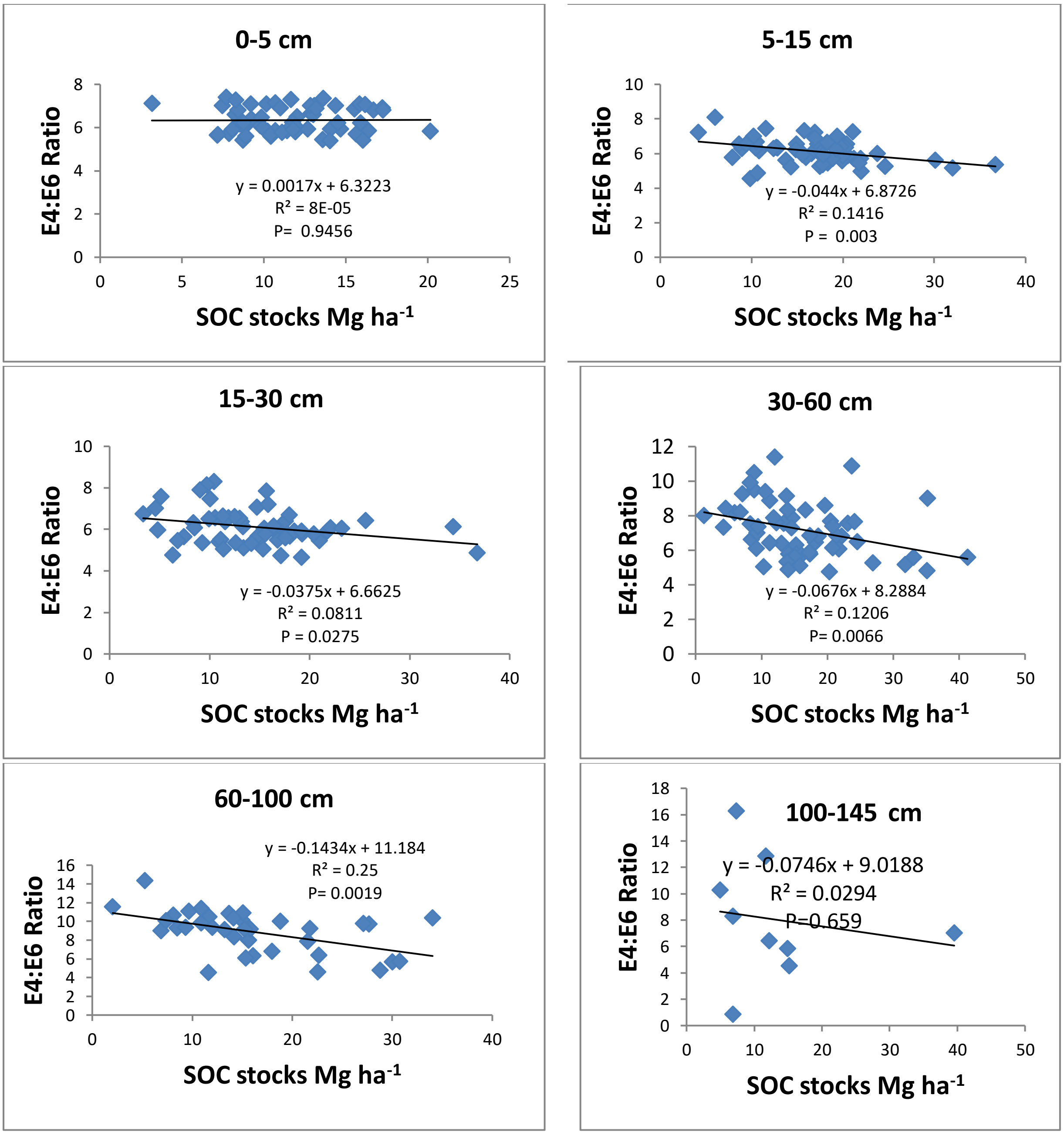


Figure 4.5 Relationships between E4:E6 ratios and SOC stocks pertaining to two landuses and six soil depths in soil profiles down to 145 cm.

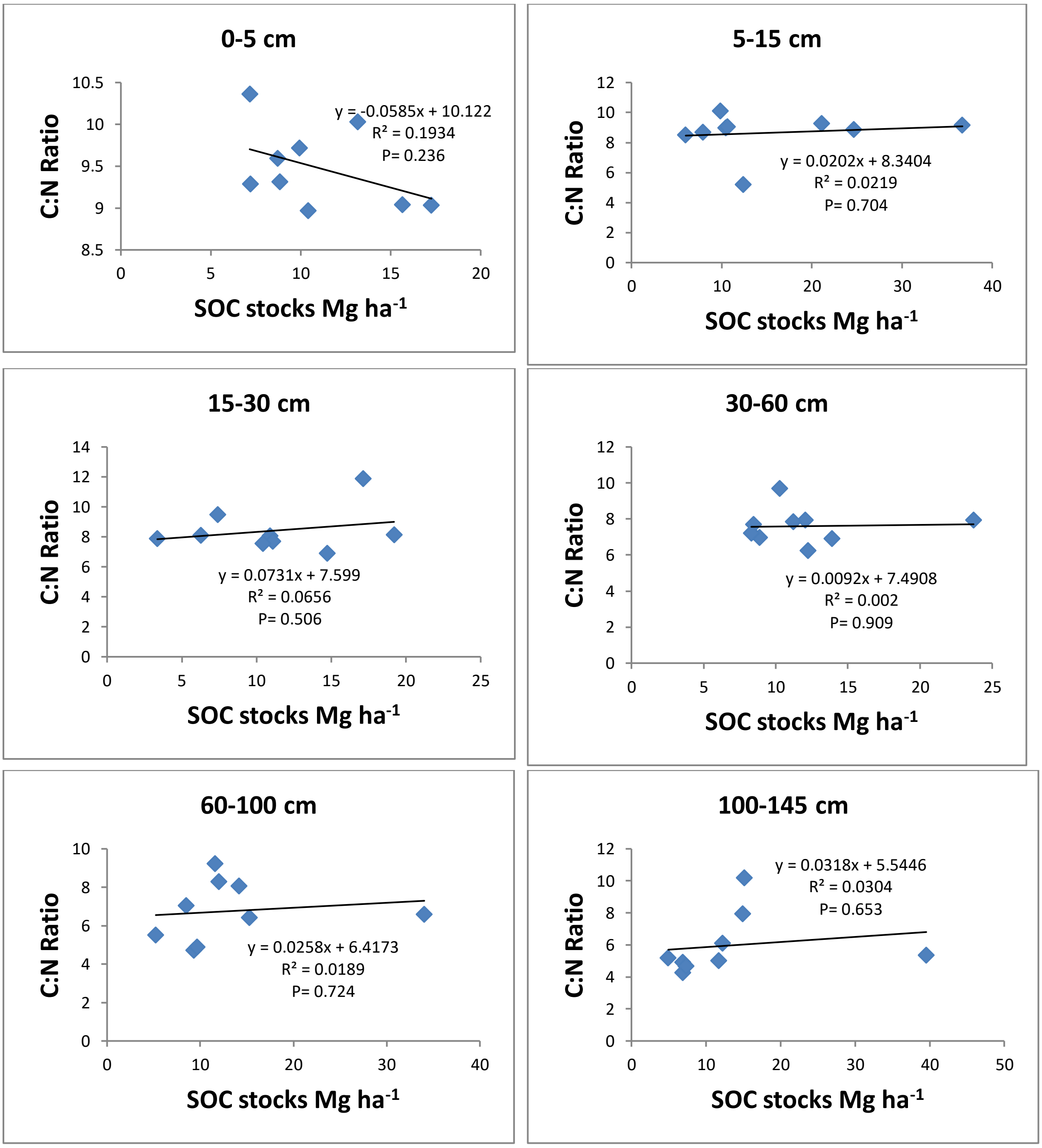


Figure 2.6 Relationships between C:N ratios and SOC stocks pertaining to two landuses and six soil depths in soil profiles in soil profiles down to 145 cm.

With respect to the relationship between E4:E6 and pH, the regressions revealed a weak and non-significant relationship in cocoa systems (Figure 4.7a) while a stronger and highly significant ($p < 0.001$) relationship was observed in the forest system (Figure 4.7b). 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.

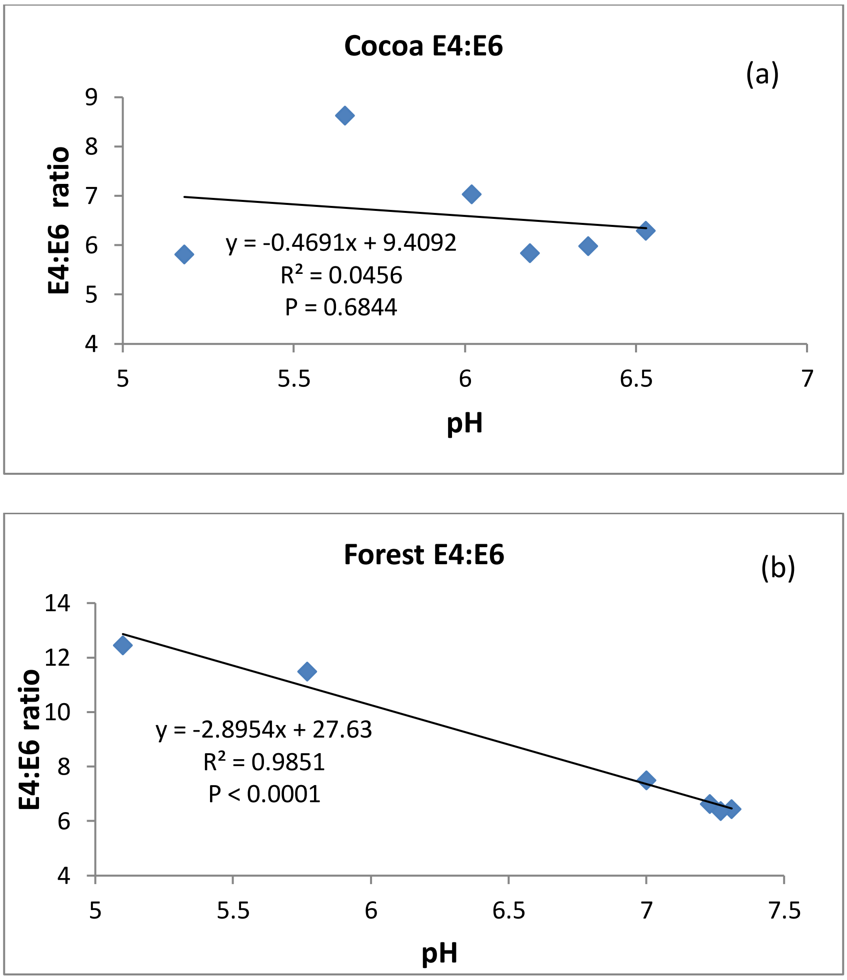


Figure 4.7 Regressions of E4:E6 and pH

4.2.4 Relationships between SOC and selected soil physical and chemical properties in the studied landuses

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 4. 5 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

A number of studies (e.g., Noordjik et al 1997; McLauchlan, 2006; Gami et al 2009, Lui et al 2013; Benefoh, 2018) have also looked at correlations among soil physical and selected chemical properties and have reported statistically significant relationships similar to what we found in this study. Significant ($p < 0.001$) correlations of SOC to BD, E4:E6, silt and clay (0-30 cm soil depths) were observed showing the significant role and influence of SOC on soil physico-chemical properties. 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. This may be a reflection of the fact that changes in soil physical and chemical properties with landuse change is by no means universal but dependent on a number of other factors including soil type, climatic conditions, tree species and the type of management practices adopted. 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). 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. A linear regression analysis showed no relationship between humic substances and SOC stocks. Similar relationship was also observed between C:N and SOC stocks. The generally stronger and significant relationship between E4:46 ratios and soil pH observed in forests compared to the weaker and non-significant relationship for the cocoa system may be attributed to the inherent differences in chemical composition and molecular weights of HA and FA in these systems (Reddy et al., 2014).

4.2.5 Vertical distribution of selected nutrients, CEC and B% in the studied landuse systems

Table 4.6 shows chemical properties of cocoa and forest soils at the various profile depths. Generally, most of the nutrients of both land-uses decreased as depth increased. TN content was similar in cocoa and forest soils in individual layers ($P < 0.05$). In the case of TP, forest soils recorded significantly higher values than cocoa soils in 0-5 and 5-15 cm soil depths, values in the 15-30 cm depth were similar In the case of TP, a significant difference was observed only at 0-5 cm between land-uses ($P < 0.01$). Exchangeable bases were all not significantly different in cocoa and forest soils.

Table 4. 6 Mean values (±SEM) of concentrations of soil chemical properties in cocoa and forest soils at different depths

Soil chemical properties	Depth (cm)	Land-use	
		Cocoa	Forest
TN (%)	0-5	0.30±0.08^{a}	0.45±0.12^{a}
	5-15	0.16±0.01^{a}	0.24±0.23^{a}
	15-30	0.09±0.03^{a}	0.14±0.07^{a}
TP (mg kg^{-1})	0-5	8.10±6.87^{b}	25.06±5.37^{a}
	5-15	0.57±0.89^{b}	10.69±12.87^{a}
	15-30	0.96±2.34^{a}	0.15±0.26^{a}
TK (mg kg^{-1})	0-5	162.61±17.24^{b}	405.00±67.11^{a}
	5-15	116.15±12.87^{a}	185.50±33.10^{a}
	15-30	120.41±7.44^{a}	129.83±4.888^{a}
Exchangeable Ca (cmol kg^{-1})	0-5	5.29±0.56a	5.68±0.59a
	5-15	2.23±0.42a	3.51±0.31a
	15-30	1.91±0.33a	2.51±0.39a
Exchangeable K (cmol kg^{-1})	0-5	0.21±0.04^{a}	0.32±0.04^{a}
	5-15	0.10±0.03^{b}	0.25±0.05^{a}
	15-30	0.08±8.22E-03^{a}	0.15±0.05^{a}
Exchangeable Mg (cmol kg^{-1})	0-5	1.33±0.18^{a}	1.68±0.13^{a}
	5-15	0.63±0.11^{b}	1.23±0.19^{a}
	15-30	0.72±0.08^{a}	0.90±0.31^{a}
Exchangeable Na (cmol kg^{-1})	0-5	6.000E-03±3.688E-03^{a}	0.01±4.817E-03^{a}
	5-15	5.200E-03±4.488E-03^{a}	0.11±0.05^{a}
	15-30	5.778E-03±3.398E-03^{b}	0.41±0.13^{a}
CEC (cmol kg^{-1})	0-5	18.20±0.37^{a}	17.00±0.95^{a}
	5-15	13.40±1.21^{a}	13.20±1.20^{a}
	15-30	11.00±0.90^{a}	11.30±0.54^{a}
Base Saturation (%)	0-5	37.37±2.79^{a}	45.56±4.71^{a}
	5-15	22.69±4.33^{b}	40.37±4.89^{a}
	15-30	25.74±3.89^{a}	35.36±3.79^{a}

Values in the same row followed by the same superscript for the different land-uses are not significantly different at $P < 0.05$ according to Tukey’s HSD test.

Soil depth negatively influenced the distribution of TP, TK, and exchangeable K, Mg and Na basic cations, with quantities generally decreasing with increasing depth (Table 4.6). This is in agreement with Han et al. (2015) and Ahukaemere et al. (2019). Hartemink (2005) has posited that most of the nutrients in soils in the tropics has been found in the top 25 cm (Hartemink 2005). The adsorption and storage of nutrients on soil surfaces is important in determining soil fertility. Such adsorption is dependent on the attraction of positively charged nutrient elements (cations) to negatively charged soil particles. Soil surfaces have been observed to possess negative charges, especially, where organic carbon (humus) and clay minerals are present (Rai, 2002). This explains the higher soil organic carbon and nutrient contents (TN, TP, TK, and exchangeable Ca, Mg, K and Na) recorded in upper layers across cocoa and forest soils in our study. In this regard SOC and nutrients are being returned to soil through accumulation and subsequent turnover of leaf litter, fine roots and woody materials from shade and cocoa trees (Montagnini & Nair 2004; Oelbermann et al., 2006).

The forest and cocoa systems have been observed to have similar nutrient additions, losses and transfers (Dawoe et al., 2014). Nutrient additions in both forest and cocoa systems are through depositions (wet and dry) rain and dust in tropical areas and N_2 fixations by leguminous shade trees. Furthermore, nutrient transfers in these ecosystems are similar through litterfall, rain-wash, and fine-roots turnover. The practice of cocoa agroforestry increases nutrient use efficiency in cocoa ameliorating adverse micro-climatic conditions and reducing soil erosion, etc. (Beer et al., 1998; Johns, 1999).

In this study, land-use did not significantly affect N content and this is most likely due to the fact that both are morphologically similar, being tree-based ecosystems which according to Guo et al. (2004) and Dawoe et al. (2014) are returning N to the soil in above-ground litterfall and also through turnover of fine roots. Generally, different plant uses would have different impact on N availability and induced organic matter accumulation as reported by Oelmann et al. (2011a). N increased along with increasing C and this is because an increase in N facilitates the buildup of C in soils, leading to increase in rates of nutrient cycling (Yuan et al., 2012). According to Monroe et al. (2016), after 4 years of establishment, the cocoa agroforestry was the most efficient system in the accumulation of soil carbon and nutrients in the top 20 cm and consequently up to 100 cm deep. This could probably explain why TN, and in some parts of the profile TP and TK concentrations in cocoa soils were not significantly different from the forest, since our cocoa system was matured (fifteen years old) and exhibited similar management system as that of the forest. Again, the occasional application of inorganic fertilizers is a source of nutrient in cocoa systems in our study area which could explain an improvement in nutrient concentration in the cocoa system. Hartemink (2005) in his review on nutrient under cocoa systems observed that in cocoa systems under unfertilized conditions in Malaysia and Cameroon, yearly losses of N are about two to four times higher than nutrient addition.

Phosphorus is the primary limiting nutrient for crop production in tropical soils (Cardoso et al., 2003). Soil available P was lower in all land-uses and this may be attributed to the fact that forest soils are extremely low in P, and this according to Oelmann et al. (2011b) is because P availability is dependent on the interactions with Iron (Fe) and aluminum (Al) and the uptake of P by the above biomass. In cocoa systems, P is normally present in very low concentration, typically around 0.1% (Hartemink, 2005). A relatively large amount (6 to 8%) of the available P in the soil is removed by the cocoa beans. Although P was lower, values were significantly higher in the secondary forest soils than in the cocoa system which is confirmed by Gao et al. (2014) on significant declines in soil P in farmlands and orchards than forested soils. Differences could also be explained by P export though harvest of beans and husk. Furthermore, P cannot be easily resupplied compared to N, which can be introduced by N-fixing plants hence forest soils are resupplied with P almost entirely from the weathering of parent material, which takes place at very slow rates. The cocoa farm can be resupplied through the application of P fertilizers and manure but in our study sites this is limited because of financial constraint. According to Hartmink (2005), K is a major nutrient in mature cocoa systems, especially in topsoil, hence, in our study, K varied from 597 to 1401 kg ha^{-1} which was higher than the values recorded by Hartmink (100 to 550 kg ha^{-1}) in a review of nutrient in cocoa systems. Soil exchangeable K in cocoa systems is derived from deep rooting cocoa and shade trees as well as decomposing leaf litter in the cocoa systems (Dawoe et al., 2014). Despite the higher K in cocoa systems, K was significantly higher in forest soils compared to the cocoa systems in the 0-5 and 5-15 cm.

4.2.6 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. 4.8 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. 4.8a). TP stocks in forest soils were significantly higher in 0-5 and 5-15 cm compared to cocoa soil (Fig 4.8b). 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. Thus, for all three nutrients, stocks were significantly higher in forests compared to cocoa plots at 0-30 cm aggregated depth.

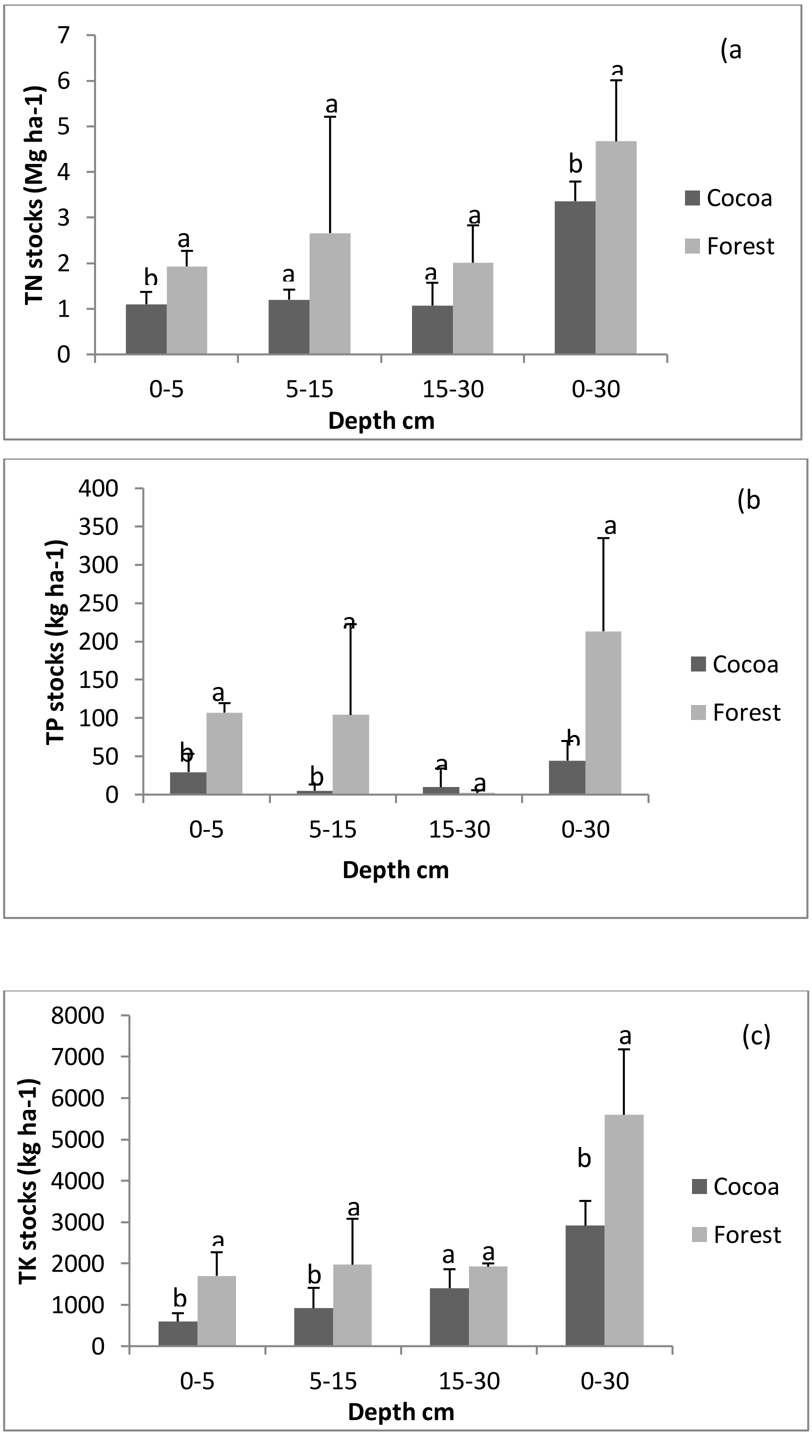


Figure 4.3 Land-use effect on nutrient stocks in the topsoil of soil profiles(a) total nitrogen (b) total phosphorus, and (c) total potassium stocks at 0-5, 5-15, and 15-30 cm individual depths, and at 0-30 cm aggregated depth. Error bars represent standard deviation of the mean.

Nutrient stock measurements in this study have been restricted to the upper 30 cm because the feeding roots of cocoa are concentrated to that depth (Wood & Lass, 1985). According to Hartemink (2005) the total TN stocks in the upper 30 cm in most tropical soils varies from about 4800 to 18, 750 kg ha^{-1} which was higher than TN stocks recorded in our study. In the whole profile 0-30 cm significant differences in TN, TP and TK stocks were observed between cocoa and forest soils with higher stocks found in the forest. Owusu-Sekyere et al. (2006), observed higher contents of TN and TK nutrients in secondary forest than cocoa soils. 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 TN, TP and TK, 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 TN, TP and TK, respectively from 1000 kg of dry cocoa beans in Ivory Coast. Furthermore, Wessel (1985) recorded nutrient losses of 17.0, 2.3, 77.2 kg of TN, TP and TK through the harvesting of husks respectively, and nutrient losses of 13.2, 1.8, 43.0 kg of N, P and K respectively through husk were also recorded by Snoeck & Jadin (1992). The above studies show TK losses through cocoa bean and husk is high which could explain the marked difference of TK stocks observed between the studied land-uses in our study. 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. Another possible explanation to differences in nutrient stocks between land-uses could be through nutrient leaching which is an important pathway for nutrient losses in soils of the tropics. Comparatively, cultivated soils have a high tendency to be leached of its nutrients than forest soils because of soil disturbances through weeding and harvesting. Even though, the application of inorganic fertilizer is a direct source of nutrient to the cocoa soil pool, significant amounts may be lost through leaching and volatilization directly after application (Hartemink, 2005).

4.2.7 Correlation between SOC, nutrient and other soil properties in relation to land-uses

Correlation coefficients between SOC, nutrient and other soil properties in 0-30 cm depth are shown in Table 4.7, and 4.8, . It was observed in both systems (cocoa and forest) that SOC significantly positively correlated with TK (Table 4.7). TK significantly positively correlated with TP only in the cocoa system. Again, there was a significantly negative correlation between BD and TP (Table 4.7). Positive correlations were found between TN and TK and

TP (Hartemink, 2005; Dawoe et al., 2014; Ahukaemere et al., 2019; Mohammed et al., 2020) but were not significant. SOC and nutrients also positively correlated with pH in both systems except TN in the cocoa sytem and TP in the forest system showing the buffering effects of SOC and nutrient on pH in soil surfaces (Hong et al., 2019).

Table 4. 2. Pearson correlation showing relationships between selected soil properties at 0-30 cm depth in cocoa landuse.

	CN	TN	pH	BD	Sand	Silt	Clay	TK	TP	CEC
SOC	0.64	0.14	0.80*	-0.56	-0.67	0.83*	-0.24	0.84*	0.66	0.09
CN		0.10	-0.59	-0.19	-0.63	0.85*	-0.33	0.55	0.26	0.45
N			-0.28	-0.50	-0.17	0.45	-0.38	0.64	0.79	-0.48
pH				-0.50	-0.46	0.57	-0.18	0.40	0.28	0.22
BD					0.02	-0.57	0.67	-0.61	-0.80*	0.19
Sand						-0.61	-0.34	-0.67	-0.43	0.22
Silt							-0.54	0.87*	0.69	-0.45
Clay								-0.33	-0.38	0.77
TK									0.91*	-0.18
TP										-0.14

SOC- soil organic carbon; BD-bulk density, TN-total nitrogen, TP-total phosphorus, TK-total potassium CEC-cation exchange capacity, C:N-carbon –nitrogen ratio. Significant levels *< 0.05, **<0.01 and ***<0.001

Table 4.8 Pearson correlation showing relationships between selected soil properties at 0-30 cm depth in forest land-use

	CN	TN	pH	BD	Sand	Silt	Clay	TK	TP	CEC
SOC	0.45	0.97	0.63	-0.99	0.70	0.93	-0.99*	0.99**	0.03	-0.94
CN		0.66	0.98	-0.54	0.95	0.09	-0.48	0.45	-0.88	-0.72
N			0.80	-0.99	0.85	0.81	-0.98	0.97	-0.21	-0.99*
pH				-0.71	0.99*	0.30	-0.66	0.63	-0.75	-0.85
BD					-0.77	-0.89	0.99*	-0.99	0.07	0.97
Sand						0.39	-0.72	0.70	-0.69	-0.89
Silt							-0.92	0.93	0.40	-0.76
Clay								0.99*	0.003	0.96
TK									0.04	-0.94
TP										0.30

SOC- soil organic carbon; BD-bulk density, TN-total nitrogen, TP-total phosphorus, TK-total potassium CEC-cation exchange capacity, C:N-carbon –nitrogen ratio. Significant levels *< 0.05, **<0.01 and ***<0.001

Table 4. 9 Pearson correlation coefficients showing relationship between nutrient concentrations and stocks at 30 cm depth in cocoa landuse

	CN	**KCONC**	**KSTOCKS**	**NCONC**	**NSTOCKS**
KCONC	0.55				
KSTOCKS	0.95**				
NCONC	0.10	0.64	0.17		
NSTOCKS	0.26	0.06	0.11		
PCONC	0.26	0.91*	0.47	0.79	0.04
PSTOCKS	0.02	0.78	0.32	0.38	-0.41

C:N- carbon to nitrogen ratio, KCONC- potassium concentration, NCONC- nitrogen concentration, PCONC- phosphorus concentration, K stocks- potassium stocks, N stocks- nitrogen stocks, P stocks- phosphorus stocks. Significant levels *< 0.05, **<0.01 and ***<0.001.

Table 4. 10 Pearson correlation coefficients showing relationship between nutrient concentrations and stocks at 30 cm depth in forest land use

	CN	**KCONC**	**KSTOCKS**	**NCONC**	**NSTOCKS**
KCONC	0.45				
KSTOCKS	0.47				
NCONC	0.66	0.97	0.98		
NSTOCKS	0.66	0.97	0.97		
PCONC	-0.88	0.04	0.01	-0.21	-0.21
PSTOCKS	-0.98	-0.25	-0.28	-0.48	-0.48

C:N- carbon to nitrogen ratio, KCONC- potassium concentration, NCONC- nitrogen concentration, PCONC- phosphorus concentration, K stocks- potassium stocks, N stocks- nitrogen stocks, P stocks- phosphorus stocks. Significant levels *< 0.05, **<0.01 and ***<0.001.

Significant positive correlations were observed between SOC and TK (0.99) for the forest (Table 4.10) and between SOC and TK (0.84), SOC and pH (0.80), and SOC and silt (0.83) for cocoa systems (Table 4.9). Soil pH significantly influences SOC because it regulates soil nutrient bioavailability, organic matter turnover and other processes (Kemmitt et al., 2006). Zhou et al. (2019) observed that silt positively correlated with TOC and TON in their study which is in agreement with our results. The study shows the importance of texture (especially, the silt component) in stabilizing SOC and nutrients in soils. Cultivation practices before and a few years after the planting of cocoa trees expose soil surfaces to erosion. This exposes the medium size silt particles which are more prone to erosion. Wu et al. (2020) reported that grasslands and scrublands generally performed better in controlling erosion in moderately coarse soils whilst forests are effective on medium-textured and moderately fine soils. The authors further indicated that vegetation cover, especially, on slopy lands reduces both runoff and sediment yield and becomes more stable as vegetation cover is ≥ 60 %. Six et al. (2002) attributed the positive correlation between SOC and TN to macro- and microaggregates protection against mineralization, and Waldrop et al. (2004) explained that greater availability of N regulates the production and activity of microbial extracellular enzymes which reduces decomposition of SOC. CEC positively correlated with SOC, TN, TP, TP and pH improving the ability of soils under cocoa and forest to hold nutrient and improve soil fertility especially in the topsoil.

Linear regressions of TN, TP and TK stocks on SOC stocks are depicted in Figure 4.9, showing that N, P and K stocks all increased with increasing SOC stocks. The regressions were strong for TK and moderate for TN. Though positive, it was relatively weak for P stocks.

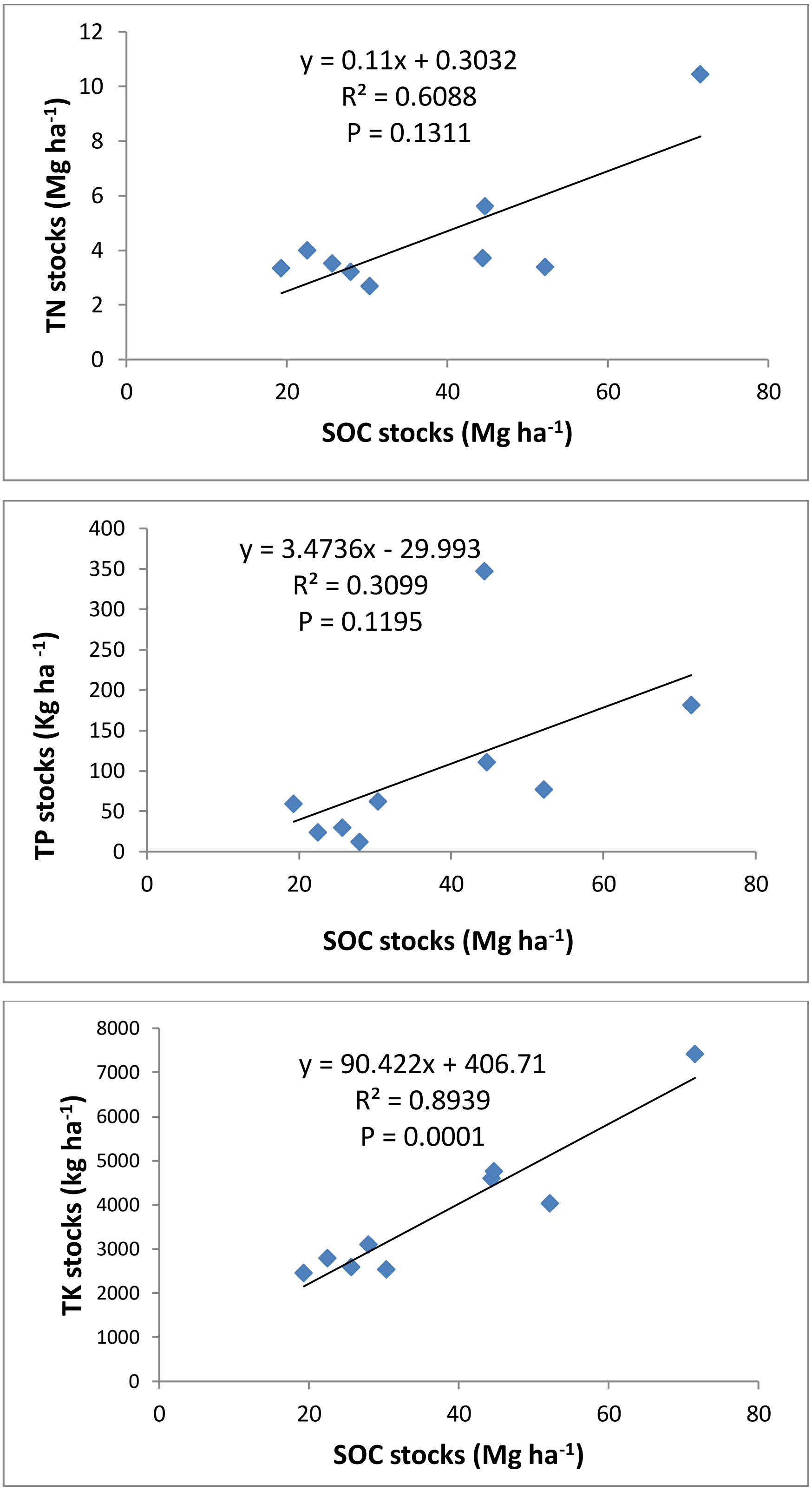


Figure 4.4 Linear regressions showing the relationship between SOC and nutrient in the 0-30 cm depth in land-uses (a, b and c).

SOC stocks strongly correlated with TN stocks (Zeng et al., 2017). Both land-uses showed that their vegetation could help sequester N. Litter fall constitutes a large proportion of nutrient input in cocoa and forest soils (Owusu-Sekyere et al., 2006). A significant correlation was also observed between SOC and TK, similar to the results of Khadka (2016). SOC also correlated positively with TP. Thus the results of our study support the hypothesis that an increase in SOC progressively increases TN, TP and TK.

4.3 Determine the effects of topography (slope position) on the depth distribution of SOC content, quality, stocks and macro-nutrients in selected shaded-cocoa and connected forest soils.

This chapter presents the results and discussions based on objective:

3. Determine the effects of topography (slope position) on the depth distribution of SOC content, quality and SOC stocks in selected shaded-cocoa and connected forest soils.

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

Generally, there were no significant effects of slope position on SOC concentration in both land use at all depths except at depth 5-15 cm (Table 4.11).

Table 4. 11 Effect of slope position on SOC in cocoa and forest land use systems at different depths

Parameters	Depth	Slope position
SOC	0-5	0.288
	5-15	0.016 *
	15-30	0.146
	30-60	1.000
	60-100	1.000
	100-145	1.000

Asterisk show level of significance $*p \leq 0.05$

Variations in SOC stocks across the different topographic positions for each of the studied depths in the two landuse systems are shown in Table 4.12. Soil organic carbon stocks ranged between 10 Mg ha^{-1} on the middle slope of the cocoa plantation at 0-5 cm and 18.6 Mg ha^{-1} on the lower slope at the 30-60 cm depth of the cocoa system (Table 4.12). No significant ($p > 0.05$) differences were observed between cocoa and forest mean SOC stocks at the individual depths (0-5, 5-15, 60-100, and 100-145 cm). However, mean carbon stocks differed significantly between forest and cocoa soils at the 15-30 and 30-60 cm depths (Table 4.12). Total stocks across the three slope positions were about 21 and 33 %, respectively greater ($p < 0.05$) in cocoa compared to the forest (Table 4.12). At the landscape level, Figure 4.8 shows that in both the forest and cocoa systems, SOC stocks were similar ($p>0.05$) for similar profile depths. Carbon stocks generally decreased from the highest to the lowest topographic positions at the 0-30 and 0-60 cm layers. However, the pattern was inconsistent in the 30-60 cm layer. 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 (Table 4.12). Values provided for the 60-100 and 100-145cm depths are only indicative as the collection of undisturbed cores was a bit problematic due to the extremely rocky nature of the two depths. For both depths however, it appears organic carbon stocks were similar in both systems at corresponding depths.

Table 4. 12 SOC stocks in the upper, middle and lower hillslope positions at varying depths in the forest and cocoa landuses systems

Depth cm	**Slope**	**Cocoa** **Mg C ha^{-1}**	**Forest** **Mg C ha^{-1}**
0-5	Upper	11.17±0.82^{a}	11.06±2.27^{a}
	Middle	10.03±1.05^{a}	11.88±1.55^{a}
	Lower	12.00±1.21^{a}	10.12±0.77^{a}
	Mean	10.12±0.60^{a}	11.14±0.92^{a}
5-15	Upper	17.71±1.91^{a}	20.14±4.17^{a}
	Middle	13.41±1.63^{a}	13.97±2.03^{a}
	Lower	12.78±1.59^{a}	9.29±3.17^{a}
	Mean	14.54±1.02^{a}	14.40±1.87^{a}
15-30	Upper	16.68±0.82^{a}	11.57±5.49^{a}
	Middle	14.93±2.14^{a}	14.21±1.43^{a}
	Lower	12.91±1.69^{a}	10.01±1.38^{a}
	Mean	14.85±1.01^{a}	12.26±1.67^{b}
30-60	Upper	15.67±0.93^{a}	15.10±4.91^{a}
	Middle	16.29±2.37^{a}	11.29±1.97^{a}
	Lower	18.64±3.46^{a}	12.25±2.83^{b}
	Mean	16.82±1.41^{a}	12.63±1.74^{b}
60-100	Upper	8.56 ±1.74^{b}	15.24±2.31^{a}
	Middle	10.9 ±1.54 ^{a}	9.65 ±1.99^{a}
	Lower	27.3 ±4.54^{a}	5.23±1.5^{b}
	Mean	15.58±5.89^{a}	10.04±2.90^{a}
100-145	Upper	8.6±1.87^{a}	6.89±1.6^{a}
	Middle	10.93±2.14^{a}	11.74±1.5^{a}
	Lower	27.32±2.37^{a}	7.32±2.83^{b}
	Mean	13.02±4.91^{a}	8.6±1.55^{a}

Values in the same row followed by the same superscript for different landuses are not significantly different at $\alpha = 0.05$ using Tukey's HSD test.

Slope positioning influenced SOC stocks distribution with stocks increasing with increasing slope at the 5-15 cm (Table 4.12) and, 0-30 and 0-60 cm depths (Figure 4.10). Results are in accordance with the findings of other studies (Leifeld et al., 2005; Fernández-Romero et al., 2014; Rezaei et al., 2015; Zhu et al., 2019; 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. Results also suggest 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.

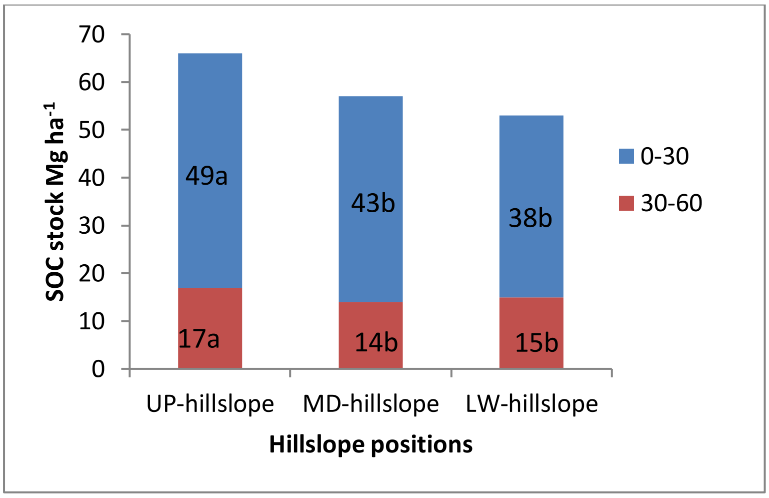


Figure 4.10 Soil carbon stocks along varying topographic positions.

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

Generally, significant effects of slope position on E4:E6 was found in both land uses at depth (0-5, 5-15 and 15-30) cm (Table 4.13). Across all depths, E4:E6 ratios were similar ($p > 0.05$) between the forest and cocoa systems at the upper and middle slopes (Table 4.14). Differences were however significant between the cocoa and forest systems at all the lower slope positions with the ratios being higher in the forest landuse system (Table 4.14). The C:N ratios in the two landuses were similar for all slope positions (0-145 cm) (Table 4.15).

Table 4. 13 Effect of slope position on E4:E6 and C:N ratios in land use systems at different depths

Parameters	Depth	Slope position ($p \leq 0.05$)
E4:E6	0-5	0.0004***
	5-15	0.0002***
	15-30	0.0003***
	30-60	1
	60-100	0.462
	100-145	1
C:N	0-5	1
	5-15	0.375
	15-30	0.938
	30-60	0.284
	60-100	0.236
	100-145	1

Table 4. 14 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 4. 15 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}

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.

The C:N ratios along the slopes were not significantly ($p > 0.05$) different between the studied landuses. This is contrary to He et al. (2016) who observed significant increase in C:N ratios with increasing elevation, while Muller et al. (2017) observed a gradual decreases of soil C:N ratio with increased elevation. 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. Therefore, it is not surprising that SOC stocks were significantly higher in the upper slope positions. While there was a clear trend of E4:E6 ratio generally appearing to increase down the slope for all depths in forest system, increases along the slope was observed only in the top 0-5, and 5-15 cm depths in cocoa system. This could suggest the existence of differences in the availability or release of carbon and nutrients at different depths of the three hillslope positions, showing the effects of landuse change and management (human influence) on humic substances. This result agrees with several other studies (e.g., Guimarães et al., 2013; Seddaiu et al., 2013; Mulyani et al., 2021 and Tripolskaja et al., 2022), all of which observed that fulvic acids leach out faster and more intensively from the upper layers, compared to humic acids. Subsequently fulvic acids can move more easily depth-wise in the profile with percolating water and down the hillslope positions as well. This may well be the case in this study.

4.3.3 Slope effects on nutrient content and stocks in soils

The nitrogen and potassium concentration in cocoa system was significantly ($p < 0.05$) different from the forest system in the upper slope positions with forest recording higher contents (Table 4.16).

Table 4. 16 Slope positions on soil nutrient content (±SEM) at 0-30 cm depth in cocoa and forest soils

Nutrient	Slope position	Land-use	
		Cocoa	Forest
N conc.	Upper	0.12 ± 0.02^{b}	0.24 ± 0.07^{a}
	Middle	0.13 ± 0.02^{a}	0.12 ± 0.04^{a}
	Lower	0.10 ± 0.02^{a}	0.15 ± 0.04^{a}
	Mean	0.12 ± 0.01^{b}	0.17 ± 0.03^{a}
P conc.	Upper	3.82 ± 1.80^{a}	12.30 ± 6.05^{a}
	Middle	3.74 ± 1.83^{a}	15.74 ± 9.06^{a}
	Lower	2.41 ± 1.12^{a}	8.17 ± 5.47^{a}
	Mean	3.32 ± 12.07^{b}	12.07 ± 3.89^{a}
K conc.	Upper	151.34 ± 26.16^{b}	346.33 ± 142.26^{a}
	Middle	136.25 ± 21.37^{a}	184.83 ± 53.23^{a}
	Lower	111.57 ± 8.37^{a}	225.25 ± 82.25^{a}
	Mean	133.06 ± 11.60^{a}	255.50 ± 58.78^{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.

Topography (hillslope positions) generally did not significantly affect the distribution of TN, TP and TK in individual layers as well as total 0-30 cm depth along slopes (Figure 4.11). The TN stocks were significantly ($p < 0.05$) different between cocoa and forest systems in the upper and lower slope positions (Table 4.17). 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 4.17).

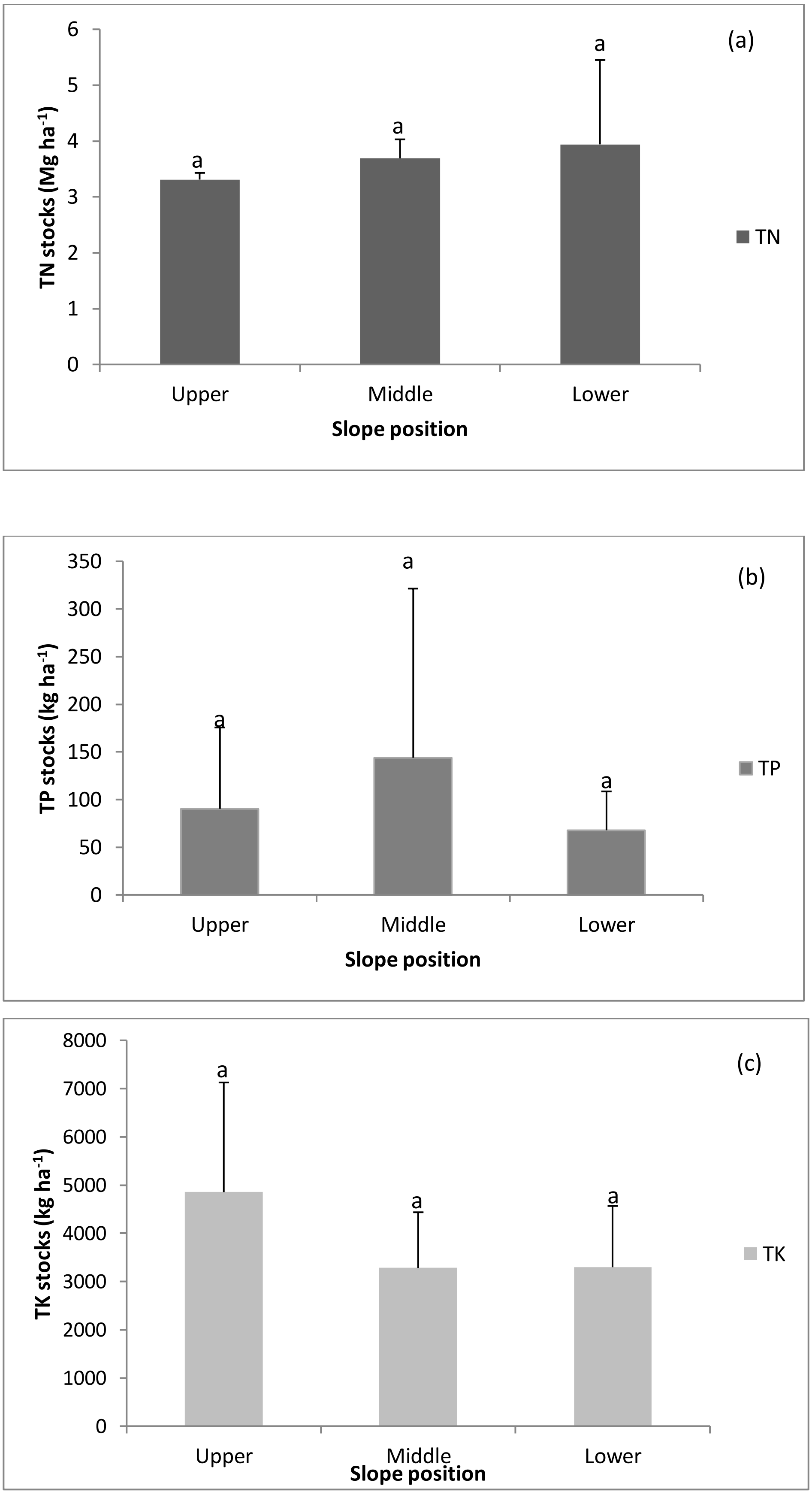


Figure 4.11 Effects of slope positions on stocks of (a) TN (b) TP and TK under cocoa and forest soils. Mean values are indicated with error bars-STD. Different lowercase letters indicate significant differences of stocks between slope positions ($p < 0.05$).

Generally, nutrient removal through soil erosion is high when cocoa is grown on steep slopes without shade and when cocoa is young (Roskoski et al., 1982) which in this study was not so. Hashim et al. (1995) observed in a monocropping cocoa in Malaysia a soil erosion loss of 11 Mg ha^{-1} year^{-1}, but losses were very low when *Indigofera spicata* were planted with cocoa. Therefore, nutrient loss through erosion is negligible in mature cocoa agroforestry systems. This could explain the non-significant differences observed in slope positions since cocoa systems were matured, mixed with agroforestry and found on undulating to rolling slopes. Contrary to Ahukaemere et al. (2019) slope significantly affected organic carbon and nitrogen in 0-30 cm recording higher stocks in foot slopes comparatively, but also observed that slope did not significantly affect available P in soils in Mbano Imo State, Nigeria. Result shows minimum movement of sedimentation and leaching of SOC and nutrient concentrations possibly due to the management of land-uses.

Table 4. 17 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.

4.4 Changes in SOC stocks under cocoa farms with time.

This chapter presents the results and discussions related to objective 4:

4. Evaluate the changes of SOC stocks in selected shaded-cocoa systems over a 15-year period.

In this study the chronosequence approach is used to assess SOC changes in shaded-cocoa farm fields of 18, 30 and 45 years. Data from this study were compared with data from Dawoe (2009) for an adjacent secondary forest (representing 0 years) and shaded-cocoa farm fields of 3, 15, and 30 years (2004), giving a chronosequence of fields aged 0, 3, 15, 18, 30 and 45 years.

4.4.1 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 4.18, 4.19 and 4.20, 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 4.18). SOC changes in the 0-60 cm depth were not significantly different between the different plot ages.

Table 4. 18 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.

Depth (cm)	Landuse						
	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±0.026 b	0.437±0.099a	0.764±0.164 b	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).

Soil organic carbon concentrations were higher in surface layers than deeper in the profiles across all the studied cocoa farms which confirm that majority of SOC is returned to the soil in the form of above-ground litterfall and through turnover of fine roots, found predominantly in the topsoil. 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. This is probably expected because of regular litterfall and subsequent dynamic decomposition processes at play in all the systems. SOM turnover is dependent on other interacting variables such as moisture, temperature, clay content, soil porosity and the composition of microbes (Six et al., 2002; Aguilera et al., 2013; Don et al., 2017). However, the most important driver for SOC turnover and changes is the carbon input via root litter and exudates, above-ground litter, and organic amendments (Rasse et al., 2005; Kutsch et al., 2009).

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 4.19. 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 4.19).

Table 4. 19 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).

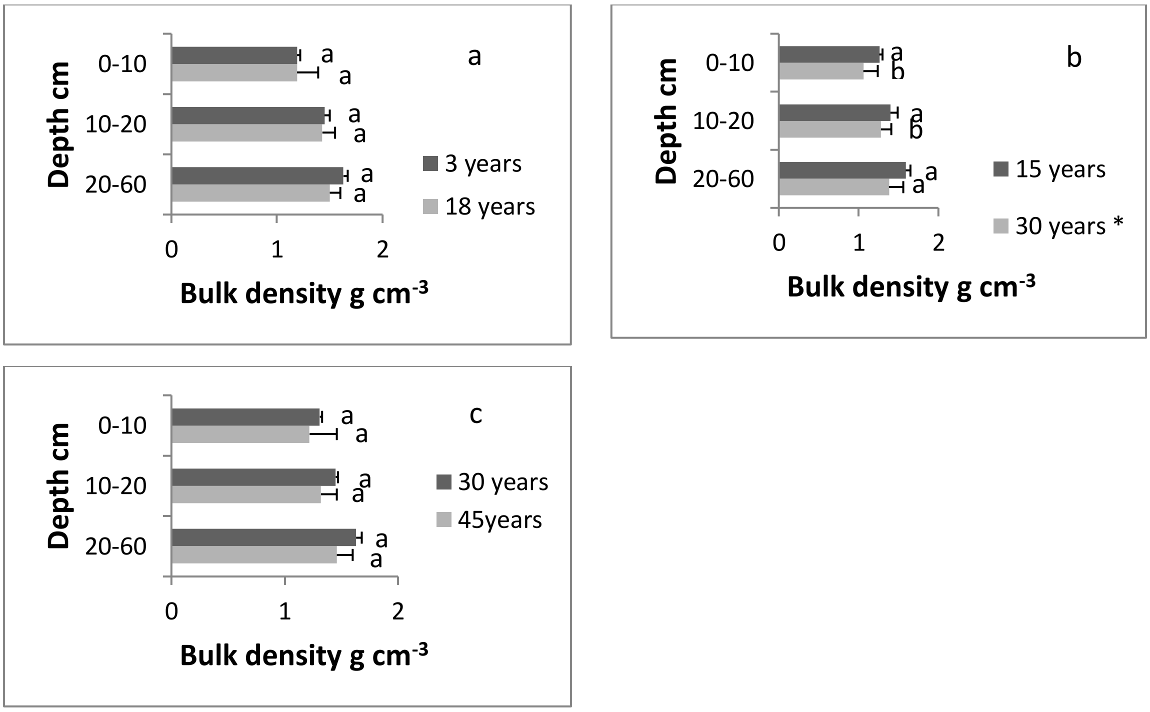


Figure 4. 12 Changes in bulk density at 3 depth intervalls between 0-60 cm from the soil surface in farms of different age groups of (a) 3 and 18 years (b) 15 and 30 years, and (c) 30 and 45 years in the Atwima Nwabiagya Municipality, Ashanti Region, Ghana. . The "*Cocoa 30 years" represents a 30 year old cocoa farm sampled in this current study whilst "Cocoa 30 years" represents a cocoa farm sampled in 2004 by Dawoe (2009).

The conversion of forest to perennial cocoa systems, according to Dawoe et al. (2014) can be considered as the beginning of a controlled forest fallow having cocoa trees as the main layer. Practices such as cutting back of some of the shade trees, weeding and brushing of weeds between crop plants in canopy gaps, and harvesting of cocoa pods and other management operations seem to have a strong influence on bulk density especially in the 0-10 and 10-20 cm depths. This effect is apparently most visible in the 18 years cocoa farm.

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 4.20. 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 4. 20 Quantities of carbon (Mg ha^{-1} ± SEM), at the different depths in forest and cocoa landuse systems in the Atwima Nwabiagya Municipality

Depth (cm)	Land-use						
	Forest Mg C ha^{-1}	Cocoa 3 yrs Mg C ha^{-1}	Cocoa 15 yrs Mg C ha^{-1}	Cocoa 18 yrs Mg C ha^{-1}	Cocoa 30 yrs Mg C ha^{-1}	*Cocoa 30 yrs Mg C ha^{-1}	Cocoa 45 yrs 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).

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 4.13 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.

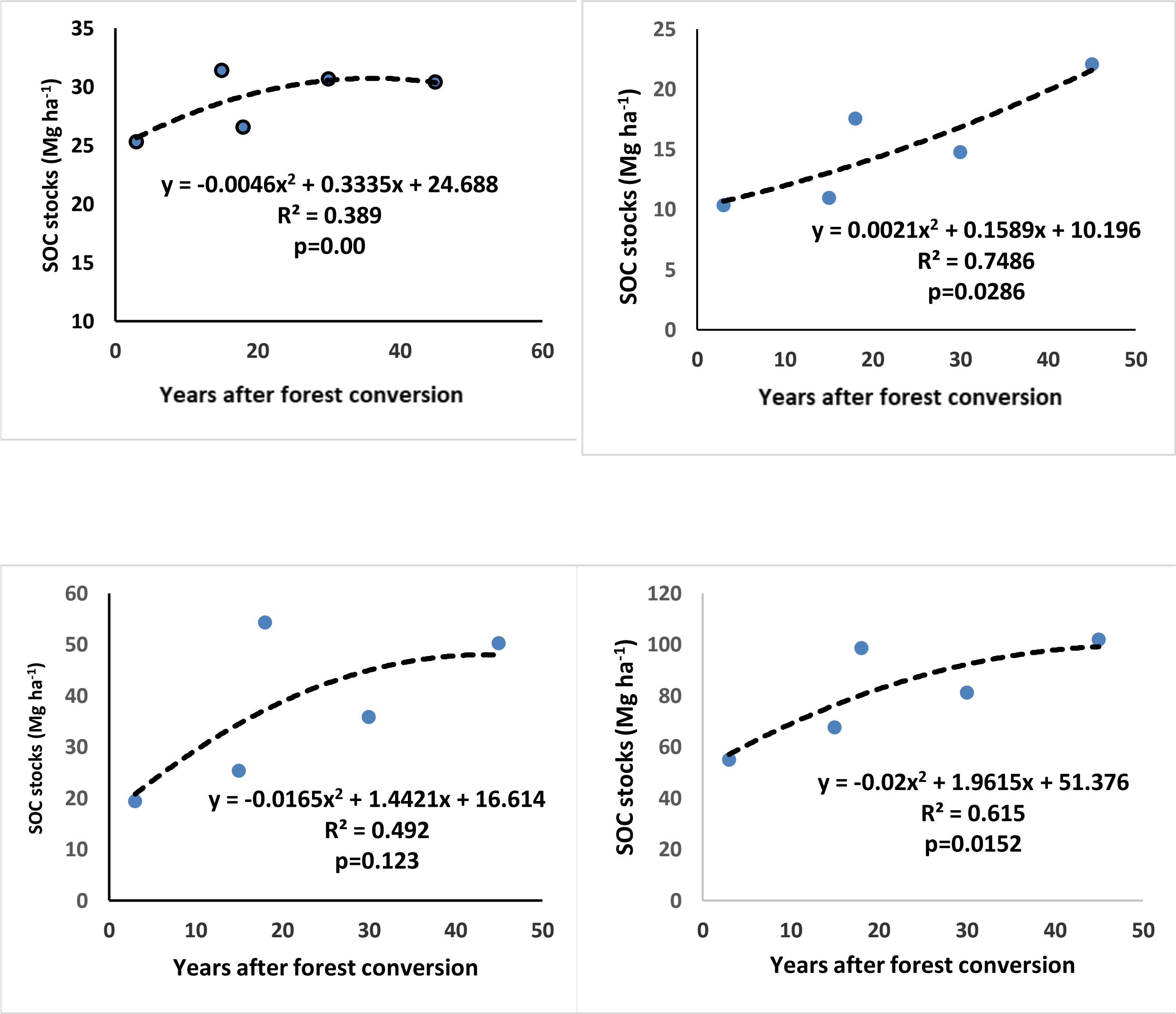


Figure 4.13 **Regressions of SOC stocks at 0-10, 10-20, 20-60 and 0-60 cm depths along a chronosequence of cocoa farms in the Atwima Nwabiagya District of the Ashanti Region, Ghana**

4.4.2 Changes in SOC stocks and bulk densities over the 15-year period from 2004-2019

Changes in SOC stocks in shaded-cocoa farms over the 15-year period (2004-2019) for plots from 3-18 years, 15-30 years and 30-45 years after forest conversion, and the proportional increases in stocks are shown in Tables 4.21, 4.22 and 4.23, respectively. While there were gains in all the stocks (5.93-142.9%) at nearly all the depths compared, there were only marginal declines (-9.25 and -11.1%) at the 0-10 cm soil depth in the 30- 45 and 15-30 year-old sites, respectively. Changes in bulk densities over the same period for the studied plots are shown in Figure 4.12. Whereas after a 15-year time span, there were no significant differences in bulk densities recorded in 2004 and 2019 (3 and 18-year-old plots) at all depths, significant differences were found in the other plots (15 and 30-year-old) and in the oldest (30 and 45-year-old) plots. Differences however did not follow any particular trend.

Table 4. 21 Mean values of SOC (soil organic carbon) stocks (Mg/ha) and standard error of the mean in 2004 and 2019 (15 years interval) after conversion to cocoa agroforestry in the Atwima Nwabiagya Municipality, Ashanti Region, Ghana.

Depth (cm)	SOC Stocks(Mg ha^{1}) **3 years after forest conversion (2004)**	SOC Stocks(Mg ha^{1}) **18 years after forest conversion (2019)**	ΔSOC Stocks Mg ha^{-1}	Gain/Loss Mg ha^{-1}	% Change
0-10	25.3±1.32	26.6±2.88	1.3	Gain	5.13
10-20	10.4±4.82	17.6±1.72	7.2	Gain	69.2
20-60	19.5±1.46	54.4±4.57	34.9	Gain	179
0-60	55.2±4.51	98.6±7.8	43.4	Gain	78.6

Table 4. 22 Mean values of SOC (soil organic carbon) stocks (Mg/ha) and standard error of the mean in 2004 and 2019 (15 years interval) after conversion to cocoa agroforestry in the Atwima Nwabiagya Municipality, Ashanti Region, Ghana.

Depth (cm)	SOC Stocks **15 years after forest conversion (2004)**	SOC Stocks ***30 years after forest conversion (2019)**	ΔSOC Stocks Mg ha^{-1}	Gain/Loss Mg ha^{-1}	% Change
0-10	31.4±1.08	27.9±8.01	-3.5	Loss	-11.1
10-20	11.0±0.96	17.0±4.64	6	Gain	54.5
20-60	25.4±2.11	43.6±14.9	18.2	Gain	71.6
0-60	67.7±0.07	88.5±1.8	20.8	Gain	30.7

***30 years after conversion: Plot was 15 years after forest conversion in Dawoe (2004)**

Table 4. 23 Mean values of SOC (soil organic carbon) stocks (Mg/ha) and standard error of the mean in 2004 and 2019 (15 years interval) after conversion to cocoa agroforestry in the Atwima Nwabiagya Municipality, Ashanti Region, Ghana.

Depth (cm)	SOC Stocks **30 years after forest conversion (2004)**	SOC Stocks **45 years after forest conversion (2019)**	ΔSOC Stocks Mg ha^{-1}	Gain/Loss Mg ha^{-1}	% Change
0-10	33.5±3.79	30.4±0.29	-3.1	Loss	-9.25
10-20	12.5±2.77	22.1±2.12	9.6	Gain	76.8
20-60	28.2±5.92	68.5±6.57	40.3	Gain	142.9
0-60	74.1±12.4	121.0±4.74	46.9	Gain	63.3

The study shows overall increases in SOC stocks over time after conversion to shade cocoa systems, both in individual depths and total studied depth across all the age groups (3-15 years, 15-30 years and 30-45 years). 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). Average rates of SOC accumulation itself varied between the different age groups ranging from 0.427 Mg ha^{-1} year^{-1} (15 to 30 years) to 2.37 Mg C ha-1 (30 to 45years) age groups. The higher rate of stock increases with time observed in our study could be attributed to several factors including the land-use, vegetation and shade tree type, soil type and management practices of the study area (Lal, 2004b; Ledo et al., 2020). Differences among crops and geographic areas may also be variables contributing to the different accumulation rates recorded in this study compared to Ledo (2020). Shaded-cocoa farms generally have the potential to sequester C mainly due to the presence of upper canopy /shade trees which constitute the bulk of the carbon stored in these systems (Dawoe et al., 2014; Nair et al., 2010, Mohammed et al., 2016; Lorenz & Lal, 2014). The root-derived C inputs from trees could be a critical source for SOC pool in the 20-60 cm depths in our study area (Kell, 2012). Moreover, perennial crops develop larger roots that penetrate and develop fine roots deeper in soil. Thus, agroforestry systems store more C in deeper layers near trees than away from trees (Nair et al., 2010). Furthermore, the presence of nitrogen fixing shade/upper canopy trees may enhance higher biomass production and, thus SOC sequestration. Again, management practices such as pruning of woody species from cocoa trees and other trees are left on cocoa farms as mulch to decompose into the soil; a decrease in cultivation intensity in all studied cocoa farms potentially avoiding SOC loss by mechanical soil disturbances; the incorporation of organic residues is part of the management practices observed in our study sites (Nair et al., 2010; Ledo et al., 2018), are all factors which may explain the recorded increases in SOC stocks.

Increases of stocks in upper layers (0-10 cm) especially of the 3 year old farm after 15 years could be attributed to a combination of several factors including increase in plant residues (litterfall of cocoa and shade trees as well as and food crops) as cocoa matures serving as protective cover for soils and providing a continuous stream of organic materials to surface soils (Montagnini & Nair, 2004; Utomo et al., 2016); reduced carbon breakdown through oxidation /leaching compared to when land is cleared/devoid of vegetation (Dawoe et al., 2014).

Thus, the overall trend in the SOC dynamics in the 0-60 cm soil depth of our sites is an observed steady gain in SOC stocks over the 45-year period with SOC stocks exceeding stocks (pre-conversion level) in forest systems recorded by Dawoe (2009). This observation is inconsistent with the acknowledged patterns of SOC accumulation, where stocks accumulate in the initial years and level off as the system ages. This could be probably explained by the fact that the forests in Dawoe's study (2009) were secondary forests less than 45 years at the time the data was collected. The observed positive correlation between SOC stocks and age is an apt reflection of the above trend. This trend was also observed for bulk densities of soils under cocoa agroforestry.

4.4.3 Correlations between parameters

Correlations between studied parameters for the total sampled depths are shown in Table 4.24. Though bulk density and SOC % appeared to increase with age along the chronosequence, these were not significant (p>0.05). Similarly, the relationships between SOC stocks, bulk density, and SOC % though positive were also non-significant. Understandably, SOC stocks increased significantly with age while SOC% declined significantly with depth, and SOC stocks did not have any significant relationship with SOC %.

Table 4. 24 Correlations (correlation coefficients and p-values) among studied parameters at the 0–60 cm soil depth under different cocoa land-use ages in the Ashanti region, Ghana

	Age	BD	DEPTH
BD	0.0021		
P-Value	0.9871NS		
DEPTH	0.0000*	0.5462*	
P-Value	1.0000	0.0000	
SOC%	0.1480	-0.6301*	-0.7370*
P-Value	0.2590NS	0.0000	0.0000
SOC stocks	0.3354*	0.1875	0.3539*
P-Value	0.0088	0.1514NS	0.0055

* Significant at α =0.05 level ; NS = Not significant at α =0.05 level

4.5 Assessing cocoa farmer’s local knowledge and perceptions of SOC and its effects on fertility and management practices.

This chapter presents the results and discussions related to specific objective 5:

5. Assess cocoa farmers’ local knowledge of SOC and its effects on fertility and management practices.

4.5.1 Farmers’ Activities and Farm Management Practices

Our study revealed that all farmers cultivated cocoa, but most of them also had other farms for growing food crops (plantain, cassava, cocoyam, maize), vegetables and spices (e.g., tomatoes, pepper, and ginger). Others had tree crops comprising oil palm, orange, and coconut etc. Farm sizes ranged from 0.8 to 6 hectares, with the majority having between 1.2 and 1.6 hectares, with cocoa trees aged from1 to 33 years. Cocoa plantations were seen as a source of income and a property (security) that will be left behind for the children of these farmers. “My main aim of cultivating cocoa is to leave it as a legacy for my children ’’(Cocoa farmer S2_4). A cash crop like cocoa is cultivated usually also on a small scale; it is seen as a source of income and household security (Isaac et al., 2009). Few of them admitted to getting subsidies from either the government or non-governmental organizations. The majority of the farmers' subsidy was from the government and this came in the form of the Mass Cocoa Spraying exercise conducted every year to control black pod and pest infestation of cocoa. A few of the farmers added that they get inorganic fertilizers from the government as well.

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 4.25. 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 4.25 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	-

Farmers' perceived trees to be very important as they provided organic matter through litterfall, and also provide shade against intense sunshine, and regulation of soil moisture (Hartemink, 2005; Afrifa & Acquaye, 2010; Blaser et al., 2017; Wartenberg et al., 2018). Soil moisture also creates a conducive atmosphere for micro- and macrofauna to help in the decomposition of litter into humus and improving organic carbon content in the soil (Jobbágy & Jackson, 2000; Lal, 2004).

Table 4.26 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 4. 26 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	

With the high cost of fertilizers and their inability to pay for them, farmers have developed indigenous approaches involving nutrient cycling to sustain fertility. Management practices in the current study area have consequently developed over time and have been influenced by the training and other capacity-building programs farmers have had. The readily available source of SOC to farmers are crop residues which include leaves (litterfall), cocoa pod husks and fine roots turnover (Sollins et al., 1996; Dawoe et al., 2012;). Adejuwon & Ekanade (1988) in their study also reported the use of cocoa pod husks as a residue to increase organic matter in the soil. These residues are used as mulch on the soil surface to enhance water availability to crops due to reduced evaporation from the soil and better and inproved infiltration (López-Vicente et al., 2020). This practice also controls the growth of unwanted weeds and regulates soil temperature (USDA, 2007). The farmers also use the application of manure amendments (organic fertilizers) to increase soil organic matter, as also reported by Paul et al. (2017) on the adoption of compost by farmers in tropical Caribbean islands. Poultry litter, goat, sheep, and cattle manure are some of the common manures applied by farmers in Ghana, and this is considered best in regulating soil acidity (Ayalew & Dejene, 2012). Most times, manure is added to green and processed food wastes to form compost, which is applied to the soil to increase SOC content.

Most of the farmers used inorganic fertilizers (when available) to increase soil nutrients. Adjei-Nsiah et al. (2004) has made similar observations about migrant and native farmers in the Wenchi district of the Brong-Ahafo region in Ghana. Despite the unavailability of inorganic fertilizers, majority of farmers in the study area apply them almost once every year to increase crop yield as also reported by Ayalew and Dejene (2012). Farmers apply any type of inorganic fertilizers when they have access to them, for example, free or subsidized fertilizers from the government (Omoshola, 2015). Inorganic (mineral) fertilizers boost soil nutrients for crop growth, which can improve organic carbon through litterfall, crop residue, and root exudates (Lal, 2010). Even though inorganic fertilizers boost soil nutrients in the short term, over application negatively affects the soil biota and ground and surface waters through leaching and erosion, respectively, in the long term (Mcisaac, 2003; Henneron et al., 2014; Khan et al., 2018). Another important practice is regular pruning in farms, which prevents organic carbon sharing between cocoa trees and unwanted wood and plant climbers (Isaac et al., 2009; Dawoe et al., 2014).

4.5.3 Changes in farm management practices and their effect on SOC

Changes in management practices; fertilizer, manure, and compost application have been made since the start of the plantation, whereas at first, none of these mentioned was applied. “Ever since I learned about the importance of SIDALCO’s liquid fertilizer on my soils, I have applied it for the past 7 years, and I have seen tremendous changes in my yield”(Cocoa farmer K1_7). Also, farmers now practice regular weeding and pruning, mulching to increase organic matter in soils. Farmers said they do not burn their plots; instead, weed residues and litter are used for mulching, which improves soil moisture and micro and macrofauna functioning, leading to carbon increase in the soil. Cocoa pod husks are also applied as mulch material. Farmers’ said they avoid management practices that decrease their soil fertility (Table 4.26). Land cultivation in Ghana is usually manually done using cutlass and hoe for weeding and planting (Akowuah, 2010; Omoshola, 2015). Weeds were cleared and burned to make land accessible for cultivation in the past. In recent years, however, the land is cleared, and weed residues are spread on the field to serve as mulch and organic matter input as they decomposed and mix with the soil (Dawoe et al., 2012). According to Adeyolanu et al. (2013), SOC decreased after the land was slashed and burned in a study conducted in Nigeria. Farmers were aware that their management practices affect the quantities of soil organic matter. While a few said their practices affect only the top layer of organic matter on their farms, the majority said both the topsoil and subsoil are affected.

Most of them said within the period ranging from the past four (4) months (prior to the interviews) dating far back as 25 years ago; they had made changes in their farm management practices. The majority of those who had done major changes said this was within the last 10 years. Changes included:

i) weeding and using of residue as mulch,
ii) application of inorganic and organic fertilizers,
iii) reduction in the use of weedicides and herbicides,
iv) use of pesticides,
v) organic amendment (local compost and manure).

The key challenge mentioned by farmers was a monetary constraint that hinders the continuity and implementation of old and new management practices that increase soil fertility, increasing crop yield.

Since the 1960s, traditional cocoa farms in Ghana are generally characterized with high shade trees density with little shade management, irregular weeding, rare diseases, and pest control, and irregular harvesting (Craswell & Lefroy, 2000). Omoshola (2015) observed that lack of these management practices normally resulted in low soil fertility hence low yield with an average yield of 32- 46.8 kg per 0.4 hectares on some farms in the Ashanti region. Cocoa trees free from pests and diseases grow and develop well vegetatively, producing abundant aboveground biomass in the form of litter contributing to increased litter fall. This increased litterfall comes with an increase in soil organic matter from litterfall decomposition. An increase in SOM content of the soil improves CEC, soil structure, water-holding capacity, and adsorption capacity thereby minimizing nutrient loss through leaching. In this way, the soil's fertility is sustained.

Most farmers said they modified these traditional farm management practices and adopted more ecologically friendly and sustainable methods. According to them, slash and burn, which was an easy and inexpensive way of clearing land for cultivation, is hardly practiced anymore. It leads to soil degradation, fertility loss, increased erosion, and leaching of SOC. Adeyolanu et al. (2013) has made a similar observation about farmers in Nigeria. Another implemented change is the use of herbicides to kill weeds and unwanted plants. This practice was introduced to substitute the slash and burn practice, but currently, farmers said they use it on the minimum rate because it can negatively affect soil biota, which eventually affects SOC formation. Pruning of side branches and climbers from cocoa trees, weeding, and leaving the residues to decompose on farms (proka) is currently being implemented (Isaac et al., 2009; Dawoe et al., 2012). Though farmers claim they are challenged with this practice because it was labour-intensive and expensive to sustain, they nevertheless believe the practice has helped to maintain SOC and nutrient levels compared to the old practice. They believe competition between cocoa trees and unwanted plants and climbers and epiphytes is also reduced. Application of organic and inorganic fertilizers has become very important for restoring soil productivity (SOC and nutrient levels). Therefore farmers now apply fertilizer on their farms, whereas in the past, they did not apply fertilizers (Olutokunbo & Ibikunle, 2011; Ayalew & Dejene, 2012; Hijbeek et al., 2017). This practice also depends on the farmer's socio-economic environment (Baah & Anchirinah, 2010; Janvry et al., 2016). Manure application and local composting are used by a few farmers on their farms in small quantities, especially poultry waste, food waste, and sawdust, to increase SOC and fertility in general, but that was not the case in the past. All these practices increase SOC in soils, which aids in a continuous carbon cycle between the soil and the atmosphere.

4.5.4 Farmers’ access to training and their impacts on management practices

Most farmers attest to or claim to have observed improvement in the SOC content or fertility status of their fields, and they were therefore optimistic that if this trend continued, there would be an increase in cocoa beans yield in the next 10 to 20 years. This understanding of associating increased cocoa beans yield with increased SOC and fertility over time is likely to have been informed by their involvement in training and capacity building activities organized by Ministry of food and agriculture (MoFA) and some NGOs.

Out of the 33 interviews, 20 farmers had gone through training related to agriculture, farming, and soil management. Training undertaken by farmers is likely to have significantly influenced their adoption of new and improved farm management practices. The training was organized for farmer groups and facilitated by field extension officers from the Ministry of food and agriculture (MoFA) and the Howard G. Buffet Foundation Centre for No-till Agriculture (NGO). “Through this foundation, I have learned about the importance of mulching on soil fertility. I now have a job with them which enables me to transfer this knowledge to other farmers in the community.” (Cocoa farmer S2_2) Training methods included seminars, field demonstrations, and farmer field schools under special cocoa farming-related programs. According to some farmers, the Howard G. Buffet Foundation Centre for No-till Agriculture had a school located in the Amanchia community for the training of farmers on acceptable agricultural management practices about climate change effects on crop growth, organic matter, and soil fertility in general. Farmers also learned from their fellow farmers and shared their good management practices when they visited each other’s farms. “I have not had any formal training on any management practice, but I learn a lot from my colleague farmers when I visit their farms.” (Cocoa farmer K1_1)

Results show that current management practices adopted by farmers were as a result of their traditional knowledge and skills as well as that acquired through their involvement in training and other capacity-building activities provided by extension officers, NGOs, and also by fellow farmers. Other studies (e.g., Ketterings, 2014; IPA, 2015; Janvry et al., 2016) have also emphasized the importance of farmer training in the adoption of innovative agricultural practices. The scarcity of farmlands has led to agricultural (cocoa) intensification (Gockowski & Sonwa, 2011), putting pressure on the soil as a resource and increased the need for conservation practices and sustainable use of the soil (UN, 1992). This has influenced farmers within the current study area in the adaptation of management practices through the training given by extension officers, NGOs, and their fellow farmers (Olutokunbo & Ibikunle, 2011). A study conducted by IPA (2015) in Ghana also confirmed that the knowledge of farmers was improved, and farmers were more likely to adopt best practices as a result of receiving extension services and training from community extension agents. The study of Baah & Anchirinah (2010) showed that training activities were mainly centered on soil management emphasizing on soil organic matter and soil fertility, which affected SOC. The adoption of these strategies is greatly influenced by the economic status of farmers (Craswell & Lefroy, 2000; Janvry et al., 2016). In the interviews farmers mentioned lack of money as the main constraint in the implementation of these strategies since their incomes did not allow them to hire labourers and buy fertilizers which are key components in their farming.

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 4.27 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 4.27 ***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

All farmers knew what organic matter was and called it in the Twi language 'Asaase mu Sradee'which literally means 'Fat in the Earth.' All the farmers mentioned at least 3 to 4 of the soil organic matter indicators shown in Table 4.28. A majority said the organic matter could be found both in topsoil and subsoil at depths of 30 to 120 cm. "I believe that organic matter can also be found in deeper layers, if not how does the cocoa grow considering its root depth." (Cocoa farmer K2_5) The majority said that excessive rainfall and sunshine affect soil organic matter negatively with quantity. Farmers mentioned that litterfall (from cocoa and shade trees) and cocoa pod husks contribute to increasing organic matter and fertilizing the soil and acting as shade to protect the soil. They explained that microorganisms and larger animals like earthworms, termites, ants, caterpillars, millipedes, rodents, etc. aid in soil aeration, water infiltration, and movement of organic matter into the subsoil. One farmer also mentioned the importance of dead tissues of microorganisms that add to the organic matter in the soil. According to farmers, soil organic matter improves soil moisture, soil structure, colour, and soil nutrient content.

To farmers, the soil is the most important terrestrial system since their livelihood depends on it. In their estimation, good soil, therefore, is one that can support plant growth and increased crop yield, which translates into increased household income and better living standards. The current study showed that soil type (texture), organic matter, soil organisms, management practices, and climate are the main drivers of SOC and cocoa yield in the Atwima Nwabiagya district. Bationo et al. (2007) made similar observations concerning agroecosystems in West Africa. Our study showed that soil organic matter (asaase mu sradee) is the most important soil ingredient. According to them, without it, there is no soil fertility. This corroborates the findings of Dawoe et al. (2012) in the same district. According to (Quansah et al., 2001), farmers from the southern part of Ghana also view SOM and soil fertility as interrelated. Many studies (e.g., Quansah, et al., 2001; Desbiez et al., 2004; Dawoe et al., 2012).have linked soil colour (black) to the presence of soil organic matter as perceived by local farmers. Farmers in the study area also have similar perceptions. The decomposition of leaves, weeds, and crop residues gives soil its dark colour (Lal, 2004, 2005; Lal et al., 2015). Organic matter and iron oxides add most to soil colour (Owusu-Bennoah et al., 2000; Rowe, 2005); hence farmers' perception that black or dark soil represents the presence of organic matter in the soil in this study. Quansah et al. (2001) observed that 91% of farmers in Ghana's humid forest sector assessed SOM status by colour. Dark soil colour enhances the rate of soil warming (temperature) in the wet season and cooling in the dry season and improves soil moisture availability (Jackson, 2014).

Farmers explained the importance of the cocoa tree in forming organic matter through the decomposition of litterfall and cocoa pod husks. This is confirmed by other studies (Isaac et al., 2005; Isaac et al., 2009). Decomposed and partially decomposed litter generally aids in humus (SOC) formation in tropical forest ecosystems (Malhi & Grace, 2000; Sanchez et al., 2003). SOC is the primary provider of organic nutrients to the soil. It also acts as a binding agent that makes it easy for nutrients from organic and inorganic fertilizers to be adsorbed onto soil surfaces (Lorenz & Lal, 2005; Chabbi et al., 2009; Lal et al., 2015). Farmers perceptions of the importance of macro-fauna (earthworm, termites, millipedes, and beetles) and microorganisms in organic matter/SOC formation which has been shown in other studies (Dawoe et al., 2014; Henneron et al., 2014; Chen et al., 2015; Kuria et al., 2018) was also investigated and confirmed in the current study. Through their activities such as mixing, breaking, and burrowing, leaves, weed, and crop residues are broken down into pieces and mixed with soil. Also, through burrowing, there is litter sequestration into nests, termitaria, and biogenic pits that affects SOC content in subsoils (Chabbi et al., 2009). Their activities aid in aeration and water movement in the soil improving soil fertility (Chabbi et al., 2009). Most farmers reported that organic matter is not only found in the topsoil but also deeper layers of soil and related the existence of soil organic matter in subsoils to the root depth of cocoa trees, which is in relation to the natural science findings on the depth distribution of SOM and SOC (Jobbágy & Jackson, 2000; Sommer et al., 2000; Lorenz & Lal, 2005; Chabbi et al., 2009). These studies identified root exudates and DOC as sources of organic matter and organic carbon in subsoils.

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.

With regards to soil fertility properties, farmers were of the opinion that the presence of and addition of SOM to soil and its subsequent breakdown influence soil water holding capacity creates a conducive habitat for soil biota (earthworm), and improves soil structure and infiltration of water into the soil thereby minimizing soil erosion.

According to farmers, they were not aware of the effect of SOC on climate change. Nevertheless, they have observed that in recent years, ambient temperatures have risen (Buxton et al., 2018), (which has led to atmospheric warming) negatively affecting their crop yield. Some of the effects of organic matter breakdown on climate, according to FAO (2017), including worsening drought, rains with thunderstorms, and rising temperatures. Direct sunshine on soil aids in rapid mineralization and subsequent breakdown and release of carbon compounds back into the atmosphere, serving as a source of CO_2. Yaro (2013), in his work on a small-scale and commercial farmers' perceptions of and adaptation to climate variability in Ghana, made similar observations about how farmers are aware of the changes in temperatures, rainfall, and sunshine and how it has been affecting their livelihoods. Buxton et al. (2018) indicated that 33% of farmers interviewed observed longer dry period than before making it difficult to predict rainfall pattern. These findings are in line with this current study showing the experience farmers have in observing climate change over time.

In the current study, farmers have continued to experience the negative effects of climate change. Therefore in pursuit of mitigation, they perceive some of their management practices as adaptation strategies. Mulching (using cocoa leaves, plantain and cassava leaves, etc.) is one of the strategies for adaptation. Whiles increasing organic matter, it also reduces evaporation, thereby retaining water for plant use during hot temperatures. Also, they perceive that mulching reduces erosion. With soils covered with litter, soils are not easily washed away even with heavy and intense rainfall, thereby protecting SOC. They believed that in the dry season when there is no rainfall, soil biota can survive because of mulching due to the coolness it gives to the soil (USDA NRCS, 2014). Most of the farmers practicing shaded cocoa cultivation systems were of the view that shading is mainly to protect cocoa seedlings from excessive sunshine, and this also true for mature cocoa trees. Isaac et al. (2009); Dawoe et al. (2012) emphasized that trees planted among cocoa protect their leaves and fruits from the hot sun, preventing them from drying and dying.

5 Conclusions and Recommendations

5.1 Conclusions

From the results obtained the following conclusions can be drawn for the specified objectives:

(i) Determine soil characteristics and classify soils of the study site. (general mean)
The conclusion for this objective is based on aggregated soil propertities 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.

(ii) **Determine the effects of landuse and land management practices on the depth distribution of SOC content, quality and SOC stocks in selected shaded-cocoa and connected forest soils**

The conclusion for this objective is based on both cocoa and forest soils sampled from the catena study. 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.

(iii) Determine the effects of topography (slope position) on the depth distribution of SOC content, quality and SOC stocks in selected shaded-cocoa and connected forest soils

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.

(iv) Evaluate the changes of SOC stocks in selected shaded-cocoa systems over a 15-year period.

This 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. We 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.

(v) Assess cocoa farmers' local knowledge of soil organic carbon and its effects on fertility and management practices.

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.

5.2 Recommendations

Based on the findings of the study, the following recommendations are proffered:

- Farmers in the study area should be encouraged to integrate appropriate shade tree species into cocoa systems as a number of farms in the area are still being managed under low shade regimes. Introduction of appropriate shade tree species would contribute to improved micro-climatic conditions of the soils, and increased organic matter addition through leaf litterfall for improved soil physico-chemical properties.

- Farmers lack of scientific knowledge about soil organic carbon impacts on soil properties and climate change suggest the need for more training aimed at enhancing their knowledge on important soil fertility processes. Improved extension delivery is therefore required for training to improve farmer knowledge about soil management required to mitigate the negative effects of climate change and improve soil fertility and fertility enhancing processes.

- There is the urgent need for policy makers, researchers and extension officers to develop approaches for farmer integration and participation in the national agricultural development planning and policy formulation processes. This would promote the integration of locally specific SOC management packages into soil management to improve yields and enhance cocoa's contribution to the national economy.

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 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 had 5.11 % and 7.39 % of more SOC stocks than the middle and lower slope positions, respectively, in the total profile. The slope influence on the topsoil was however statistically not significant between the 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 prevent 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 while increasing clay content promoted the release of humic substances. 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
5. 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.

SUMMARY

With an economy dominated by the agricultural sector in terms of its share of Gross Domestic Product (GDP), employment and foreign exchange earnings, Ghana is principally an agricultural country and agriculture is the major occupation of about 47 percent of the economically active age group. Ghana's agricultural productivity is however very low, and this has been attributed to soil organic carbon (SOC) and soil fertility degradation. For policymakers, agricultural practitioners and farmers to be able to make informed decisions that may contribute to the development of environmentally sustainable management practices as well as developing principles and management strategies to enhance SOC stocks in in shaded-cocoa systems, there is the need for a better understanding of the dynamics of SOC and its importance to soil fertility and climate change. farmers' local knowledge of soil organic carbon and its effects on fertility and management practices.

The overall goal of this study was to provide quantitative information on the effects of forest conversion to shaded-cocoa systems on the depth distribution of SOC stocks under shaded cocoa systems and provide qualitative information about farmers understanding about their soils. To achieve this aim of the study, five specific objectives were pursued. For the first objective, the characteristics of the soils in the study site were determined and the soils classified. In the second objective, the effects of landuse and land management practices on SOC accumulation, quality and distribution in shaded-cocoa and forest soils at different depths was determined. The third objective determined the effects of topography (slope position) on SOC distribution in shaded-cocoa and forest soils in different depths. In the fourth objective, changes in SOC stocks in shaded-cocoa systems over a 15-year period was evaluated. The last objective assessed cocoa farmers' local knowledge of soil organic carbon and its effects on fertility and management practices.

The study was conducted in small-holder farms in the Atwima Nwabiagya Municipality of the Ashanti Region of Ghana. The municipality falls within the wet semi-equatorial rainforest climate zone and is situated in the western part of the region and covers an area of about 264.62 square kilometers, with Nkawie as the capital. Rainfall is bimodally distributed with mean annual rainfall ranging from 170 cm-185 cm per annum, with mid-March to July (major rainfall season) and September – November (minor rainfall season) as peaks. Temperatures are uniformly high throughout the year with average monthly temperature range between 27 ^{o}C and 31 ^{o}C. The relative humidity is generally high throughout the year. Soils of the site are mainly Acrisol (have low activity clay and low base saturation). These are moderately good agricultural soils. They are deep and moderately well-drained with a subsoil texture ranging from silty-clay loam to silty-clay, which gives it a fairly high moisture retention capacity.

Sites for the study were selected based on earlier research (Dawoe, 2009) conducted in farming communities (Seidi, Kobeng, Apaakrom, Nkonteng and Amanchia) in the area between 2004-2008. Eleven (11) previously studied shaded-cocoa farms were chosen from these 5 communities based on the geomorphology of the area, management practices and the time factor to compare with the previous study conducted by Dawoe (2009). Sites with different land-uses i.e., forest reserve and cocoa farms were selected. Ten cocoa farms and one forest reserve (Jimira forest) were selected eventually.

Data for the study was obtained from both primary and secondary sources. To characterize and classify soils of the study site, and determine landuse, land management practices and topography effects on SOC accumulation, quality and distribution, soil samples were collected using the concept of soil catena sampling. A total of nine catenas were dug in cocoa and forest landuse systems. The profiles were sampled to a depth 145 cm in each catena at three different hillslope positions (upper, middle and lower hillslopes positions,) for SOC and BD determinations. Profiles were described and classified according to the WRB soil classification system. To assess carbon stock changes, soil samples (0-10, 10-20 and 20-60 cm soil depths) were collected from 35 m x 40 m plots established in forest and cocoa sites for chemical analysis using standard procedures. Details of the analytical methods used are described in the materials and methods sections of chapter 3 of the thesis.

To evaluate the effects of age (duration after forest conversion to cocoa agroforestry system) on SOC, shaded-cocoa farms from 3 different age groups, 18, 30 and 45 years after forest conversion, were selected. Sampling plots (35×40 m) were established in each age group and replicated soil samples were collected by augering to depths of 0-10, 10-20 and 20-60 cm bagged, and analysed for SOC. Undisturbed core samples were also collected for bulk density estimation from mini profiles from the same soil depths. Data thus collected were combined with data from Dawoe 2009 for farms established 3, 15 and 30 years after forest conversion. Changes in SOC stocks from 3 to 45 years after forest conversion were evaluated, and specifically stock increases over the 15-year period from 3, 15 and 30-year-old plots compared to 18-, 30- and 45-year-old after forest conversion respectively, i.e., differences between 3 to 18 years, 15 to 30 years, and 30 to 45 years after forest conversion were compared using one-way analysis of variance (ANOVA) using generalized linear model was performed to establish significant effects of age on SOC stocks and bulk density. Multiple comparisons of means using post hoc Tukey HSD test was used to determine significant differences among farms. 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 among soil properties and land-uses.

Cocoa farmers' local knowledge of SOC and its effects on soil fertility was assessed through semi-structured interviews conducted with 33 cocoa farmers in July and August 2018 from 5 purposively selected communities. Interview questions were framed to 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. Collected data were summarized and analyzed with the qualitative content analysis using emergent codes and assisted by the QCAmap software. Quotes were used as illustrations, and numbers were assigned to each quote for identification purposes.

Results of the study indicate that, pH of soils of the sites range from slightly acidic to neutral (6.51-6.92) with relatively high soil organic matter content of 1.5%. CEC values were generally low and ranged from 9.95±0.55-17.60±0.60 $\text{cmol}_{(+)}$/kg and are a reflection of the very low Na^+, low K^+ and Ca^{2+} and moderate levels of Mg^{2+} in the soils. Soil profiles had A horizons showing a darker surface horizon with some organic matter accumulation, with all profiles characterized by an Argic (clay-enriched) Bt horizon as the major diagnostic horizon in the subsoil.

The presence of trees in agricultural and forest landuse systems has a strong impact on soil physico-chemical properties. The results showed that changing landuse from forest to shaded cocoa agroforestry did not affect particle size (sand %, silt % and clay %) distribution at corresponding depths in forest and cocoa systems. On the other hand, coarse fragments changed significantly only in the topsoil layers but was similar in the subsoil in both landuse systems. Bulk density generally increased with increasing depth in forest and cocoa systems but was significantly higher in the topsoil (0-5 cm) and subsoil (60-100 and 100-145 cm) layers in cocoa compared to forest systems. Farm management activities apparently had a strong influence on bulk density in the top 0-10 cm layer, in cocoa systems probably due to the human traffic associated with these plantation management operations

SOC stocks in the secondary forest was not different from the cocoa system. Presumably, the presence of trees in the cocoa systems is the biggest contributing factor to the high and comparative carbon stocks in cocoa systems following landuse change from forest to shade cocoa. Landuse change affected carbon quality in terms of change in molecular size of humic substances in the cocoa system making carbon more stable. The lower/narrower E4:E6 ratio in cocoa systems is a reflection of higher humification. More stable organic molecules are found under cocoa systems whereas higher proportion of less stabilized, more soluble organic molecules (higher E4:E6 ratio) are in forest soils in the form of fulvic acids. Depth wise, carbon in the forest system was more stabilized in the upper horizons preventing the leaching and mineralization of SOC and nutrients in the soil. The higher rate of fulvic acid at lower, backslope and toeslope positions may be the result of leaching as well, as fulvic acids being more soluble and can therefore move with percolating water movements along the slope at low pH environments.

Hillslope position also significantly affected soil organic carbon stocks, with higher stocks in the upper hillslope positions compared to the middle and lower hillslope positions. 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. Results also suggest minimal erosion, sedimentation and leaching of organic carbon at the study site, with the limited possibility of decadal movement of soil from middle to lower slope positions across both landuse systems.

Our long-term study clearly indicates a steady buildup of SOC along the chronosequence of shaded-cocoa farm fields with increasing duration after forest conversion to levels comparable to natural secondary forests. Substantial changes in SOC stocks were observed in the early years following forest conversion. While SOC concentrations remained relatively constant across the 0-60 cm profile across all land-uses except in the second 30-year-old plot which recorded the highest C concentration, 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 there were gains in all the stocks (5.93-142.9%) at nearly all the depths compared, there were only a marginal decline (-9.25 and -11.1%) at the 0-10 cm soil depth in the 30- 45 and 15-30 year-old sites respectively. The absence of annual soil disturbance and the lack of frequent mechanical interventions in shade cocoa systems may not only reduce SOC losses but may also contribute C inputs to soil since litterfall layer is not removed.

Our study showed that mean bulk densities for similar depths appeared to generally increase with increasing duration after forest conversion in the topsoil layers. This is most likely to be associated with farm management activities which seems to have a strong influence on bulk density especially in the top 0-10 cm layer, which was significantly greater under cocoa at 3 years compared to forest soil probably due to the human traffic associated with these plantation management operations. Mean bulk density (0-60 cm soil depth) for the various age groups did not change.

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Farmers' knowledge and perceptions about the fertility of their soils and management practices they adopt to sustain fertility on their farms have evolved over time. Their knowledge of soil organic carbon and its impact on climate change and soil properties was non-existent they knew a lot about soil organic matter and its influence on soil fertility, being consciously aware that soils would not be fertile without organic matter but would be less productive. This knowledge is based on their farming experiences and information acquired from their forefathers, fellow farmers, and formal training acquired through interactions with agricultural extension officers and NGOs. Even though they did not have a scientific understanding about this, they knew that soils would not be fertile without organic matter but would be less productive. This research also shows that farmers perceive their management practices to affect organic matter and soil fertility.

REFERENCES

Acheampong, E., Dawoe, E., Bosu, P. & Asntae, W. (2014). Moving Forward With Redd + in Ghana : a Closer Look At Shade Systems , Crown Cover , Carbon Stocks and Socio-Economic Dynamics of Smallholder Cocoa Agroforestry Systems. (August), pp. 1–132. www.snvworld.org/en/sectors/redd/publications.

Adeyolanu, D. O., Are, K. S., Oluwatosin, G.A., Ayoola, O.T., & Adelana, A. O. (2013). Evaluation of two methods of soil quality assessment as influenced by slash and burn in tropical rainforest ecology of Nigeria. *Archives of Agronomy and Soil Science*, 59(12), 1725-1742.

Adejuwon, J. O., & Ekanade, O. (1988). A comparison of soil properties under diverent land use types in a part of the Nigerian cocoa belt. *Catena* 15, 319–331.

Adiyah, F., Fuchs, M., Michéli, E., Dawoe, E., & Kovács, E. (2021). Cocoa farmers' perceptions of soil organic carbon effects on fertility, management and climate change in the Ashanti region of Ghana. *African Journal of Agricultural Research*, 17(5), 714-725.

Adjei-Gyapong, T. and Asiamah, R.D. (2002). The Interim Ghana Soil Classification System and Its Relation with the World Reference Base Soil Resources. Rapport sur les Ressources en Sols du Monde (FAO).

Adjei-Nsiah, S., Leeuwis, C., & Giller, K. E. (2004). Land tenure and differential soil fertility management practices among native and migrant farmers in Wenchi Ghana: implications for interdisciplinary action research. NJAS-Wageningen. *Journal of Life Sciences*, 52(3-4), 331-348.

Adu, S. V., & Mensah-Ansah, J. A. (1971). The classification of Ghanaian soils for cocoa rehabilitation. 3rd Inter. Cocoa Res. Conf. Ghana. Nov. 1969. pp. 56-64.

Adu, S.V. (1992). Soils of the Kumasi region, Ashanti Region, Ghana. Ghana Ministry of Food and Agriculture Scientific Services Division. Soil and Land use Survey Branch. Memoir 8, Kumasi.

Afrifa, A. A., & Acquaye, S. (2010). Impact of shade and cocoa plant densities on soil organic carbon sequestration rates in a cocoa growing soil of Ghana. *African Journal of Environmental Science and Technology*, 4(9), 621–624. doi: 10.4314/ajest.v4i9.71321.

Afrifa, A. A., Ofori-Frimpong, K., Acquaye, S., Snoeck, D., & Abekoe, M.K. (2009). Soil nutrient management strategy required for sustainable and competitive cocoa production in Ghana. *16th International Cocoa Conference*, (January 2014), pp. 16–21.

Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment* 168, 25–36. https://doi.org/10.1016/j.agee.2013.02.003

Ahukaemere, C.M., Irokwe, I.F., Onwudike, S.U., Agim, L.C., & Aririguzo, B.N. (2019). Topography and Depth Influences on Soil Nitrogen and Carbon Sequestration. *Journal of Soil Science & Plant Health* 3,1.

Ajami, M., Heidari, A., Khormali, Farhad., Gorji, M., & Ayoubi, S. (2016). Environmental factors controlling soil organic carbon storage in loess soils of a subhumid region, northern Iran. *Geoderma*. Elsevier B.V., 281, 1–10. doi: 10.1016/j.geoderma.2016.06.017.

Akowuah, P. (2010). Farmers Experience and Practice of No-tillage System :Towards the Adoption of Conservation Agricultural Production in Atwima-Nwabiagya District of Ashanti Region Ghana. *Journal of Developments in Sustainable Agriculture*, 5(2),191-202.

Allen, D. E., Pringle, M. J., Page, K. L., & Dalal, R. C. (2010). ‘A review of sampling designs for the measurement of soil organic carbon in Australian grazing lands’, *Rangeland Journal*, 32(2), 227–246. doi: 10.1071/RJ09043.

Amoah, J. E. K. (1995). Cocoa Outline Series: Development of consumption, commercial production and marketing. Jemre Enterprises Ltd. Takoradi, Ghana.

Amundson, R. (2001). The carbon budget in soils. Annu. Rev. Earth Planet. *Sci*. 29, 535–562. doi: 10.1146/ annurev.earth.29.1.535.

Aneani, F. & Ofori-Frimpong, K. (2013). An analysis of yield gap and some factors of cocoa (Theobroma cacao) yields in Ghana, Sustain. Agric. Res. 2 (4).

Ansong, O. R., Fujii, Y., Sarkodee-Addo, E., Oikawa, Y., Onwona-Agyeman, S., &,Bellingrath-Kimura S. D. (2018). Organic and chemical fertilizer input management on maize and soil productivity in two agro-ecological zones of Ghana. *Environmental Sustainability*, 1,437–447 https://doi.org/10.1007/s42398-018-00040-2

Aranibar, J. N., Otter, L., Macko, S. A., Feral, C. J., Epstein, H. E., Dowty, P. R., & Swap, R. J. (2004). Nitrogen cycling in the soil–plant system along a precipitation gradient in the Kalahari sands. *Global Change Biology* 10(3): 359-373.

Aranda V. Ayora-Cañada, M.J., Domínguez-Vidal, A., Martín-García, J.M., Calero, J., Delgado, R., Verdejo, T., & González-Vila, F.J. (2011). Effect of soil type and management (organic vs. conventional) on soil organic matter quality in olive groves in a semi-arid environment in Sierra Mágina Natural Park (S Spain). *Geoderma,* 164, (1-2) 54–63. DOI:http://dx.doi.org/10.1016/j.geoderma.2011.05.010

Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J., Heuvelink, G.B.M., Hong, S.Y., Lagacherie, P., Lelyk, G., McBratney, A.B., McKenzie, N.J., Mendonça Santos, M.L., Minasny, B., Montanarella, L., Odeh, I.O.A., Sanchez, P.A., Thompson, & J.A., Zhang, G.L. (2014). GlobalSoilMap: Toward a Fine-Resolution Global Grid of Soil Properties. *Adv. Agron*., 125, 93-134.

Asiamah, R. D., Senayah, J. K., Adjei-Gyapong, T., & Spaargaren, O. C. (1997). Ethnopedological surveys in the semi-arid savanna zone of Northern Ghana. *An ILEIA initiated project. Report 97/04. SRI, Kumasi*.

Atwima Nwabiagya Municipal Assembly (ANMA) (2018). The Profile of Atwima Nwabiagya Municipal Assembly Nkawie, Ashanti Region Ghana. (unpublished), 65 pp.

Aune, J. B., & Lal, R. (1997). Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols, and Alfisols. *Tropical agriculture-London then Trinidad* 74, 96-103.

Ayalew, A., & Dejene, T. (2012). Combined Application of Organic and Inorganic Fertilizers to Increase Yield of Barley and Improve Soil Properties at Fereze, In Southern Ethiopia. *Innovative Systems Design and Engineering*, 3(1), 25-34.

Baah, F., & Anchirinah, V. (2010). Looking for convergence stakeholders perceptions of cocoa extension constraints in Ghana. *Journal of Science and Technology,* 30(3),51-63.

Baalousha, M. (2009). Aggregation and disaggregation of iron oxide nanoparticles; influence of particle concentration, pH and natural organic matter. *Sci. Total Environ.*, 407 (6), 2093–2101.

Bakhshandeh, S., Norouzi, M., & Heidari, S. (2014). The role of parent material on soil properties in sloping areas under tea plantation in lahijan , Iran. (May).

Baldock, J. A., & Skjemstad, J. O. (1999). Soil organic carbon/soil organic matter. In: 'Soil Analysis: An Interpretation Manual'. (Eds K. I. Peverill, L. A. Sparrow and D. J. Reuter.) pp. 159–170. (CSIRO Publishing: Melbourne

Baldock, J.A., & Skjemstad, J.O. (2000). Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Organic Geochemistry* 31, 697-710.

Barrios, P.G., Bidegain, M.P., Gutiérrez, L. (2015). Effects of tillage intensities on spatial soil variability and site-specific management in early growth of Eucalyptus grandis. *Forest Ecol. Manag*., 346, 41–50.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., & Kimetu, J. (2007). Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*, 94(1),13-25.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *Eur. J. of Soil Sci,* 47, 151 – 163.

Batjes, N.H., & Sombroek W.G. (1997). Possibilities for carbon sequestration in tropical and subtropical soils. *Global Change Biology* 3, 161–173.

Barrera-Bassols, N., & Zinck, J. A. (1998). The other pedology: empirical wisdom of local people. *Proceedings of 16th World Congress of Soil Science*. ISSS?AFES, Montpellier, France: CD-ROM.

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.

Bazas, I., (1993). Manual of Soil and Agrochemical Analysis. 2. Physical, Water management and Mineralogical Analysis of the soil. INDA 4231. Budapest. Hungary. (In

Hungarian)

Beer, J., Muschler, R., Kass, D., & Somarriba, E. (1998). Shade management in coffee and cacao plantations. *Agrofor Syst,* 38, 139–164.

Benefoh, D.T. (2018). Assessing land-use dynamics in a Ghanaian cocoa landscape. *PhD Thesis, Friedrich-Wilhelms-Universität Bonn,* 182pp

Berhe, A.A., Harden, J.W., Torn, M.S., & Harte, J. (2008). Linking soil organic matter dynamics and erosion-induced terrestrial carbon sequestration at different landform positions. *J. Geophys. Res. Biogeosci*. 113 (G4). https://doi.org/10.1029/2008JG000751

Bhojvaid, P. P. & Timmer, V. P. (1998) Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. *Forest Ecology and Management* 106:181-193.

Bird, S. B., Herrick, J. E., & Wander, M. M. (2001). Exploiting Heterogeneity of Soil Organic Matter in Rangelands: Benefits for Carbon Sequestration. In: 'The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect'. (Eds R. F. Follet, J. M. Kimble and R. Lal.) pp. 121–138. (CRC Press: Boca Raton, FL.)

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.

Blaser, W. J., Oppong, J., Yeboah, E., & Six, J. (2017). 'Shade trees have limited benefits for soil fertility in cocoa agroforests', *Agriculture, Ecosystems and Environment*, Elsevier, 243(October 2016)83–91. doi: 10.1016/j.agee.2017.04.007.

Bockheim, J.G., & Hartemink A.E. (2013). Distribution and classification of soils with clay-enriched horizons in the USA. *Geoderma,* 209-210 153-160.

Bohn, H. L., Myer, R. A., & O'Connor, (2001). Soil Chemistry, 2nd ed, Wiley.

Brady, N.C. & Weil, R.R. (1999) The Nature and Properties of Soils. 12th Edition, Prentice Hall Publishers, London.

Brady, N.C., & Weil, R.R.(2002). The nature and properties of soils (No. Ed. 13). PrenticeHallInc. https://www.scirp.org/reference/ReferencesPapers.aspx?ReferenceID=184527

Brady, N.C., & Weil, R.R. (2008). The Nature and Properties of Soils. 14th ed. P*earson Educa- tion Inc., Upper Saddle River, New Jersey* .

Bragança, Raphael Alves Fernandes, Ildeu Afonso de Carvalho Junior, Emerson Silva Ribeiro Junior, & Eduardo de Sá Mendonça. (2015). Comparison of different methods for the determination of total organic carbon and humic substances in Brazilian soils. *Revista Ceres*, 62(March 2016), pp. 496–501. doi: 10.1590/0034-737X201562050011.

Brammer, H. (1962). Soils: In Agriculture and Landuse in Ghana. J.B Wills ed. Oxford University Press London , Accra, New York. Pp 88-126.

Brash, H. T. (1962). Geomophology: In Agriculture and Land-use in Ghana (ed. J.B. Wills) Ch.5 pp 81-84. London Oxford Univ. Press.

Breuning-Madsen, H., Awadzi, T. W., Koch, C. B., & Borggaard, O. K. (2007). Characteristics and genesis of pisolitic soil layers in a tropical moist semi-deciduous forest of Ghana. *Geoderma*, 141(1–2), 130–138. doi: 10.1016/j.geoderma.2007.05.009.

Bruce, R. C., & Rayment, G. E. (1982). Analytical methods and interpretations used by the Agricultural Chemistry Branch for Soil and Land Use Surveys. *Queensland Department of Primary Industries*. Bulletin QB8 (2004), Indooroopilly, Queensland.

Buri, M. M., Issaka, R. N., Wakatsuki, T. & Otoo, E. (2004). Soil organic amendments and mineral fertilizers: Options for sustainable lowland rice production in the Forest agro-ecology of Ghana. *Agriculture and Food Science Journal of Ghana*, (Vol., 3, 237-248).

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.

Buxton, D., Lamptey, B., & Nyarko, B. (2018). Cocoa Farmers and their perceptions of Climate change: A case study of the Central and Western regions of Ghana. *International Journal of Research Studies in Agricultural Sciences* 4(2), 1-7.

Bymolt, R., Laven, A., Tyszler, M. (2018). Demystifying the cocoa sector in Ghana and Côte d'Ivoire. Chapter 10, Production and yield. The Royal Tropical Institute (KIT).

Cardoso, I.M., Janssen, B.H., Oenema, O., & Kuyper, T.W. (2003). Phosphorus pools in Oxisols under shaded and unshaded coffee systems on farmers' fields in Brazil. *Agrofor Syst*, 58, 55–64.

Carter, M.R. & Gregorich, E.G. (eds.), (2006). Soil sampling and methods of analysis. 2nd edition. Taylor & Francis Group.

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.

Chabbi, A., Kögel-Knabner, I., & Rumpel, C. (2009). Stabilised carbon in subsoil horizons is located in spatially distinct parts of the soil profile. *Soil Biology and Biochemistry*, 41(2), 256–261. doi: 10.1016/j.soilbio.2008.10.033.

Chagas, T., O'Sullivan, R., Bracer, C., & Streck, C. (2010). Consolidating national REDD + accounting and subnational activities in Ghana. UNDP, Global Environment Facility, NORAD, and Gordon and Betty Moore Foundation, p. 36.

Charman, P. E. V., & Roper, M. M. (2007). Soil organic matter. In 'Soils – their properties and management'. 3rd edn. (Eds P. E. V. Charman and B. W. Murphy.) pp. 276–285. (Oxford University Press: Melbourne.)

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.

Chen, X. W., Shi. X. H., Liang, X. P., Jia, S. X., Fan. R. Q., & Wei, S. C. (2015). Least limiting water range and soil pore-size distribution related to soil organic carbon dynamics following zero and conventional tillage of a black soil in Northeast China. *Journal of Agricultural Science*, 153(2), 270-281.

Chen, L.F., He, Z.B., Du, J., Yang, J.J., & Zhu, X. (2016). Patterns and environmental controls of soil organic carbon and total nitrogen in alpine eco- systems of northwestern China. *Catena* 137,37–43

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

Chiti, T., Grieco, E., Perugini, L., Rey, A., & Valentini, R. (2014). Effect of the replacement of tropical forests with tree plantations on soil organic carbon levels in the Jomoro district, Ghana. *Plant Soil,* 375(1-2) 47-59. DOI 10.1007/s11104-013-1928-1

Coetsee, C., Bond, W. J., & February, E. C. (2010). Frequent fire affects soil nitrogen and carbon in an African savanna by changing woody cover. *Oecologia* 162, 1027–1034. doi:10.1007/s00442-009-1490-y

Commission, E. (2013). *Soil Atlas of Africa*, *Soil Atlas of Africa*. doi: 10.2788/52319.

Conklin, H. (1957). *Hanunoo agriculture. A Report on an Integrated System of Shifting Cultivation in the Philippines*. FAO, Rome.

Craswell, E. T., & Lefroy, R. D. B. (2001). The role and function of organic matter in tropical soils. In Managing organic matter in tropical soils: Scope and limitations. *Springer*, Dordrecht pp. 7-18.

Crosbie, A. J. (1954). Preliminary soil survey of Kumasi water-catchment area. S. R. I. Tech Report No.2.

Crosbie, A. J. (1955). Soils of the Tinte-Bepo Forest Reserve. S.R.I Tech Report No. 11.

Crosbie, A. J. (1956). Soils of the Asenanyo Forest Reserve, S.R.I Tech Report No. 19.

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., Isaac, M. E., & Oppong, S.K. (2012). Exploring farmers' local knowledge and perceptions of soil fertility and management in the Ashanti Region of Ghana. *Geoderma*, 179,96-103.

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.

Desbiez, A., Matthews, R., & Tripathi, B. (2004). Perceptions and assessment of soil fertility by farmers in the mid-hills of Nepal. *Agriculture, Ecosystems and Environment*, 103, 191-206.

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., & Kögel-Knabner, I. (2005). Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years Soil and Tillage Research, 81, 87-95.

Dixon, J.B. (1977). Kaolinite and serpentine group minerals. In: Dinauer, R.C. (Ed.), *Minerals in Soil Environments*. SSSA, Madison, (pp. 357–403).

Dixon, R. (1995). Agroforestry systems: sources of sinks of greenhouse gases? *Agrofor Syst*, 31(2), 99–116.

Doetterl, S., Berhe, A.A., Nadeu,E., Wang, Z., Sommer, M., & Fiener, P. (2016). Erosion, deposition and soil carbon: a review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth Sci Rev*, 154, 102–122.

Dominy, C. S., Haynes, R. J. & van Antwerpen, R. (2002) Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. *Biology and Fertility of Soils* 36: 350-356.

Don, A., Schumacher, J., Scherer-Lorenzen, M., Scholten, T., & Schulze, E.D. (2007). Spatial and vertical variation of soil carbon at two grassland sites – implications for measuring soil carbon stocks. *Geoderma* 141, 272–282.

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.

Duah-Yentumi, S., Ronn, R., & Christensen, S. (1998). Nutrients limiting microbial growth in a tropical forest soil of Ghana under different management. *Applied Soil Ecology*, 8(1–3), 19–24.

Duguma, B., Gochowski, J., & Bakala, J. (2001). Smallholder cacao (Theobroma cacao Linn.) cultivation in agroforestry systems of West and Central Africa: Challenges and opportu- nities. *Agrofor. Syst*, 51, 177–188.

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.

Duxbury, J. M., Smith, M. S., & Doran, J. W. (1989). Soil organic matter as a source and a sink of plant nutrients. In 'Dynamics of soil organic matter in tropical ecosystems. (Eds D. C. Coleman, J. M. Oades, and G. Uehara.) pp. 33-67. (University of Hawaii Press: Honolulu.)

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.

Ekanade, O., Adesina, F. A., & Egbe, N. E. (1991). Sustaining tree crop production underintensive land use: An investigation into soil quality diverentiation under varying cropping paterns in western Nigeria. *J. Environ. Manage*, 32, 105–113.

Ellerbrock, R. H., Hohn, A., & Rogasik, J. (1999). Functional analysis of soil organic matter as affected by long-term manurial treatment. *European Journal of Soil Science*, 50, 65-71.

Emerson, W. W. (1991). Structural decline of soil, assessment and prevention. *Australian Journal of Soil Research* **29**, 905–922.

Emiru, N., & Gebrekidan, H., (2013). Effect of landuse changes and soil depth on soil organic matter, total nitrogen and available phosphorus contents of soils in Senbat watershed, Western Ethiopia. ARPN J. *Agric. Biol. Sci*, 8, 206–212.

Eze, P. N. (2015). Spatial variability and classification of soils on a Legon hill catena in the Accra Plains , Ghana. 6(8), 204–214. doi: 10.5897/JSSEM15.0495.

FAO. (1988). FAO/Unesco Soil Map of the World Revised legend, with corrections. World Soil Resources Report 60. Rome. (Reprinted as Technical Paper 20, ISRIC, Wageningen, 1994).

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

FAO. (2015). 'CAN CARBON (SOC) offset the Climate Change', *Food and Agriculture Organization of the United Nations*, (December), p. 4.

FAO. ITPS. (2015). Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

FAO. (2017). *Soil Organic Carbon the Hidden Potential.* Global Symposium on Soil Organic Carbon (GSOC) held at FAO headquarters Rome, Italy 90 p doi: 10.1038/nrg2350.

FAO. (2017a). *Unlocking the Potential of Soil Organic Carbon*: Outcome Document of the Global Symposium on Soil Organic Carbon, 21–23 March 2017, FAO Headquarters, Rome. Food and Agriculture Organization of the United Nations (FAO), Rome, 22 pp (Available: http://www.fao.org/3/b-i7268e.pdf (accessed: 14th June 2018)).

FAOSTAT. (2020). License: CC BY-NC-SA 3.0 IGO. Extracted from: www.fao.org/faostat/. Data of Access: 08-04-2021.

Feller, C., & Beare, M.H. (1997). Physical controls of soil organic matter dynamics in the tropics. *Geoderma*, 79: 69-117.

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.

Fernández-Ugalde, O., Barré, P., Hubert, F., Virto, I., Girardin, C., Ferrage, E., Caner, L., & Chenu, C. (2013). Clay mineralogy differs qualitatively in aggregate-size classes: clay-mineral-based evidence for aggregate hierarchy in temperate soils. *Eur. J. Soil Sci*., 64 (4), 410–422.

Fontaine, S., Barot, S., Barre, P., Bdioui, N., Mary, B., & Rumpel, C. (2007). Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, 450, 277–281.

Foster, N. W. (2015). 'Forest Ecosystems : Nutrient Cycling Forest Ecosystems : Nutrient Cycling', (August). doi: 10.1081/E-ESS-120001709.

Galantini, J.A., Senesi, N., Brunetti, G., & Rosell, R. (2004). Influence of texture on organic matter distribution and quality and nitrogen and sulfur status in semiarid Pampean grassland soils of Argentina. *Geoderma*, 123, 143-152.

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

Gao, Y., He, N., Yu, G., Chen, W., & Wang, Q. (2014). Long-term effects of different land use types on C, N, and P stoichiometry and storage in subtropical ecosystems: A case study in China. *Ecological Engineering*. 67, 171–181.

Gami, S.K., Lauren, J.G., & Duxbury, J.M. (2009). Influence of soil texture and cultivation on carbon and nitrogen levels in soils of the eastern Indo-Gangetic Plains. *Geoderma*, 153(3–4), 304–311. Available at: http://dx.doi.org/10.1016/j.geoderma.2009.08.003.

Ghartey, E. O., Dowuona, N.N. G., Nartey, K. E., Adjadeh, A. T., & Lawson, Y.D.I. (2012). Assessment of Variability in the Quality of an Acrisol under Different Land Use Systems in Ghana. *Open Journal of Soil Science*, 02(01), 33–43. doi: 10.4236/ojss.2012.21006.

Giardiana. C., Sanford, R. L., Dockersmith, I. C., & Jaramillo, V. J. (2000). the effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil*, 220,247-260.

Gibbs, H. K., Brown, S., Niles, N. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environmental Research Letters*, 2(4). doi: 10.1088/1748-9326/2/4/045023.

Gile, L.H., & Grossman, R.B. (1968). Morphology of the argillic horizon in desert soils of southern New Mexico. *Soil Science*, 106, 6–15.

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.

Gockowski, J., & Sonwa, D. (2011). Cocoa intensification scenarios and their predicted impact on CO 2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa. *Environmental Management*, 48(2), 307–321. doi: 10.1007/s00267-010-9602-3.

Goidts, E., Van Wesemael, B., & Crucifix, M. (2009). Magnitude and sources of uncertainties in soil organic carbon (SOC) stock assessments at various scales. *European Journal of Soil Science*, 60(5), 723–739. doi: 10.1111/j.1365-2389.2009.01157.x.

Goma-Tchimbakala, J., Moutsambote, J. M., & Makosso, S. (2008). Comparison of soil chemical properties in four Terminalia superb plantations and a natural forest in Mayombe Congo. *J Appl Sci*. 8(22),4152–4158.

Gondar, D., Lopez, R., Fiol, S., Antelo, J.M., & Arce, F. (2005). Characterization and acid–base properties of fulvic and humic acids isolated. *Geoderma*, 126, 367–374. 10.1016/j.geoderma.2004.10.006

Gregorich, E., & Monreal, C. (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Canadian journal of soil …*. Available at: http://pubs.aic.ca/doi/abs/10.4141/cjss94-051.

Gregorich, E. G., Greer, K. J., Anderson, D.W., & Liang, B.C. (1998). Carbon distribution and losses: erosion and deposition effects. *Soil Till Res,* 47:291–302.

Grüneberg, E., Schöning, I., Kalko, E.K.V., & Weisser, W.W., (2010). Regional organic carbon stock variability: a comparison between depth increments and soil horizons. *Geoderma*, 155, 426–433.

Guimarães, D.V., Gonzaga, M.I.S., da Silva, T.O., da Silva, T.L., Dias, N.S., Matias, M.I.S., (2013). Soil organic matter pools and carbon fractions in soil under different land uses. Soil Tillage Res. 126, 177–182.

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

Hall, G.F., & Olson, C.G. (1991). Predicting variability of soils from landscape models. In:

Maubach, M.J., Wilding, L.P. (Eds.), Spatial Variabilities of Soils and Landforms. *Soil Sci. Soc. Am.*, Madison, WI, USA, pp. 9–24.

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

Han, G.L., Li, F.S., & Tang, Y. (2015). Variations in soil organic carbon contents and isotopic compositions under different land uses in a typical karst area in Southwest China. *Geochemical Journal*, 49, 63–71. DOI 10.2343/geochemj.2.0-331.

Harms, B., & Dalal, R. C. (2003). Paired Site Sampling for Soil Carbon (and Nitrogen) Estimation – Queensland. National Carbon Accounting System Technical Report No. 37. (Australian Greenhouse Office: Canberra.

Hartemink, E. A. (1998) Soil chemical and physical properties as indicator of sustainable land management under sugar cane in Papua New Guinea. *Geoderma* 85:283-306.

Hartemink, A. E. (2005). Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: A review. *Adv. Agron*, 86, 227-253.

Hashim, G. M., Ciesiolka, C. A. A., YusoV, W. A., Nafis, A. W., Mispan, M. R., Rose, C. W., & Coughlan, K. J. (1995). Soil erosion processes in sloping land in the east coast of Peninsular Malaysia. *Soil Technol*, 8, 215–233.

Haverkort, B. & de Zeeuw, H. (1992). Development of Technologies towards Sustainable Agriculture: Institutional Implication. 231-242, In W.M Rivera and D.J Gustafson (eds), Agricultural Extension: Worldwide Institutional Evolution and Forces of Change. New York: Elsevier Science Publishing Company. Kegan Paul International, New York, USA.

Hazelton, P.A., & Murphy, B. W. (2007). CSIRO Publishing *INTERPRETING SOIL TEST RESULTS: what do all the numbers mean?* [2nd ed.] 150 Oxford Street (PO Box 1139) Collingwood VIC 3066 Australia.

He, X.J., Hou, E.Q., Liu, Y., & Wen, D.Z. (2016). Altitudinal patterns and controls of plant and soil nutrient concentrations and stoichiometry in subtropical China. *Sci*, 6, 24261.

Henneron, L., Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Girardin, & Blanchart, E. (2014). Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. *Agronomy for Sustainable Development,* 35(1), 169-181.

Hijbeek, R., Cormont, A., Hazeu, G., Bechini, L., Zavattaro, Janssen, B., Werner, M., Schlatter, N., Guzman, G., Bijttebier, J., Pronk, A. A., Van Eupen, M., & Van Ittersum, M. K. (2017). Do farmers perceive a deficiency of soil organic matter ? A European and farm level analysis. *Ecological Indicators,* 83,390-403.

Hobley, E., & Willgoose, G. (2010). *Measuring soil organic carbon stocks – issues and considerations* 19th World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Hobley, E. U., & Wilson, B. (2016). The depth distribution of organic carbon in the soils of eastern. 7, 1–21.

Hole, F.D. (1953). Suggested terminology for describing soils as three-dimensional bodies. *Soil Sci. Soc. Am. J.*, 17, 131–135.

Huang, P.M. (2004). Soil mineral –organic matter- micro organisms interactions: Fundamentals and impacts. *Advances in Agronomy*, 82, 391- 472.

Hurd, R. G. & Cunningham, R. K. (1961). A cocoa shade manurial experiment at the West African Cocoa Research Institute. III. Phsyiological results. *Journal of Horticultural Science*, 36, 1326-1337.

Hutchinson, J.J., Campbell C.A., & Desjardins, R.L. (2007). Some perspectives on carbon sequestration in agriculture. *Agriculture and Forest Meteorology*, 142, 288-302.

Igwe, C.A., (2005). Erodibility in Relation toWater-Dispersible Clay for some Soils ofEastern Nigeria. *Land Degradation and Development*. Vol. 16, pp. 87–96.

Infonet. (2019). Kenyan Soils. Infonet Biovision. https://www.infonetbiovision.org/EnvironmentalHealth/Kenyan-Soils

Innovations for Poverty Action (IPA) (2015). *Disseminating Innovative Resources and Technologies to Smallholders (DIRTS) Androidbased Extension Intervention*. Study summary Available at: https://www.poverty-action.org/printpdf/7351 (accessed December 2019).

IPCC, (2007). Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva

Isaac, M. E., Gordon. A. M., Thevathasan, N., Oppong, S.K., & Quashie- Sam, S. J. (2005). Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems : a chronosequence of pools and fluxes. *Agrofor. Syst.*, 65, 23–31. doi: 10.1007/s10457-004-4187-6.

Isaac, M. E., Dawoe, E. K., & Sieciechowicz, E. K. (2009). Assessing Local Knowledge use in Agroforestry Management with Cognitive Maps. *Environmental Management*, 43(6), 1321-1329.

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.

Ito, A., Wagai, R. (2017). Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. *Sci.*, Data 4, 170103.

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).

Jackson, R. S. (2014). Site Selection and Climate. In Wine Science, Jackson R (Eds). *Food Science and Technology*, San Diego. Academic Press pp. 305-346.

Jacobi, J., Andres, C., Schneider, M., Pillco, M., Calizaya, P., & Rist, S. (2014). Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia. *Agrofor. Syst.*, 88, 1117–1132

Janik, L. J., Skjemstad, J.O., Shepherd, K. D., & Spouncer, L. R. (2007). The prediction of soil carbon fractions using mid-infrared-partial least square analysis. *Australian Journal of Soil Research*, 45, 73-81.

Janvry, A., Macours, K., & Sadoulet, E. (2016). Learning for adopting: Technology adoption in developing country agriculture, Policy briefs from the workshop organised by FERDI and SPIA in Clermont - Ferrand, (January), 120 p. Available at:https://ispc.cgiar.org/sites/default/files/pdf/Learning for adoption_monograph.pdf

Jia, S., & Akiyama, T. (2005). A precise, unified method for estimating carboncarbon storage in cool-temperate deciduous forest ecosystems. *Agricultural and Forest Meteorology*, 134,70–80. doi:10.1016/j. agrformet.2005.08.014.

Jobbágy, E. G., & Jackson, R. B. (2000). The Vertical Distribution of Soil Organic Carbon and Its' relation to climate and vegetation. *Ecol. Appl*., 10(2), 423–436. doi: 10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.

Johns, N.D. (1999). Conservation in Brazil's chocolate forest: the unlikely persistence of the traditional cocoa agroecosystem. *Environ. Manag.*, 1, 31-47.

Jones, A., Henrik, B. M., Michel, B., Almami, D., Olivier, D., H., H. S., A, J. R. J., Method, K., Pieter, L. R., Erika, M., Luca, M., Otto, S., Gallali, T., Lamourdia, T., Eric, V. R., Martin, Y., & Robert, Z. (2013). Soil Atlas of Africa. European Commission, Publications Office of the European Union.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *Agrofor. Syst*., 76, 1–10.

Junner, N. R. (1940). Geology of the Gold Coast and Western Togoland. Gold Coast Geol. Surv. Bull. No. 11.

Kauffman, J. B., Cummings, D. L., & Ward, D. E. (1998). Fire in the Brazilian Amazon. 2. Biomass, nutrient pools and losses in cattle pastures. *Oecologia* 113, 415-427.

Kawaguchi, K., & Kyuma, K. (1977). Paddy soils of tropical Asia, their material nature and fertility. Honolulu, Hawaii. The University Press of Hawaii.

Keestrea, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., van der Putten, W. H., Bardgett, R. D., Moolenaar, S., Mol, G., Jansen, B. & Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil*, 2, 111-128.

Kemmitt, S.J., Wright, D., Goulding, K.W.T., & Jones, D.L. (2006). pH regulation of carbon and nitrogen dynamics in two agricultural soils. *Soil Biology and Biochemistry*, 38(5),898–911 DOI 10.1016/j.soilbio.2005.08.006.

Ketterings, Q. (2014). Extension and knowledge transfer: Adaptive management approaches for timely impact. *The Journal of Agricultural Science*, 152(S1), 57-64.

Khadka, D. (2016). Assessment of Relationship between Soil Organic Matter and Macronutrients, Western Nepal. *Journal of Biological and Pharmaceutical, Chemical Research*, 3(1), 4-12.

Khan, F., Hayat, Z., Ahmad, W., Ramzan, M., Shah, Z., Sharif, M., Mian, I.A. & Hanif, M. (2013). Effect of slope position on physico-chemical properties of eroded soil. *Soil Environment*, 32(1), 22-28.

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.

Kome, G. K., Enang, R. K., & Yerima, B. P. K. (2018). Knowledge and management of soil fertility by farmers in western Cameroon. *Geoderma Regional*, 13, 43–51.

Kotto-Same, J., Woomer, P. L., Appolinaire, M., & Louis, Z. (1997). Carbon dynamics in slash-and-burn agriculture and land-use alternatives of the humid forest zone in Cameroon. *Agric. Ecosyst. Environ*., 65, 245-256.

Krasilnikov, P., Ibanez, J. J., Arnold, R., & Shoba, S. (2009). A handbook of soil terminology, correlation and classification. Published by Earthscan in the UK and USA in 2009.

Kunlanit, B., Butnan, S., & Vityakon, P. (2019). Land-use changes influencing C sequestration and quality in topsoil and subsoil. *Agronomy*, 9(9), 1–16. doi: 10.3390/agronomy9090520.

Kuria, A. W., Barrios, E., Pagella, T., Muthuri, C., Mukuralinda, W., & Sinclair, F. L. (2018). Farmers’ knowledge of soil quality indicators along a land degradation gradient in Rwanda. *Geoderma Regional*, 15, e00199.

Kutsch, W. L., Bahn, M., & Heinemeyer, A. (2009). Soil carbon dynamics: An integrated methodology. Cambridge, UK: Cambridge University Press.

Kuyper, T. W., Abekoe, M., & Giller, K. E. (2004). Land tenure and differential soil fertility management practices among native and migrant farmers in Wenchi, Ghana: implications for interdisciplinary action research. NJAS - *Wageningen Journal of Life Sciences,* 52, 331-348.

Lal, R. (2004a). Agricultural activities and the global carbon cycle. *Nutrient Cycling in Agroecosystems,* 70(2), 103–116. doi: 10.1023/B:FRES.0000048480.24274.0f.

Lal, R. (2004b). Soil carbon sequestration impacts on global climate change and food security. *Science,* 304(5677), 1623–1627. doi: 10.1126/science.1097396.

Lal, R. (2010). Beyond Copenhagen: Mitigating climate change and achieving food security through soil carbon sequestration. *Food Security,* 2(2), 169-177.

Lal, R. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability,* 15(C), 79-86.

Laurenz, K., & Lal, R. (2016). Soil Organic Carbon - An appropriate Indicator to Monitor Trends of Land and Soil Degradation within the SDG Framework? Dessau-Roßlau: Umweltbundesamt.

Lawrence, C.R., Harden, J.W., Xu, X., Schulz, M.S., & Trumbore, S.E. (2015). Long–term controls on soil organic carbon with depth and time: A case study from the Cowlitz River Chronosequence, WA USA. *Geoderma,* 247, 73–87.

Lawrence P.G., Roper, W., Morris, T.F., & Guillard, K., (2020). Guiding soil sampling strategies using classical and spatial statistics: A review. Agronomy Journal, vol 112 (1), 493-510.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Goldewijk, K. K., Jain, A. K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J. R., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S-I, O’Brien, K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J. & Zaehle, S. (2016). Global Carbon Budget 2016. *Earth System Science Data,* 8, 605-649.

Ledo, A., Heathcote, R., Hastings, A., Smith, P., & Hillier, J. (2018). Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops. *Environmental Modelling and Software,* 102, 292– 305.

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.

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.

Lettens, S., De Vos, B., Quataert, P., Van Wesemael, B., Muys, B., & Van Orshoven, J. (2007). Variable carbon recovery of Walkley-Black analysis and implications for national soil organic carbon accounting. *European Journal of Soil Science*, 58(6), 1244–1253. doi: 10.1111/j.1365-2389.2007.00916.x.

Lilienfein, J., Wilcke, W., Ayarza, M. A., Vilela, L., Lima, S. D. C. & Zech, W. (2000) Chemical fractionation of phosphorus, sulphur, and molybdenum in Brazilian savannah Oxisols under different land uses. *Geoderma* 96: 31-46.

López-Vicente, M., Calvo-Seas, E., Álvarez, S., & Cerdà, A. (2020). Effectiveness of cover crops to reduce loss of soil organic matter in a rainfed vineyard. *Land*, 9(7), 1-16.

Lorenz, K., & Lal, R. (2005). The Depth Distribution of Soil Organic Carbon in Relation to Land Use and Management and the Potential of Carbon Sequestration in Subsoil Horizons. *Advances in Agronomy,* 88(05), 35–66. doi: 10.1016/S0065-2113(05)88002-2.

Lorenz, K., & Lal, R. (2016). Soil organic carbon an appropriate indicator to monitor trends of land and soil degradation within the SDG Framework? Umweltbundesamt [GermanEnvironmentAgency]Text77/2016.

Liu, D., Wang, Z., Zhang, B., Song, K., Li, X., Li, J., Li, F., & Duan, H. (2006). Spatial distribution of soil organic carbon and analysis ofrelated factors in croplands ofthe black soil region, northeast China. *Agriculture Ecosystems & Environment*, 113,73–81. doi:10.1016/j.agee.2005.09.006

Liu, Z.P., Shao, M.A., & Wang, Y.Q. (2013). Spatial patterns of soil total nitrogen and soil total phosphorus across the entire Loess Plateau region of China. *Geoderma*, 197(198), 67–78. Available at: http://dx.doi.org/10.1016/j.geoderma.2012.12.011.

Ludwig, J. A., & Tongway, D. J. (1995). Spatial organisation oflandscapes and its function in semi-arid woodlands, Australia. *Landscape Ecology*, 10,51–63. doi:10.1007/BF00158553

Mairura, F.S., Mugendi, D. N., Mwanje, J. I., Ramisch, J. J., Mbugua, P. K., & Chianu, J. N. (2007). Integrating scientific and farmers' evaluation of soil quality indicators in Central Kenya. *Geoderma*, 139 (1–2), 134–143.

Malhi, Y., Baldocchi, D. D., & Jarvis, P. G. (1999). The carbon balance of tropical, temperate and boreal forests. *Plant Cell Environ*, 22, 715–740.

Malhi, Y., & Grace, J. (2000). Tropical forests and atmospheric carbon dioxide. *Trends in Ecology & Evolution*, 15(8), 332–337. doi: 10.1016/S0169-5347(00)01906-6.

Manu, M., & Tetteh, E. K. (1987). A guide to cocoa cultivation. (eds) Cocoa Research Institute of Ghana (CRIG), Tafo.

Marinho, M.A., Pereira, M.W.M., Vázquez, E.V., Lado, M., & González, A.P. (2017). Depth distribution of soil organic carbon in an oxisol under different land uses: stratification indices and multifractal analysis. Geoderma 287, 126–134.

Martin, A., Mariotti, A., Balesdent, J., Lavelle, P., & Vuattoux, R. (1990). Estimate of organic matter turnover rate in a savanna soil by 13C natural abundance measurements. *Soil Biology and Biochemistry* 22: 517-523.

Marques, R. & Ranger, R. (1997). Nutrient dynamics in a chronosequence of Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) stands on the Beaujolais Mounts (France): Qualitative approach. *Forest Ecolology and Management* 91: 255-277.

Metson, A. J. (1961). Methods of chemical analysis for soil survey samples. Soil Bureau Bulletin No. 12, New Zealand Department of Scientific and Industrial Research, pp. 168–175. (Government Printer: Wellington, New Zealand.)

McBratney, A.B., Field, D.J. & Koch, A. (2014). The dimensions of soil security. *Geoderma*, 213, 203–213.

MacCarthy, P., Malcolm R.L., Clapp C.E., & Bloom P. R. (1990b). An introduction to soil humic substances. p. l-12. In P. MacCarthy, R.L. Malcolm, C.E. Clapp, and PR. Bloom. (ed.) Humic substances in crop and soil sciences: Selected readings. Soil Science Society of America, Madison, WI.

McDonald, R. C., Isbell, R. F., Speight, J. G., Walker, J., & Hopkins, M. S. (1994). Australian Soil and Land Survey Field Handbook. (Inkata Press: Melbourne.)

McDonagh, J. F., Thomsen, T. B. & Magid, J. (2001). Soil organic matter decline and compositional change associated with cereal cropping in southern Tanzania. *Land Degradation and Development* 12: 13-26.

Mcisaac, G. (2003). Surface Water Pollution by Nitrogen Fertilizers. *Encyclopedia of Water Science*, 950-955.

McLauchlan, K.K. (2006). Effects of soil texture on soil carbon and nitrogen dynamics after cessation of agriculture. *Geoderma*, 136(1–2), 289–299.

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.

Miltz, J., & Don, A. (2012). Optimising Sample Preparation and near Infrared Spectra Measurements of Soil Samples to Calibrate Organic Carbon and Total Nitrogen Content. *Journal of Near Infrared Spectroscopy*, 20(6), 695-706.

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.

Monroe, P. H. M., Gama-Rodrigues, E.F., Gama-Rodrigues, A.C., & Marques, J. R. B. (2016). Soil carbon stocks and origin under different cacao agroforestry systems in Southern Bahia, Brazil Agriculture. *Ecosystems & Environment*, 221, 99-108.

Montagnin, I. F., & Nair, P.K.R. (2004). Carbon sequestration: an un- derexploited environmental benefit of agroforestry systems. *Agrofor Syst*., 61, 281–295.

Mu,L., Liang,Y., Xue, Q., Chen, C., & Lin, X. (2014). Using the DNDC model to compare soil organic carbon dynamics under different crop rotation and fertilizer strategies. *Spanish J. Agric. Res.* 12(1), 265–276.

Muhati, G. L., Olago, D., & Olaka, L. (2018). Quantification of carbon stocks in Mount Marsabit Forest Reserve, a sub-humid montane forest in northern Kenya under anthropogenic disturbance. *Global Ecology and Conservation*. Elsevier, 14, p. e00383. doi: 10.1016/j.gecco.2018.e00383.

Muller, M., Yvonne, O., Schickhoff, U., Bohner, J., & Scholten, T. (2017). Himalayan treeline soil and foliar C:N:P stoichiometry indicate nutrient shortage with elevation. *Geoderma*, 291, 21–32.

Mulyani, O., Benny, J., & Kurnia, D. (2021). A case study in Cianjur West Java, Indonesia: A correlation humic and fulvic acids with mineralogical composition and physico-chemical analysis using partial least square. J. Ecol. Eng. 22, 191–204.

Murty, D., Kirschbaum, M.U., McMurtrie, R.E., & McGilvray, H. (2002). Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Glob. Chang. Biol*., 8, 105–123.

Nair, P.K.R., Kumar, B.M., & Nair, V.D. (2009). Agroforestry as a strategy for carbon sequestration. *J. Plant Nutrit. Soil Sci*., 172, 10–23.

Nair, P.K.R., Nair, V.D., Kumar, B.M., & Showalter, J.M. (2010). Carbon sequestration in agroforestry systems. *Adv. Agron*., 108, 237–307. doi:10. 1016/S0065-2113(10)08005-3

Nelson, D.W., & Sommers, L.E. (1996). Total Carbon, Organic Carbon, and Organic Matter, pp. 961-1010 in: Methods of Soil Analysis. Part 3. Chemical Methods—*SSSA Book Series no. 5, Soil Science Society of America and American Society of Agronomy*, Madison, WI, USA.

Novak, J. M., & Bertsch, P. M. (1991). The Influence of Topography on the Nature of Humic Substances in Soil Organic Matter at a Site in the Atlantic Coastal Plain of South Carolina. Biogeochemistry, 15,111-126.

Nye, P. H. & Stephens, D. (1958). Soil fertility, In Agriculture and Land Use in Ghana. J. B. Wills (ed), 127-143 pp. Oxford University Press.

Nye, P. H. & Greenland, D. J. (1960). Changes in the soil after clearing tropical forest. *Plant and Soil*, 21 101-112.

Oades, J.M. (1988). The relention of organic matter in soils. Biogeochem. 5:35-70.

Oades, J. M. (1989). An introduction to organic matter in mineral soils. In 'Minerals in soil environments. (Eds J. B. Dixon and S. B. Weed.) pp. 89-159. (Soil Science Society of America: Madison, WI.) 124

Oades, J. M., Gillman, G. P., & Uehara, G. (1989). Interactions of soil organic matter and variable-charge clays. In 'Dynamics of soil organic matter in tropical ecosystems. (Eds D. C. Coleman, J. M. Oades, and G. Uehara.) pp. 69-95. (University of Hawaii Press: Honolulu.)

Obeng, E.A., & Aguilar, F.X. (2015). Marginal effects on biodiversity, carbon sequestration and nutrient cycling of transitions from tropical forests to cacao farming systems. *Agrofor. Syst.*, 89, 19–35.

Oelbermann, M., Voroney, R.P., Naresh, V., Thevathasan, N.V., Gordon, A.M., Kass, D.C.L., & Schlonvoigt, A.M. (2006). Carbon dynamics and residue stabilization in a Costa Rican and southern Canadian alley cropping system. *Agrofor Syst.*, 68, 27–36.

Oelmann, Y., Buchmann, N., Gleixner, G., Habekost, M., Roscher, C., Rosenkranz, S., Schulze, E.D., Steinbeiss, S., Temperton, V.M., Weigelt, A., Weisser, W.W., & Wilcke, W. (2011a). Plant diversity effects on above- and belowground N pools in temperate grassland ecosystems: development in the first five years after establishment. *Global Biogeochem. Cycles*, 25, GB2014.

Oelmann, Y., Richter, A.K., Roscher, Christiane, Rosenkranz, Stephan, Temperton, V.M., Weisser, W.W., & Wilcke, W. (2011b). Does plant diversity influence phosphorus cycling in experimental grasslands? *Geoderma*, 167(168), 178–187.

Ofori-Frimpong, K., Asase, A., Mason, J., Danku, L. (2007). Shaded versus unshaded cocoa: implications on litter fall, decomposition, soil fertility and cocoa pod development. *In: Proceedings 2nd Int. Symposium on Multistrata Agroforestry Systems with Perennial Crops: Making Ecosystem Service Count for Farmers, Consumers and the Environment CATIE. Turrialba*.

Ogunkunle, A. O., & Eghaghara, O. O. (1992). Influence of land use on soil properties in a forest region of Southern Nigeria. *Soil Use and Management*, 8 (3), 121–125.

Olson, K.R., Jones, R.L., & Lang, J.M. (2005). Soil formation at Millstone Bluff and Johnson Ridge in southern Illinois. *Soil Science*, 170, 457–468.

Olutokunbo, B., & Ibikunle, E. (2011). Farmers' Perceptions of Organic Farming in Selected Local Government Areas of Ekiti State, Nigeria. *Journal of Organic Systems*, 6(1), 20-26.

Oke, D., & Olatiilu, A. (2011).Carbon storage in agroecosystems: a case study of the cocoa based agroforestry in Ogbese forest reserve, Ekiti State, Nigeria. *J Environ Prot*., 2(8)1069–75.

Omoshola, A. (2015). The Future Cocoa Farmer: Soil Quality in Existing Traditional, Organic and Hi-Tech Conventional Cocoa Production in Ashanti Region of Ghana. Available at: http://edepot.wur.nl/399297.

Opakunle, J. S. (1989). Nutrient distribution and cycling in a Theobroma cacao L. agro-ecosystem in Southwestern Nigeria. Acta Oecol 10,347–357.

Orlov, D. (1990). Humic acids of soils and general theory of humification. Moscow State University, 1990. 1: p. 325.

Osunade, M. A. (1992). Identification of crop soils by small farmers of South-western Nigeria. *Journal of Environmental Management*, 35, 193-203.

Ouédraogo, E., Mando, A., Stroosnijder, L. (2006). Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West AfricaSoil and Tillage Research, 91, 57-67.

Owusu-Bennoah, E. Awadzi, T. W., Boateng, E., Krogh, L., Breuning-Madsen, H., & Borggaard, O. K. (2000). Soil Properties of a Toposequence in the Moist Semi Deciduous Forest Zone of Ghana.pdf. (pp. 1–10).

Owusu-Sekyere, E., Cobbina, J., & Wakatsuki, T. (2006). Nutrient Cycling in Primary, Secondary Forests and Cocoa Plantation in the Ashanti Region, Ghana. *West Africa Journal of Applied Ecology*, 9.

Owusu, S., Yigini, Y., Olmedo, G. F., & Omuto, C. T. (2020). Spatial prediction of soil organic carbon stocks in Ghana using legacy data. *Geoderma*, Elsevier, 360(October 2018), p. 114008. doi: 10.1016/j.geoderma.2019.114008.

Parras-Alcantára, L., Lozano-García, B., & Galán-Espejo, A. (2015). Soil organ ic carbon along an altitudinal gradient in the Despenaperros Natural Park, southern Spain. *Solid Earth*, 6:125–134.

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

Paul, J., Sierra, J., Guindé, L., & Blazy, J. M. (2017). Factors affecting the adoption of compost use by farmers in small tropical Caribbean islands. *Journal of Cleaner Production*, 142, 1387-1396.

Pauli, N., Abbott, L. K., Negrete-Yankelevich, S., & Andrés, P. (2016). Farmers' knowledge and use of soil fauna in agriculture: a worldwide review. *Ecology and Society*, 21(3),19. http://dx.doi.org/10.5751/ES-08597-210319

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.

Poeplau, C., Vos, C., & Don, A. (2016). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil,* 3, 61–66, doi:10.5194/soil-3-61-2017.

Porder, S., Paytan, A., & Vitousek, M. P. (2005) Erosion and landscape development affect plant nutrient status in the Hawaiian Islands. Oeclogia 142, 440-449.

Quansah, C., Drechsel, P, & Yirenkyi, B. B. (2001). Farmers' perceptions and management of soil organic matter a case study from West Africa. *Nutrient Cycling in Agroecosystems*, 61(1), 205-213

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

Rai, M. (2002). Principles of Soil Science, Macmillan, New York, NY, USA, 2002.

Raper, R.L., & Erbach, D.C. (1987). Bulk density measurement variability with core samplers, Trans. ASAE 30 (1987) 878–881.

Rasse, D. P., Rumpel, C., & Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilization. *Plant and Soil*, 269(1-2), 341–356. https://doi.org/10.1007/s11104-004-0907-y

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., & Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma*, 116 (2003) 61–76.

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.

Regelink, I.C., Weng, L., Koopmans, G.F., & Van Riemsdijk, W.H. (2013). Asymmetric flow field-flow fractionation as a new approach to analyse iron-(hydr) oxide nanoparticles in soil extracts. *Geoderma*, 202, 134–141.

Regelink, I. C., Stoof, C. R., Rousseva, S., Weng, L., Lair, G. J., Kram, P., Nikolaidis, N. P., Kercheva, M., Banwart, S., & Comans, R. N. J. (2015). Linkages between aggregate formation, porosity and soil chemical properties. *Geoderma*, Elsevier B.V., 247(248), 24–37. doi: 10.1016/j.geoderma.2015.01.022.

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

Robertson, J., & Pérez-Fernández, E. (2017). Interpretation of Mid Infrared Spectra of Soils. *Introduction to MIR Spectra of Soil, Wagengen, June 26, 2017*.

Roskoski, J. P., Bornemisza, E., Aranguren, J., Escalante, G., & Santana, M. B. M. (1982). Report of the work group on coffee and cocoa plantations. *Plant Soil*, 67, 403–407.

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.).*

Rowe, W. F. (2005). Encyclopedia of Soils in the Environment D. Hillel (Ed.) *Reference work Forensic Applications Amsterdam* pp. 67-72.

Rumpel, C., & Kögel-Knabner, I. (2011). Deep soil organic matter-a key but poorly understood component of terrestrial C cycle. *Plant and Soil*, 338(1), 143–158. doi: 10.1007/s11104-010-0391-5.

Sanchez, P. A., Palm, C. A., & Buol, S. W. (2003). Fertility capability soil classification : a tool to help assess soil quality in the tropics. *Geoderma*, 114(3-4), 157-185.

Seddaiu, G., Porcu, G., Ledda, L., Roggero, P.P., Agnelli, A., Corti, G. (2013). Soil organic matter content and composition as influenced by soil management in a semi-arid Mediterranean agro-silvo-pastoral system. Agric. Ecosyst. Environ. 167, 1–11.

Senanayake, S. G. J. N. (2006). *The Journal of Agricultural Sciences,* vol., no.1.

Schaetzl, R.J., Anderson, S. (2005). Soils Genesis and geomorphology. Cambridge University Press.

Schnabel, R. R., Franzluebbers, A. J., Stout, W. L., Sanderson, M. A., & Stuedemann, J. A. (2001). The effects of pasture management practices. In 'Potential of US Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect'. (Eds R. F. Follet, J. M. Kimble and R. Lal.) (CRC Press LLC: USA.)

Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kögel-Knabner, I., & Schulze, E.-D. (2013). Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. Biogeosciences 10, 1675–1691. https://doi.org/10.5194/bg-10-1675-2013

Sharma, P., Rai, S. C., Sharma, R., & Sharma, E. (2004). Effects of land- use change on soil microbial C, N and P in a Himalayan Watershed. *Pedobiologia* 48,83–92.

Shaw, J.N., West, L.T., Bosch, D.D., Truman, C.C., & Leigh, D.S. (2004). Parent material influence on soil distribution and genesis in a Paleudult and Kandiudult complex, southeastern USA. *Catena* 57, 157–174.

Shi, P., Duan, J., Zhang, Y., Li, P., Wang, X., Xiao, Z., Li, L., Xu, G., Lu, K., Cheng, S., Ren, Z., Zhang, Y., & Yang, W. (2019). The effects of ecological construction and topography on soil organic carbon and total nitrogen in the Loess Plateau of China. *Environmental Earth Sciences*, 78, 5 doi: 10.1007/s12665-018-7992-3.

Sillitoe, P. (1998). Knowing the land: soil and land resource evaluation and indigenous knowledge. *Soil Use and Management* 14, 188–193.

Six, J., Elliott, E.T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biol. Biochem*., 32, 2099–2103.

Six, J., Conant, R., Paul, E., & Paustian, K., (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, 241, 155–176. https://doi.org/10.1023/A:1016125726789

Smiley, G., & Kroschel, J. (2008). Temporal change in carbon stocks of cocoa– gliricidia agroforests in Central Sulawesi, *Indonesia. Agrofor Syst.*, 73(3):219–31.

Smith, S.V., Renwick, W.H., Buddemeier, R.W., & Crossland, C. J. (2001). Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. *Glob. Biogeochem. Cycles*, 15, 697–707.

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

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).

Sollins, P., Homann, P. & Caldwell, B. A. (1996). Stabilization and destabilization of soil organic matter.1.pdf. *Geoderma*, 74(1–2), 65–105. doi: 10.1016/S0016-7061(96)00036-

5.

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

Sommer, M. & Schlichting, E. (1997). Archetypes of Catenas in Respect to Matter—A Concept for Structuring and Grouping Catenas. Geoderma, 76, 1-33.

Sommer, R., Denich, M. & Vlek, P. L. G. (2000). Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. *Plant and Soil*, 219, 231–241. doi: 10.1023/a:1004772301158.

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.

Stevens, A., van Wesemael, Bas., Bartholomeus, H., Rosillon, D., Tychon, B., & Ben-Dor, E. (2008). Laboratory , field and airborne spectroscopy for monitoring organic carbon content in agricultural soils. *Geodema*, 144, 395–404. doi: 10.1016/j.geoderma.2007.12.009.

Strong, W. M., & Mason, M. G. (1999). Nitrogen. In ‘Soil analysis: An interpretation manual’. (Eds K. I. Peverill, L. A. Sparrow and D. J. Reuter.) (CSIRO Publishing: Melbourne.)

Swift, R. & Hayes, M. (1989). Humic Substances II. In Search of Structure. John Wiley: Chichester, 449.

Tate, K. R. (1992). Assessment, based on a climosequence of soils in tussock grasslands, of soil carbon storage and release in response to global warming. *Journal of Soil Science.* 43:697-707.

Tesfahunegn, G. B. (2019). Farmers’ perception on land degradation in northern Ethiopia: Implication for developing sustainable land management. *The Social Science Journal*. 56, 268–287.

Toxopeus, H. (1986). Botany, types and populations. In Wood GAR, Loss RA (ed) Cocoa 4th Edition. Longman Scientific and Technical. pp. 11- 37.

Tripolskaja, L., Kazlauskaite-Jadzevice, A., Baksiene, E. Razukas, A. (2022). changes in organic carbon in mineral topsoil of a formerly cultivated Arenosol under different landuses in Lithuania. Agriculture, 12, 488. https://doi.org/10.3390/agriculture12040488

Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Holscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., & Wanger, T.C. (2011). Multifunctional shade-tree management in tropical agroforestry landscapes – a review. *J. Appl. Ecol*., 48, 619–629.

Tsui, C. C, Chen, Z. S., Hsieh, C. F. (2004). Relationships between soil properties and slope position in a lowland rain forest of southern Taiwan. *Geoderma*, 123(1),131–142.

Twongyirwe, R., Sheil, D., Majaliwa, J. G. M., Ebanyat, P., Tenywa, M. M., van Heist, M., & Kumar, L. (2013). Variability of Soil Organic Carbon stocks under different land uses: A study in an afro-montane landscape in southwestern Uganda. *Geoderma*, Elsevier B.V., 193(194), 282–289. doi: 10.1016/j.geoderma.2012.09.005.

UN. (United Nations) (1992). Agenda 21 United Nations Conference on Environment and Development UNCED the Earth Summit, Rio de Janeiro, Brazil.

U.S. Department of Agriculture (USDA) (2007). Managing Cover Crops Profitably, Clark A (third edition) *A publication of the Sustainable Agriculture Network, Beltsville*, pp. 144-150.

Utomo, B., Prawoto, A. A., Bonnet, S., Bangviwat, A., & Gheewala, H. S. (2016). Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. *Journal of Cleaner Production*, 134 (Part B), 583–591. doi: 10.1016/j.jclepro.2015.08.102.

VandenBygaart, A. J., & Kay, B. D. (2004). Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. *Soil Science Society of America Journal* 68, 1394–1402.

VandenBygaart, A. J. (2006). Monitoring soil organic carbon stock changes in agricultural landscapes: Issues and a proposed approach. *Canadian Journal of Soil Science*, 86, 451–463.

Van der Wal, A. & De Boer, W. (2017). Dinner in the dark: Illuminating drivers of soil organic matter decomposition. *Soil Biology and Biochemistry*, 105, 45-48.

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

Vervuurt, W., Slingerland, M. A., Pronk, A. A., & Van Bussel, L. G. J. (2022). Modelling greenhouse gas emissions of the cacoa production in the republic of Cote d'Ivoire. Agroforest Syst. 96, 417–434.

Viscarra -Rossel, R. A., Walvoort, D. J. J, McBratney, A. B., Janik, L. J., & Skjemstad, J. O. (2006). Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. *Geoderma*, 131, 59-75.

Viscarra Rossel, R.A., Fouad, Y., Walter, C. (2008). Using a digital camera to measure soil organic carbon and iron contents. Biosyst. Eng. 100, 149–159.

Von Lutzow, M., Kogel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., & Marschners, B. (2006). Stabilization of Organic Matter in Temperate Soils: Mechanisms and Their Relevance under Different Soil Conditions. *European Journal of Soil Science*, 57, 426-445. https://doi.org/10.1111/j.1365-2389.2006.00809.x

Waldrop, M. P., Zaka, D. R., & Sinsabaugh, R. L. (2004) Microbial community response to nitrogen deposition in northern forest ecosystems. *Soil Biology & Biochemistry*, 36, 1443–145.

Walkley, A., & Black, I. A. (1934). An examination of the Dedtjarff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci*., 37, 29–38.

Walter, K., Don, A., Tiemeyer, B., & Freibauer, A. (2016). Determining soil bulk density for carbon stock calculations a systematic method comparison. *Soil Sci. Soc. Am. J.*, 80 579–591.

Wang, X., Wang, J. & Zhang, J. (2012) ‘Comparisons of Three Methods for Organic and Inorganic Carbon in Calcareous Soils of Northwestern China’, *PLoS ONE,* 7(8). doi: 10.1371/journal.pone.0044334.

Wartenberg, A. C., Blaser, W. J., Janudianto, K . N., Roshetko, J. M., van Noordwijk, M., & Six, J. (2018). Farmer perceptions of plant–soil interactions can affect adoption of sustainable management practices in cocoa agroforests: A case study from Southeast Sulawesi. *Ecology and Society*, 23(1),18.

Wattel-Koekkoek, E.J.W., P. Buurman, J. Van der Plicht, E. Wattel, & N. Van Breemen. 2003. Mean residence time of kaolinite and smectite-associated soil organic matter. Eur. J. Soil Sci. 54:269–278.

Wawire, A. W., Csorba, A., Toth, J. A., & Michéli, E. (2020). Integration of manure and mineral fertilizers among smallholder farmers in Kenya: a pathway to sustainable soil fertility management and agricultural intensification. *International journal of Agricultural Extension and Rural Development Studies,* 7(2), 1–20. Available at: https://www.eajournals.org/wp-content/uploads/Integration-of-manure-and-mineral-fertilizers-among-smallholder-farmers-in-Kenya.pdf.

Webster, R., & Lark, M., (2012). Field Sampling for Environmental Science and Management.

Wessel, M. (1985). Shade and nutrition of cocoa. In “Cocoa” (G. A. R. Wood and R. A. Lass, Eds.), 4th edn. Longman Scientific and Technical, Essex.

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.

Willson, K. C. (1999). Coffee, Cocoa and Tea. CAB International, Wallingford, U.K.

Wilson, M. A., Indorante, S. J., Lee, B. D., Follmer, L., Williams, D. R., Fitch, B.C., McCauley, W. M., Bathgate, J. D., Grimley, D. A., & Kleinschmidt, K. (2010). Location and expression of fragic soil properties in a loess-covered landscape, southern Illinois, USA. *Geoderma*, 154, 529–543.

WinklerPrins, A. (1999). Local soil knowledge: a tool for sustainable land management. *Society and Natural Resources*, 12, 151–161.

Wood, G. A. R., & Lass, R. A. (1985). "Cocoa", 4th edn. Longman Scientific and Technical, Essex.

WRB. (2014). World Reference Base for Soil Resources 2014. *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. World Soil Resources Reports No. 106. Rome: FAO.

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.

Yamashita, T., Feiner, H., Bettina, J., Helfrich, M., & Ludwig, B. (2006). Organic matter in density fractions of water-stable aggregates in silty soils: effect of land use Soil Biology and Biochemistry, 38, 3222-3234.

Yang, Y., Fang, J., Ma, W., Smith, P., Mohammat, A., Wang, S., & Wang, W. (2010). Soil carbon stock and its changes in northern China's grasslands from 1980s to 2000s. *Glob. Change Biol*., 16, 3036–3047.

Yaro, J. A. (2013). The perception of and adaptation to climate variability change in Ghana by small-scale and commercial farmers. Regional Environmental Change, 13(6), 1259-1272.

Young, A. (1991). Soil monitoring: A basic task for soil survey organizations. *Soil Use and Management* 7:126-129.

Yuan, J.Y., Ouyang, Z.Y., Zheng, H., Xu, & W.H. (2012). Effects of different grassland restoration approaches on soil properties. *Appl. Soil Ecol.*, 61, 34–39.

Zhang, X., Liu, M., Zhao, X., Li, Y., Zhao, W., Li, A., Chen, S., Chen, S., Han, X., & Huang, J. (2019). Topography and grazing effects on storage of soil organic carbon and nitrogen in the northern China grasslands. *Ecological Indicators*, 93, 45–53. doi: https://doi.org/10.1016/j.ecolind.2018.04.068.

Zhang, Y., Li, C., & Wang, M.L. (2018). Linkages of C: N: P stoichiometry between soil and leaf and their response to climatic factors along altitudinal gradients. *J. Soils Sediments,* *19*, 1820–1829.

Zhang, Y., & Hartemink, E. A. (2017). Sampling designs for soil organic carbon stock assessment of soil profiles. *Geoderma*, 307, 220–230 DOI: 10.1016/j.geoderma.2017.08.013

Zhang Y., Hartemink A. E., & Huang, J. (2019). Quantifying Coarse Fragments in Soil Samples Using a Digital Camera. *Soil Physics Published in Russian in Pochvovedenie*, 8, 956–965.

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.

Zhao, F., Li, D. D., Jiao, F., Yao, J., & Du, H.T. (2019). The Latitudinal Patterns of Leaf and Soil C:N:P Stoichiometry in the Loess Plateau of China. Front. *Plant Sci*., 10.

Zhou, W, Han, G., Liu, M., & Li, X. (2019). Effects of soil pH and texture on soil carbon and nitrogen in soil profiles under different land-uses in Mun River Basin, Northeast Thailand. *PeerJ* 10.7717/peerj.7880.

Zuo, X., Zhao, H., Zhao, X., Zhang, T., Guo, Y., Wang, S., & Drake, S. (2008). Spatial pattern and heterogeneity of soil properties in sand dunes under grazing and restoration in Horqin Sandy Land, Northern China. *Soil & Tillage Research*, 99, 202–212. doi:10.1016/j.still.2008.02.008.

APPENDICES

Appendix A

INTERVIEW QUESTIONS FOR FARMERS IN THE ATWIMA NWABIAGYA DISTRICT

INTRODUCTION - ACTIVITIES OF THE FARMERS

1. How would you describe what you do in general?

2. How long have you worked on this farm?

3. What kind of activities do you do?

4. What are some of the benefits you get from cocoa farming?

5. Do you get any subsidies from the government or NGOs which improve your farming activities? Please elaborate if you do.

SOCIAL CAPITAL (RELATION) –ACCESS TO TRAINING

6. Are you a member of any farmer groups?

7. If yes, what are some of the benefits you drive from this farmer group?

8. Do you usually participate in training related to farming, agriculture, soil management?

PERCEPTION OF FARMER ABOUT SOIL

9. In your opinion, what do you think the most important factors that affect crop yield?

10. What is the importance of soil?

11. What makes good soil?

12. Do you know what organic matter is?

13. And what are some of the indicators that show the presence of organic matter on your farm?

14. Do you have any idea if the organic matter can be found in the deeper layers of soil?

15. Do you have any knowledge of soil being able to store atmospheric carbon dioxide? If yes, can you speak a little on that?

16. Do you have any idea of how climate affects organic matter/organic carbon?

17. Does the vegetation (cocoa tree) affect the presence of organic matter/ organic carbon? If yes, how?

18. Can you tell me the importance of macrofauna on organic matter

19. Do you think soils with high organic matter /organic carbon have good water holding capacities?

MANAGEMENT PRACTICES

20. In your view, what are some of the management practices that can increase or decrease soil fertility (SOM/SOC)?

21. How do your management practices affect soil fertility (SOM/SOC) on your farm?

22. Do your management practices on the farm affect the quantities of soil organic matter/ soil organic carbon in deeper layers?

23. What are some of the good management practices you would want to implement on your farm, but you cannot? Why? (e.g., because it is expensive)

PERCEIVED CHANGES (in the past and the future)

24. Since you have been working on this farm, do you perceive any changes in the landscape, organic matter content, and soil fertility in general?

25. How do you think the farm will look like in 10-20 years? How do you perceive changes in 10 years?

26. Can you suggest some other farmers visit?

Appendix B

Table A 1. Soil properties in catena 1 (C1) in the cocoa agroforestry system

Horizon	Depth	Sand	Silt	Clay	Colour	BD	H2O	KCl	Ca	Mg	K	Na	CEC	BS
A	0-10	21.15	54.29	24.56	7.5YR ¾	1.42	6.33	5.6	3.90	0.10	0.88	0.00	15	32.5
E	10-30	18.45	51.99	29.56	7.5YR 4/4	1.51	6.2	5.39	1.33	0.03	0.26	0.01	13	12.5
EBt	30-50	16.14	50.94	32.91	5YR 4/6	1.55	6.17	5.13	1.30	0.20	0.37	0.00	9	20.7
2Bt	50-80	18.08	46.30	35.62	10R 3/6	1.62	6.03	4.95	0.94	0.19	0.25	0.04	8	17.7
3Bt	80-110	14.58	48.71	36.71	5YR 5/6	1.56	5.75	4.7	0.52	0.05	0.18	0.01	7	10.8
4B/C	110-130	15.14	58.26	26.59	5YR 5/6	1.53		4.1	0.10	0.01	0.07	0.04	6	3.6
Ap	0-15	28.43	49.11	22.46	7.5YR 4/6	1.45	5.73	4.78	3.15	0.08	0.98	0.00	13	32.3
B	15-40	14.70	58.31	26.99	5YR 5/6	1.55	5.53	4.54	0.93	0.04	0.55	0.00	12	12.6
2Bt/C	40-80	7.67	51.29	41.04	5YR 4/6	1.7	5.54	4.48	0.63	0.02	0.27	0.00	10	9.2
2Bt	80-140	6.78	55.93	37.29	10R 3/6	1.71	5.09	4.13	0.40	0.01	0.18	0.02	9	6.7
A	0-15	19.32	56.37	24.31	7.5YR ¾	1.34	6.61	5.78	5.70	0.21	1.13	0.00	17	41.4
Eg	15-30	21.06	50.10	28.84	7.5YR 4/4	1.44	6.27	5.34	3.40	0.12	1.00	0.00	12	37.6
EBtg	30-60	23.66	41.45	34.89	5YR 4/6	1.45	5.84	4.85	0.90	0.18	0.37	0.00	10	14.5
Btg1	60-80	16.87	40.34	42.79	10R 3/6	1.55	5.29	4.45	0.65	0.11	0.28	0.00	10	10.4
BtgC	80-100	13.14	46.03	40.83	5YR 4/6	1.42	5.29	4.45	0.40	0.04	0.19	0.00	8	7.8
Btg3	100-140	9.23	56.98	33.78	5YR 4/4	1.56	4.9	4	0.25	0.06	0.17	0.00	5	9.6

Table A 2. Soil properties in catena 2 (C2) in the cocoa agroforestry system

Horizon	Depth	Sand	Silt	Clay	Colour	BD	H2O	KCl	Ca	Mg	K	Na	CEC	BS
A	0-20	14.64	65.84	19.52	7.5YR 4/6	1.23	6.60	5.96	3.73	0.22	1.37	0.01	18	29.6
E	20-50	19.91	49.42	30.68	7.5YR 4/6	1.39	6.27	5.18	0.70	0.03	0.84	0.00	13	12
2Bt/C	50-100	12.40	46.93	40.66	5YR 5/8	1.48	5.78	4.80	0.80	0.01	0.52	0.01	12	11.1
C	100-	20.56	51.61	27.83	5YR 5/8	1.55			0.10	0.05	0.30	0.01	9	5.1
A	0-15	27.08	45.45	27.47	7.5YR 5/6	1.39	6.53	5.81	4.68	0.25	1.43	0.00	19	33.4
AE(g)/C	15-40	14.58	49.14	36.28	7.5YR 5/8	1.42	6.27	5.30	1.18	0.03	0.72	0.02	13	15
2Bt/C	40-100	10.95	41.51	47.54	5YR 4/6	1.53	6.13	4.88	1.00	0.01	0.86	0.03	12	15.8
Ap	0-20	28.67	52.96	18.37	7.5YR ¾	1.25	6.77	6.18	4.98	0.11	0.88	0.02	19	31.5
Eg	20-40	31.69	46.88	21.43	7.5YR 4/4	1.4	6.54	5.48	0.98	0.05	0.44	0.01	11	13.4
2Bg	40-60	32.42	46.20	21.38	5YR 4/6	1.59	6.28	5.08	0.55	0.01	0.32	0.02	4	22.5
3Bg	60-100	12.89	60.24	26.87	10R 3/6	1.7	6.09	4.95	0.05	0.16	0.74	0.02	10	9.7
3Bt	100-145	27.24	48.35	24.41	10R 3/6	1.59			0.02	0.01	0.20	0.01	4	6

Table A 3. Soil properties in catena 3 (C3) in the forest system

Horizon	Depth	Sand	Silt	Clay	Colour	BD	H2O	KCl	Ca	Mg	K	Na	CEC	BS
A	0-6	14.52	69.96	16.52	5YR ¾	0.98	7.45	6.41	5.30	1.60	0.44	0.02	20	36.8
AB	6-11	21.73	58.87	20.42	5YR 4/6	1.29	6.95	6.08	3.37	0.80	0.24	0.00	13	33.9
BA	11-26	23.47	50.19	26.34	5YR 5/8	1.41	6.92	6.11	1.30	2.00	0.18	0.06	10	35.4
Bt1	26-60	26.71	43.98	29.32	2.5YR 4/6	1.55	7.19	6.43	0.29	0.88	0.11	0.03	11	11.9
Bt2	60-106	19.88	48.81	35.31	2.5YR 4/8	1.53	7.3	5.75	0.19	0.26	0.04	0.02	10	6.9
Bt3	106-145	32.44	56.42	11.14	2.5YR 5/8	1.53	5.4	3.7	0.10	0.01	0.03	0.01	6	2.5
A	0-9	15.58	61.75	22.67	7.5YR ¾	1.25	7.19	6.43	3.50	1.74	0.18	0.00	17	31.8
AB	9-19	14.35	54.07	31.59	7.5YR 4/4	1.25	7.31	6.49	0.90	0.80	0.14	0.02	13	14.3
Bt1	19-35	13.56	50.01	36.42	5YR 4/6	1.39	7.27	6.27	0.42	1.05	0.15	0.00	10	16.2
Bt2	35-78	19.79	41.14	39.07	10R 3/6	1.23	6.92	6.09	0.35	0.20	0.03	0.03	8	7.6
BC	78-124	16.94	35.59	47.47	10R 3/6	1.28	5.05	3.9	0.20	0.18	0.01	0.03	9	4.6
C	124-145	14.87	28.78	56.35	10R 3/6	1.39	4.8	3.85	0.14	0.10	0.01	0.05	7	4.2
A	0-11	18.27	51.75	29.99	10R ¾	1.28	7.03	6.75	6.01	1.90	0.50	0.02	19	44.3
AB	11-38	17.47	45.79	36.74	7.5YR 5/8	1.46	7.50	6.59	3.95	0.75	0.42	0.01	10	51.3
Btcs1	38-70	15.99	37.68	46.33	5YR 5/8	1.22	7.03	6.29	1.01	1.20	0.30	0.01	9	28
Btcs2	70-105	15.98	33.66	50.36	5YR 5/6	1.33	4.95	3.9	0.54	0.13	0.27	0.00	7	13.4
BC	105-155	6.34	40.17	53.49	5YR 5/6	1.35	5.1	3.85	0.17	0.05	0.10	0.02	6	5.6

Appendix C

Table A 4. Chemical properties of soils from forest and cocoa land-use systems on sites in relation to time factor

Land-use/Age of Plots	Depths (cm)	pH 1:2.5 H_2O	SOC %	OM %	BD g/cm^3	SOC Stocks M ha^{-1}
Forest	0-10	5.81	2.95	5.07	1.02	30.09
Forest	10-20	5.43	1.75	3.01	1.48	25.9
Forest	20-60	6.25	0.55	0.95	1.42	31.24
Forest	0-10	6.19	2.94	5.05	1.03	30.28
Forest	10-20	5.55	0.74	1.28	1.34	9.92
Forest	20-60	4.43	0.3	0.52	1.18	14.16
Forest	0-10	5.72	2.96	5.09	0.98	29.01
Forest	10-20	5.63	0.83	1.43	1.38	11.45
Forest	20-60	4.49	0.35	0.60	1.42	19.88
Cocoa 3 yrs	0-10	5.16	2.19	3.77	1.25	27.38
Cocoa 3 yrs	10-20	4.37	0.17	0.29	1.43	2.431
Cocoa 3 yrs	20-60	6.81	0.28	0.48	1.58	17.70
Cocoa 3 yrs	0-10	6.48	2.02	3.47	1.13	22.83
Cocoa 3 yrs	10-20	6.06	0.7	1.21	1.37	9.59
Cocoa 3 yrs	20-60	5.58	0.35	0.60	1.6	22.4
Cocoa 3 yrs	0-10	7.12	2.15	4.30	1.19	25.59
Cocoa 3 yrs	10-20	5.28	1.23	2.12	1.55	19.07
Cocoa 3 yrs	20-60	4.63	0.27	0.46	1.71	18.47
Cocoa 15 yrs	0-10	6.13	2.84	4.89	1.18	33.51
Cocoa 15 yrs	10-20	4.71	1.05	0.95	1.23	12.92
Cocoa 15 yrs	20-60	6.10	0.36	0.62	1.47	21.17
Cocoa 15 yrs	0-10	6.13	2.39	4.13	1.27	30.35
Cocoa 15 yrs	10-20	6.14	0.68	1.17	1.51	10.27
Cocoa 15 yrs	20-60	5.05	0.41	0.71	1.66	27.22
Cocoa 15 yrs	0-10	5.81	2.27	3.91	1.33	30.19
Cocoa 15 yrs	10-20	5.47	0.67	1.61	1.47	9.85
Cocoa 15 yrs	20-60	4.94	0.42	0.72	1.65	27.72
Cocoa 30 yrs	0-10	6.12	2.74	4.72	1.31	35.89
Cocoa 30 yrs	10-20	5.56	1.01	1.74	1.45	14.65
Cocoa 30 yrs	20-60	6.21	0.56	1.26	1.54	34.50
Cocoa 30 yrs	0-10	5.38	2.85	4.91	1.35	38.48
Cocoa 30 yrs	10-20	5.54	1.12	1.93	1.41	15.79
Cocoa 30 yrs	20-60	4.69	0.51	1.43	1.65	33.66
Cocoa 30 yrs	0-10	4.75	2.05	3.54	1.27	26.04
Cocoa 30 yrs	10-20	4.73	0.47	0.81	1.48	6.96
Cocoa 30 yrs	20-60	4.72	0.24	0.41	1.7	16.32

Table A 5. Chemical properties of soils from forest and cocoa land-use systems on sites in relation to time factor

Land-use/Age of Plots	Depths (cm)	pH 1:2.5 H_2O	SOC %	OM %	BD g/cm^{-3}	SOC Stocks M ha^{-1}
Cocoa 18 yrs	0-10	6.3	1.93	3.33	1.56	30.16
Cocoa 18 yrs	10-20	6.17	1.25	2.15	1.67	20.96
Cocoa 18 yrs	20-60	6.07	0.93	1.60	1.70	63.07
Cocoa 18 yrs	0-10	7.06	2.68	4.62	1.11	28.71
Cocoa 18 yrs	10-20	6.97	1.19	2.05	1.33	15.26
Cocoa 18 yrs	20-60	6.61	0.86	1.48	1.38	47.53
Cocoa 18 yrs	0-10	6.18	2.38	4.10	0.89	20.90
Cocoa 18 yrs	10-20	5.78	1.33	2.29	1.29	16.57
Cocoa 18 yrs	20-60	5.69	0.94	1.62	1.43	52.69
Cocoa 30 yrs	0-10	6.25	3.15	5.43	1.40	43.90
Cocoa 30 yrs	10-20	5.92	1.72	2.96	1.53	26.27
Cocoa 30 yrs	20-60	5.70	1.09	1.87	1.73	73.53
Cocoa 30 yrs	0-10	6.71	2.65	4.57	0.79	20.91
Cocoa 30 yrs	10-20	6.61	1.26	2.17	1.08	13.37
Cocoa 30 yrs	20-60	6.47	0.62	1.07	1.15	28.36
Cocoa 30 yrs	0-10	6.2	1.97	3.39	0.98	18.96
Cocoa 30 yrs	10-20	5.89	0.94	1.62	1.23	11.50
Cocoa 30 yrs	20-60	5.77	0.58	1.00	1.26	28.86
Cocoa 45 yrs	0-10	6.59	2.17	3.74	1.46	30.74
Cocoa 45 yrs	10-20	6.40	1.39	2.40	1.46	19.97
Cocoa 45 yrs	20-60	6.46	1.16	2.00	1.60	75.04
Cocoa 45 yrs	0-10	6.69	3.07	5.29	0.98	30.15
Cocoa 45 yrs	10-20	6.19	2.07	3.57	1.18	24.21
Cocoa 45 yrs	20-60	5.56	1.18	2.03	1.33	61.91

Appendix D

Table A 6. pH ratings

pH	Ratings
7.8-7.4	mildly alkaline
7.3-6.6	Neutral
6.5-6.1	slightly acid
6.0-5.6	moderately acid
5.5-5.1	strongly acid
5.0-4.5	very strongly acid

Source: Bruce and Rayment (1982)

Table A 7. SOC ratings

OC %	Rating
<0.40	very low
0.60-0.99	Low
1.00-1.59	Moderate
1.60-1.99	High
2.00-2.99	very high
3.00-8.70	extremely high
>8.70	organic soil material

Adapted from Emerson (1991); Charman and Roper (2000).

Table A 8 TN ratings

Rating (%)	Description
<0.0.5	very low
0.05-0.15	Low
0.15-0.25	Medium
0.25-0.50	High
>0.5	very high

Source: Bruce and Rayment (1982).

Table A 9 Levels of exchangeable cations (cmol(+)/kg)

Cation	Very low	Low	Moderate	High	Very high
Na	0-0.1	0.1-0.3	0.3-0.7	0.7-2.0	>2
K	0-0.2	0.2-0.3	0.3-0.7	0.7-2.0	>2
Ca	0-2	2-5	5-10	10-20	>20
Mg	0-0.3	0.3-1.0	1-3	3-8	>8

Source: Metson (1961)

Table A 10 Bs ratings

Range (%BS)	Rating
0-20	very low
20-40	low
40-60	moderate
60-80	high
>80	very high

Source: Metson (1961)

Table A11 Levels for C:N ratio

Range of CN ratio	Rating
<10	very low
10-15	low
15-25	medium
25-70	high

Source: Metson (1961)

Appendix E Particle size distribution (%) of 0-10, 10-20 and 20-60 cm soil depths forest and cocoa systems following forest conversion in the Atwima Nwabiagya District, Ashanti Region.

Soil physical parameters	Depth (cm)	Duration after forest conversion to cocoa landuse (yrs)			
		0 (Forest)	18	30	45
Sand (%)	0-10	20.8 (±2.4)	24.0 (±1.3)	19.7 (±2.7)	21.8 (±1.90)
	10-20	20.3 (±1.1)	28.6 (±2.4)	19.5 (±2.6)	22.7 (±1.3)
	20-60	19.5 (±0.6)	32.9 (±4.5)	19.7 (±2.8)	27.7 (±0.4)
Mean	**0-60**	**20.2 (±0.8)**	**28.5 (±1.9)**	**19.6 (±1.4)**	**24.1 (±1.1)**
Silt (%)	0-10	68.2 (±2.5)	64.5 (±0.3)	68.6 (±2.1)	63.9 (±3.6)
	10-20	62.2 (±2.1)	59.8 (±1.8)	60.2 (±2.1)	54.8 (±0.4)
	20-60	55.3 (±3.0)	48.2 (±8.4)	55.2 (±4.0)	48.0 (±1.1)
Mean	**0-60**	**61.9 (±2.3)**	**57.5 (±4.1)**	**61.4 (±2.4)**	**55.6 (±2.54)**
Clay (%)	0-10	11.0 (±1.5)	11.6 (±1.4)	11.6 (±0.7)	14.4 (±3.6)
	10-20	17.5 (±1.3)	11.6 (±0.7)	20.3 (±1.0)	22.5 (±1.3)
	20-60	25.2 (±2.8)	18.9 (±4.7)	25.1 (±1.5)	24.3 (±5.7)
Mean	**0-60**	**17.9 (±2.3)**	**14.0 (±1.9)**	**19.0 (±2.0)**	**20.4 (±1.92)**
Texture	Silty Loam	Silty Loam	Silty Loam	Silty Loam	Silty Loam

Source: Modified from Dawoe (2009)

Appendix F: Mean physico-chemical properties of the study site in the cocoa and forest soils.

Land use	**Cocoa**	**Forest**	**Cocoa**	**Forest**	**Cocoa**	**Forest**	**Cocoa**	**Forest**	**Cocoa**	**Forest**
Depth	**0 – 5 cm**		**5-15 cm**		**15-30 cm**		**30-60 cm**		**60-100 cm**	
	Mean ±SEM/SD		**Mean ±SEM/SD**		**Mean ±SEM/SD**		**Mean ±SEM/SD**		**Mean ±SEM/SD**	
Sand	22.34±2.66	16.19±1.18	23.06±2.40	18.12±2.13	21.07±2.56	18.17±2.88	18.26±3.32	20.83±3.14	11.79±1.11	17.60±1.17
Silt	58.10±2.30	63.46±2.81	52.58±2.86	54.56±1.78	50.61±2.77	48.66±1.44	47.12±1.57	40.93±1.82	49.89±2.82	38.02±3.44
Clay	19.56±1.61	20.35±1.93	24.37±1.99	27.33±3.49	28.32±2.84	33.17±3.41	34.63±3.18	38.24±4.93	38.32±2.78	44.38±4.61
CF	36.83±4.15	22.33±2.60	43.50±5.41	18.67±3.48	47.50±3.78	30.00±4.04	50.17±2.17	44.00±7.23	49.67±3.13	50.67±4.37
BD	1.20±0.19	1.13±0.11	1.38±0.10	1.27±0.02	1.45±0.07	1.42±0.03	1.58±0.07[a]	1.32±0.15	1.57±0.10	1.38±0.13
SOC	2.78±0.81	2.76±0.62[a]	1.65±0.47	1.76±0.64	0.96±0.38	0.93±0.48	0.57±0.23[a]	0.58±0.29	0.41±0.17	0.40±0.20
pH	6.53±0.5	7.31±0.27	6.36±0.64	7.27±0.55	6.19±0.65	7.23±0.46	6.02±0.66	7.00±0.63	5.65±0.70	5.77±1.33
TN	0.30±0.08	0.45±0.12	0.16±0.01	0.24±0.23	0.09±0.03	0.14±0.07				
AL-P_2O_5	8.10±6.87	25.06±5.37	0.57±0.89	10.69±12.87	0.96±2.34	0.15±0.26				
AL-K_2O	162.61±17.24	405.00±67.11	116.15±12.87	185.50±33.10	120.41±7.44	129.83±4.888				
Ca	5.29±0.56	5.68±0.59	2.23±0.42	3.51±0.31	1.91±0.33	2.51±0.39	0.98±0.13	1.74±0.16	0.45±0.05	0.97±0.04
K	0.21±0.04	0.32±0.04	0.10±0.03	0.25±0.05	0.08±8.22E-03	0.15±0.05	0.08±0.04	0.11±0.04	0.03±8.090E-03	0.04±7.839E-03
Mg	1.33±0.18	1.68±0.13	0.63±0.11	1.23±0.19	0.72±0.08	0.90±0.31	0.50±0.08	1.46±0.03	0.46±0.30	1.54±0.04
Na	6.000E-03±3.688E-03	0.01±4.817E-03	5.200E-03±4.488E-03	0.11±0.05	5.778E-03±3.398E-03[b]	0.41±0.13	0.01±7.473E-03	0.02±0.01	4.333E-03±4..333E-03	0.035±3.383E-03
CEC	18.20±0.37	17.00±0.95	13.40±1.21	13.20±1.20	11.00±0.90	11.30±0.54	10.50±0.84	9.40±0.37	8.50±0.29	9.50±0.29
BS	37.37±2.79	45.56±4.71	22.69±4.33	40.37±4.89	25.74±3.89	35.36±3.79	15.05±0.97	35.65±2.13	11.18±4.13	27.27±1.66