UNIVERSITY OF CAPE COAST

CHARACTERIZATION, CLASSIFICATION AND SPATIAL VARIABILITY OF SOILS OF THE UNIVERSITY OF CAPE COAST WAMASO RESEARCH STATION

BY

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Thesis submitted to the Department of Soil Science of the School of Agriculture, University of Cape Coast, in partial fulfillment of the requirements for the award of Doctor of Philosophy degree in Land Use and Environmental Science

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: .... Date: 28/07/2022

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Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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ABSTRACT

Pedogenic information is of utmost importance in addressing food security issues and future projections of soils. The University of Cape Coast recently acquired 419 acres of land at Twifo Wamaso purposely for commercialization and research. For efficient utilization of the land, there is an urgent need to investigate the dynamism in soil physicochemical properties. This research was hypothesized that various topographic features and current land uses potentially influence soil physical and chemical properties for productive use.

The study was carried out in an area in Wamaso in order to map out some properties of soils and assess their variability within the area. A total of 290 composite soil samples (0 – 20 cm) were collected from the area by using five line transects which were 400 m apart. Collection of samples was done using a core cylinder. A portable global positioning system (Garmin 64st) was used to take coordinates of each sampling site. Soil properties (Ca, Mg, Na, K, Zn, Cu, Fe, clay, silt and sand) were further analysed in the laboratory. Classical statistics were used to describe the soil properties and geostatistical analysis was used to illustrate the spatial variability of the soil properties. The results indicated that within small or large scale, spatial dependencies of soil properties can be different. Maps were further generated by using the kriging tool.

A topographic map of the area was generated in the ArcGIS 10.7 environment. Five slope classes were considered with five pedons; one on each were opened, described, sampled (composite soils using the diagonal pattern) and analysed for morphological and physicochemical properties. In all, 18 composite soil samples from the individual pits. The results showed moderate to deep soils with drainage ranging from very poorly drained (PP4 and PP5) to well drained (PP1, PP2 and PP3). pH values obtained (4.8 – 5.1) revealed that the soils were strongly- moderately acidic. Organic C and exchangeable bases were low in all positions per required agriculture standards.

The generated maps of soil properties that indicate soil nutrient status over the study area could be helpful for decision makers to enhance site specific nutrient management Soils will therefore require some level of amendments for optimum production.

KEYWORDS

Classification

Geostatistical Analysis

Food security

Kriging

Pedogenesis

Soil science

Soil Genesis

Soil Health

Soil Quality

Precision Agriculture

Physicochemical properties

Toposequence

Wamaso

World Resource Base

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DEDICATION

This thesis is dedicated to my family for having the understanding and forbearance as I had to pursue this dream at the slight expense of family demands.

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CHAPTER ONE

INTRODUCTION

Background

Every culture and economy is built on the foundation of 'Life and Land' (Bonfante et al., 2020). The term "land" refers to anything on the ground, including the soil. According to reports, practically all landed and accessible areas suitable for agricultural production are being cultivated to fulfill rising and future food demand (Havlin and Heiniger, 2020). Furthermore, it is predicted that 50-70 percent of worldwide soils are deteriorated or poisoned as a result of excessive anthropogenic activity, posing a threat to food demand (Gomiero, 2016). In terms of classification, approximately 11% of global land surface is available in the Class I-II arable land categories to fulfill the growing demand for 50% agricultural produce by 2050 to feed 9.5 billion people (Zilberman et al., 2013).

Understanding soil resources is consequently critical in focusing on its creation, distinctive behavior, and landuse possibilities, all of which have an impact on its long-term yield and vitality (Havlin and Heiniger, 2020). Soil health is a term used in the literature to describe these characteristics. Soil health is important for ecosystems, economies, and human populations, according to (Fierer et al., 2021). Soil health reflects and establishes the potential of soils to support ecosystems, according to (Williams et al., 2020). As a result, maintaining healthy soil conditions is critical for soils to produce any substantial agricultural output (Larkin, 2020). As a result, soil health is widely recognized as an important indicator for quantifying soil production and a tool for guiding management techniques. Fertilization, controlled irrigation, enhanced agricultural practices (including precision agriculture and crop rotation), liming, and mulching have all been widely used to promote long-term soil productivity (Sindelar et al., 2015). Because soil undergoes few and slow changes in its surroundings, it's important to think about how they manifest at different stages of evolution. Pedology is a branch of soil science that studies the creation of soils, while polygenesis describes their evolution. Pedogenesis is the integration of specific processes that contribute to the unique and precise creation of solid-phase soils (Targulian and Krasilnikov, 2007). It encapsulates the idea of soil genesis and the morphology that results from it, which is made up of two linked paths, one developmental and the other regressive, both reflecting external and endogenous pedogenesis interactions (factors, processes, and environments) (Johnson and Watson-Stegner, 1987). The author discusses a historical example of pedeogensis (Bajard et al., 2017)

Classification, taxonomy, and cartography are acknowledged as important parts of pedogenesis that must be established in order to lay the foundation for efficient and long-term agriculture need (Ma et al., 2019b). Soil classification is categorizing soils from specific places based on evidence of distinguishing characteristics that influence the soil's response to treatment and its potential agricultural value, among other things (Braimoh, 2002). These groupings are referred to as 'classes' based on their relative permanent qualities that can be observed in the field or deduced from set limits of studied samples by comparing them to others (Fitzpatrick, 2013). Soil classification also allows for the comparison and transfer of research findings between soils in different places with or without similar characteristics and climatic circumstances (Buol & Denton, 1984).

The main objective of internationally recognized soil classification systems such as the Soil Taxonomy of the United States Department of Agriculture and the World Reference Base (WRB) has been generally acknowledged for its efficacy in providing critical information on diverse types of soils (Shi et al., 2010). Recently, regional and country-specific soil categorization systems have been published, including the Australians thus according to Hughes et al (2018), Chinese by Gong et al (2003), and Polish, by Kabała et al (2016) systems.

Knowing about soil formation, distribution, and processes can help map the distribution of different soil components (Ma et al., 2019b). To improve efficiency, traditional soil surveys typically involve incorporating existing pedological knowledge (Walter et al., 2006). Some soil scientists claim, for example, that conducting soil surveys at depths below 2 m is capable of clarifying critical information for comprehending sub-solum (i.e. morphology and substratum connection) conditions. Block diagrams, parent material maps, pedo-stratigraphic and lithostratigraphic maps can also be used to get concise and thorough soil substratum information (Wysocki et al., 2005).

These data sources facilitate and improve communication on soil qualities. Because soil classification systems give a consistent foundation for observation, a map unit defined by the name of a profile class could imply that the majority of the soil in each delimited region belongs to that class, while non-conforming soils could belong to different or related classes (Avery, 1973).

In order to build logical land use plans for agriculture, local knowledge of different types of soil and their spatial distribution must be instilled. An inventory of soil resources like this might reveal the possibilities and constraints of their effective utilization. Soil surveys provide the possibility to acquire precise scientific data, such as the types of soils, their characteristics, and the extent to which they are distributed, allowing for the forecast of agricultural potential. For planning and development, information on the influence of various land forms, terraces, vegetation, and general characteristics of soils (e.g. texture, depth, structure, stoniness, drainage, acidity, salinity) can be used (Lee and Griffiths, 1987). There is no question that soil survey benefits have been related to the survival of 'life on earth' (Manchanda et al., 2002).

Agriculture is the economic backbone of Ghana, as it is in most African countries. As a result, measures to maintain and manage resources, particularly soil, which serves as a basis for optimum crop yields, are critical. The Council for Scientific and Industrial Research (CSIR) founded the Soil Research Institute (SRI) (previously, West Africa Cocoa Research Institute) in this light. In 1945, the first such inquiry was carried out to better understand the physical and chemical components that shape soil formation. It was done as one of the post-measures to see if there was a link between the disease infestation and plant types (Asiamah, 2008). The investigations were inconclusive, according to reports, but important data acquired from numerous soil surveys enabled the construction of a "databank" on soil distribution and crop suitability.

In 1946, soil mapping, categorization, and evaluation began, leading to the creation of multi categorical soil classes with levels of generalization, such as Order, Suborder, Soil Group, Great Soil Group, and Soil Series (Brammer, 1962). The classification is based on the country's major river basins, resulting in the division of the country into 35 Soil Survey Regions (Asiamah, 2008).

Ghana is currently positioned as a critical economic development priority within the African sub-region, particularly given its rapid population expansion from 5 million in 1950 to around 30 million in 2019 and an expected 50 million by 2050 (Coulter et al., 2016). To fulfill the rising food demand, we must make the most of our limited land. However, due to human influence on the natural environment, such as landuse and landcover changes (LULC) for agricultural expansion and urbanization, there is rivalry for land for housing, real estate, and other industry (Kleemann et al., 2017).

The type of parent materials, climatic circumstances, time, the nature of the weathering process, and the topography or relief of the location all influence the chemical and physical qualities of soil. Despite these, soil fertility issues are becoming more of a worry as a result of indiscriminate pollution and contamination. Expansion of agricultural land and assets appears to be the only viable option for meeting the expected rise in food demand. According to FAO (2020), during October and December 2020, approximately 328,000 persons in Ghana (almost 1% of the population) required food assistance. Despite predictions that this number would fall, it was later expected that roughly 164,000 people will require food assistance between June and August 2021. These are alarming data that necessitate the development of agricultural measures, particularly soil management, in order to maintain a consistent high crop output.

Institutional assistance for resolving potential food shortages has been encouraged throughout the country, from national to district levels. To avert any major downturns, a number of initiatives have been implemented to encourage investment in the agricultural industry. 'Planting for Food and Jobs,' a recent policy, has succeeded in achieving its goals (Ansah et al., 2020; Tanko et al., 2019). The University of Cape Coast's School of Agriculture has purchased a 419-acre (1.62-square-kilometer) block of land in Twifo Wamaso, in the Twifo -Atti-Mokwa District of Ghana's Central Region, for development as a research and commercial station. In light of the Wamaso land's development, it's become critical to do a complete baseline research of the soils there.

Statement of the Problem

Food security is a growing global concern thus according to Andree et al. (2020), and significant food shortages have been observed in Ghana around 1983 as stated in Puplampu (1999) and more recently in some Northern Regions of the country over a six-month period (Quaye, 2008). Food shortages are caused by a combination of economic and environmental factors. As a foundation for food production, soil plays a vital function as an environmental component. The complexity of soils is further is explained in Johnson and Schaetzl (2015) who revealed soils undergo rigorous modifications during formation and usage. A number of techniques have been utilized to explore the dynamism of soil physical and chemical properties including traditional classical descriptive statistics Phoon (1995); Wielemaker et al. (2001) and spatial modelling Krasilnikov (2008); López-Granados et al. (2002) have been applied to gain more insights into spatial trends in soil property distribution.

Classical statistics has been employed in a number of studies to present objective accounts on soil property distribution and dispersions and are able to produce polygon-based maps. Geostatistics however, is able to analyze how soil properties are spatially distributed. It provides insight about the magnitude and structure of the spatial variability of soil physical and chemical properties (Azevedo et al., 2015). The study of these spatial trends of soil properties is very important for agriculture as it aims to minimize the impact of variability on crop yield and also maximize crop productivity (Acosta et al., 2018; José et al., 2005). However, this geostatistical technique is in its incipient stage in Ghana. Thus, not much work has been done to outline the spatial details of soil properties on agricultural lands despite its significance and interrelatedness to effective land management and optimum crop yield.

The lack of any previous studies pertaining to chemical and physical properties of soils of the wamaso research station makes it hard to assess the nutrient profiles of the soil and suggest proper management protocols. Consequently, this research is to correlate data acquired on soil physical and chemical properties of wamaso research station and geostatistics for site specific nutrient management systems.

Research Questions

- Are there variations in the soil physical and chemical properties along a toposequence on the UCC WRS?
- Are there any variations in soils on different topographical positions and hence different soil types?

- Do soils on the UCC WRS exhibit spatial variations and dependencies?

Hypothesis

- Topography has no influence on variations in soil physical and chemical properties along a toposequence within the UCC-WRS
- Topographic positions does not influences soil formation and hence differences in soil types at the UCC-WRS
- Soil properties in the study area are not spatially dependent

Objectives

The main objective was to develop digital maps of some soil properties and assess the impact of topography on soils of the study area.

The specific objectives of the study were to:

- Develop slope and elevation profile maps
- Locate a higher degree slope (toposequence) within the study area and sink profile pits at distinctive locations (based on the elevation map)
- examine the morphological, physical and chemical properties of soils along a toposequence
- establish the influence of different topographic positions on the formation of soils along the slope
- examine properties of soils at depth 20 cm and spatially assess the distribution of some chemical and physical properties of the soils in the study area

Purpose of the Study

Agriculture has been a cornerstone and a vital economic indicator in Ghana, and it will continue to be so for future generations (Antwi et al., 2016). However, trustworthy soil data, which is essential for establishing appropriate landuse systems and management approaches, is scarce. There is a growing demand for information about soils used to grow food (Fasina et al., 2007). The preservation of high soil quality is critical for long-term environmental and economic viability. For maximum crop production, research and understanding of the nature and properties of soils, as well as control of nutrient requirements, become essential (Antwi et al., 2016).

As a result, the UCC WRS demands a complete description, research, categorization, and characterization of the soil types to aid in the creation of alternative land use patterns as well as management strategies that are appropriate for the soils indicated.

Organization of the Thesis

The chapters of this thesis present the research objectives, thoroughly answering the questions on characterization, classification and variability of soil physicochemical properties of the UCC WRS. It is structured into six (6) chapters.

Chapter one presents a general overview and background to the research. It further highlights the research objectives, research questions put forward, hypothesis, justification and the statement of problem. **Chapter two,** presents a literature review in the study area. Matters related to functional role of soil, soil formation process and factors, soil survey and characteristics are reviewed. **Chapter three** describes the study site and methods employed in this research. **Chapter four** presents field observations and analytical results from the laboratory. In **Chapter five**, gives detailed discussion on the various findings from the field investigation and the laboratory and their connection with existing literature. **Chapter six** provides a general summary and discussion on the results obtained in this research and conclusion to the research study and puts forward some recommendations.

CHAPTER TWO

LITERATURE REVIEW

Overview of Agriculture, Soil and Landuse Practices

Rapid urbanization, industrialization and social progress has resonated global efforts to ensure food security (Miller and Small, 2003). Adverse conditions of over-crowding, inadequate infrastructure, shortages in housing space and rising problems in urban climate and ecology are anticipated to have significant impacts on available agricultural lands thereby impacting food security in the longer term. There are two major studies that have projected future food demand to 2050. Alexandratos and Bruinsma from the Food and Agriculture Organization (FAO) projected that aggregate agricultural production (of all crop and livestock products) will increase 60% by 2050, compared to a 2005/2007 baseline (Alexandratos and Bruinsma, 2012). The authors also estimated demand for different commodity groups on a tonnage basis, and found that between 2005/2007 and 2050, global demand for meat production and sugarcane & sugarbeet production will increase by 76%, oilcrop production by 90%, and cereal production by 50%. David Tilman and colleagues also projected future food demand to 2050 using future projections of population growth and GDP coupled with income-dependent estimates of per capita crop demand (Tilman et al., 2011). Their analysis projected a 100% increase in global demand for calories and a 110% increase in protein by 2050. These knowledge systems make it imperative to continually determine practices which can maximize food crop production to meet future growing demands. Nonetheless, agriculture, however, is already one of the greatest environmental threats (Mahato et al., 2021). Clearing forests and other natural vegetation results in climate change and biodiversity loss. Agriculture is the biggest user of freshwater on this planet, and is the major cause of freshwater eutrophication. Balancing the environmental costs of agriculture with the need to feed current and future populations is a major challenge (Waheed et al., 2018).

Several research works have highlighted the importance of agriculture to the Ghanaian economy (Afful and Doucha, 2013; Osei, 2000). The agricultural terrain is generally rain-fed and represented largely by smallholder activity farming on plots less than 1.5 ha. Productivity is generally low mainly due to the use of low-input traditional farming systems and the erratic nature of rainfall in the country (Worqlul et al., 2019). In parts of the country where opportunities for improved water management and irrigation exist, agriculture has offered many natural advantages (Mellon-Bedi et al., 2020). Despite the challenges to successful agricultural production, it is still the dominant sector in the Ghanaian economy. Agriculture employs about 60% of the labor force, mainly as small landholders, contributes about 40% to GDP and accounts for over 57% of foreign exchange earnings (Sumberg et al., 2016). The agricultural sector is the major source of government revenue, mainly through duties paid on exports of agricultural commodities, particularly cocoa. The contribution of agriculture to government revenue was 26% in 1987, but it declined to an average of about 20% in the first half of the 1990s (Seini and Nyanteng, 2005). By 2004, however, real GDP grew at 5.8%, the agriculture sector led with a growth rate of 7.5% and contributed 46.7% of overall growth (Aryeetey and Fosu, 2008). Agriculture also plays important roles in the socioeconomic development of Ghana. It contributes to ensuring food security, provides raw materials for local industries, and provides incomes for much of the population, thereby contributing to poverty reduction.

Agricultural land is defined as the sum of arable crops (land under food crop production, mostly temporary), permanent crops (land used for the cultivation of perennial tree crops), and permanent pasture (land used for herbaceous forage). Most research papers on agricultural productivity use this definition in their analysis, which does not include fallow lands. When fallow lands are not considered in such analyses, the results can be deceptive by portraying that land is not limiting (Lu et al., 2019). However, when in non-industrialized agricultural farming systems, fallow is essential. Many solutions have been proposed for navigating the pathways to sustainable food system (Gaupp et al., 2021;Tui et al., 2020; Vicente-Vicente et al., 2021). Some scholars advocate for new technological systems, such as genetic modificationGao, (2021) or vertical farming Jurkenbeck et al., (2019), while others argue for organic agriculture (Muller et al., 2017). Still others argue that agriculture does not need a revolution and that we simply need to improve current farming practices (Adegbeye et al., 2020). Other arguments shift the focus from farm-level solutions to the entire food supply chain from production to processing to consumption (Patidar et al., 2018).

Researchers have posed the question "if there will be an era of peak cropland, considering the growing food demands?" Peak cropland is a term used to describe a time when humanity might reach its most extensive use of the earth's land surface area for agriculture (Rajagopal, 2016). Analyzing historical trends, some researchers have shown that there is global reduction in rates of cropland expansion (Waldner et al., 2016). It is debatable whether these projections are realistic. But whether cropland actually peaks or not, the FAO study of Alexandratos and Bruinsma (2012) supports the slowdown of cropland expansion. Looking forward into 2050, it was projected that 80% of future production growth will come from yield growth, and 10% each from cropland expansion and increases in cropping intensity (Eigenbrod et al., 2020; Liu et al., 2021).

Soil properties vary spatially and can be affected by several landuse management practices such as irrigation and fertilization (Morugan-Coronado et al., 2020). Efficient management of agricultural landuse are therefore an essential aspect on the agenda for many countries if continual food security is to achieved. Obtaining soil associated information on various landuse practices has therefore become imperative in that manner since they have direct impact on the quality of soil which determines food crop production (Silvero et al., 2021). In addition, land managers need comprehensive knowledge base regarding the impacts of agricultural landuse on environmental, economic and social dimensions of sustainable development (Hamidov et al., 2016). The soils of Ghana are highly weathered with predominantly light textured surface horizons in which sandy loams and loams are the common textural classes. Thus, most lands are characterized by poor fertility and are subjected to degradation due to erosion (Diao and Sarpong, 2011). To sustain increases in crop production and therefore ensure food security, soil nutrient and quality must be managed properly and conserved (Kongor et al., 2019).

Historical Perspectives of Soil Formation

Early reports on soil formation was put forward by Vasliy Dokuchaev and Charles Darwin (Johnson and Schaetzl, 2015). Both contributors although different in basic nature and approach presented an impressive opinion to soil science and pedology. It is in no doubt that most past studies and contributions have thus far been aligned and widely applied to the theories of Dokuchaev's contributions. Although accredited in history, Dokuchaev's ideas were not independent as researchers including F. A Fallow and A. Orth were reported to have understood the soil profile as a product of soil forming factors. Also, Avon Humboldt had earlier reported on the climatic zonality of vegetation and E.W. Hilgard had indicated that soil distribution is dependent on climate (Tandarich, 1998). The striking significance is, that Dokuchaev was able to transform many of these hypotheses into a logical theory that was useful for predicting soil distribution and formation.

In Dokuchaev's approach, soils are a function of four environmental cum landscape (or state) factors including., climate (cl), organisms (o) relief (r) and parent material (p) which act over time (t) as shown in equation 1. The ''O'' factor was ascribed a flora focus with animals considered as afterthoughts and minor components or not at all. Since soils were viewed as a function of these five states, the model has over time been known as the Functional-Factorial Model or the State Factor Model. It has served as the foundation of for discussion around soil science (Simonson, 1997).

Darwin although credited as the father of evolution made some significant strides as a theoretical pedologist (Fey, 2010). Although his contributions have been applied in research and practice, the discussion isn't in mainstream textbooks and journals. These are scattered among electronic venues and hence not been cited widely. Darwin's foremost contribution to the field may be related to bioturbation which was only popular a few Russian pedologist as reported by (Alexandrovskiy, 2003). According to (Johnson and Schaetzl, 2015), there is not yet a substantive reference Darwin's work in any inspired soil science publication. A summary description of the various soil formation factors is indicated in the following sub-sections.

Parent material

Parental material determines mineralogy of soils out of which contributes widely to most inherent characteristics for instance, texture, color, pH etc of the soil and also influences the rate of soil formation (Oyonarte et al., 2007). From these mineral components is parent material which are derived from the various attributes of the soils. Non-identical soils are encountered based on the types of parent materials they evolve from.

Climate

The average weather conditions of a place constitute its climate. Climate is nevertheless described as the most controlling or perhaps of the five named soil producing factors that act on parent material as it controls the nature, severity of the weathering and also the type of biota and biological activities such as decomposition that transpire over large geographic areas. It affects the distribution of flora which in turn effect to some extent the processes of soil formation. Temperature and precipitation are the principal climatic variables involved in this process because they initiate and control the extent of breakdown of the bedrock (Weil and Brady, 2016).

Topography

Topography is the configuration of a land surface and the relations among its man-made and natural features (Crutzen, 2016). Soil formation is influenced by landforms and their associated flow systems. Topography influences several factors, such as runoff and erosion rates, so that soil development is inhibited on steep slopes compared with flatter surfaces. Erosion occurring on upper hillslopes often results in deposition and increases soil thickness at lower slopes (Agbenin and Tiessen, 1995). Residual soils are found more often in areas of gentle topography where soil thickness slowly builds over time whereas lateral transport of surface materials is enhanced by convex topography and deposition occurs in areas of concave topography which can result in a rapid build-up of soil thickness (Minasny et al., 2009). Soil formation processes are sensitive to topography, creating catena's of soils from upper to lower areas that often determine vegetation patterns (Lavelle et al., 2004). Given the same parent material, soils along a slope will develop and evolve in an interdependent manner. On level topographic regions, almost the entire water received through rainfall percolates through the soil. Soils formed may be considered a true reflect of the regional climate.

On the other hand, soils on steep slopes are generally shallow, stony and have weakly- developed profiles with less distinct horizons. This occurs as a result of the intensity of erosion, which removes surface material before it has the time to develop. Soil found within these regions are poorly developed due to reduced percolation of water through soil and lack of water for the growth of plants, which are responsible for checking of erosion and soil formation. Understanding topography effects and assessing soil properties on different slope positions is a first-hand step in ensuring proper soil management practices (Agbenin and Tiessen, 1995).

Time

It takes millions of years for soils to form and also to undergo significant changes. This long-term soil formation process is most often facilitated by weathering, erosion and the deposition of eroded soils. The short-term processes however are hastened by the introduction of organic materials to the surface horizon. Horizon differentiation develops when the soils are matured with younger soils having less soil profile differentiation. Organic matter coupled with climatic and environmental factors may change some features of a soil and this may be evident in surface layers of soils in a matter of decades or centuries whereas the translocation of minerals to subsurface layers and the formation of distinctive horizons may require thousands of years (Bradshaw, 2000).

Organisms

Living organisms play active role in the formation of soils. Organisms such as fungi, bacteria, animals, humans, and vegetation are the major determinants and they impact on the physical and chemical environments of the soils. Activities of soil microorganisms within soils alter soil chemistry and eventually determines the kind of soil forming process that occur. Microbes also helps in the decomposition of organic matter, the organic matter which in turn changes some features of the soils. The microbial community in a typical grassland soil is dominated by bacteria, while that of the forest soil is dominated by fungi (Weil and Brady, 2016). Humans influence the other soil forming factors simultaneously and can accelerate, decelerate, or redirect soil forming processes (Evans and Willgoose, 2000). Other animals like the earthworm mixes and turns soils in a process known as bioturbation, affecting the physical attributes of soils.

Termites for instance, are macro organisms within the soils. They promote changes in soil structure by termite mound, channel and gallery building, usually resulting in increased soil porosity and aeration (Sarcinelli et al., 2009).

Miscellaneous factors

Fire could be perceived as one of the many ways man influences pedogenesis. Nonetheless, fire is per se independent of man and well before the emergence of people on Earth, it played a key role in plants adaptation and ecosystems distribution (Pausas and Keeley, 2009). Fire would not be an exception in this regard, because it depends on at least vegetation, climate, topography, and man. In turns, fire affects all known soil-forming factors (Pausas and Keeley, 2009):

i. biota, by changing its biomass and specific composition
ii. (micro) climate, by changing canopy structure, ground albedo, and hydrological processes
iii. parent material, by consuming organic matter, and forming charcoal and new minerals,

iv. topography, by reshaping the ground morphology, in particular via erosion,

v. man, influencing human ecology and behavior. In affecting other soil-forming factors, fire of course gives an additional, indirect contribution to pedogenesis

For a given soil, its properties depend on the history of the soil formation and can be substantially modified by human intervention (e.g. through agricultural practices). A proper understanding of soil characteristics and adequate interpretation of the magnitudes of its properties, both combined under the broader term of soil quality is required for proper management of agricultural soils.

Fundamental Soil Forming Processes

Humification

It is the transformation of raw organic matter into humus. It is extremely a complex process involving various microorganisms. First, simple compounds such as sugars and starches are attacked followed by proteins and cellulose and finally very resistant compounds such as tannins, are decomposed and the dark coloured substance, known as humus is formed (Weil and Brady, 2016).

Elluviation

It is the process of removal of constituents by percolation from the upper layers to the lower layers. This layer of loss is called eluvial and designated as the A-horizon (Bradshaw, 2000).

Illuviation

It is accumulation of material like sand, silt, clay, salts and organic matter into a horizon; e.g., in subsurface Argillic and Spodic horizons there is accumulation of phyllosilicate clays and organic matter (Targulian and Krasilnikov, 2007).

Specific Soil Forming Processes

Calcification

This mostly occurs when the rate of evapotranspiration far exceeds precipitation rate in an area causing the upward movement of dissolved alkaline salts from the groundwater. At the same time, the movement of rain water causes a downward movement of the salts. The net result is the deposition of the translocated cations in the B horizon. Mostly, these deposits can form a hard layer called caliche. The most common substance involved in this process is calcium carbonate. Calcification is common in the prairie grasslands. The process of precipitation after mobilization under these conditions is called calcification and the resulting illuviated horizon of carbonates is designated as Bk horizon (Bca) (Stockmann et al., 2011).

Podzolization

It is a process of soil formation resulting in Podzols and Podzolic soils and this results from the downward movement of cations and organic matter through a profile (Buol, 2003). In many respects, podzolization is the negative of calcification. Podzolization is associated with humid cold mid-latitude climates and coniferous vegetation. Decomposition of coniferous litter and heavy summer precipitation create a soil solution that is strongly acidic. This acidic soil solution enhances the processes of eluviation and leaching causing the removal of soluble base cations and aluminum and iron compounds from the A horizon (Musielok, 2022). This process creates a sub-layer in the A horizon that is white to gray in color and composed of silica sand. The calcification process tends to concentrate calcium in the lower part of the B horizon, whereas podzolization leaches the entire solum of calcium carbonates. It mostly occurs in Siliceous (Sandy) material, having poor reserves of weatherable minerals (Lundstrom et al., 2000).

Leaching and translocation of sesquioxide in podzolization process

In the process of decomposition of organic matter various organic acids are produced. The organic acids thus formed act with Sesquioxide and the remaining clay minerals, forming organic- Sesquioxide and organic clay complexes, which are soluble and move with the percolating water to the lower horizons (Bh, Bs). Aluminum ions in a water solution hydrolyze and make the soil solution very acidic. As iron and aluminum move about, the A horizon gives a bleached grey or ashy appearance (Samonil et al., 2018).

Laterization

Laterization is a pedogenic process common to soils found in tropical and subtropical environments. This process removes silica, instead of sesquioxides from the upper layers and thereby leaving sesquioxides to concentrate in the column (Rego et al., 2016). High temperatures and heavy precipitation are responsible for this process (operates most favorable in warm and humid (tropical) climate with 2000 to 2500 mm rainfall and continuous high temperature (25°C) throughout the year). This causes a rapid increase in the weathering process of the parent material and minerals. High and frequent precipitation influences the movements of large amounts of water through the soil cause eluviation and leaching of some base cations to occur (Pidwirny, 2006).

Almost all of the byproducts of weathering, ranging from very simple small compounds or nutrient ions, are translocated out of the soil profile by leaching if not taken up by plants for nutrition. The two exceptions to this process are iron and aluminum compounds which are insoluble and therefore remain within the soil. The rain forests of tropical areas are favorable for the process. Mostly occur in parent materials, having sufficient iron bearing ferromagnesian minerals (Pyroxene, amphiboles, biotite and chlorite), which on weathering release iron and are congenial for the development of laterites (Rego et al., 2016).

Gleization

The term glei is of Russian origin means blue, grey or green clay. Gleization is a process of soil formation resulting in the development of a glei (or gley horizon) in the lower part of the soil profile above the parent material. It is a pedogenic process associated with poor drainage. This process involves the accumulations of organic matter in the upper layers of the soil. In lower horizons, mineral layers are stained blue-gray because of the chemical reduction of iron due to poor drainage condition (lack of oxygen) and where waterlogged conditions prevail (Pidwirny, 2006). Such soils are called hydro orphic soils. This poor drainage conditions could result from (Pidwirny, 2006):

i. Lower topographic position, such as depression land, where water stands continuously at or close to the surface
ii. Impervious soil parent material, and
iii. Lack of aeration

Under such conditions, iron compounds are reduced to soluble ferrous forms. The reduction of iron is primarily biological and requires both organic matter and microorganisms capable of respiring anaerobically. The solubility of Ca, Mg, Fe, and Mn is increased and most of the iron exists as Fe^{++} organo-complexes in solution or as mixed precipitate of ferric and ferrous hydroxides. This is responsible for the production of typical bluish to grayish horizon with mottling of yellow and or reddish-brown colors (Nobrega et al., 2018).

Salinization

It is the process of accumulation of salts, such as sulphates and chlorides of calcium, magnesium, sodium and potassium, in soils in the form of a salty (salic) horizon. It also occurs when soil evapotranspiration exceeds precipitation of which the resulting salts are not leached but remain in the upper soil layers in low lying areas (Fitzpatrick, 2013). It is quite common in arid and semi-arid regions. Salinization occurs from the combiner action of evaporation, salt precipitation and dissolution, salt transport, and ion exchange (Shimojima et al., 2000). It may also take place through capillary rise of saline ground water and by inundation with seawater in marine and coastal soils. Salt accumulation may also result from irrigation or seepage in areas of impeded drainage. Soils formed mostly under this condition are highly dispersed and this significantly reduces porosity and permeability of such soils (Shimojima et al., 2000).

Desalinization

It is the removal by leaching of excess soluble salts from horizons or soil profile (that contained enough soluble salts to impair the plant growth) by ponding water and improving the drainage conditions by installing artificial drainage network (Sharma and Manchanda, 1996).

Solonization or alkalization

The process involves the accumulation of sodium ions on the exchange complex of the clay, resulting in the formation of sodic soils. All cations in solution are engaged in a reversible reaction with the exchange sites on the clay and organic matter.

Solodization or dealkalization

The process refers to the removal of Na^+ from the exchange sites. This process involves dispersion of clay. Dispersion occurs when Na^+ ions become hydrated. Much of the dispersion can be eliminated if Ca and or Mg ions are concentrated in the water, which is used in leaching. These Ca and Mg ion can replace the Na on exchange complex, and the salts of sodium are leached out (Jiang et al., 2021; Li et al., 2022).

Pedoturbation

It is the process of mixing of the soil. Mixing to a certain extent takes place in all soils (Slukin et al., 2014). The most common types of pedoturbation are:

i. Faunal pedoturbation: It is the mixing of soil by animals such as ants, earthworms, moles, rodents, and man himself

ii. Floral pedoturbation: It is the mixing of soil by plants as in tree tipping that forms pits and mounds

iii. Argillic pedoturbation: It is the mixing of materials in the solum by the churning process caused by swell shrink clays as observed in deep Black Cotton Soils (Slukin et al., 2014).

Importance of Soils

Food security

The most reported function of soil, is its support for food production (Kopittke et al., 2019). It is the foundation for agriculture and the medium by which nearly all food producing plants grow. The FAO further estimates that 95% of food consumed is either directly or indirectly produced on soils. Healthy soils produce healthy crops and that in turn produce nourish people and animals (FAO, 2020). It is estimated that nearly 66% of the world's population are malnourished, Micha (2020) and nearly 842 million people worldwide do not have food to eat (Pawlak, 2020). This scenario could be as a result of man mishandling the soils and as such reducing their productive potentials. Maintaining and augmenting the world food supply primarily depends on the productivity and the quality of agricultural soils. Soil quality is therefore directly linked to food quality and quantity and a soils deficiency in essential nutrients impacts crop production (Havlin and Heiniger, 2020).

Climate change adaptation and mitigation

Rising atmospheric concentrations of Carbon dioxide (CO_2) is an indication of human alteration of the Earth system (Vitousek, 1997). Since preindustrial years (pre-1800), atmospheric CO_2 concentrations have risen by more than 50% from 278 to 417 parts per million (ppm), due mostly to dramatic increases in the burning of fossil fuels and clearance of primary lands for agriculture. By the end of the 21st century depending on future industrial trends the CO_2 concentrations are predicted to reach 540–970 ppm (Liang, 2020). The general view among climatologists is that the rise in CO_2 has already substantially affected the world's climate and it is expected to further change in the coming years, leading to a rise in average temperatures and a greater occurrence of extreme weather events (Liang, 2020). Soils are major terrestrial sink for organic carbon. Wang, (2020) reported that soils contain at least 1500Gt of organic carbon and the potentials of soils to sequester carbon may have significant effects on climate change mitigation (Freibauer et al., 2004).

In managed soils, carbon storage is also dependent on the farming system and soil management strategies. While climate and land-use determine net primary productivity and carbon input, soil properties such as texture, mineralogy and structure have been identified as important factors in SOC storage. Aggregate formation is known to protect SOC from microbial decomposition as stated in Baldock and Skjemstad (2000) research, while the molecular structure of some carbon compounds and their supposed resistance to decomposition have been considered essential to SOC storage.

Ecosystem services

Ecosystem services are the conditions and processes through which natural ecosystems and the species that make them up, sustain and fulfill human life. They maintain biodiversity and the production of ecosystem goods such as seafood, forage, timber, biomass fuels, natural fiber and many pharmaceuticals, industrial products and their precursors (Zhang, 2007). Soils are highly diverse; they serve as a habitat to millions of living organisms. Bardgett et al. (2005) estimated that 1 g of soil contains up to 1billion bacteria cells consisting of tens of thousands of taxa, up to 200 million fungal hyphae and a wide range of mites, nematodes, earthworms and arthropods.

Biological diversity is the foundation for the maintenance of ecosystems. Consequently, it is thought that anthropogenic activities reduce the diversity and this threatens ecosystem performance. A large population of the biodiversity within the terrestrial ecosystems is hidden belowground in soils. van der Heijden and Wagg (2013) used a novel experimental system to alter levels of soil biodiversity, community composition and detected reductions in the abundance and presence of soil organisms'. They attributed this decline to multiple ecosystem functions including plant diversity and nutrient cycling and retention.

Health

Amongst the benefits of soils is the issue of health. Clays according to the ancient tablets of Nippur, written approximately 5,000 years ago, is medication for healing wounds and stopping ''fluxes from the body'' (Incledion, 2021). The Ebers Papyrus, the world's oldest medical text, dated approximately 1600 BC, lists clay as a mineral remedy for ailments such as diarrhoea, dysentery, tapeworm, hookworm, wounds, and abscesses (Nunn, 2002). During the late 19th century, clays were used as topical treatments for surgical wounds with demonstrated beneficial effects on pain management, inflammation, putrefaction, and healing processes (Nadziakiewicza, 2019). More recently, clays have been applied in a similar manner for the treatment of bacterial infections caused by *Mycobacterium ulcerans,* the causative agent of Buruli ulcer, which is a difficult-to-treat necrotic skin disease (Williams, 2010). A French humanitarian worker working in Cote D'Ivoire, Africa, applied thick clay poultices daily, alternating between two types of clay, to individuals afflicted with Buruli ulcer. After several months of treatment, the infections often healed with some scarring and a resumption of normal motor function (Williams et al., 2008).

According to Otto and Haydel (2013), natural clay mixtures can exhibit in vitro antibacterial activity against a broad spectrum of bacterial pathogens. They collected four samples from the same source and demonstrated through antibacterial susceptibility testing that these clay mixtures have markedly different antibacterial activity against *Escherichia coli* (EC) and methicillin-resistant *Staphylococcus aureus* (MRSA). They noted that the clays were able to carry out their antibacterial activity solely due to pH and the ion concentrations of specific species (Fe^{2+}, Cu^{2+}, and Zn^{2+}). The healing property of clay has been attributed to both the physical and chemical properties of the minerals (Cunningham et al., 2010). Healthy soils produce quality foods. A soil deficient in some essential nutrients when consumed could lead to some human diseases. According to Swaminathan and Gerner-Smidt (2006), soil anemia also breeds human anemia and also micronutrients deficiency in the soil results in micronutrients malnutrition in people, since crops grown on such soils tend to be deficient in the nutrients needed to fight hidden hunger.

Soil Chemical Forming Properties

The degree of acidity or alkalinity of a soil is a very relevant property affecting many other physicochemical and biological properties (Penn and Camberato, 2019). Problems derived from acidic soils or acidification of agricultural soils can be overcome by increasing base saturation and pH with soil amendments (liming). Basic or alkaline soils are the consequence of the buffering of soil pH by base elements or by the presence of buffering compounds such as carbonates. Calcareous soils are those with an appreciable concentration of $CaCO_3$ which buffers soil pH near 8.5; the presence of other carbonates (Mg or Na in sodic soils) can buffer soil pH well above 8.5 (Xu et al., 2012). The pH of a calcareous soil cannot be changed due to its high buffering capacity and its limitations for agricultural use, mainly related to restrictions in nutrient uptake and in plant nutrition, may be overcome with special fertilizer products and fertilization strategies. Some of the soil fertility features affected by soil pH include (Xu et al., 2012):

i. Availability of mineral elements to plants in the soil. At low pH, the risks of deficiency of base nutrients (Ca, Mg, and K) increases due to their low content; also the solubility of Mo and P compounds is decreased, thus decreasing its availability. On the contrary, Al concentration is increased (usually at pH <5.5) and thus its toxicity effects; the concentration of Fe and Mn, essential nutrients for plants, can be high enough at low pH as to cause toxicity. At high pH, the solubility of many metals and trace elements is decreased, including essential nutrients for plants such as Fe, Mn, Cu or Zn.

Deficiency of Fe, known as iron chlorosis, is frequent in basic soils (typically in calcareous ones).

ii. Biological properties: extreme pH values decrease microbial activity in soils, which affects many soil processes (for instance, soil organic matter decomposition, nitrification, and biological N_2 fixation under acidic conditions)

iii. Physical properties: low Ca concentration in acidic soils is usually related to an increased dispersion of colloids if Al is not present at high concentration. Thus, acidic soils can have poor soil physical properties, including poor structural stability or low permeability.

According to Xu et al. (2012) the CEC is usually dominated by Ca, Mg, Na, K, Al, and protons. The selectivity or relative affinity of cation by sorbent surfaces is based on the ion's charge and size: the smaller the hydrated radius (cation + water molecules strongly interacting by ion-dipole interaction) the greater the affinity (ions with small dehydrated radius have large hydrated radius), and the higher the valence the greater the exchanger preference for the cation; the affinity scale for dominant cations in soils can be summarized:

$$Al^{3+}>Ca^{2+}>Mg^{2+}>NH^{4+}>K^{+}>Na^{+}Al^{3+}>Ca^{2+}>Mg^{2+}>NH^{4+}>K^{+}>Na^{+}$$

Base saturation is defined as ratio of base exchangeable cations (Ca, Mg, K, and Na) to total CEC, which decreases at decreased pH in the soil (Nelson and Su, 2010). Ca, Mg, and K are nutrients for plants; thus a high base saturation means a greater nutrient reserve than a low base saturation for the same CEC. Low base saturation related to soil acidity can determine Ca deficiency for crops. In order to guarantee good physical soil properties (soil aggregation, structure stability, good aeration, and drainage) and nutrition for crops, Ca must be the dominant cation in the exchange complex (ideally >50 % of CEC); also it is desirable that the Ca/Mg ratio would be 5–10 and the K/Mg ratio 0.2–0.3 in order to avoid nutritional disorders (antagonisms) for plants which can lead to a deficiency of a nutrient promoted by a high level of the antagonistic nutrient (Jiang et al., 2011).

The redox status of a soil is determined by the availability of electrons which can participate in redox reactions (logarithm of the activity of electrons) and it is controlled by physical conditions (water content and porosity) and biological activity (Husson, 2013). It affects the solubility and speciation of elements with different redox states, such as N, S, Fe, Mn, some toxic trace elements (e.g. As, Se), and even C. Reducing conditions in agricultural soils usually occur at very high-water contents (saturation) since, under these conditions, oxygen is quickly consumed by biological activity. Reducing conditions increase the solubility of Fe and Mn compounds, enhancing the uptake of these nutrients by plants (which can become toxic) and of elements adsorbed on Fe and Mn oxides (e.g. P and heavy metals) (Weaver et al., 2004).

Ions can be retained in soils by precipitation and adsorption processes. Precipitation means the formation of a new solid phase, e.g. when P fertilizer is applied to a soil with a high Ca concentration, new crystals of Ca phosphates can be formed. Adsorption is the accumulation of chemical species (sorbate) on the surfaces of an existing solid in the soil (sorbent). Precipitated and adsorbed species are in equilibrium with the soil solution (precipitation/dissolution and adsorption/desorption equilibria).

Adsorption can be the consequence of chemical reactions with functional groups of sorbent surface which is sorbate specific (e.g. P on hydroxilated surfaces), or electrostatic attraction by sorbent surface which is not sorbate specific. Charge associated with mineral and organic surfaces can be permanent and variable. Permanent charge arises from isomorphic substitution within clay minerals. Variable charge is the result of unsatisfied bonds at the edge of minerals and organic matter and is pH dependent (Jansen et al., 2002).

Toposequences in Soil Formation and Quality

Soil quality refers to the function of soil living ecosystems to support plants, animals and human activities including agriculture (Williams et al., 2020). Soil quality can be assessed by a set of indicators involving physical, chemical and biological soil properties. According to Andrews et al. (2004), a suitable indicator should have a strong relationship to the particular soil function, replicable and inexpensive to analyze. Reliance on soil physicochemical properties to establish the soil health of particular ecosystems has been applied across several studies Musa and Gisilanbe (2017) hence makes it a suitable indicator for this study. Recent reports have observed a decline in soil quality across the African region caused by a loss in biological activity, soil structural degradation and reduction in the availability of micro and macronutrients (Gachimbi, 2002). Other research has confirmed that a negative soil nutrient balance is prevalent across the region and includes an average of 0 - 63% soil organic carbon (SOC) as well as macronutrients (N: 22 kg ha^{-1}), (P: 2.5 kg ha^{-1}) and (K: 15 kg ha^{-1}) (Vågen et al., 2005). The negative soil nutrient balance infers that primary soil nutrients are being diminished potentially of which reduced landuse management practices is considered a notable cause (Sanchez, 2002). In Ghana, the situation isn't different as the extent of soil macronutrient depletion across the various agro-ecological zones continuously rises. From 1982 to 1984, the annual per hectare depletion rate of nitrogen (N), phosphorus (P) and potassium (K) were reported as (30 $kgha^{-1}$), P (3 $kgha^{-1}$) and K(17 $kgha^{-1}$) respectively

Natural landscapes are found to have a direct influence on soil chemical and physical properties and also affects the pattern of soil distribution even when the soils are derived from the same parent material (Lawal et al., 2014). Particularly, slope gradients can significantly change soil properties through water control movement and distribution of materials which affect the spatial distribution of soil properties (Wang et al., 2001). Musa and Gisilanbe (2017) reported that variability in soil properties across a slope can result in detachment, transportation and accumulation of soil materials. Steeped slopes also influence the direct and indirect distribution of soil physicochemical properties as observed in the loss of soil organic matter and nitrogen from several higher to lower slopes (Afshar et al., 2010). Also, coarser soil particles are found to accumulate at upper slopes positions mostly while finer particles accumulate at lower slope positions. A similar trend is observed in Ghana, where generally eroded sediments contained a higher concentration of organic matter and plant nutrients in available forms than their parent soils (Quansah et al., 2000). Topography-induced microclimate differences, are also attributable causes (Esu, 2010)

Studies on the various soil formation factors have been reported (Jenny, 1994; Johnson and Schaetzl, 2015). The significant influence of topography and slope gradient towards soil formation is reported and are mostly characterized by well drained to silt loam or sandy loam structures (Javadi et al., 2020). Although they become prone to erosion when the top soils are exposed, soil present in the middle and toe slopes are usually deep in formation with well drained sandy loam textures (Liu et al., 2020). In low-lying topography's, special profile features characteristic of wetland soils may also develop (Brady and Weil, 2008b).

Dash et al. (2019) defined a toposequence as the occurrence of soils that can be related to a defined geographical area with a regular sequence and differing soil formations due to existing topographic features. A narrower description is offered by Gessler et al. (1996) as a spatial object that maintains flow connectivity from the summit to its base of a sloping or inclined landform. It practically defines the process resulting in differentiation in properties i.e. (Physical, chemical, mineralogical and morphological) across soil horizons Sağlam and Dengiz, (2015). Hence, the location of specific soil types in the toposequence can be used to differentiate soil types as they are linked to variation in geomorphic features (Conforti et al., 2020). Further, these topographic positions of soils play critical roles in establishing local soil classification guides for proper landuse management (Braimoh, 2002). According to Dipak Sarkar et al. (2001), a typical toposequence has its lower part of the slope deeper and retains the most amount of soil moisture. The toe of the slope merges with the depressions resulting in hydromorphic conditions resulting in gleying. Therefore, consideration of soil properties at the toe end for optimum and sustained utilization should be critical to assess its vitality.

The complexity of the relationship between management of agricultural landscapes and soil health can be site-specific (Ibrahim et al., 2020; Vanacker et al., 2019) According to a significant relationship among soil moisture (SM), soil organic matter (SOM), bulk density (BD), pH, sand, silt, available phosphorus (P_{av}), exchangeable acidity (EA) and land topography. Similarly, the trend in change and variation of soil properties along various slope positions revealed that clay, bulk density, pH, soluble salt, cation exchange capacity (CEC) were more significant in lower topographic regions of landscapes (Deressa et al., 2018). Extractible bases and micronutrients are reported as highly prominent at surface layers of the upper topographic (Nahusenya et al., 2014). The relationship between CEC, OM, and TN is higher along a slope compared to the upslope position of a hill in Nigeria Ezeaku and Eze (2014) and similar results have been described across slopes in the African region (Dessalegn et al., 2014). Also Seifu et al. (2020) showed that altitudinal gradient affected BD, total porosity (TP), whilst P_{av} of soils in watershed influenced landscape. Likewise, variation in electrical conductivity (EC), SOM, soil organic carbon (SOC), TN were associated with interaction effects of landuse types and slope gradient. Nevertheless, results contrary to these associations were recently reported by Tamene et al. (2020) indicating that establishing a relationship between soil properties and topography is highly dependent on regional analysis.

Concept of Soil Genesis

Toposequences due to their unique features define an entire landform or topographic feature (Dash et al., 2019). They represent spatial objects that establishes and maintains flow connectivity from the summit to the base of inclined landforms hence capable of revealing physical, chemical, mineralogical and morphological) features across soil horizons (Sağlam and Dengiz, 2015). By this, the location of specific soil types in the toposequence can be used to differentiate various soil types across a landscape or region as they are linked to variation in geomorphic features (Conforti et al., 2020).

The sustainable use of soil resource requires an extensive knowledge about its genesis, morphology and properties. Consequently, soil data are the basis for the assessment of soil fertility and for making decisions on land management and soil conservation (Benedet, 2021). The classification of soils according to internationally accepted systems is also helpful for soil conservation because it supports communication between users and scientists of different disciplines and countries. It also supports a better transfer of technologies and facilitates land use planning (ISSS, 1998). FAO describes the soil as a natural body consisting of soil horizons and a medium for the plant growth. In other words the soil can also be described as a product of weathering and erosion of rock into smaller particles (Hartemink, 2016).

Soil genesis also termed as Pedogenesis is the process of soil formation which is regulated by the effects of place and environment. It is a complex phenomenon that leads to soil formation from mineral and organic parent materials through a number of factors and processes (Brady and Weil, 2008a).

In the genesis of soil, climatic factors influences the physical and chemical weathering of initial materials. Soil genesis therefore is a combination of structural development, differentiation into horizons and its translocation (Wakatsuki and Rasyidin, 1992). An instance of soil genesis is the classical example of Eckmeier et al. (2007) who attributed the formation and development of mollic topsoils which are characteristic for chernozems to the clearing of forests by slash and burn and also with the burning of agricultural vegetation residues, soil tillage practices, amendments with combustion and other organic residues.

Overall soil genesis captures the developmental processes that the soil, as a natural entity, has undertaken over long time periods as the result of the complex interactions of physical, chemical and biological processes. Soil forming processes usually refer to the results of the interaction of these processes of different nature, such as the accumulation of soil components (e.g. organic matter), formation on site of new ones (e.g. clay minerals or oxides), transport within the soil profile (e.g. clay, carbonate or soluble salts), or changes in the aggregation state of soil particles (e.g. formation of a structure) (Brevik et al., 2016).

Soils host a complex of properties which can influence soil evolution and specific soil physical and chemical properties. For instance, earthworm activity increases infiltration rate, or microbial activity decreases soil organic matter due to mineralization (Gul et al., 2015). Soil microbiota has also been described as significant contributor towards soil formation. For instance, the influence of earthworms is well documented and it is the dominant member of the soil macrofauna influencing the soil formation processes in the temperate zone. In the tropics, termites and ants play the major role in the nutrient recycling and the movement and transportation of soil material (Awadzi et al., 2004). Soil biological properties are also interconnected with other soil physical and chemical properties; e.g. aeration, soil organic matter or pH affect the activity of many microorganisms in soils which in turn perform relevant activities in carbon and nutrients cycling.

Changes in soil properties due to management can significantly affect biological properties in soils, some of them being extremely sensitive to soil management; e.g. soil microbial activity can be greatly increased by improved drainage, liming or organic amendments. That is why some soil biological properties can be used as indirect indicators of appropriate soil management and good soil quality, like soil respiration rate or some enzymatic activities that can be derived from living organisms in soil (Blanco-Canqui and Ruis, 2018).

Soil organic matter is a key factor affecting biological activity in soils. It is the carbon source for many organisms, including soil microbiota. Not only the amount, but also the type of organic compounds in the soil determines its biological activity; e.g., microbial activity is greatly increased by incorporating fresh organic residues (such as green manure or crop residues), which can be readily mineralized by microbes. On the other hand, stable forms of organic matter (humic and fulvic compounds), which constitutes most of the organic matter of soils in temperate regions, is not a very suitable carbon source for soil microbiota, which explains the long half-life of these compounds in soils (usually >1000 years); thus, stable organic compounds do not contribute significantly to soil microbial activity but constitutes an stabilized stored soil carbon pool which is very relevant to the carbon global cycle, partially buffering the consequences of increasing C emissions to the atmosphere (Palansooriya et al., 2020).

The rhizosphere is the volume of soil altered by the root system and is the part of the soil profile where the concentration of suitable carbon sources for many microorganisms is greatest. Organic compounds exuded by plant roots (including organic anions of low molecular weight) alter soil chemical properties and greatly increase the biological activity in comparison to the bulk soil (Cotrufo et al., 2015). The rhizosphere is a space of intense interaction of plant roots with soil microorganisms. Rhizospheric microorganisms can significantly affect plant development through the production of growth regulators, by decreasing the incidence of plant diseases, and by increasing nutrient availability to plants (Wei et al., 2020). Understanding soil biological properties is therefore important for soil management but also for prevention and control of crop pests and diseases. Some biological properties of soil are indicated.

Pedogenic studies and systematic classification of various soil types in Ghana can be attributed to earlier works of C. F Carter in the 1940's, Borden et al., (2021); Asiamah (2008) and Effland (2009) also provided a compendium of various soil resources in Ghana. Previous studies however identified significant lapses in the soil series classification system originally adopted thus according to Asiamah and Adjei-Gyapong (2001) hence a corroboration with internationally accepted soil classification systems such as the World Reference

Base (WRB) are currently in use (Adjei-Gyapong and Asiamah, 2002). A comparative evaluation of this system was first tested along local farmers description of various soil types in the Northern part of Ghana (Mikkelsen and Langohr, 1997). Clear differences were observed with the classification systems as the farmer-based classification systems concentrated precisely on good crop yields based on colour, texture while the national soil classification system is focused on higher pedogenic formation such as secondary carbonate formation. This reveals that soil classification at more local and site levels are essential which may contribute towards agriculture and food security.

Soil Classification Systems

Knowledge of soils and their management play an important role in developing sustainability of agricultural systems. In developing countries, few farmers from major population groups get access to any form of soil science training, but they usually have a good comprehension of their soils and crops that are better suited to specific locations (Payton et al., 2003). For farmers to enhance their reflective minds like scientists do, they generate classification systems based on comparable needs and physical soil-landscape realities of their environments. Farmers' knowledge of soils is largely ignored across Africa countries (Rushemuka et al., 2014). Farmers differentiate soils by naming them with respect to observed and experienced unique properties. Their experience with local soils enables them to generate village's soil maps. Farmers' ability to recognize constraints on each soil unit is a guide for practicing precision agriculture. For example, a farmer's soil selection may include attention to depth appropriate for potato growing.

Soil classification is an orderly way of grouping soils based on similarity of observable and/ or measurable attributes, thereby improving systemization of knowledge and enhancing communication. Classification opens new lines of research and allows for exchange of knowledge amongst scientists, policy makers and other stake holders. Although some countries e.g. Canada, France, South Africa and many more have developed their national soil classification systems, there are two major system which are the foundations of those mentioned earlier i.e. the Food and Agriculture Organization of the United Nations (UN-FAO) World Reference Base for Soil Resources (WRB) or the United States Department of Agriculture (USDA) US Soil Taxonomy classifications, become a useful resource and can provide some broad indications of a soil's properties relevant to various crop growth (Schaetzl et al., 2012). This by far is the truest if the full/comprehensive classification (e.g., to the family level for US Soil Taxonomy) is known. Nonetheless, obtaining knowledge on local relevance and soil survey data, farmers' knowledge of soil characteristics needs to be considered which can be corroborated to international systems. This is because local farmers' knowledge is rapidly accessed, less costly, highly reproducible, and may offer long term insights into human response to nature (Payton et al., 2003). In the literature context, Stewart et al. (2020) have investigated development of a an indigenous soil classification system in Uganda by contrasting local knowledge with the World Reference Base system. Similarly, a comparison of the WRB to Australlian soil classification system was reported by (David et al., 2010).

Soil Profile Nomenclature

The vertical section of soil shows the presence of distinct horizontal layers is known as the soil profile. Where the term horizon refers to the individual or distinct layers within the soil profile. In Soil Taxonomy, a horizon is defined as "a layer, approximately parallel to the surface of the soil that is distinguishable from adjacent layers by a distinctive set of properties produced by the soil-forming processes" (USDA, 2017b). Many of our soils are composed of several horizons. Typically, horizons of a soil profile will follow the topography of a landscape. Also, all the soil forming processes influence the formation of soil horizons.

Thus, in a broad sense soil forming processes which consist mainly of loses, translocation, gains and transformation of minerals and organic materials in a soil profile affects soil horizonation. Designation of horizon boundaries also comes from measurements of soil color, texture, structure, consistence, root distribution, effervescence, rock fragments, and reactivity. Soil profile is an important tool in soil nutrient management. By examining it, we can be able to understand and characterize soils in order to deduce their fertility level. Delineating the soil into horizon is a shorthand way of recording and communicating soil profile observation (Bridges, 1993). Horizon designation have seen some tremendous changes due to different soil classification systems, thus according to (Gerasimova and Bogdanova, 2013).

However, soil taxonomy and the WRB uses three types of symbols. They are, capital letters, lower case letters and Arabic numerals. The capital letter purposely designate the master horizons whereas the lower case horizon suffixes communicates observations such as silica clay accumulation (USDA, 2017b; WRB, 2015c). The Arabic numerals are used as suffixes to indicate vertical subdivisions within a horizon or layer and as prefixes to indicate lithological discontinuities. Mostly, horizons are delineated based on onsite observation of soil properties and characteristics and may vary from different school of thoughts. Horizon delineation could also be based on subjective judgement (Boone et al., 1999; Hartemink and Minasny, 2014).

Variations in horizon delineation could also be attributed to the "a'lumper' versus 'splitter' approach to description and sampling." The splitters (some soil scientists), tend to differentiate horizons based on small changes in properties such as color, texture, and structure, whereas other soil scientists, the lumpers, differentiate horizons only if they consider the changes in at least one property to be large. It is also possible that discontinuous or thin horizons may be overlooked in horizon delineation or sampling (Boone et al., 1999).

O Horizon

IUSS Working Group describes O horizon as the uppermost layer, which consists primarily of organic material, undecomposed, partially and highly decomposed litter (WRB, 2015c). Forested areas usually have a distinct O horizon. However, in some settings such as a grassland or cultivated field, there may be no O horizon present. Factors such as erosion or constant tillage contribute to the lack of organic matter. The O horizon has three major sub-classifications, or subordinate distinctions (designated by the lowercase letter): hemic (O_e), fibric (O_i), and sapric (O_a), these names are derived according to the level of organic matter decomposition (Cooper et al., 2005).

Fibric: These soil materials commonly have a bulk density of less than 0.1, an unrubbed fibre content exceeding two-thirds of the volume, and a water content, when saturated, ranging from about 850 percent to over 3000 percent of weight of oven-dry material (USDA, 2017b). According to the Munsell notations their colours are commonly light yellowish brown, dark brown or reddish brown. The colour of the sodium pyrophosphate extract on white chromatographic paper has values and chromas of 7/1, 7/2, 8/1, 8/2 or 8/3 (Thompson, 2013).

The hemic layer consists of soil materials that are intermediate in degree of decomposition. Bulk density is commonly between 0.07 and 0.18 and the fibre content is normally between one-third and two-thirds of the volume before rubbing. Maximum water content when saturated ranges from about 450 to 850 percent. The sapric layer consists of fully decomposed material whose origin is completely unidentifiable.

A Horizon

The A horizon is a mineral horizon that is formed at or just below the soil surface. It is commonly referred to as the "surface soil." Some characteristics of an A horizon may include the accumulation of organic matter mixed with mineral fraction; properties resulting from cultivation, pasturing, or similar disturbance; or a morphology different from that of the underlying E, B, or C horizons, resulting from the processes related to the soil surface and/or the presence of a plow pan (WRB, 2015b). A plow plan (or plow layer) is a common characteristic of soils that have undergone conventional tillage at some point in recent time. An A horizon is often used with a p suffix indicating that is has been cultivated (p for plowed). The darkness of the A horizon can sometimes be attributed to the movement of organic matter from the overlying O horizon. Soils under intense cultivation will incorporate materials that would normally be considered part of the O horizon. These organic materials also contribute to the A horizon leading to a higher organic content than other horizons.

E Horizon

The E horizon (eluvial layer) is a common mineral horizon in forest soils that is distinguished by its lack of clay, iron (Fe), or aluminum (Al) leaving a residual concentration of sand and silt particles (WRB, 2015c). The loss of the above materials is known as eluviation, which entails that these substances and dark minerals have been stripped from the soil particles. Clay, Fe, and/or Al are removed from the E horizon via leaching, which causes its light color compared to the adjacent horizons (pale yellow). Leaching is the loss of nutrients from the root zone due to the movement of water through the soil profile. The E horizon is comprised of concentrations of quartz, silica, or other minerals that are less susceptible to leaching.

B Horizon

The B horizon, known as the "zone of accumulation", occurs below the O, A, and/or E horizons, if present. In their work, Churchman et al. (2016) postulated that, the processes that form the B horizon includes illuvial concentration, alone or in combination, of (alumino) silicate clay, iron, aluminum, humus, carbonates, gypsum, or silica; removal of carbonates; residual concentration of sesquioxides; coatings of sesquioxides not coupled with illuviation of iron; alteration in situ that forms crystalline aluminosilicate clays, nanocrystalline clays, or oxides or hydroxides The common presence of Fe and Al oxide coatings often give the B horizon a redder or darker color than the adjacent horizons.

C Horizon

The C horizon is the soil layer that generally sees little influence from pedogenic weathering processes and is therefore comprised of partially weathered parent material. The C horizon represents a transition between soil and bedrock. As the upper portion of the C horizon undergoes weathering, it may eventually become part of the overlaying horizons. There is an obvious shift in soil structure between strongly developed B and C horizons that aids in identifying the horizon in the field; however, the structure shift may be subtler in weakly developed soils. Under the C horizon comes the R horizon, or bedrock (Boone et al., 1999).

Depending on the geographic location, environmental conditions, and landscape position, bedrock may be found in excess of 100 feet deep or merely centimeters from the soil surface. Bedrock is a consolidated layer of rock material that gave way to the soil properties found on the site. Bedrock is occasionally disrupted or broken up by tree roots, but roots generally cannot cause enough stress on the rock to fracture it, so much of the deeper bedrock weathering is biochemical in nature. The layer of freshly weathered material, in contrast to the solid rock (i.e., bedrock), is generally termed saprolite/saprock (USDA, 2017).

Spatial Variability in Soils

The heterogeneous, diverse and dynamic nature of soil makes its properties change in time and space continuously (Cichota et al., 2006). To curb down the incidence of crop failure, food shortage and soil degradation, it is prudent to carry out soil management practices obtained by the understanding of the dynamics of soil properties (physical, chemical and biological). Soils are heterogeneous in structure which in turn affect ecosystem processes which controls nutrient cycling (Fitter et al., 2005). Understanding that soils physical and chemical properties exhibit inherent temporal or spatial variability and assessing these soil properties is evident in suggesting appropriate and precise soil management tools to optimize productivity (Gajda et al., 2016). Spatial variability is said to have occurred when a quantity measured at different spatial locations exhibit different values across the locations. Soils are uniquely different from geologic parent materials such as loess, glacial tills and sedimentary rock because soils develop horizons in which each horizon has distinct set of characteristics and diagnostic soil properties. Obtaining such information therefore, could help in saving effort, time, and cost for any cultivation development process. Furthermore, collecting accurate and continuous spatial data is important for justified decision making. However, the availability of data is not only difficult but also an expensive process (Mohamed et al., 2020).

Farming systems have various types of soils, habitats, microclimatic features, and crop varieties, which result in wide variations in soil fertility, water retention and crop productivity (Sciarretta and Trematerra, 2014). Variations in crop yield on a field can largely be due to factors like spatial variability of soil types and within soils, landscape position, crop history etc. (Gaston et al., 2001). There are several documented studies on soil properties varying across farm fields causing spatial variability in crop yields (Gaston et al., 2001). Understanding the spatial variability of soil physicochemical characteristics, in both its static (e.g. texture and mineralogy) and dynamic (e.g. water content, compaction, electrical conductivity and carbon content) forms is necessary for site-specific management of agricultural practices, as it is directly contributing to variability in crop yields and quality (Jabro et al., 2010; Silva et al., 2011). This is because productivity is influenced by soil characteristics and the spatial pattern of productivity could be caused by a corresponding variation in certain soil properties. Determining the source of variation in productivity can help achieve more effective site-specific management.

In their study, Mzuku et al. (2005) on variability across some crop site specific management zone found out that soil physical properties exhibited significant spatial variability across production fields. The trends observed for the measured soil physical properties in their study corresponded to the productivity potential of the management zones. They therefore proposed that utilizing site-specific management zones could help manage the in-field variability of yield-limiting soil physical properties.

The variability in the bare soil reflectance can be ascribed to the non-uniform distribution of certain soil properties that influence crop productivity. Site-specific practices could help significantly in managing productivity of agricultural soils by tailoring the agricultural inputs to fit the spatial requirements of soil and crop (Fraisse et al., 1999). Therefore, determination of the major sources of variation in productivity is a key parameter in achieving efficient site-specific management practices (Mzuku et al., 2005). Soil parameters are the most important factors in crop production systems. Hence, understanding their spatial variability across agricultural fields is essential in optimizing the application of agricultural inputs and crop yield.

Causes of variability in soils

Spatial variability in soils occur naturally from pedogenic processes. The natural variability in soils occurs due to the complex interactions between geology, topography, climate as well as soil use (Quine and Zhang, 2002). The main sources of variability have been shown to relate to soil forming factors, topography and management practices (Ozpinar and Ozpinar, 2015).

Parent material

Soil parent material constitute the initial state of the soil system and the material from which soils are derived (Jenny, 1994). Soil types, soil development, physical and chemical properties of soils tend to be influenced by parent material. Information on parent material and its texture is therefore recognized as useful factor in soil erosion amongst other factors. Also, parent material is useful to the evaluation of agricultural productivity potential, hydrologic characteristics of watersheds, suitability of materials and assessment of terrain stability (Brandon et al., 2014)

Soil parent material is essential regardless of its state of weathering or consolidation and is the material responsible for soil formation (Lacoste, 2018). Essentially, the nature of parent rock in a particular region will affect the type of soil that eventually develops thus, in effect, the differences in soil characteristics such as texture, water holding capacity, acidity, etc is as per the influence of soil parent materials (Gökbulak and Özcan, 2008). For example, in an area of mainly sandstone, the soil formed due to the weathering of the rock is likely to be well-drained, course and sandy.

Management practices

Since spatial variability in soils occur naturally from pedogenetic factors, much variability can occur as a result of land use and management. As a consequence, soils can exhibit marked spatial variability at the macro- and micro-scale. The need for intensive grid sampling for the evaluation of the spatial variability and/or the diversity of different soil and agronomic properties has been frequently emphasized. Studies of the effect of land management on nutrients has also shown that cultivation generally increases the potential for soil erosion due to the breakdown of soil aggregates and reduction of soil cohesion and thus decreases soil nutrient content along profiles. By this extension, tillage types such as cross-slope tillage tend to reduce soil loss compared to down-slope tillage and can be anticipated that the nutrient levels would also be less affected (Shaoliang et al., 2010).

The physical and chemical properties of soils are strongly influenced by management practices and changes in landuse (Hulugalle and Entwistle, 1997). In their study Chan and Hulugalle (1999), compared some chemical and physical attributes of soils within a cultivated field and soils with pasture. They observed a greater percent of mechanical dispersible clay, lower pH and electrical conductivity in the cultivated soils. Several studies have revealed that a lack of plant nutrients is one of the principal causes for low agricultural productivity and food insecurity in Africa (Sanchez, 2002). This is illustrated by small increases in crop productivity, even in years with adequate rainfall. As a result, more intensive land use (e.g. by fertilizer application) has become necessary to reverse the trend of declining per capita food production. Agriculture in Ghana is no exception: more soil nutrients are exported compared to natural and anthropogenic inputs (Okumu, 2000). In the quest to address the pertaining food crisis in African, farmers tend to overly apply fertilizers to soils.

Topography

Topography of the landscape play a leading role in the variability of soil properties across and along a plane. According to Moulin et al. (2014), the variation in soil thickness reflects the topography of the landscape and its influence on hydrology, biologic activity, and soil forming processes. High degree of soil development variability is commonly found in a hilly region. In such region, the variability of soil development is mainly caused by geomorphic processes where the heterogeneity of relief is dominated (Conforti, 2020). Landslides become a dominant geomorphic process causing the variability of soil development in hilly region (Pannekoek, 1949). Landslides transport the residual soils to other places and/or mix the residual soils with other deposited soils. Furthermore, this variability can be varied by human activities which generate soil re-distribution Crutzen (2002) in the form of terraces and other land management practices.

The topographical influence on soil properties such as soil moisture has been studied and a positive association was established. Almost 22-61% of variation in soil moisture was determined by correlating terrain data with potential solar radiation indices (Jan et al., 2007). In a related study, the topography explained for almost 0-40% of the spatial variability of soil moisture where the temporal variation of soil moisture was 10 times greater than the spatial variation. Also Wilson et al. (2004) found that topography explained between 26-64 % of soil moisture variation. The slope and slope position were found to be useful for determining soil water retention at particular locations.

Further, investigation on the indirect influence of topography through hydrology on soil properties have been reported widely in literature. According to Brubaker et al. (1993), there were observed increases in pH, $CaCO_3$, Ca and Mg including base saturation downslope of a toposequence gradient. Along the same gradient, were observed decreases in cation exchange capacities (CEC).

It was reported that that foot and toe slopes of toposequences had higher soil concentrations on backslope positions. According to Okusami et al. (1985) there is a strong correlation between topography and soils in the high rain forest zones of West Africa. The topography of most slope regions are closely related to their underlying parent rock. This results in the classification of soils considering topographic positions, hence the formation of sedentary soils (formed in-situ at the crest and/or upper slope) and drift soils (those formed at the lower slope or valley) through transportation and deposition of sediments. This leads to the formation of soils with different taxonomic classes from the crest to lower slope positions (Olusegun, 2015)

Vegetation

The type of plant life which covers a certain area of land can exert its influence in several ways. Several studies have looked at the influence of vegetation recovery on soil properties, Fu et al. (2003; Stolte et al. (2003) and found a significant associations. In their study Wilson et al. (2005) evaluated the changes of soil macropore behaviour under different tillage conditions (i.e., 1 year following tillage, 6 years following tillage, 6 years following contour ditching, and greater than 15 years following tillage) along a plateau. Important observation in terms of total number of macropores (> 1 mm), number of large (> 5 mm) macropores, and the macroporosity increased with revegetated time. Further, the soil matrix infiltration rate was highest in the newly established (1 year) and the oldest (> 15 years) revegetated areas. Changes in soil composition can occur when plant residue is incorporated into the soil, often the case after harvesting. Also, the structure of the soil is affected. The crop canopy and rooting system protect the soil from rain damage and severe temperatures, and make soil less susceptible to erosion and leaching. Vegetation has been recognized as an effective agent not only for protecting soil from erosion resulting from impacting raindrops and water flow, but also as a factor for significantly increasing the shear resistance of the slope soil (Waldron and Dakessian, 1982).

Benefits of Spatial Variability

There are several spatially variable factors influencing crop yields. These are usually soil related, anthropogenic, topographic, biological, and meteorological factors. Knowledge of the spatial variation of soil properties is important for crop production in precision agricultural management systems. It has been known that most soil properties are spatially variable in a field and that spatial variability of soil properties in any field position is inherent in nature due to geologic and pedologic soil forming factors, but some of the variability may be induced by tillage and other management practices.

According to Redulla et al. (1996), three potential benefits of site specific management as a result of spatial variability in soils can be described. They are; increasing input efficiency, improving the economic margins of crop production and lastly, reducing environmental risks. It gives the farmer the potential nutrient requirement on a field for optimal output. Assessing the variability in nutrient distribution in relation to site specific characteristics which includes climate, landuse, landscape position and other variables is critical in predicting rates of ecosystem processes (Schimel et al., 1991). Also to understand how the ecosystem works Townsend et al. (1995) and Kosmas et al. (2000) further investigated the effects of future land use change on nutrients.

Different land use and management practices greatly impact soil properties Spurgeon et al. (2013), and knowledge of the variation in soil properties within farmland use is essential in determining production constraints related to soil nutrients. It is also important to suggest different remedial measures for optimum production and appropriate land use management practices (Pandey et al., 2018). Sustainable land management practices are necessary to meet the changing human needs and to ensure long-term productivity of farmland.

Availability of new and better technologies facilitates the introduction of site-specific management systems in agriculture. Site-specific agriculture creates high expectations: higher financial returns, increased product quality and decreased environmental risks. Not only the farmer is interested in the benefits of precision agriculture; world-wide an increasing interest exists among agro-business, traders, researchers, and advisers. Variable rate application of nutrients is possible only if experts can give correct site-specific recommendations. Therefore precise information about nutrient status of the soil is required (Hergert et al., 1997). Knowledge of the variability in space and time of soil fertility parameters is one of the most important keys in further development of precision agriculture. Reliable information on the range of spatial relationship enables defining the sampling strategy needed to perform accurate soil nutrient maps (Geypens et al., 1999).

Assessment of Soil Spatial Variability

The toposequence concept provides a useful approach to understand relationships between soil and land cover at a spatial dimension. Moreover, a stratified sampling method along several toposequences is particularly suited to characterize areas where little data are available, as they provide a cost-effective alternative to conventional grid inventories that require high-density observations (Gobin and Deckers, 2000). Various disciplines study variations along gradients in the landscape. A historical overview of the catena concept in soil science is provided by Sommer and Schlichting (1997), who identified three archetypes of catenae depending on immobilisation processes and hydrological regimes. Surface and near-surface processes such as soil formation Moore et al.

(1993), soil hydrology Saulnier et al. (1997) and soil erosion Poesen et al. (1998) are studied along toposequences, following the underlying knowledge that toposequence development often relates to water movement through and over the landscape. Transects are used in ecology to describe vegetation changes across landscape and plant community boundaries whereas, agro-ecosystem and land use analysis employ transect methodologies to generate data on the biophysical environment and on actual land use. In their study, Andriesse et al. (1994) developed a multi-scale approach to characterise inland valley agro-ecosystems in West Africa, whereby transects are used to collect biophysical and land use information at a semi-detailed scale (1:25,000 to 1:50,000).

However, these techniques results in data discontinuities which limits effective management practices. In line with modern and precision agriculture, digital soil mapping (DSM) has become an impactful approach towards addressing some of these pitfalls associated with traditional soil surveys (Ma et al., 2019a). This approach also establishes a knowledge system for participatory learning and easy communication to non-pedologists (Bui, 2004). The reliability and effectiveness of DSM depends on adequate sampling data i.e. number of samples and corresponding distances of sampling units.

Geostatistics provides a set of statistical tools for incorporating the spatial coordinates of soil observations in data processing, allowing for description and modeling of spatial patterns, prediction at unsampled locations, and assessment of the uncertainty attached to these predictions. Since the publication of the first applications of geostatistics to soil data in the early 1980s geostatistical methods have become popular in soil science, as illustrated by the increasing number of studies reported in literature (Goovaerts, 1998).

Digital soil mapping coupled with other geostatistical tools offer a solution to data gaps from field sampling and have become significant in precision agriculture. Sub-Saharan Africa is endowed with enormous soil resources however, these vital resources are largely unmapped and what are available were captured at large scales (Mutsaers et al., 2017). The available large spatial resolution soil maps cannot serve as useful inputs in local soil fertility management plans. Our search in the Web of Science database (WoS) revealed paucity in research applications of geostatistical approaches towards evaluation of agricultural soil properties in Ghana. Previous studies which utilized geostatistical approaches to evaluate soil properties were performed from a similar agroecological zone in the Ashanti region (Okae□Anti and Ogoe, 2006).

The geostatistical methods are robust and can be adjusted according to the case study needs (Torres et al., 2017). Predicting values of a variable in unsampled points allows to generate spatially continuous data (Li and Heap, 2008). The goal of geostatistics is therefore to examine the spatial structure of the target variable and predict its values at unsampled locations therefore, geostatistics is an important technique that can be used to characterize spatial or temporal phenomena (Zhang, 2011). The most regularly utilized interpolation techniques based on geostatistical methods are kriging and co-kriging Lark, (2012) inverse distance weighting (IDW), and linear regression model (LR) (Kravchenko and Bullock, 1999). In addition, attention has been recently paid to techniques combining two or more different approaches. Regression kriging and simple kriging are the most commonly used techniques for a regression model (Lesch and Corwin, 2008). In recent study, the combination of two kriging methods i.e. ordinary and regression were employed (Fritsch et al., 2011). Regression kriging was found more accurate for interpolating soil properties in contrasting landscapes. Nevertheless, ordinary kriging and IDW has been recommended as the most frequently used approach to predict soil properties.

Geostatistics includes ways for analyzing the autocorrelation in spatial data. An important property of geostatistics is the semivariance, which measures spatial continuity. Use of the semivariograms needs the data supplies the real hypothesis for regional variable (Journel and Huijbregts, 1976). Thus, geostatistics play an important role in representing soil analyses spatially and highlighting variations between different parts in a study area. Many of the previous studies preferred some geostatistics methods (Kriging) over others and many of the corresponding studies preferred vice versa (Mohamed et al., 2020), which necessitates studying the suitability of the method used under the actual conditions of the study area.

Kriging is a geostatistical method that can be used to predict the value of soil properties in unsampled locations, favouring the application of differentiated soil management in precision agriculture. Several authors have devised soil sampling schemes directed by properties that directly or indirectly influence crop yield Minasny and McBratney (2007), and the success of this approach depends on the use of variables that are quickly and easily measured, such as EC. Kriging is a well-established geostatistical interpolation model which is based on a logic of weighted moving average (Theodossiou and Latinopoulos, 2006). Rafiei-Alhosseini and Mohammadi (2000) applied both kriging and linear regression models to quantify spatial distribution of several soil properties, including electrical conductivity, saturation percent, sodium absorption ratio and its percentage. The study concluded that the kriging was the preferred method in estimating spatial distribution of soil properties compared to linear regression (Rafiei-Alhosseini and Mohammadi, 2000). Similarly, the kriging method was applied in many previous studies to map depth and thickness of soil materials as well as characterize soil texture (Bourennane et al., 2000; Jang et al., 2013). Meanwhile, since soil properties are complex with many variables not all of which are well understood, it is unlikely that covariance models used in soil geostatistics can be tightly linked to process understanding. The IDW, Global Polynomial Interpolation (GPI), Local Polynomial Interpolation (LPI), Radial Basis Functions (RBF), Kriging, Co-kriging and regression method have been described to produce similar results with ordinary kriging when applied under different combination of datasets to create soil concentration maps (Sayed et al., 2017).

CHAPTER THREE

MATERIALS AND METHODS

Study Area

The study area covers an estimated land-take of 169.6 hectares and is approximately 17 km northwest of Twifo Praso and 1.2 km west of Wamaso in the Twifo-Atti-Mokwa District, Central Region of Ghana. The site lies within latitudes 5° 42' 30" N and 5° 42' 00" N, and longitudes 1° 39' 30" W and 1° 39' 00" W. The location is as shown in Figure 1. It is a semi-deciduous forest with dominant vegetations being thickets consisting of an impenetrable mass of shrubs, climbers, coppice shoots and young trees and soft-stemmed leafy herbs e.g. *Ageratum conyzoid*, *Bambusa vulgaris* that appear in abandoned farms and cultivated lands grown to cocoa, maize, plantain, cassava and rice.

The topography generally shows a gentle slope that varies from 1 – 3 % in Figure 2 whilst the elevation ranges from 80 – 130 m above sea level (asl). Minimum plateaued summits were between 87.18 – 91.77 m with the highest summits ranging from 118.40 – 123.56 m as shown in Figure 3. A few seasonal streams border and runs through the study site and tend to flood during the rainy seasons. The topography of the area is generally undulating with gently rolling, steeped slope topography at few places (Gyamera, 2014).

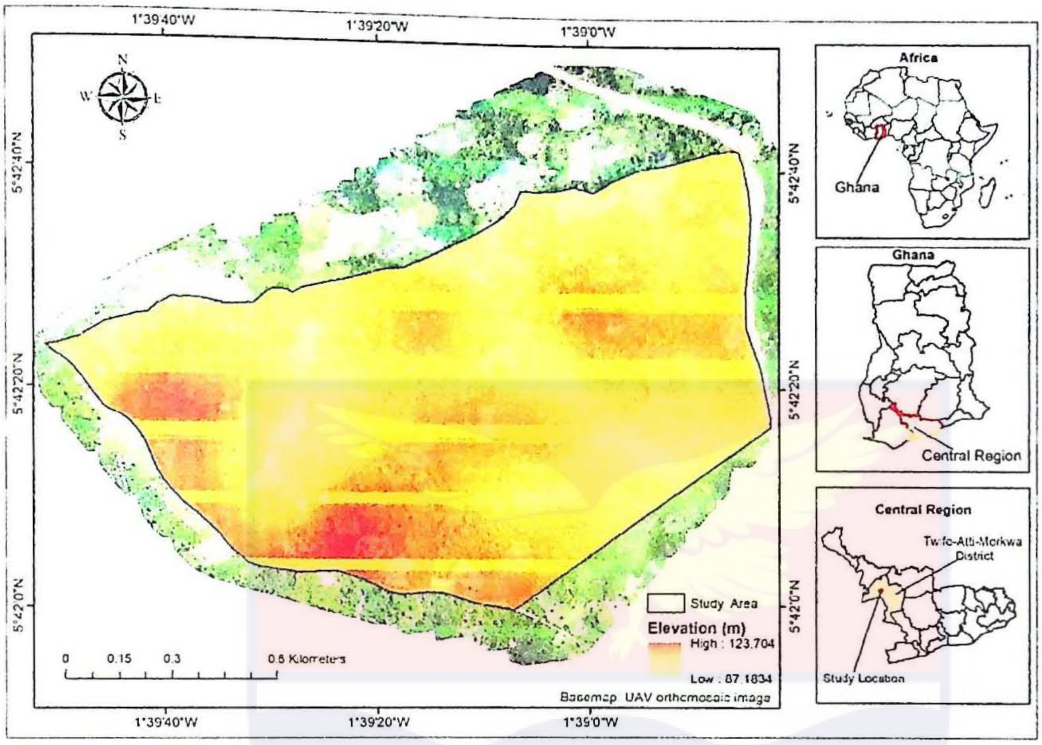


Figure 1: Map of Study Area

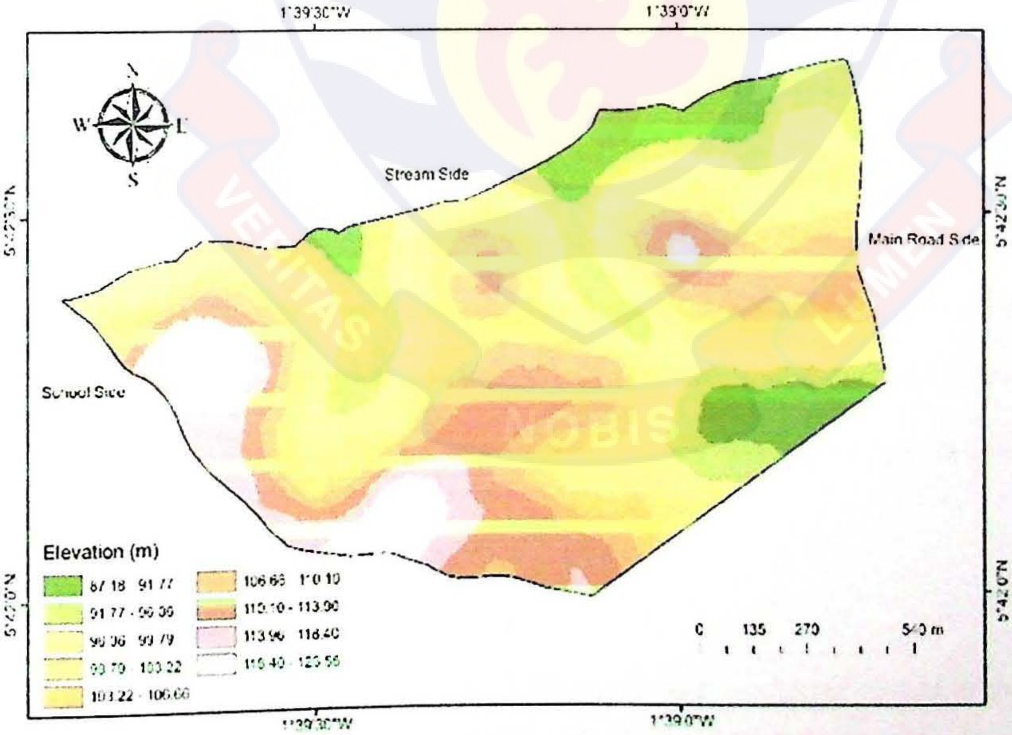


Figure 2: Elevation profile of study area

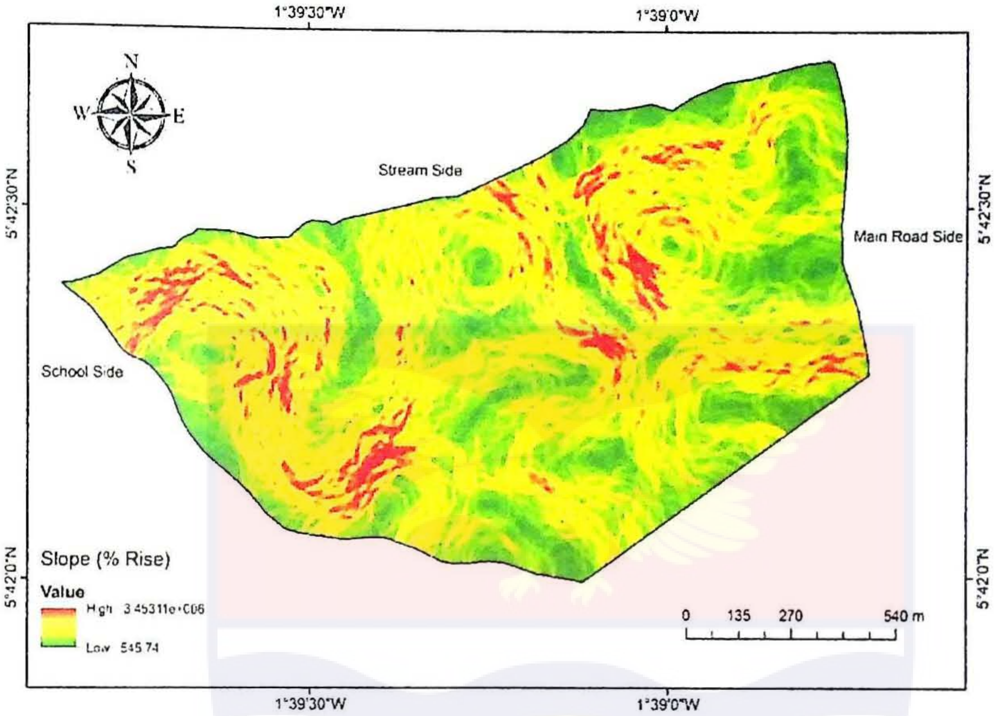


Figure 3: Slope profiles in the study area

Field Survey

The free survey method of soil investigation was adopted where the use of aerial photography obtained from the drone were used to make interpretation coupled with massive field observations to aid in characterization of the toposequence (Beckett and Burrough, 1971). This method was conducive for the field setting as there were significant open spaces that allowed for field walkovers and tracing of footpaths to broadened observations and judgement of the soil features.

Aerial Imagery and Mapping

To further obtain a wider aerial view of the study area, an Aerial vehicle drone (DJI Phantom 3 Professional) was used to obtain photographs of the approximate landmass of 169.9 hectares. The aerial photographs were processed in Pix 4D Mapper software together with Mission planning software (Map pilot) Burnham, (2019) and topographic maps were then generated in ArcGIS environment (ESRI, 2020).

Soil Profile Pits

A 3 % slope was identified from the slope processed map obtained from the drone capture. Five topographical positions were identified on the slope within the study area. Soil profile pits (PP's) were established in each of the topographic positions along the toposequence. The PP's were sunk to obtain representative soil samples along the toposequence as shown in Figure 4 and GPS coordinates shown in Table 1. They were coded as PP1 for the summit, PP2 for the shoulder, PP3 for the middle slope, PP4 and PP5 for the foot and toe slopes respectively. Three to four distinct soil horizons were observed for the various profile pits (PP1 4, PP 2 4, PP3 3, PP4 4 and PP5 3) at different depths (135, 137, 120, 66+ and 78 cm respectively). The PP's were then described per Soil Survey Manual (USDA, 2017b).

Six discrete samples were obtained and bulked from each of the identified pedogenic horizons. In all, 18 composite samples were obtained for all five profile pits. Core sampler was used to collect undisturbed soil samples from each horizon to determine bulk density. The soil samples were spread out to air dry, then crushed with a mortar and pestle and sieved with a 2 mm sieve. Soil analysis was done with fine earth. The codes/IDs on the sample labels were unique to the soil profile test pits. The study area's toposequence was stratified for classification using the US Department of Agriculture's Soil Taxonomy

USDA, (2017a) and the World Reference Base Legend (WRB, 2015a). The location/section of toposequence where profile pits were dug was provided in geographic coordinates in UTM (Universal Transvers Mercator) format.

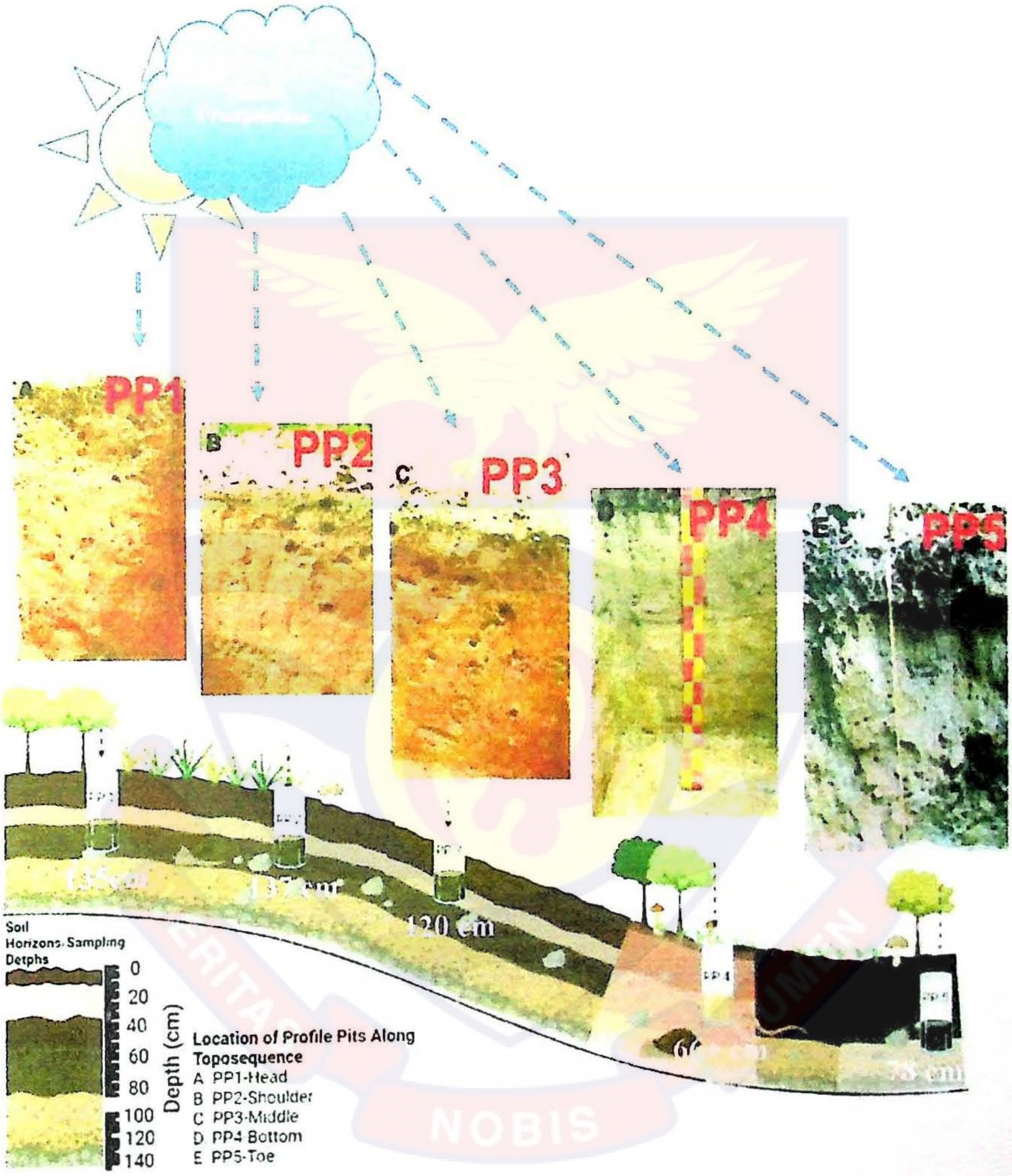


Figure 4:Cross sectional illustration of the toposequence

Table 1: GPS Coordinates of profile pits along toposequence

Profile Pit location	Northerns (N)	Westerns (W)
Head/Summit	05.11044	001.29568
Shoulder	05.70709	001.64699
Middle	05.70729	001.64725
Foot slope	05.70729	001.64725
Toe slope	05.70766	001.64745

Soils Along Transects

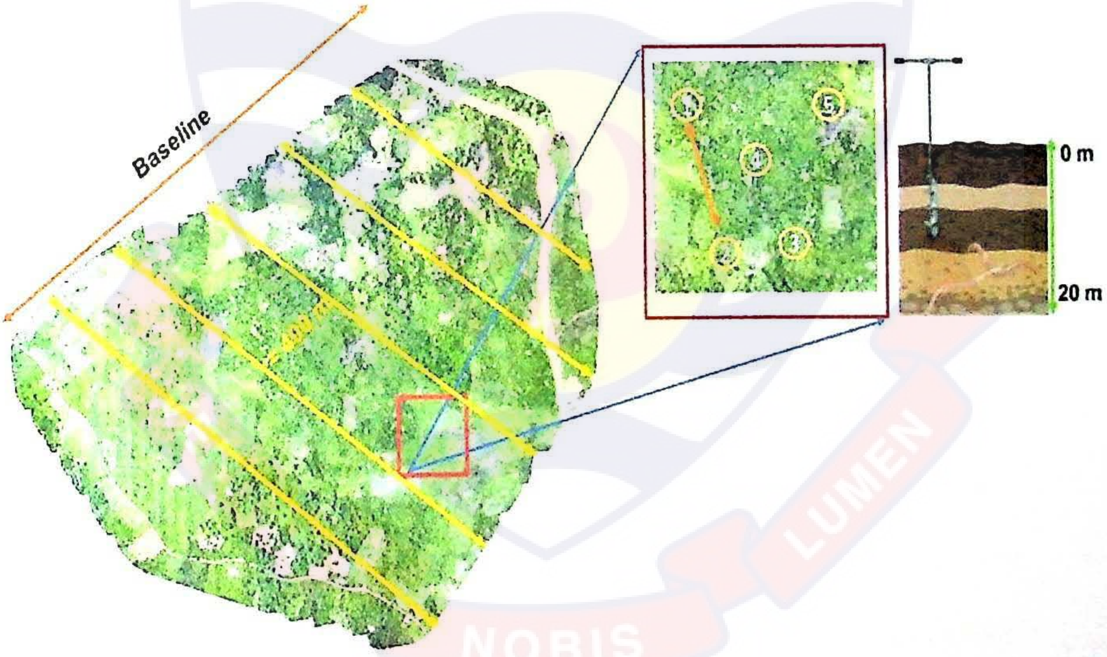


Figure 5: Schematic layout for soil sampling within the study area

Line transects method of soil sampling was employed to extensively to determine the change in nutrient distribution with distance across the study area. A base line was constructed along a stream and five transects were laid perpendicular to the baseline. The line transects were approximately 400 m apart. Soils were then sampled along and between the line transects. Due to the difficulty in assessing some of the sampling plots, the sampling strategy was adjusted in synchrony to Quesada et al. (2010) sampling strategy. Sampling took into consideration landscape features that signified variability. Apparently, on homogenous plots with flat topography, sampling of soils (20 cm depth) were done at 50 m intervals whereas areas with hilly features signifying spatial variability had sampling distances adjusted to as minimum as a 1 m interval. Soil sampling was done using a core sampler of depth 20 cm as illustrated in Figure 5.

One hundred and ninety (190) soil samples were collected along the five transects and a hundred between all five, transects accounting to a total of 290 soil samples for the entire study area. The latitude, longitude, and elevation at each of the 290-sampling point were recorded using a hand-held global positioning system (GPS). The soil samples were placed in sealable bags and labelled accordingly and transported to the laboratory, air-dried at room temperature for days and sieved using 2 mm mesh-size) for storage and further laboratory analysis.

Analytical Methods

Before any analytical analysis, glassware were washed in distilled water and hydrochloric acid (HCl) solution and oven-dried at 105°C. Fresh soil samples were used for each run of batch analysis to avoid cross-contamination of chemical parameters.

pH

Using a digital pH-meter, the soil pH was calculated using a 1:2.5 soil-water ratio as described by (Udo et al., 2009). A centrifuge tube was filled with ten (10) grams of sample and 25 mL of distilled water; the mixture was shaken with a mechanical shaker for 30 minutes and then allowed to stand for 30 minutes. Prior to an instant rapid shaking of the mixture, the electrodes of a Serie P-H_2O Research pH meter were placed into the suspension, and the pH value was read and recorded.

Exchangeable Cations

The exchangeable bases (Ca, Mg, K· and Na) were studied using the method given (Chapman, 1965). A mechanical shaker was used to agitate 30 mL 1M NH_4OAC into 5 g of material for 2 hours. The clear supernatant was carefully decanted into a 100 ml volumetric flask after centrifuging the mixture at 2000 rpm for 10 minutes. Another 30 ml of NH_4OAC solution was added and agitated for 30 minutes before centrifuging and transferring the supernatant into the same volumetric flask. After repeating the operation, the supernatant was poured into the same volumetric flask and topped up with the NH_4OAC solution. On a flame photometer (Jenway PFP 7) model, calibration graphs of six concentrations against photometer readings were constructed for potassium and sodium. Equation 2 was used to determine calcium and magnesium using the titration method. Calculations for Potassium and Sodium

$$\text{Exchangeable K} = C * \frac{\textit{Solution volume}}{\textit{sample weight}} \qquad \text{Equ. 1}$$

where C is the concentration from photometric reading (Stewart, 1974_).

Determination of Calcium and Magnesium

The sum of (Ca, Mg) was used to determine exchangeable magnesium using the difference in titre values between (Ca, Mg) and Ca alone (Rowell, 1994). Titrating a 25 mL portion of the extract into a 250 mL conical flask and diluting to 150 mL with distilled water was used to evaluate calcium and magnesium levels. Ten drops of KCN, NH_2OH, HCN, and triethanolamine, as well as ten percent NaOH, were added to raise the pH to 12 or slightly higher. Five drops of calcon indicator were added to the mixture. The solution was titrated with 0.005 M EDTA from red to blue. The same procedure was performed to determine (Ca, Mg) using murexide indicator. The following calculations were made in equations 3 and 4:

$$\text{Ca} + \text{Mg (cmol kg}^{-1}\text{) soil} = \frac{4*T}{wt} \qquad \text{Eq. 2}$$

$$\text{Ca (cmol kg}^{-1}\text{) soil} = \frac{4*T}{wt} \qquad \text{Eq. 3}$$

where, T= titre value; wt= weight of soil sample

The difference in the titre values between Σ (Ca, Mg) and Ca alone was used for calculating exchangeable magnesium.

Effective cation exchange capacity (ECEC)

To assess effective cation exchange capacity in soil, the total of exchangeable bases (calcium, magnesium, sodium, and potassium) and exchangeable acidity (aluminum and hydrogen) were supplied in cmolc kg^{-1}. Anderson and Ingram are two of the most well-known names in the (Anderson and Ingram, 1993).

Soil Organic Carbon

A carbon oxidation process by a dichromate ion was used in the Walkley-Black wet digesting procedure. In this experiment, soil (1 g) organic carbon was oxidized for 30 minutes using 0.17 M potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4). For organic carbon analysis, the digestate was placed in a spectrophotometer (Thermo Fisher Scientific model 4001/4) with an adjustable wavelength (600 nm). If C = g OC/ml as shown by the graph, then g OC/g (sample) as determined by equation 5.

$$\frac{C*dilution\ factor}{sample\ weight} \qquad \text{Eq. 4}$$

(Rhodes, 1981)

Total Nitrogen

Kjeldahl digestion was used to determine total nitrogen (Amin and Flowers, 2004). In a cracking flask, a 0.5-1.0 g soil sample was weighed, along with 0.2 g of catalyst and 3 ml of pure sulfuric acid (H_2SO_4). The contents were cooked for 2 hours at 360°C in a block cooker before being allowed to cool to room temperature. 50 mL distilled water was added, and 20 mL of the aliquot was pipetted into the steam distiller's reaction chamber. The alkaline mixture was added in 10 mL increments and then distilled. On the boric acid indicator, around 40 ml of distillate was collected.

0.007 M hydrochloric acid was used to titrate the distillate (HCl). The color change from green to burgundy defined the ultimate concentration. There was also a blank value determination. Equation 6 was the next step in the process.

% N = (S – B) * Solution volume Eq. 5

where; S = Sample titre; B= blank titre

Available Phosphorous

The amount of accessible phosphorus was determined using the Bray No. 1 method (Bray and Kurtz, 1945). Each 15 ml centrifuge tube included one gram of soil sample, followed by 10 ml of extracting solution. After shaking for 5 minutes, the contents of the tube were filtered using a Whatmann No. 42 filter paper. Two millilitre aliquots of the extract were pipetted into 25 mL volumetric flasks. The P stock solution was then used to make 100 mL 5 g P mL^{-1} for each sample or filtrate.

From the 5 g P mL^{-1} solution, a series of working standards of P containing 0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 g P mL^{-1} were made and placed into 25 mL volumetric flasks. Each flask received ten milliliters of distilled water. The reagent was then added in 4 mL increments, and the mixture was produced or brought up to volume with 52 distilled water. After allowing the blue color to develop for 15 minutes, the absorbance was measured at 882 nm using a spectrophotometer (Thermo Fisher Scientific model 4001/4).

Calculations following equation 7:

$$\text{Available Phosphorus } (\mu g/g) = \frac{C*50}{wt} \qquad \text{Eq. 6}$$

Where C is concentration derived from the standard curve; wt is the weight of soil sample

Micronutrients

1 diethylene triamine penta-acetic acid was used to extract the micronutrients (DTPA) following Lindsay and Cox, (1985) procedure. In a polypropylene bottle, ten grams (10 g) of soil sample was inserted, along with 20 mL of DTPA extraction solution. The bottle was sealed and shaken vigorously for two hours. The information was then filtered. Using an Atomic Absorption Spectrophotometer, the extract was utilized to estimate several micronutrients (Buck Scientific, model 210 VGP).

For each element, there are standard solutions and an optimal range (Linear relationship on digital readout)

i. Zn standards – 0, 0.5, 1.2 and 3 ppm Zn in aqueous solution.

ii. Cu standards – 0, 2, 10, 15 and 20 ppm Cu in aqueous solution.

iii. Fe- 0, 1, 2, 3 and 5 ppm Fe in aqueous solution.

The concentration reading was standardized by utilizing the element's standard solutions. The element concentration in the sample solution was measured and reported using equation 8.

$$\text{Fe, Cu and Zn (ppm)} = \text{ppm in extract} * \frac{A}{wt} \qquad \text{Eq. 7}$$

Where A = the total volume of the extract; wt = weight of the soil sample

Particle Size Distribution

The pipette method was used to determine the size distribution of soil particles (Rowell, 1994). In a 500 ml beaker, weigh 10 g of soil. Hydrogen peroxide (H_2O_2), 20 mL, was added and allowed to stand until foaming stopped. After that, the suspension was heated to complete the decomposition of organic particles before being allowed to cool. The peroxide-treated soil was transferred quantitatively to a 500 mL plastic bottle, the soil suspension was kept in a vibrator (150 rpm), and 10 mL of dispersant was added while shaking overnight.

Quantitatively, the contents were transferred to a 500 mL graduated cylinder and filled with distilled water to make 500 mL. The solution was allowed to stand for 40 seconds after steady agitation, then 25 ml of the suspension was decanted into a weighted beaker 10 cm below the surface to create a slurry mass. After 5 hours, the technique was repeated to obtain a clay mass. The solid precipitate residue was obtained by drying the pipette-transferred suspension at 105° C.

The precipitate was quantitatively transferred to a beaker after the supernatant was decanted, followed by repeated stirring, sedimentation, and decanting until a clear supernatant was achieved. The sand was put to a weighted beaker and dried to a consistent weight at 105°C. The particle size was estimated as follows using Equation 9:

Volume of silt + clay (a) = 25 mL

Volume of clay only (b) = 25 mL

Suspension total volume= 500 mL

X_g = weight of silt + clay

Y_g = weight of clay

W(a1) = Initial beaker weight

W(asc) = Beaker weight with silt and clay content

W(b_1) = Initial beaker with clay content

$W(b_{sc})$ = Beaker weight with clay and silt after drying

$W(c_1)$ = Empty weight of beaker containing sand.

$W(cs)$ = Weight of beaker plus sand contents after drying

I $W_{(asc)} - W_{(a1)} = Xg$ Eq. 8

Ii $W_{(bsc)} - W_{(b1)} = Y_g$ Eq. 8.1

Iii (Eq. 9.0) - (Eq 9.1) = wt of silt Eq. 8.2

Iv $W(cs) - Wc$ = Wt of sand Eq. 8.3

Data (Statistical) Analysis

Prior to analysis, the data were checked for normal distribution and variance homogeneity using Stata 16 (KolmogorovSmirnov, $p > 0.05$). To see if the data came from a normal distribution, standard bias and Kurtosis were calculated. Statistics that were not in the range of 2 to +2 were considered deviations from the norm. To analyze the differences in soil physicochemical parameters across the topo sequence, a one-way ANOVA (one-way ANOVA) and a Tukey post-test were utilized.

Geo-Statistical Analysis

To examine the correlations between soil parameters, we employed the Pearson Correlation Test and the Correlation Coefficient (R^2). The contribution of variables to the total variation in soil physicochemical parameters was investigated using principal component analysis (PCA) ($p > 0.05$) was used to test all statistical significance. OriginPro v2021 software was used for all statistical analyses and graphs (OriginLab Corporation., 2021).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z\,(x_i) - z(x_i + h)]^2 \qquad \text{Equ. 9}$$

where z (x I is the value of the variable z at sampling position xi, h is the distance lag in meters, and N(h) is the number of sample points separated by h. In irregular sampling, the distance between sample pairs is rarely exactly equal to h. As a result, a distance interval is typically used to represent h. The distance lag h has a semivariance of c (h).

Computing semivariances at various distance delays yielded semivariogram plots. In the semivariogram plot, the three main parameters to characterize the spatial dependency of soil variables are nugget (C_0), partial sill (C), and range. Partial sill reflects the level of spatial structural variability. The range is defined as the distance at which the semivariogram stabilizes around a limiting value, while the nugget is defined as variability on a scale smaller than the sampling interval and/or sampling and analytical error. The experimental semivariogram was then fitted to a stable theoretical model, which revealed the spatial organization as well as the kriging interpolation input parameters.

Kriging is the best linear unbiased estimate of regionalized variables at unknown places and is regarded the best spatial interpolation. A weighted average was used to generate the spatial forecast of the value of a soil variable z at an unknown site (x 0) (Huang, 2006).

$$\check{z} = (x_o) = \sum_{i=0}^{n} \lambda_i z(x_i) \qquad \text{Equ. 10}$$

where z (x_I) is the known value at the sampling site x*i*, and lambda i is the weight, and (x_0) is the value to be estimated at the point x_0.

The amount of n depends on the size of the moving search window and the user's definition, and the number of sites used for estimation in the search neighborhood around x_0 is n. Kriging differs from other approaches (such as inverse distance-weighted) in that the weight function lambda, *i* is computed using the parameters of the best-fitted variogram model while adhering to unbiasedness and minimum interpolation variance restrictions. In this research, ordinary kriging was used to interpolate soil variables on a grid with a spatial resolution of 10 m.

CHAPTER FOUR

RESULTS

Physico-chemical Variations of Soils Along the Toposequence

Soil Descriptive Statistics

The descriptive statistics of the soil physical and chemical properties across pits are shown in Table 2. The results about the Kolmogorov–Smirnov test indicated normality for most of the variables. Overall, the data demonstrated a platykurtic distribution indicating significant variations within the soil samples. The coefficient of variation for all variables observed was very different ranging from 6 % - 100 %. The lowest coefficient of variation was observed in pH with a value of 6 % while Available P (100 %) had the highest variation. The higher variability of soil properties in terms of coefficient of variation was observed in all examined soil properties with the exception of pH, bulk density and sand (CV < 15%). The table also indicates the skewness and kurtosis deviated considerably from the normal range of 0 and 3 respectively. As seen from the table, soil pH ranged from strongly acidic (5.8) to extremely acidic (pH 4.8). The mineral components of the soils was dominated by sand which had a mean value of 58.4 %. Exchangeable Ca with values ranging from 2.99 – 0.78 cmol/kg dominated the other exchangeable cations.

Table 2: Descriptive Statistics on Soil Physico-chemical Properties

SP	Mean	SD	SE	Skewness	Kurtosis	CV	Min	Median	Max
pH	5.06	0.318	0.075	2.02	3.80	0.06	4.75	4.99	5.89
Ca	1.50	0.62	0.148	1.13	0.33	0.41	0.78	1.265	2.99
Mg	0.66	0.455	0.107	1.61	2.59	0.68	0.23	0.515	1.95
Na	0.06	0.023	0.005	2.04	6.63	0.36	0.03	0.06	0.14
K	0.11	0.06	0.015	0.42	-1.09	0.60	0.02	0.095	0.23
Fe	13.36	6.81	1.60	0.78	1.04	0.50	3.88	14.22	30.64
Cu	0.74	0.50	0.11	0.09	-1.75	0.68	0.1	0.77	1.54
Zn	0.47	0.46	0.10	2.11	4.42	0.98	0.1	0.3	1.88
Av.P	0.32	0.32	0.07	0.88	-0.84	1.00	0.03	0.1	0.98
OC	0.70	0.53	0.12	1.06	0.06	0.75	0.07	0.54	1.83
TN	0.07	0.046	0.01	0.95	0.23	0.60	0.02	0.065	0.18
Sand	58.4	16.23	3.82	-0.52	-0.95	0.27	28.61	60.29	79.29
Silt	8.64	3.13	0.73	2.08	3.92	0.36	5.51	7.795	17.12
Clay	32.8	14.49	3.41	0.428	-1.03	0.44	12.86	31.82	56.84
EA	0.005	0.003	0.0079	0.40	-0.19	0.62	0.001	0.0055	0.013
CEC	2.35	0.93	0.22	0.86	-0.85	0.39	1.3	1.84	4.11
EC	35.7	32.96	7.77	0.83	-0.33	0.92	0.16	31.3	105.1
BD	1.34	0.23	0.05	0.38	-0.92	0.17	1.01	1.27	1.821

*Available Phosphorus (Av.P), Cation Exchange Capacity (CEC), Electrical conductivity (EC); Total Nitrogen (TN), Organic Carbon (OC), Exchangeable Acidity (EA), Bulk Density (BD), Coefficient of variation (CV), Standard Deviation (SD), Standard Error of Mean (SE), Soil Properties (SP)

The textural properties describing the morphological characteristics of the soils along the toposequence are presented in Table 3. It was observed that, the soil samples from the profile pits were mainly of three (3) textural classes i.e. sandy loam, clay and sandy clay loam. The values of bulk density increased down the pedons as shown in Table 3.

Table 3: Soil Fractions and Textural Class of Profile Pits

Profile Pit (PP) Location	Soil Layer	Depth (cm)	Bulk Density	Soil Fraction (%)			Textural Class
				Sand	Silt	Clay	
Summit	OA	0-10	1.36	73.71	6.8	19.5	Sandy loam
	AB	10-40	1.28	57.99	6.12	35.89	Sandy loam
	Btcs1	40-60	1.43	34.27	8.89	56.84	Clay
	Btcs2	60-135	1.5	28.61	16.25	55.14	Clay
Shoulder	Ap	0-18	1.13	74.5	6.51	18.99	Sandy loam
	AB	18-25	1.52	58.35	7.79	33.86	Sandy clay loam
	Btc1	52-75	1.64	41.8	6.88	51.32	Clay
	Btc2	75-137	1.5	35.15	9.48	55.37	Clay
Middle	OA	0-17	1.14	62.23	8.98	28.79	Sandy clay loam
	A/B	17-52	1.22	56.17	8.37	35.46	Sandy clay
	Btv	52-125	1.82	39.28	17.12	43.6	Clay
Foot slope	Ap	0-23	1.30	70.27	7.8	21.93	Sandy clay loam
	Btg1	23-44	1.25	67.4	7.77	24.83	Sandy clay loam
	Btg2	44-66	1.52	63.2	7.03	29.78	Sandy clay loam
	Btg3	66+	1.68	58.22	6.96	34.82	Sandy clay loam
Toe slope	Oe	0-19	1.3	79.08	5.51	15.41	Sandy loam
	A	19-78	1.55	79.29	7.85	12.86	Sandy loam
	Bw	78-96	1.62	72.79	9.57	17.64	Sandy loam

From **Figure 6** the bulk densities across the soil profile layers averagely increased with corresponding depths ranging from minimum (1.01-1.04) and maximum (1.5-1.8). Bulk density was higher in subsurface soils than surface soils. Cumulatively, PP2 and PP3 showed the highest bulk density with PP4 exhibiting the lowest in profile samples.

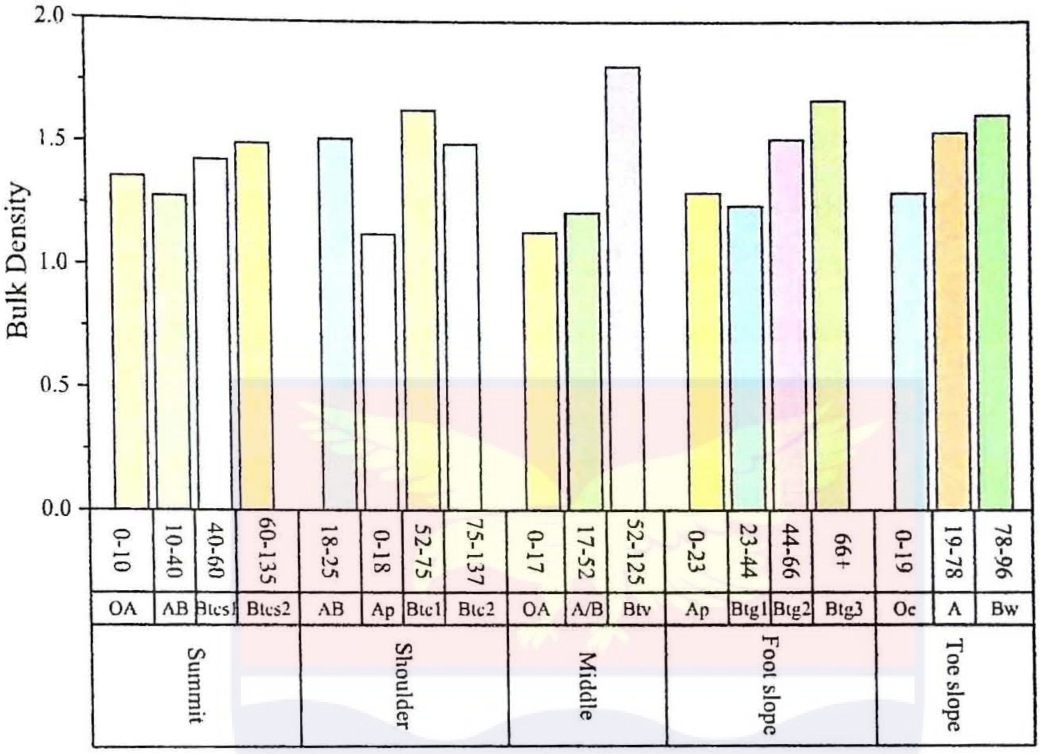


Figure 6: Bulk density across soil layers

Table 4 presents the observed colours within the various horizons of the profile pits. Surface soils at the upper layers expressed dark reddish brown colours (5YR3/3 – 5YR 3/4) whereas the color of the subsurface horizons varied from yellowish red 5YR5/6 to red (10YR4/8). The moist surface soil in the pedons at the depression however varied from dark brown (10YR3/8) to greenish black (5GY2.5/1). The subsurface soil colors at the depression (PP4 and PP5) varied from yellowish brown (10YR5/8) to grayish green (5GY5/8). The results shows that soil colour is greatly influenced by organic matter as the darkness in the surface soils decreased with depth.

Table 4: Colour observations and interpretation

Profile Pit (PP)	Soil Layer	Colour	Colour Interpretation
PP 1	OA	5YR3/3	Dark Reddish Brown
	AB	5YR3/4	Reddish brown
	Btcs1	5YR5/6	Yellowish Red
	Btcs2	2.5YR3/8	Red
PP2	Ap	5YR3/3	Dark Reddish Brown
	AB	2.5YR4/8	Red
	Btc1	10R4/8	Red
	Btc2	5YR5/8	Yellowish Red
PP3	OA	5YR3/4	Dark Reddish Brown
	A/B	5YR5/6	Yellowish Red
	Btv	5YR5/8	Yellowish Red
PP4	Ap	10YR3/8	Dark Brown
	Btg1	10YR5/8	Yellowish Brown
	Btg2	10YR6/8	Brownish yellow
	Btg3	2.5YR6/8	Olive Yellow
PP5	Oe	5GY2.5/1	Greenish Black
	A	N5/1	Greenish Gray
	Bw	5GY5/2	Grayish Green

Comparison of physicochemical properties across profile pits

The pH of the soils in the surface layers of the pedons was found to be strongly to moderately acidic, with values ranging from 4.8 to 5.12 in Figure 7. The pH values within the various profiles however, did not follow any particular trend.

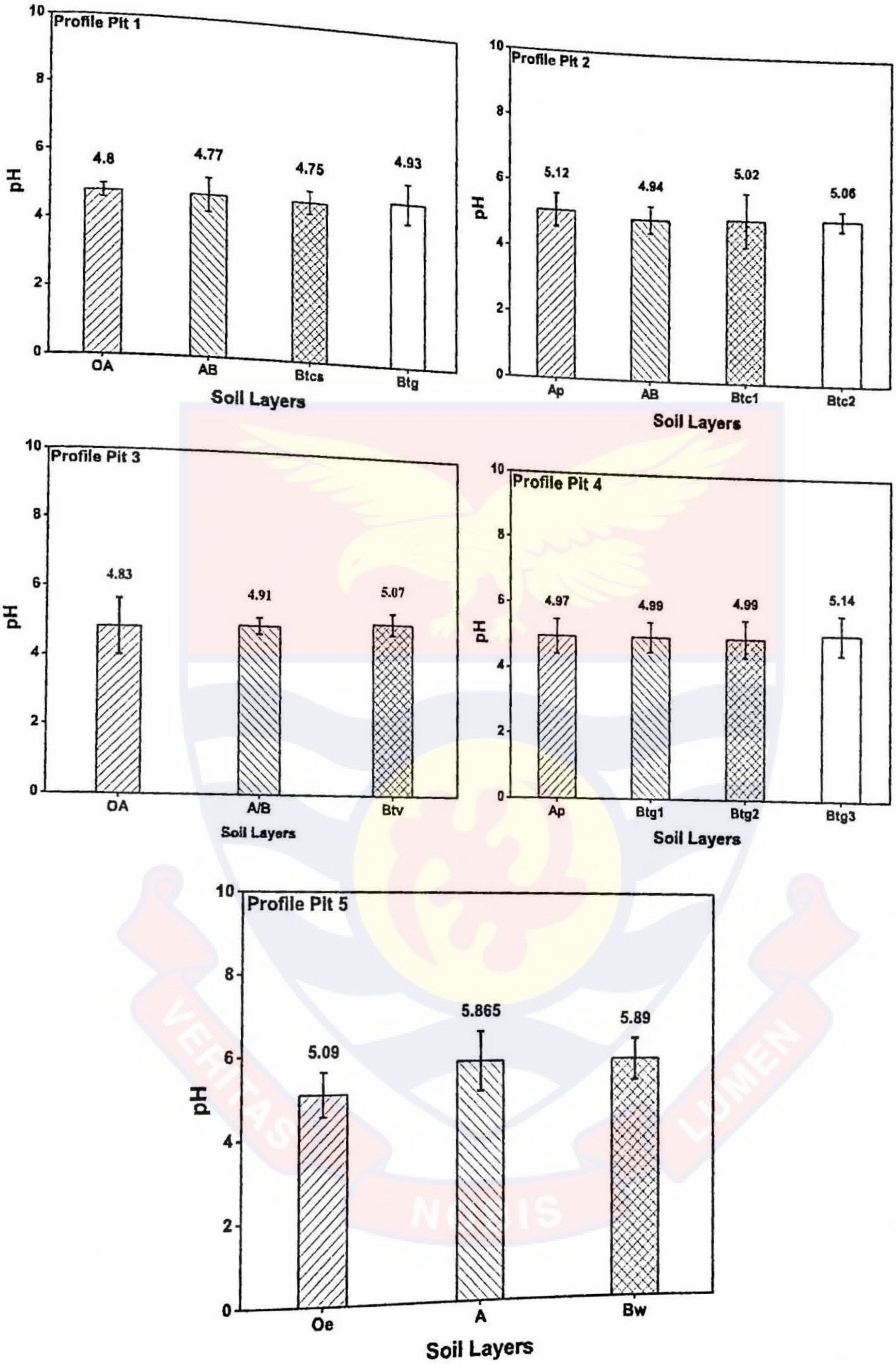
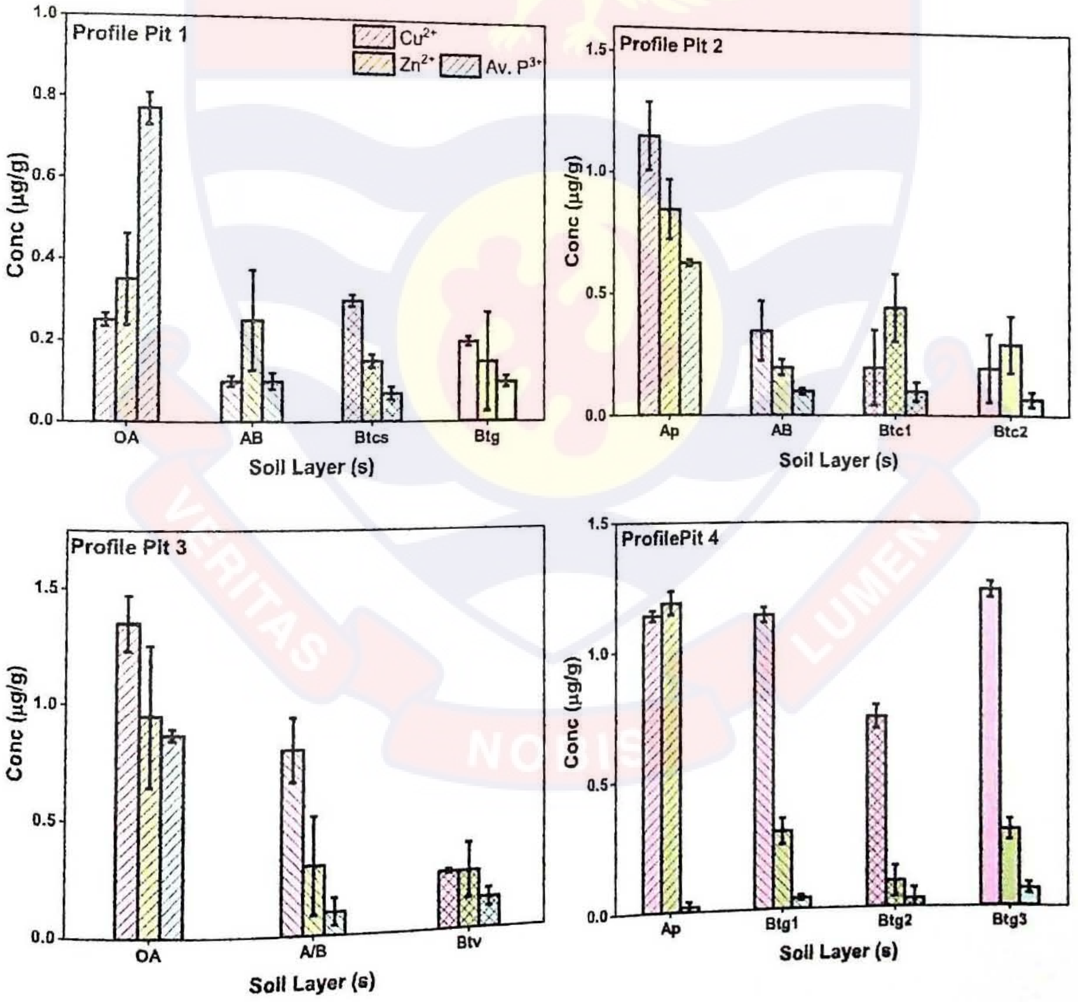


Figure 7: pH concentrations of pedons

From Figure 8, Available P was higher in surface soils (between 0.67 and 0.98 µg/g) of all pedons. The P values for both surface and subsurface soils were very low and below the critical P value of <15µg/g. Cu, Zn and Fe concentrations decreased with increasing depth. Cu concentrations ranged from 1.34 to 1.04 µg/g in the toe slope soils, soils in PP4 however recorded the highest Cu concentrations ranging from 30.64 to 13.78 µg/g. Zn and Fe also followed a similar trend with the surface soils having higher concentrations than the sub soils. Zn values varied from 0.35 to 1.88 µg/g in the top soils and 0.15 to 1.24 µg/g in the soils beneath. Distribution of Fe across the profile pits are shown in Figure 9.



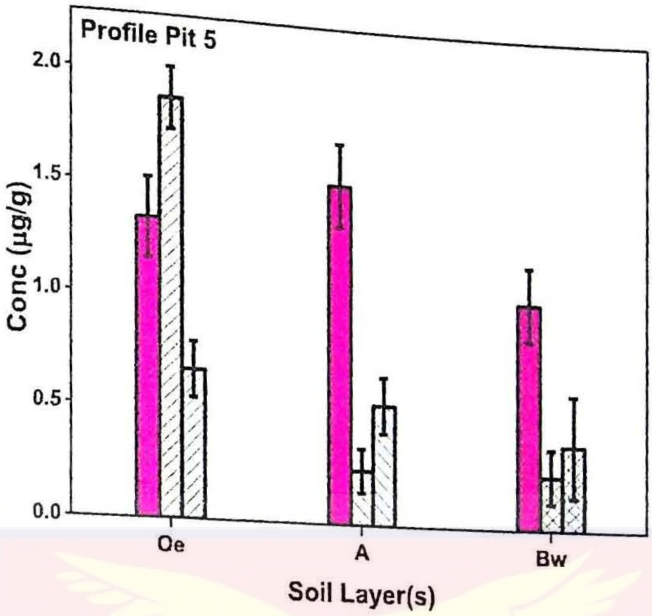
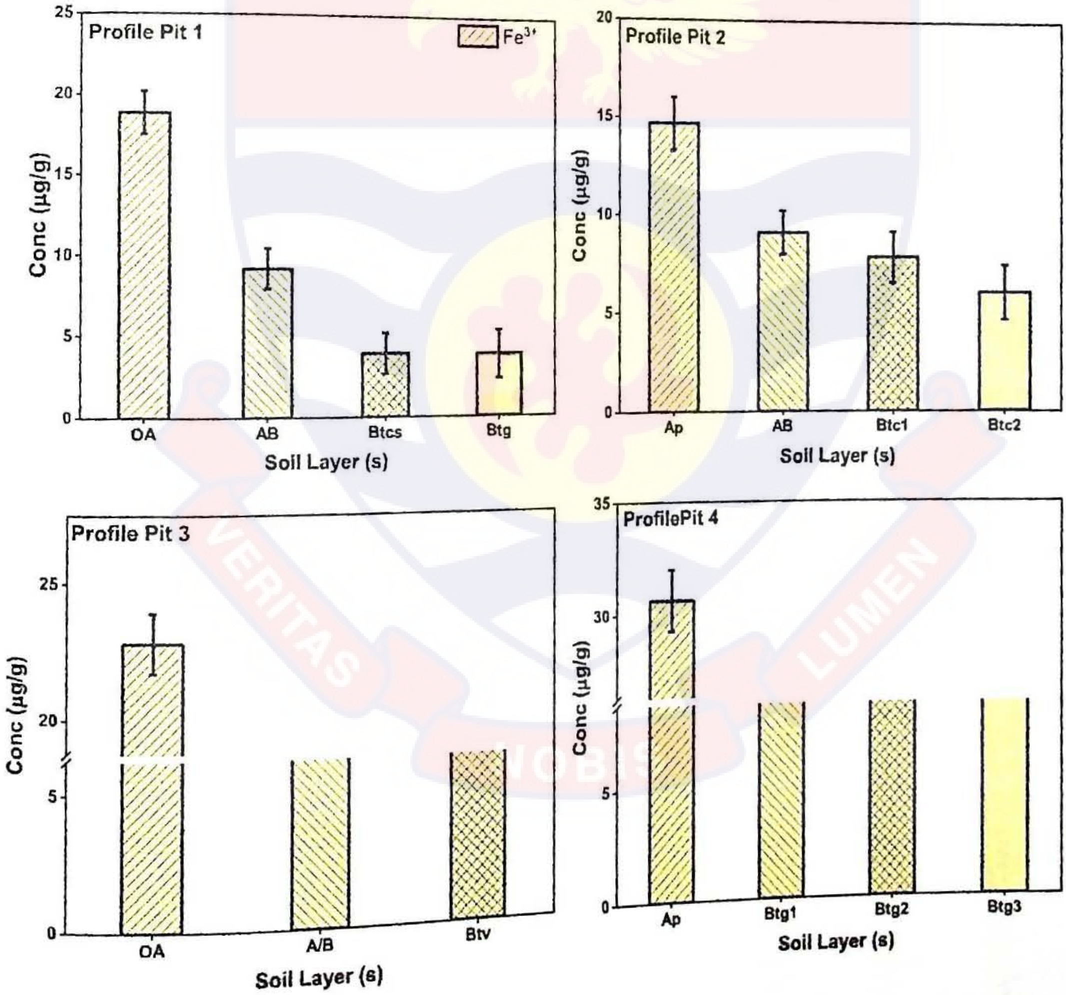


Figure 8: Cu, Zn, Available P concentration of pedons



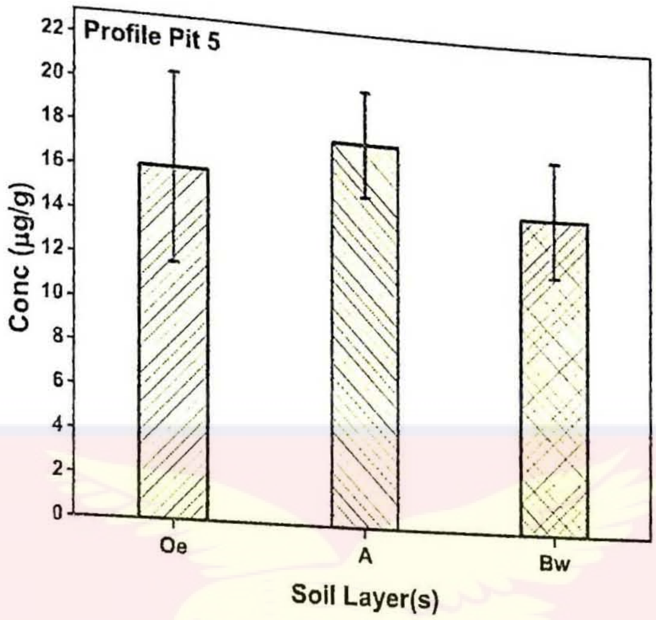
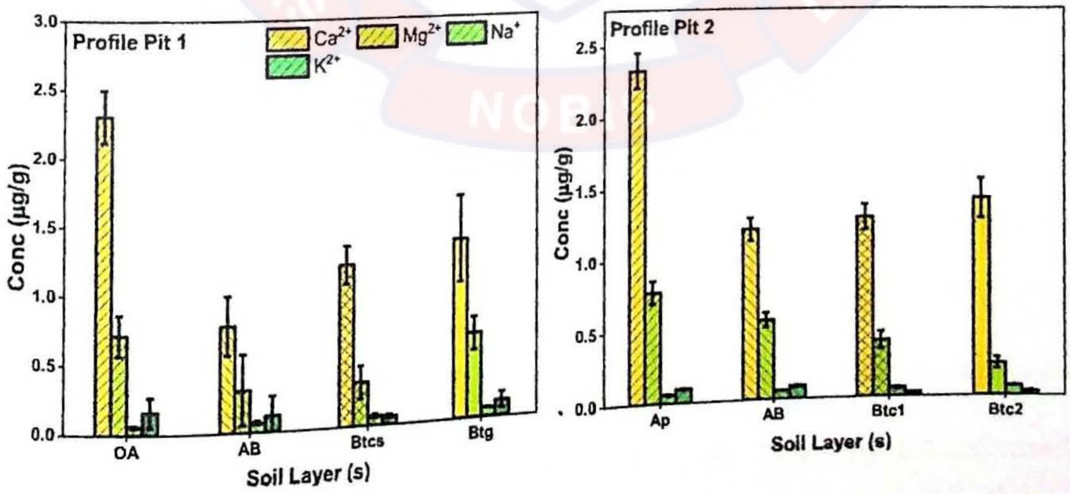


Figure 9: Fe concentrations of pedons

From the Figure 10, Ca dominated the exchangeable complexes across all the layers within the five profile pits with the exception of layer 3 of PP5 which had Mg dominating. Overly their distribution followed Ca > Mg > K > Na pattern. Ca, Mg, K and Na ranged from 0.78 (PP1) to 2.99 cmol/kg (PP4), 0.23 (PP 2) to 1.32 cmol/kg (PP3), 0.03 (PP2) to 0.23 cmol/kg (PP5) and 0.02 (PP2) to 0.14 cmol/kg (PP5) respectively. The exchangeable bases however, did not follow any trend dimensions but were higher in the surface layers than subsequent subsurface layers.



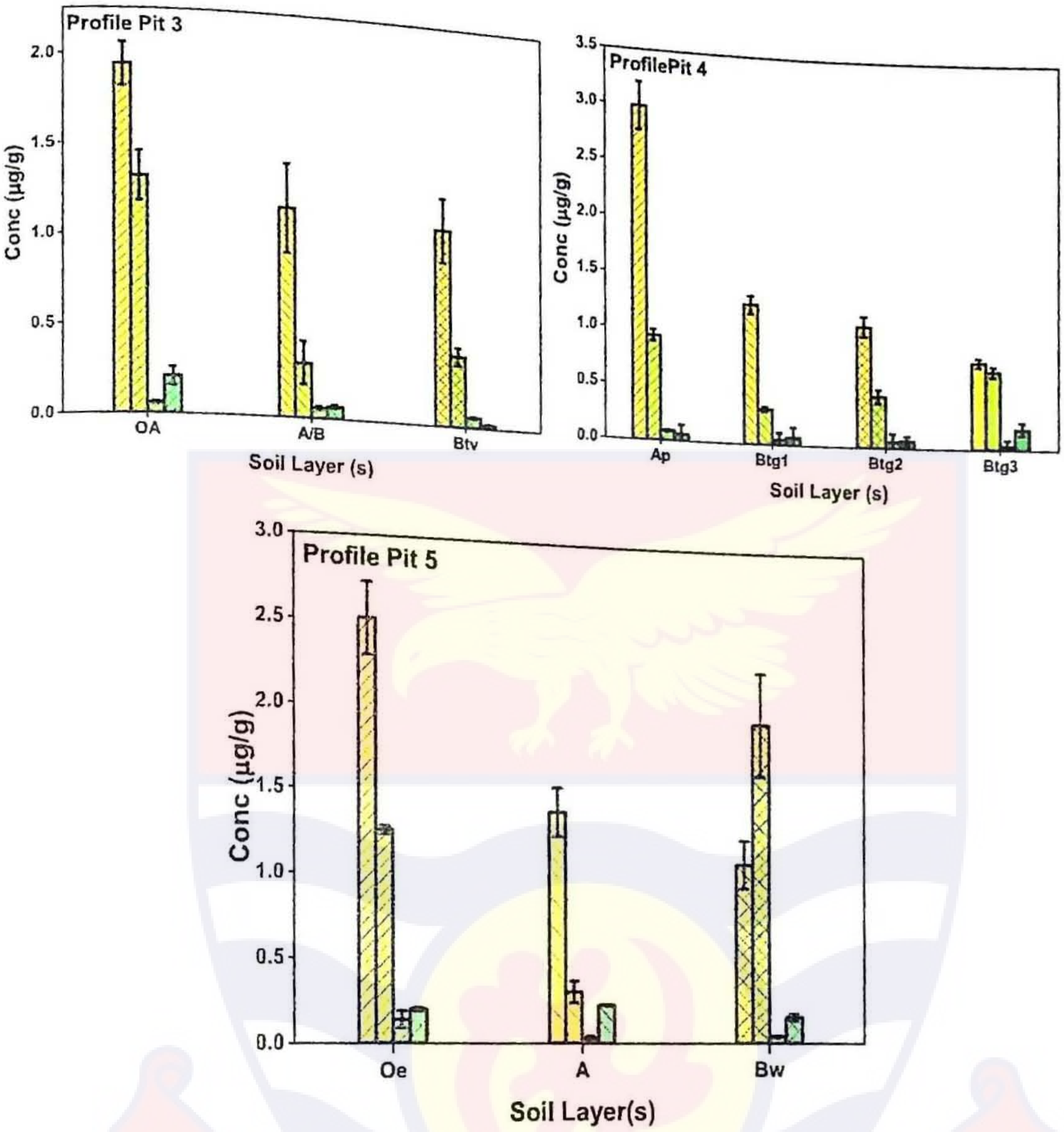


Figure 10: Ca, Mg, Na, K concentrations of pedons

A comparison of the exchangeable acidity (EA) and cation exchange capacities (CEC) across the various soil PP's is shown in Figure 11. CEC varied from 1.30 cmol/kg in subsurface layer of PP 1 to 4.11 cmol/kg in the surface layer of PP5. CEC was relatively higher at the surface soil horizon and found to decrease in depth (PP2, PP3 and PP4). Profile pits 1 and 5 however showcased irregular trend in the concentrations within the various horizons. EA nonetheless were lowest in surface soils than underlying soils. EA across the various pedons and within layers displayed fluctuating concentrations. Generally, EA increased with depth.

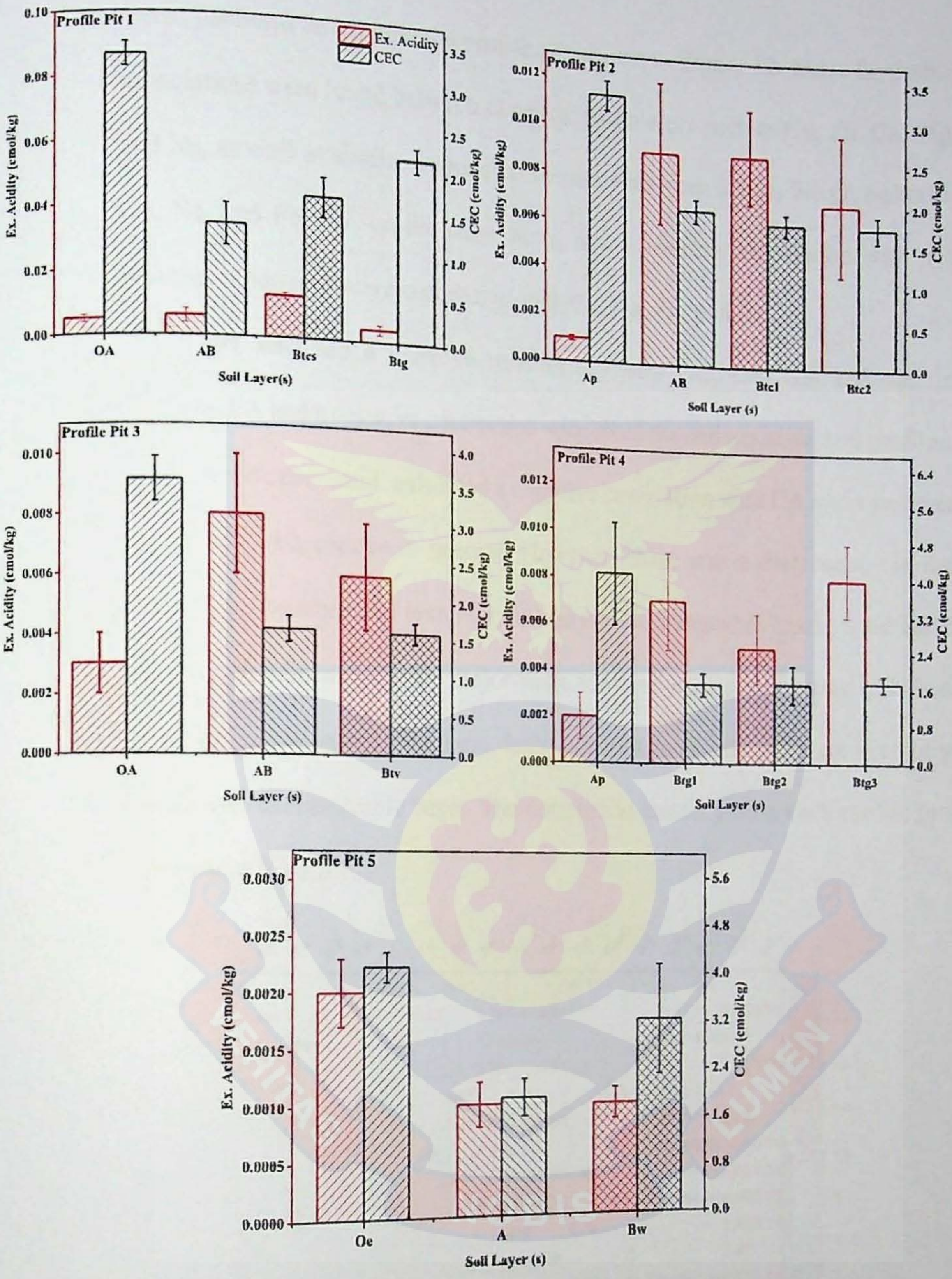
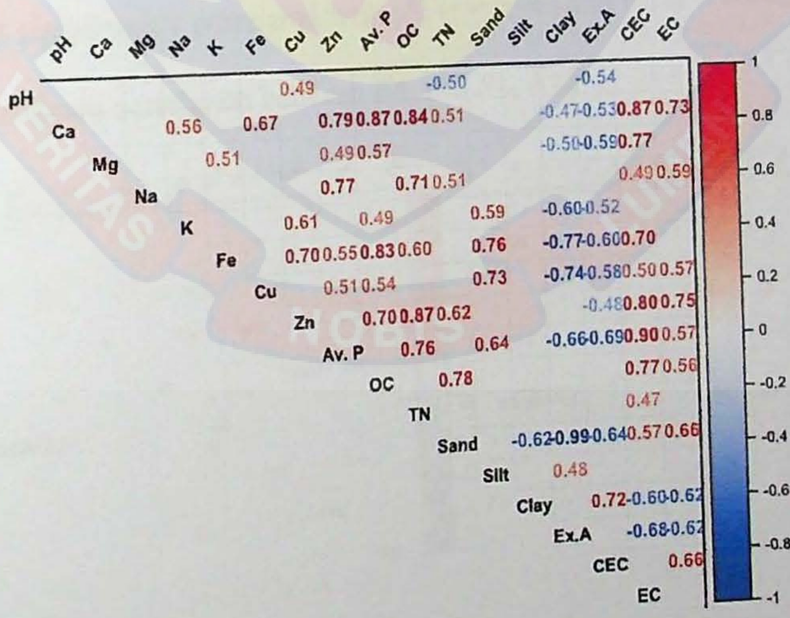


Figure 11: Comparison of EA and CEC across profile pits

Relationship between soil Physico-chemical Properties across profile pits

Pearson's correlation analysis found substantial connections between the physical and chemical parameters of the soils studied, and that the correlations were consistent throughout the profile pits shown in Figure 12. More favorable associations were found between chemical parameters such as Cu, Zn, Ca, Mg, and Na, as well as similar positive correlations between accessible phosphorus, Cu, Na, and Fe. TN, on the other hand, had a negative association with pH, whereas it had a positive correlation with Ca, Na, Zn, and OC.

pH also had a negative relationship with OC, EA, Ca, and Na. In addition, EA had a negative connection with all of the cations in the soil profiles. CEC, on the other hand, exhibited a negative correlation with EA and a positive correlation with cations in general. However, there was a discrepancy in the relationship between soil textural qualities and exchangeable bases. Sand had a positive relationship with the major basic ions, whereas silt and clay soils had the reverse relationship. Similarly, bulk densities in profile pits were inversely linked with exchangeable bases. The correlation matrix across each profile pits is shown in Figure 12.



Significance at α = 0.05 (95% confidence interval)

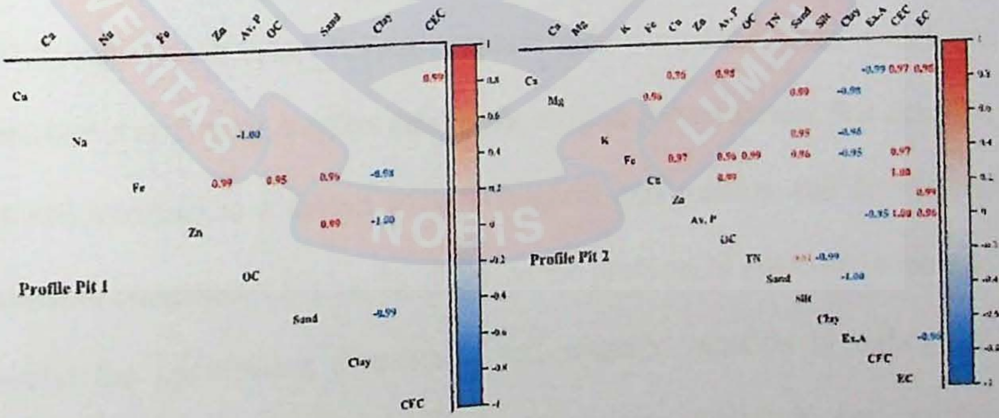
Figure 12: Pearson's correlation matrix of soil properties

Table 5: Correlation matrix of physicochemical properties between surface and sub-surface layers

Soil layers	Parameters	pH	Ca^{2+}	Mg^{2+}	%TN	Na^{+}	EA	$Av.P^{3+}$	Fe^{3+}	Cu^{2+}
Surface layers	Na^{+}			0.94						
	$Av.P^{3+}$				-0.96					
	Zn^{2+}								0.91	
Sub-surface layers	Ca^{2+}	0.90								
	Na^{+}		0.88							
	EA					0.91				
	$Av.P^{3+}$						-0.90			
	Cu^{2+}								0.99	
	Zn^{2+}								0.97	0.98

Alpha (0.05), confidence interval (95%)

Table 5 displays an overview of the interdependence of soil properties with each other in surface layers and subsurface layers using Pearson's correlation matrix shown in Figure 13. There were significant and positive correlation between Mg and Na (0.94*), Av.P and TN (0.96*), Zn and Fe (r = 0.91*) in the surface layers. Ca content in the subsurface layers was positively and significantly correlated with pH (r = 0.98) and Na (r = 0.88). Positive and significant correlation between EA and Na, Av.P



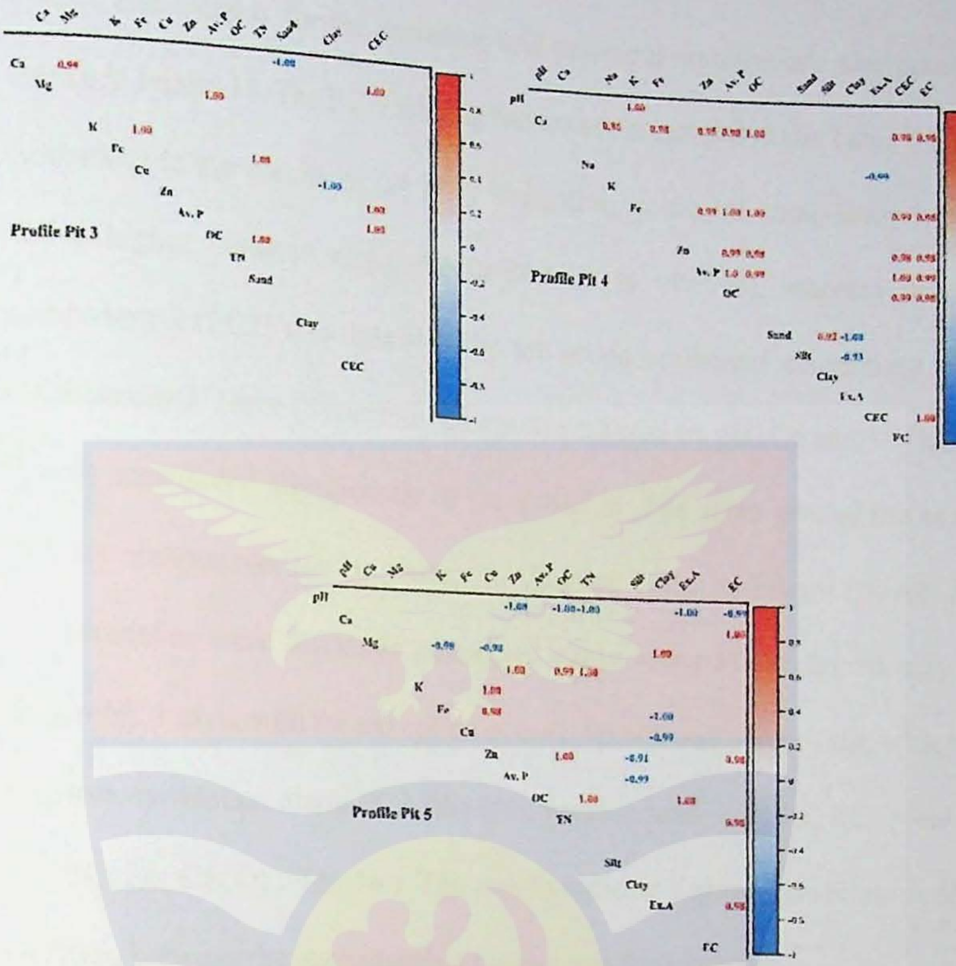


Figure 13: Pearson correlation plots of soil physicochemical properties

Principal Component Analysis of Soil Physico-chemical Properties

Principal component analysis examines the interrelationships between many variables in terms of their common underlying dimensions, which are referred to as factors. It offers data on the most important factors that describe overall variance in a dataset using orthogonal axis rotation and determined principal components (PCs). To eliminate the problem of autocorrelation and restrict the contributing elements of soil property variation to orthogonal principal components, PCA was used with varimax rotation to evaluate the overarching influence of slope gradient on the variability of these soil properties.

The weights for the variables and principal components computed are shown in Figure 14. The PCA loading factors are presented in the Table 6 below. According to the results of the PCA ordination, principal component 1 (PC1) had a higher variance along the ordinate axes (49.9%), whereas principal component 2 (PC2) was described by the second principal component (PC2) (18.4 percent). Three (3) primary components based on pH, Ca and Mg loading factors contributed significantly to the variation. The scree plot of the several primary components can be seen in the diagram below in Figure 15. All other characteristics were favorably connected either along PC2 (percent clay and EA) or PC 1 axes, with the exception of bulk density and percent silt, which had negative correlation along PC2 axis (pH, percent sand, Mg, Fe, EC, Available P, CEC, Zn, Ca, OC, TN, Na). The results indicate a strong association of the variation between the exchangeable cations and their sources.

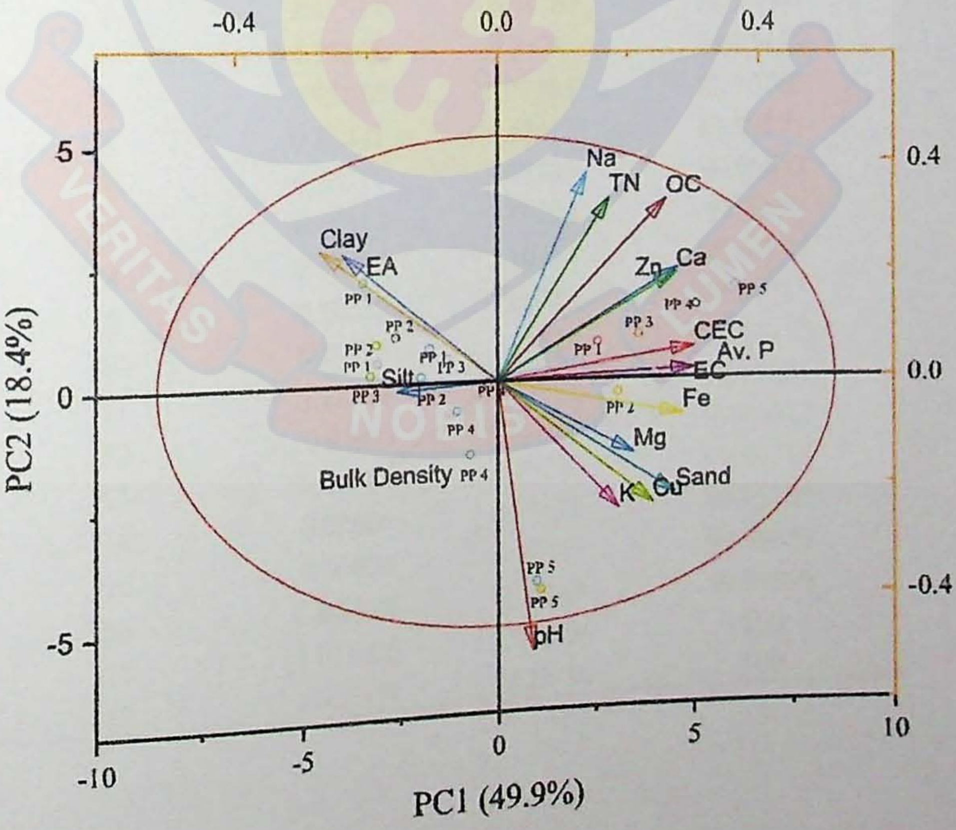


Figure 14: PCA biplot of soil physicochemical properties

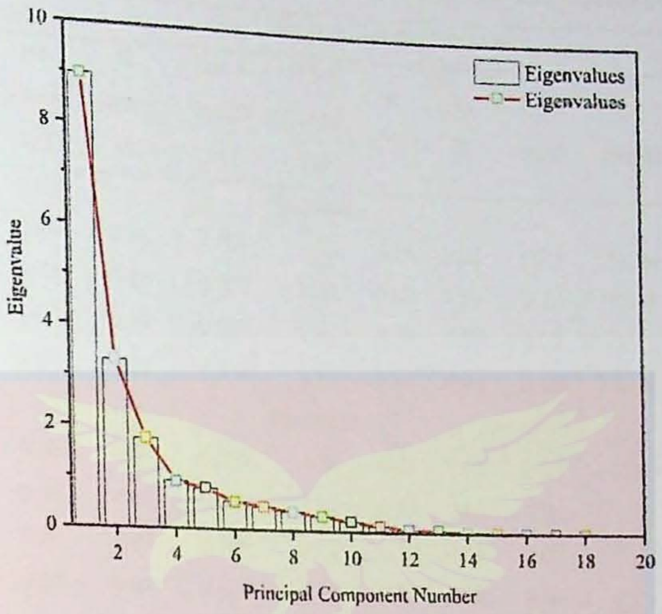


Figure 15: Scree Plot of principal components and eigenvalues

Table 6: Principal Components and Eigenvalues

Principal Component Number	Eigenvalue	Percentage of Variance (%)	Cumulative (%)
1	8.98003	49.88907	49.88907
2	3.31517	18.41761	68.30668
3	1.77262	9.8479	78.15458
4	0.93835	5.21304	83.36762
5	0.81471	4.52617	87.89379
6	0.55311	3.07283	90.96662
7	0.46314	2.57298	93.5396
8	0.37938	2.10764	95.64724
9	0.30035	1.66858	97.31583
10	0.20795	1.15529	98.47112
11	0.12594	0.69969	99.17081
12	0.0591	0.32836	99.49917
13	0.05543	0.30796	99.80713
14	0.02606	0.14475	99.95188
15	0.00804	0.04465	99.99653
16	6.24E-04	0.00347	99.99999
17	1.07E-06	5.94E-06	100
18	2.92E-31	1.62E-30	100

Table 7: Chemical properties across various soil horizons

Layer	pH	Exchangeable Complex												
		Ca (cmol/ kg)	Mg (cmol/ kg)	Na (cmol/ kg)	K (cmol/ kg)	Ex. A (cmol/ kg)	TCEC (cmol/ kg)	% OC	% N	Av.P (µg/g)	Fe (µg/g)	Cu (µg/g)	Zn (µg/g)	EC (µS/cm)
							Summit							
OA	4.8	2.31	0.72	0.06	0.16	0.005	3.25	1.14	0.11	0.77	18.84	0.25	0.35	84.34
AB	4.77	0.78	0.31	0.07	0.12	0.006	1.30	0.68	0.06	0.10	9.20	0.10	0.25	0.415
Btcs1	4.75	1.19	0.32	0.07	0.06	0.013	1.66	0.59	0.10	0.07	3.93	0.30	0.25	0.16
Btcs2	4.93	1.34	0.63	0.07	0.12	0.004	2.17	0.34	0.04	0.10	3.88	0.20	0.15	0.16
							Shoulder							
Ap	5.12	2.33	0.78	0.06	0.10	0.001	3.26	0.63	1.05	0.07	14.69	1.15	0.85	86.65
AB	4.94	1.20	0.56	0.06	0.09	0.009	1.91	0.10	0.54	0.06	9.12	0.35	0.20	0.29
Btc1	5.02	1.27	0.40	0.06	0.03	0.009	1.77	0.10	0.54	0.07	7.88	0.20	0.45	22.61
Btc2	5.06	1.40	0.23	0.07	0.03	0.007	1.74	0.07	0.28	0.04	6.09	0.20	0.30	17.355
							Middle							
OA	4.83	1.94	1.32	0.21	0.06	0.003	3.53	1.59	0.18	0.87	22.83	1.35	0.95	10.7
A/B	4.91	1.17	0.31	0.07	0.06	0.008	1.62	0.65	0.08	0.10	11.61	0.80	0.30	30.865
Btv	5.07	1.11	0.40	0.02	0.06	0.006	1.59	0.47	0.06	0.13	8.12	0.25	0.25	15.135
							Foot Slope							
Ap	4.97	2.99	0.94	0.09	0.06	0.002	4.08	1.67	0.09	0.98	79.75	30.64	1.14	1.19
Btg1	4.99	1.26	0.32	0.05	0.07	0.007	1.71	0.49	0.14	0.10	35.455	16.26	1.14	0.30
Btg2	4.99	1.10	0.47	0.06	0.07	0.005	1.72	0.36	0.04	0.03	36.285	13.78	0.74	0.10
Btg3	5.14	0.79	0.71	0.04	0.19	0.008	1.75	0.29	0.04	0.07	40.285	14.66	1.24	0.30
							Toe Slope							
Oe	5.09	2.51	1.26	0.14	0.20	0.002	4.11	1.83	0.16	0.67	161.26	1.34	1.88	105.1
A	5.865	1.39	0.31	0.03	0.23	0.001	1.95	0.14	0.02	0.55	17.89	1.54	0.25	46.595
Bw	5.89	1.09	1.95	0.04	0.16	0.001	3.24	0.07	0.02	0.39	14.93	1.04	0.25	31.85

Morphological classification of soil

The profiles sunk were reasonably deep, maximum depth of 137 cm (PP 2) and minimum of 66 cm (PP 4). PP1, PP2 and PP4 each had four generic soil horizons, whereas PP3 and PP5 had three generic horizons each. The summit, shoulder, and mid slope pedons that is, PP1, PP2, and PP3 were well-drained, whereas the lower (PP4) and valley bottom slopes (PP5) were poorly drained.

Small water pools were discovered, presumably as a result of severe rains that came in waves. Pedons from PP1 comprised of secondary forest with thicket vegetation on a soil that may have formed from the current geologic formation. Pedons PP2, PP3, PP4, and PP5 were located in abandoned cocoa plantation surrounded by thicket vegetation in a secondary forest.

All five pits showed weak fine to moderate granular structures, with the subsurface soils having moderate to strong, medium to coarse, angular and subangular blocky structures. In surface soils, non-sticky and slightly sticky (wet) soil consistencies were observed, whereas sticky (wet) and firm (moist) soil consistencies were primarily obtained in subterranean soils.

From the topsoil to the last horizon of each pit, layer boundaries were clearly evident. Ant burrows and worm casts were also discovered within the pits, indicating faunal pedoturbation. In the soil column, lateral roots, tip roots, and root hairs were found, mostly in the first three layers of the various profile pits. Both the surface and underlying soils had a wide range of coloration. In all of the profile pits, the first layer exhibited a substantial difference in soil color.

The coloration ranged from a very dark greyish brown to a very light greyish brown. 10Yr 3/2 reddish-brown for PP5, 10Yr 3/3 dark brown for PP4 PP3, reddish-brown, 5Yr 3/4 For PP2, 5Yr 3/2 greenish-black surface soils were detected, while for PP5, 5GY 2.5/1 greenish-black surface soils was noticed. Erosion was a persistent threat to the pedons. Erosion strips generated light-colored soils in the uplands and mid soils. The higher slope, which had a coarse texture and a low SOM, had the maximum erodibility, whereas the lower and valley bottom slopes, which had predominantly deep, organic-rich leached soils, had the least. The many soil types are depicted in the diagram shown in Figure 16.

The morphological properties are listed in the table below Table 8. In the surface horizon of all five profiles, the soil texture ranged from sandy loam to sandy clay loam. The bulk densities were found to increase as the depth of each profile pit was increased.

Table 8: Morphological Properties of Soil across various horizons

Horizon	Depth	Munsell	Texture	Structure	Consistency	Boundary	Root	Miscellaneous
				Summit				
OA	0 – 10	5YR 3/3	Sandy loam	wfg	ns. Fr	CS	Fmr	Few ants casts, worms
AB	10 – 40	5YR 4/5	Sandy loam	wsablk	ns. Np	CD	vfr and mr	common Fe and Mg_2O
Btg	40 – 60	5YR 5/6	Clay	msablky	ss.np	GS	vfr. Mr	common Fe and Mg_2O
Btsc	60 – 135	2.5YR 3/8	Clay	msablky	ss. Sp	CD	vfmr	
				Shoulder				
Ap	0 – 18	5YR 3/3	Sandy loam	wfg	qs. Fr	CS	fmr	Borrows of ants
AB	18 – 52	2.5YR 4/6	Sandy clay loam	wsablk	qs	CD	vffr	few ants cast
Btc1	52 – 75	10R 4/8	Clay	blky	s and p	CS	-	few gravels
Btc2	75 – 120	5YR 5/8	Clay	sblky	vm, p and s	CS	-	
				Middle				
OA	0 – 17	5YR 3/4	Sandy clay loam	wgs	ns	CS	ffr	ants, earthworms
A/B	17 – 52	5YR 5/6	Sandy clay	gs	ss, sp	GC	vffr	few quartz gravels
Btv	52 – 125	5YR 5/8	Clay	sblky	vm	WC	-	10R 4/8 mottling
				Foot Slope				
Ap	0 – 23	10YR 3/3	Sandy loam	vfg	ns, np	CS	ffr, fcr	Few ants cast
Btg1	23 – 44	10YR 5/8	Sandy clay loam	wsablk	ss, np	CS	ffr	10YR 4/6 mottling
Btg2	44 – 66	10YR 6/8	Sandy clay loam	wsablk	ss, np	CS	ffr	
Btg3	66+	2.5Y 6/8	Sandy clay loam	sablk	s	WC		
				Toe Slope				
Oe	0 – 19	5GY 2.5/1	Sandy loam	wgs	ns	CS	ffr	-
Ag	19 – 78	N5/5	Sandy loam	sblk	s	CS	ffr	-
Cr	78+	5GY 5/2	Sandy loam	sblk	se	CS	-	-

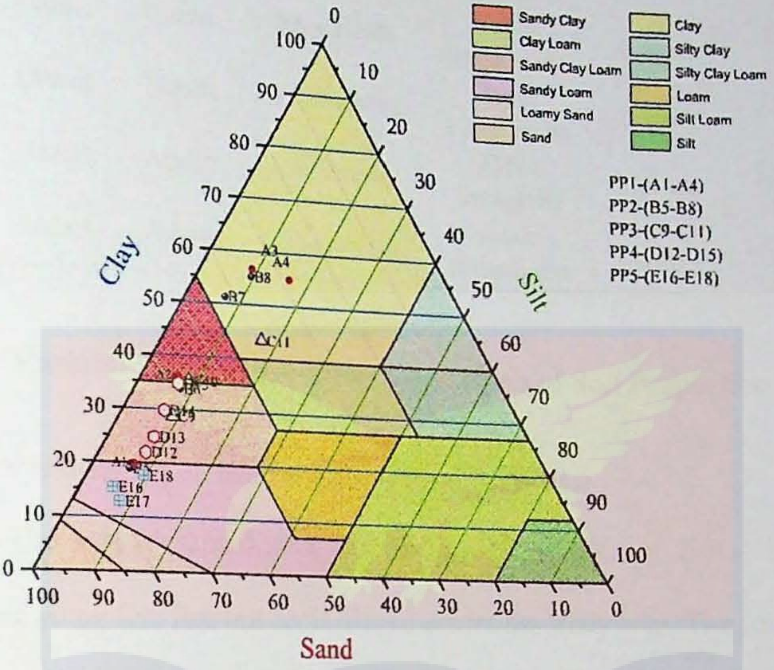


Figure 16: Various soil classes across profile pits

Soil classification by WRB

The soil orders and classes identified on the toposequence per USDA and by the World Resource Base (WRB) are depicted in Table 9. The soils were mostly of the Ultisol type, ranging from PP1 to PP4, PP5 Entisol.

Table 9: Classification of Soils Along the Wamaso Toposequence

Pedon	Groups				WRB Classes	
	Order	Suborder	Great Group	Subgroup	Major	Unit
Pit 1	Ultisol	Ustults	Haplustults	Typic Haplustults	Lixisol	Ferric Lixisol
Pit 2	Ultisol	Ustults	Rhodustults	Typic Rhodustults	Lixisol	Chromic Lixisol
Pit 3	Ultisol	Ustults	Plinthustults	Typic Plinthustults	Lixisol	Plinthic Lixisol
Pit 4	Ultisol	Aquult	Epiaquult	Typic Epiaquults	Fluvisol	Endogleyic Fluvisol
Pit 5	Entisol	Aquent	Endoaquent	Aquic Endoaquent	Regosol	Gleyic Regosol

Spatial Variability and Geo-Statistical Analysis of Soil Properties

Descriptive Statistics on Soil Physicochemical Properties

The data presented here is based on the analysis of 290 soil samples collected along five line transects placed across the study area. The summary of the descriptive statistics is shown in Table 10. The Kolmogorov-Smirnov test ($p > 0.5$) revealed that most variables were not normally distributed, implying that the majority of the soil parameters assessed in the study area were not similar in terms of mean. Large variations can also be attributable to sample method employed that left wide spaces between sampling units, because soil properties are more similar at close distances than they are at far distances.

The observed coefficients of variation (CV) ranged from 9 percent to 208 percent. The lowest CV was observed for pH and the highest obtained for Ca. Furthermore, the skewness and kurtosis indicators of soil variables deviated significantly from the usual values of 0 and 3, respectively. These significant changes in soil attributes could be attributed to a variety of soil management and land use methods in the research area, as well as the raw materials used to create the soil (Havlin and Heiniger, 2020). With an average pH of 5.22, the diverse samples were almost acidic.

Table 10: Descriptive Statistics on Major Soil Properties

	Mean	SD	SE	Skewness	Kurtosis	CV	Min	Max
Ph	5.22	0.45	0.03	0.80	3.50	0.09	4.13	7.80
EC	62.62	24.02	1.45	1.57	3.90	0.38	16.86	181.08
Fe	49.12	41.17	2.48	2.51	6.96	0.84	6.44	264.09
Cu	2.37	1.61	0.10	1.26	1.39	0.68	0.10	8.64
Zn	5.15	4.22	0.25	2.61	9.54	0.82	0.15	28.96
Ca	1.12	2.32	0.14	7.29	78.9	2.08	0.04	29.02
Mg	1.96	1.68	0.10	3.70	19.2	0.86	0.16	13.07
K	0.64	0.65	0.04	1.69	3.20	1.01	0.05	3.38
Na	0.11	0.06	0.00	2.18	5.56	0.57	0.04	0.42
EA	0.00	0.00	0.00	1.67	2.64	0.96	0.00	0.02
CEC	3.74	2.16	0.13	2.63	10.8	0.58	1.25	16.20
P	2.10	1.88	0.11	3.85	22.2	0.90	0.07	17.08
OC	1.24	0.42	0.03	0.77	0.82	0.34	0.15	2.84
N	0.14	0.06	0.00	2.65	12.7	0.47	0.04	0.61
Clay	24.42	10.10	0.61	0.34	-0.07	0.41	7.25	60.87
Silt	8.91	3.08	0.19	2.71	13.60	0.35	3.92	30.18
Sand	66.76	10.95	0.66	-0.45	-0.05	0.16	27.49	88.51
BD	1.29	0.18	0.01	-1.14	2.23	0.14	0.56	1.74

P= Available Phosphorus, EC= Electrical Conductivity, CV=Coefficient of Variation, SD=Standard Deviation, SE=Standard Error of Mean, BD=Bulk Density

Relationship between Soil Variables

To characterize the link between the chemical parameters of the selected soil, the Pearson correlation coefficient was calculated as ($p > 0.05$) for each property. A triangular matrix shown in Figure 16 depicts these relationships. Overall, there was a strong link between some of the variables. EC and pH ($R^2 = 0.267$), pH and OC ($R^2 = 0.126$) and also Ca and pH ($R^2 = 0.33$) exhibited positive connections. EC ($R^2 = 0.282$), Na ($R^2 = 0.219$), and Fe ($R^2 = 0.212$) all demonstrated a strong positive connection with P.

Soils within the study area exhibited very low concentrations of available P.

Clay was positively linked with most variables, including CEC ($R^2 = 0.42$), Cu ($R^2 = 0.28$), Zn ($R^2 = 0.30$), N ($R^2 = 0.423$) and OC ($R^2 = 0.47$), among other exchangeable cations and other physical properties. Significant but negative association was established between sand and clay ($R^2 = -0.98$) in Figure 17. A negative connection was also found between EA and Av. P ($R^2 = 0.613$) and Av. EC ($R^2 = 0.127$).

Figure 17: Pearson correlation plot of soil physicochemical properties

Principal component analysis on soil variables

Principal component analysis was applied to look into the numerous factors that contributed to the changes in the soil's physicochemical qualities. The soil variables from the sampling sources are sparsely distributed, as shown by the results in Figure 17 and the scree plot in Figure 18. The first six components (clay, potassium, pH, bulk density, Zn, and silt) provided the most variability along PC 1 shown in Table 11 This displays a positive connection with EA, bulk density, percent sand, Fe, Available P, percent clay, percent silt, percent N, Zn, Cu all showed negative correlations along PC2 (13.6%), although Av. P, Na, Av. P, ECEC, Mg, K, Ca, and percent OC were favorably associated along the same axis.

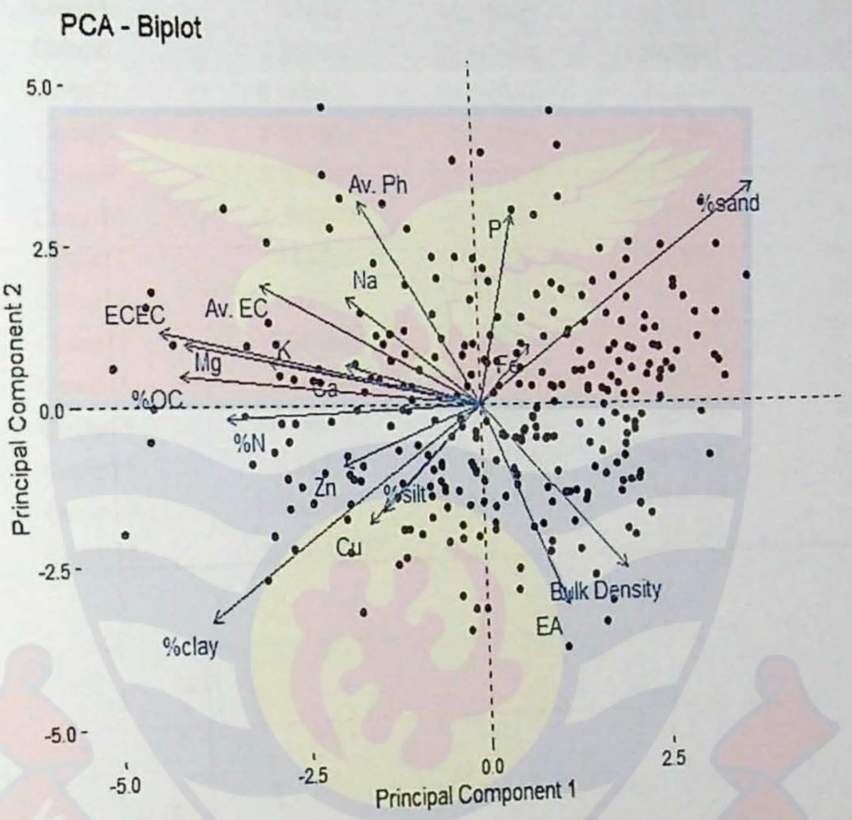


Figure 18: PCA Biplot of Soil Physicochemical Properties

Table 11: PCA results of eigenvalues

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	4.38059	1.74335	0.2434	0.2434
Comp2	2.63724	0.55352	0.1465	0.3899
Comp3	2.08372	0.556328	0.1158	0.5056
Comp4	1.52739	0.322975	0.0849	0.5905
Comp5	1.20442	0.186443	0.0669	0.6574
Comp6	1.01798	0.109399	0.0566	0.714
Comp7	0.908578	0.191515	0.0505	0.7644
Comp8	0.717064	0.100255	0.0398	0.8043
Comp9	0.616809	0.030831	0.0343	0.8385
Comp10	0.585978	0.103837	0.0326	0.8711
Comp11	0.48214	0.00972035	0.0268	0.8979
Comp12	0.47242	0.0910788	0.0262	0.9241
Comp13	0.381341	0.0724754	0.0212	0.9453
Comp14	0.308866	0.0226689	0.0172	0.9625
Comp15	0.286197	0.0691628	0.0159	0.9784
Comp16	0.217034	0.049964	0.0121	0.9904
Comp17	0.16707	0.161914	0.0093	0.9997
Comp18	0.00515588	.	0.0003	1

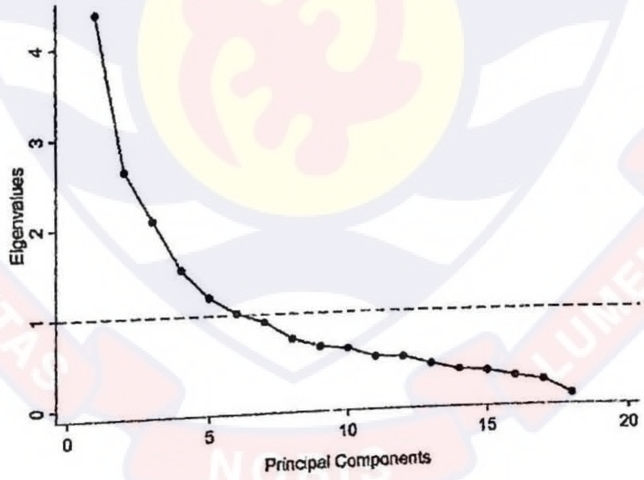


Figure 19: Screen Plot on principal component and eigenvalues

Spatial interrelationships

The spatial structures of various soil parameters were detected and the best model to describe these spatial structures was identified by computing the semivariogram. The ideal semivariogram model's model parameters are shown Table 12.

To determine unsampled site values, an optimal model was applied to each parameter, kriging was used to evaluate the accuracy of soil characteristic values, and multiple error estimates were utilized to determine unsampled site values. For each soil, the nugget effect (Co), threshold (Co + C), and range of influence are listed. We also discovered that geographical dependency was related to the degree of autocorrelation between the sample units (nugget: sill ratio).

When the ratio (nugget: threshold) was > 75 percent, spatial-dependent variables were classed as random location-dependent, and moderate location-dependent when the ratio was 25-75 percent. 25% of the total. These classifications were acceptable to me (Chiles and Delfiner, 2009). The virtual semivariogram was calculated for all parameters within ArcGIS 10.7 environment using a stable model. Nugget values are frequently signs of continuity at short intervals, as well as random fluctuations due to measurement precision or variations in qualities that cannot be noticed inside the sample region. The fitted semivariogram model's upper limit is represented by the threshold. The nugget-to-sill ratio is linked to soil characteristics' geographical dependency. On the other hand, the semivariogram range depicts the average distance traveled by the majority of the variable semivariances.

Table 12: Semiovariogram Parameters for Soil Properties

Soil properties	Model type	Nugget (C$_0$)	Partial sill (C)	Sill (C$_0$ + C)	Nugget/sill ratio (%)	Spatial class	Range (meters)
pH	Stable	0.002	0.004	0.006	38.24	Moderate	67.78
Nitrogen	Stable	0.000	0.010	0.010	0.99	Strong	14.05
Bulk Density	Stable	0.006	0.017	0.023	28.06	Moderate	9.6385
Phosphorus	Stable	0.403	0.284	0.686	58.65	Moderate	512.29
Potassium	Stable	0.335	0.693	1.029	32.60	Moderate	305.58
Zinc	Stable	0.243	0.536	0.780	31.19	Moderate	482.01
Calcium	Stable	0.202	1.518	1.720	11.76	Strong	314.59
Magnesium	Stable	0	0.311	0.311	0	Strong	10.109

§Nugget/sill ratio (%) = [C$_0$/(C$_0$+C)] *100
*Strong = % nugget < 25%; Moderate = % nugget 25-75%; Random = % nugget > 75% (Cambardella et al., 1994)

Geo-Statistical analysis of soil properties across the study area

Based on the nugget e□ect relationship between indicators and continuity and distance relationship effects can be defined. Soil properties with a lower nugget e□ect were generally defined by the stable semi-variogram model shown in Table 12. The soil parameters including, bulk density and pH (Figure 17-Figure 18) respectively was observed to follow a moderate spatial correlation and distribution across the study area.

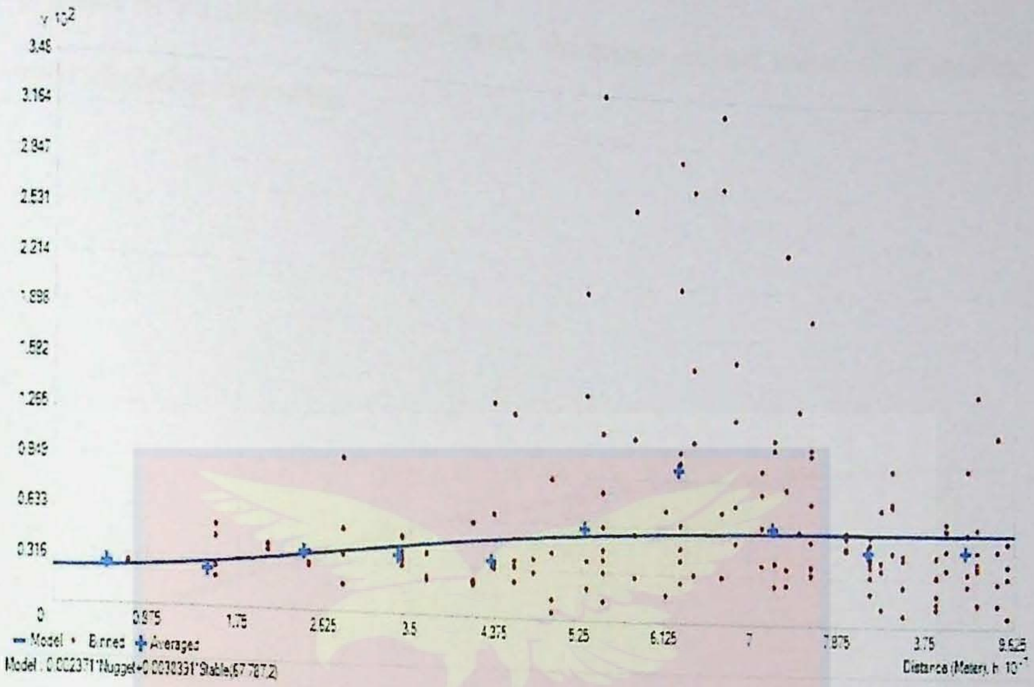


Figure 20: Variogram of pH

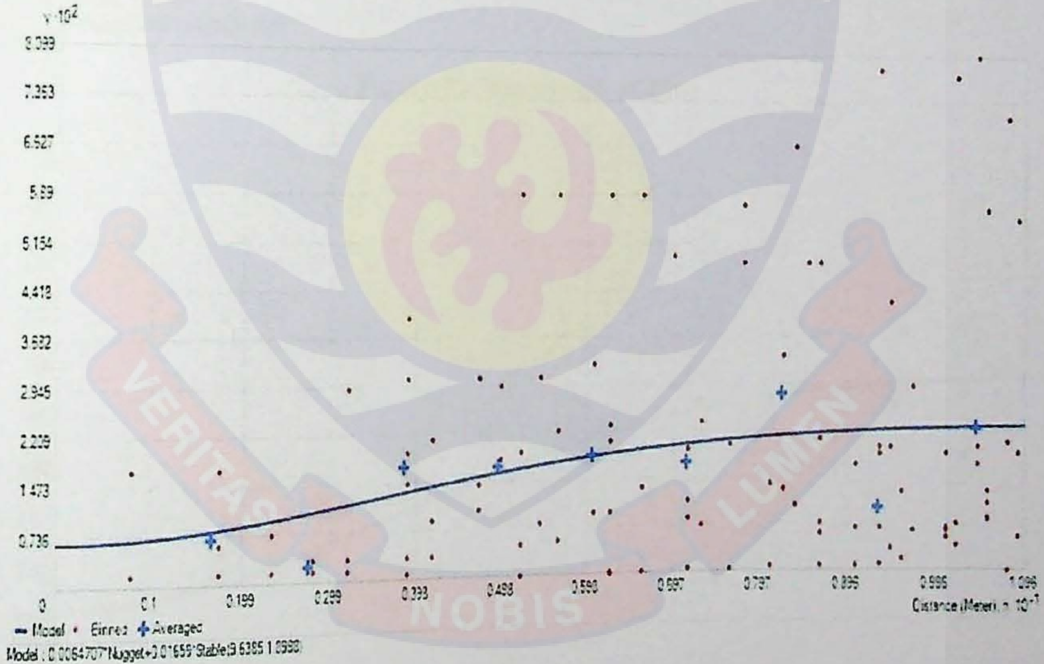


Figure 21: Variogram of Bulk Density

Figure 22 – Figure 27 shows the semivariogram models for Zn, K, Mg, N, and Ca, respectively. The nugget effect for majority of the variables was reduced across the research region at the specific determined depth, implying that the grid

variance of variables was lower. Overall, the nugget impact values were smaller, with Mg being the lowest.

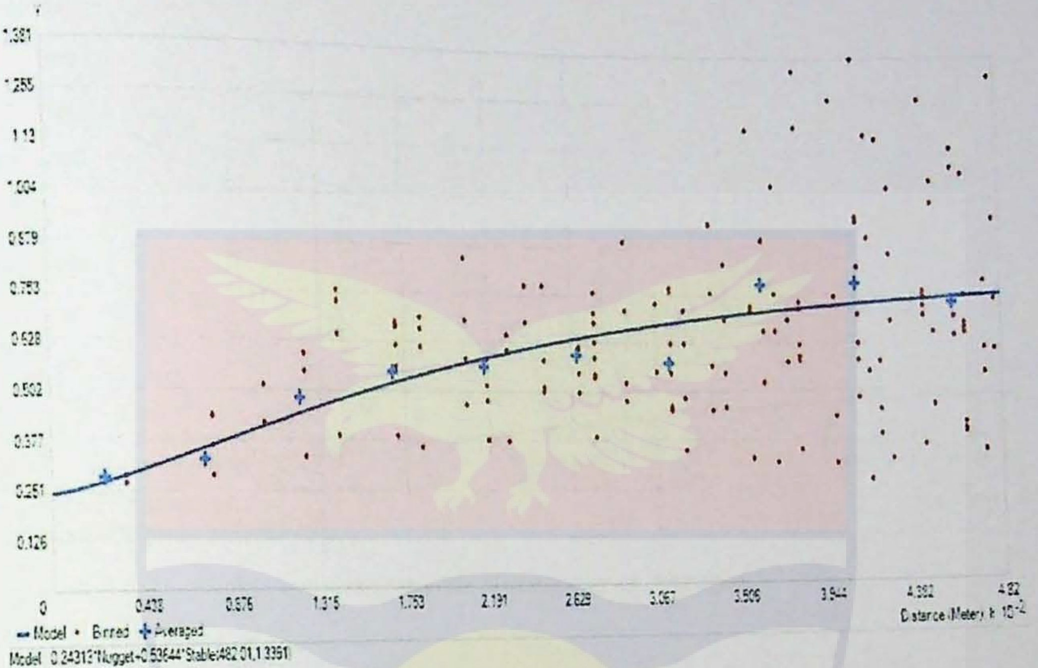


Figure 22: Variogram of Zinc

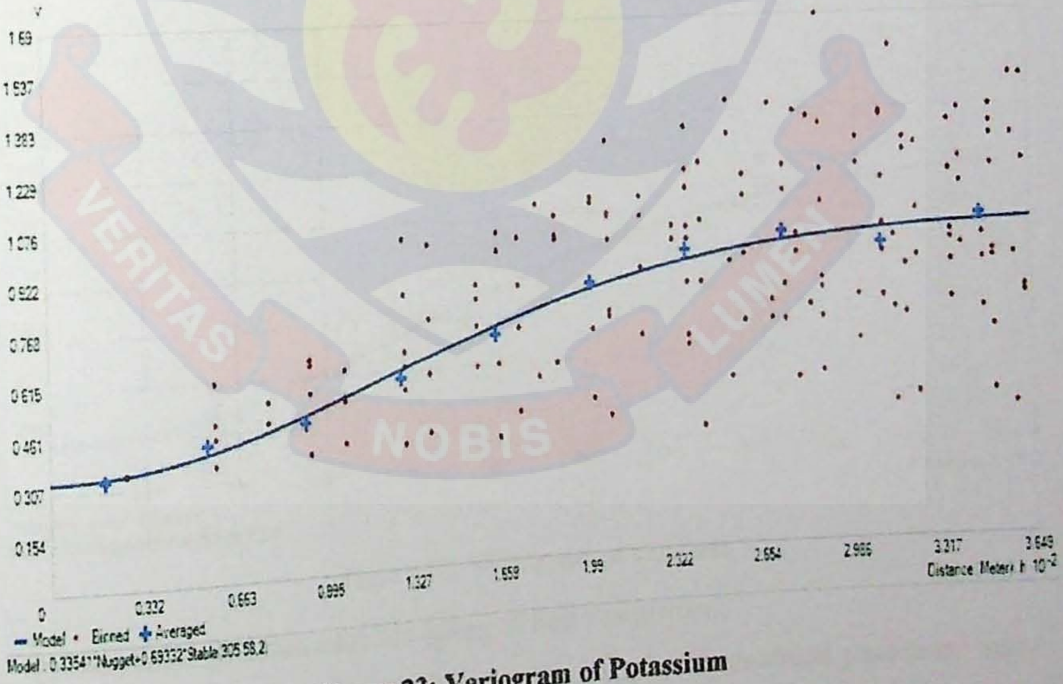


Figure 23: Variogram of Potassium

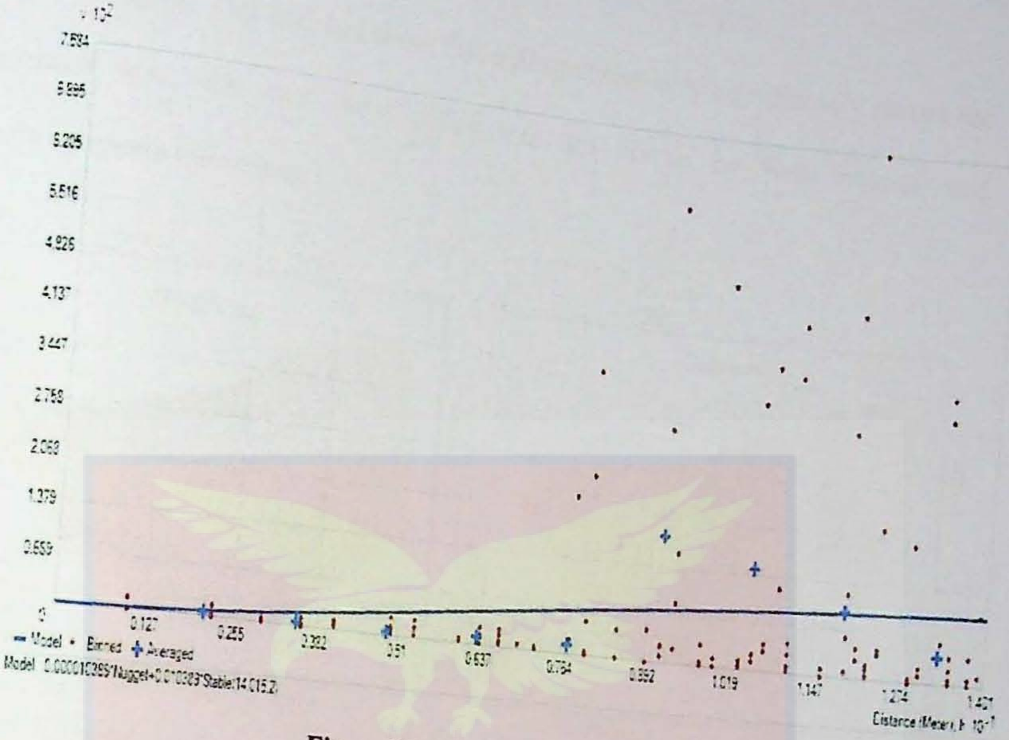


Figure 26: Variogram of Nitrogen

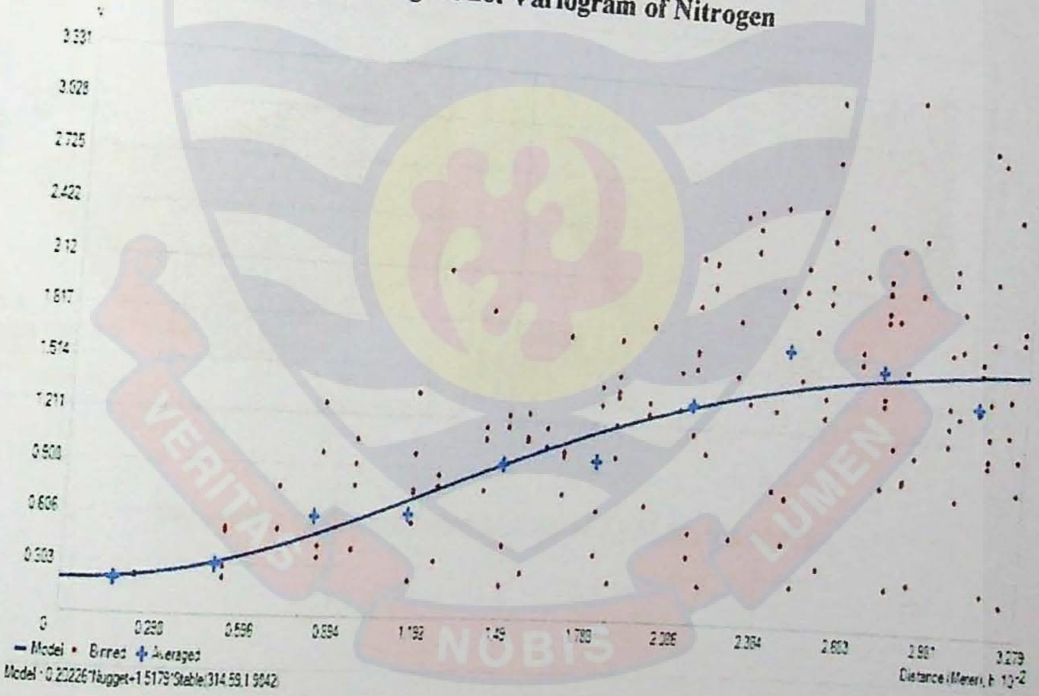


Figure 27: Variogram of Calcium

Spatial Interpolation and Mapping of Soil Properties

Figure 28 – Figure 32 demonstrate soil physicochemical parameter maps derived by ordinary kriging interpolation, as well as the spatial distribution of distinct soil types. In general, the soil qualities varied to varying degrees across the

research region. The findings show that soil qualities vary significantly across the research area, and that these differences are driven by both natural and anthropogenic influences.

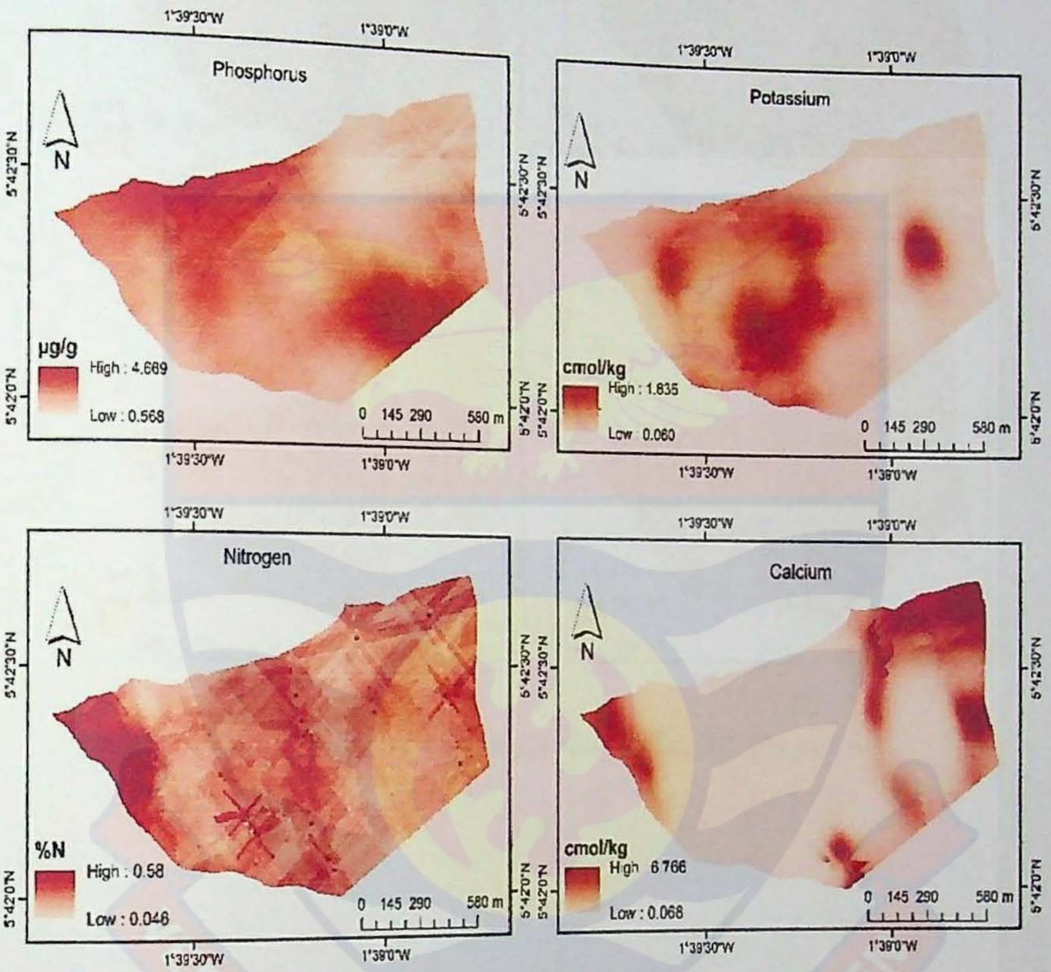


Figure 28: Geospatial distribution of Av.P, K, N and Ca

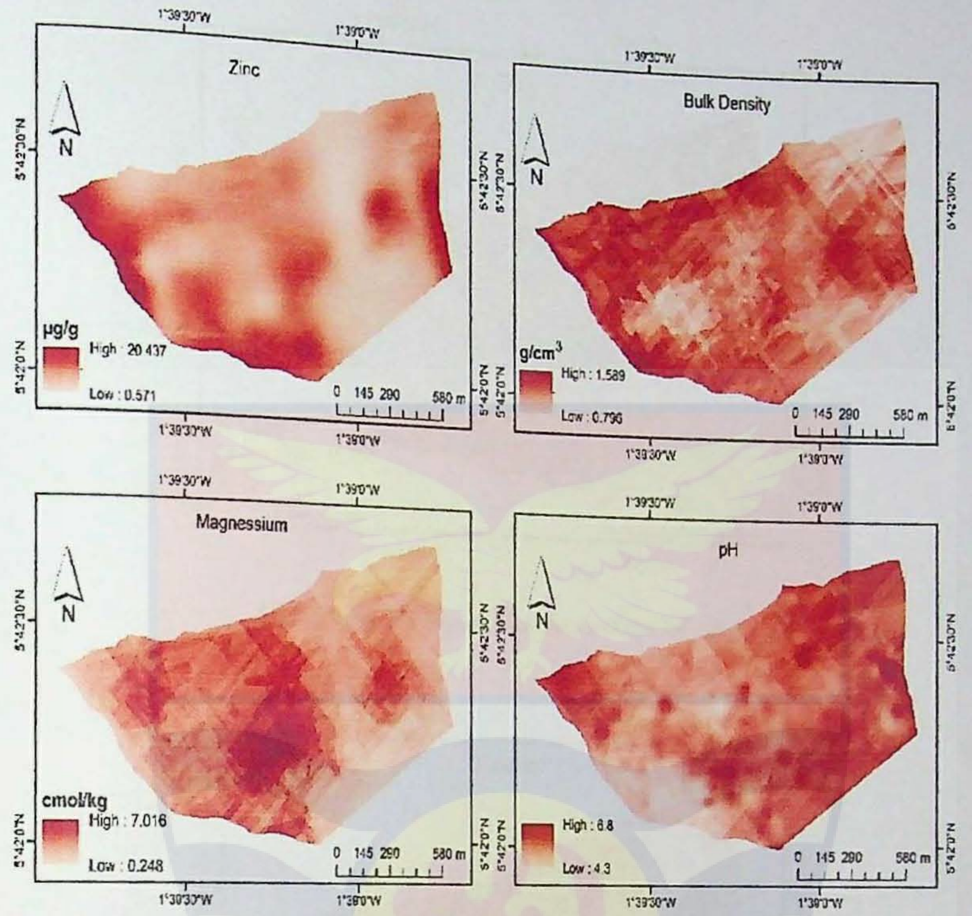


Figure 29: Geospatial distribution of Zn, BD, Mg and pH

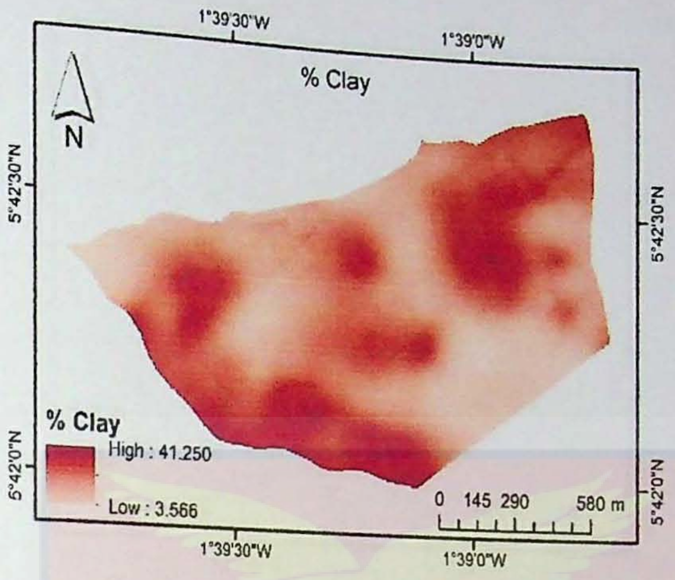


Figure 30: Geospatial distribution of clay

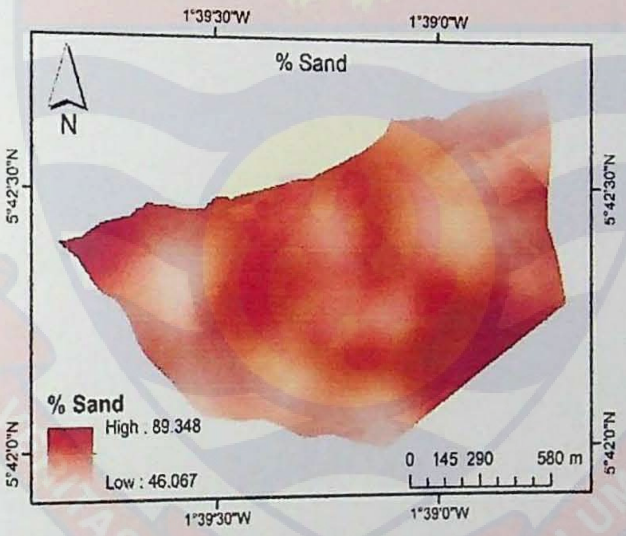


Figure 31: Geospatial distribution of sand

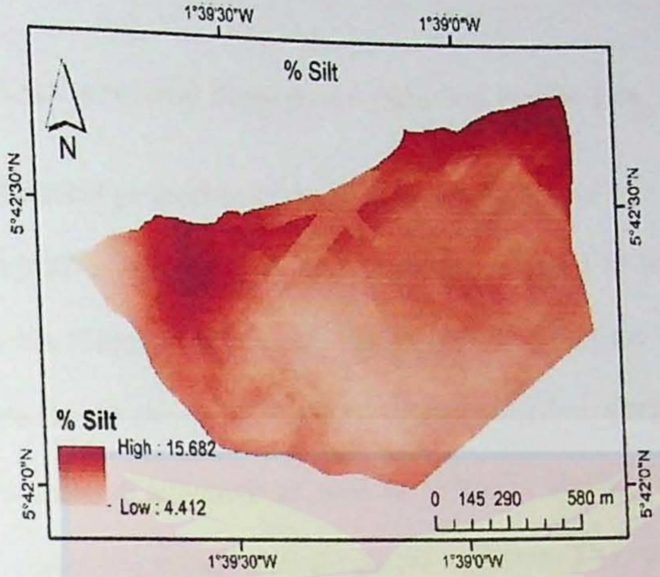


Figure 32: Geospatial distribution of silt

CHAPTER FIVE

DISCUSSIONS

Variation in Physicochemical Properties within Soil Profile Pits

Soil physico-chemical properties of the different profile pits

This objective was to see if there were any changes in soil profiles related with distinct landscape positions. The parent material of the soil and the degree of slope are the two most important drivers of soil properties. Particle size and pore space distribution, as well as hydraulic conductivity, are all inherent soil qualities obtained from the parent materials. The research area's hydrological data has previously been reported by (Gyamera, 2014).

The findings of this study reflected a typical semi-deciduous forest agro-ecological zone Issaka et al. (2016), which is characterized by moderately acidic soils with low Nitrogen and Phosphorus levels, and the results were consistent with previous reports (Bationo et al., 2018). The descriptive statistics revealed that the majority of the variation occurred on the summit (PP1) and toe slopes (PP5) of the toposequence, with relatively little variation in the intermediate (PP3) and shoulder (PP 2) portions. The CV in Table 3 revealed significant variations in the properties studied. The lowest CV value 6% was observed for soil pH and this according to Wani et al. (2017) and Denton et al. (2017) who had similar results could be attributed to the uniform conditions of the area such as little change in slope and its direction. Higher variability of soil properties in respect to coefficient of variation was revealed in TN, Zn, Av. P, OC, Clay, Silt, EA, Mg, Ca (CV > 35 %). In contrast, lower variability (CV<15%) was observed for soil pH whereas, moderate variability (CV<35%) was found for sand according to guidelines provided by Warrick (2001) for the variability of soil properties. The mineral fractions of the soils was dominated by sand and this could be attributed to the parent material granite (Gyamera, 2014). Table 1 also indicates that the skewness and kurtosis of the soil properties deviated considerably from the standard values of 0 and 3 respectively. Wani et al. (2017) who's study revealed similar trend attributed this pattern to different management practices that are been carried out on the study area.

Morphological properties

Table 4 shows the morphological properties of the five PPs. It was observed that the pedons ranged from deep (66 cm) to very deep (137 cm). The drainage status of pedons on the upper positions (summit, shoulder and middle) was well drained with pedon 4 and 5 being moderately and poorly drained respectively. The poor and moderate drainage attribute experienced at foot (PP 4) and toe (PP 5) positions was strengthen by the evidence of hydromorphic mottling and a level of gleization. The poor drainage conditions of PP 4 and PP5 was attributed to shallow water table and their topographic positions.

Most of the profiles had A – Bt horizons. The A horizons are generally influenced by the accumulation and humification of organic constituents during their formation. The eluviation–illuviation processes of clay from the soil surface layer into the subsurface horizon gave rise to argillic Bt horizons in the pedons and this is similar to the findings of (Maniyunda et al., 2014). Plowing facilitates the transportation of loose materials into the B horizon. The surface layer of PP 1 was observed to be the thinnest (0 – 10 cm). The impact of topography and patterns, as well as the influence of water penetration rates, surface runoffs, erosion, and deposition of eroded soils, could explain the large color variations across Surface soil color ranged from dark reddish brown (5YR3/3) to dark brown (10YR3/3) except for PP 5 which had a greenish black (5GY2.5/1) munsell color notation (Table 5). The subsurface soils had color notation ranging 5YR3/4 to 2.5YR4/8 in PP1 to PP3. The soils at the depression (PP4 and PP5) however, had color notation ranging from 10YR6/8 (brownish yellow) to 5GY5/2 (grayish green). This results signifies the influence of organic matter on soil color as the darkness of the various A horizons decreased with depth. Soils on the toposequence that were never saturated with water had reddish and brownish subsurface soil colors which symbolizes properly drained and well aerated conditions. According to Foth (1990), reddish color gives an indication of the presence of iron compounds in various states of hydration and oxidation and low organic matter content (Babalola and Akindolire, 2011). The horizons in PP4 and PP5 however differed in color from the others due to oxidation – reduction conditions from groundwater saturations. Mulugeta and Sheleme (2011) related the greyish color in soils to their water collection tendencies which makes them liable to water saturated much of the time.

Despite the appreciable increase in clay contents of up to 56 % in Table 4, the soil materials were not extremely sticky (Table 9). This happened probably because of the type of clay mineral present. Most tropical red colored soils have clay particles composed predominantly of kaolinite and oxides of iron and aluminum, which have little capacity to develop stickiness and to expand and contract on wetting and drying (Foth, 1990). The consistence of the surface soils varied from nonsticky to non-plastic friable. This friable consistence observed in the surface soils could be attributed to the higher organic matter content of the surface soils as compared to the subsurface soils, (Negassa and Gebrekidan, 2004). The moderate and strong, coarse, subangular and angular blocky formations, as well as the stiffness that grew with soil depth, could have been caused by increasing clay amount with depth.

Physical properties

The mineral fraction distribution as presented in Table 4 was dominated by sand in all five landscape positions and can be linked to the nature of the parent material which is rich in quartz mineral (Gyamera, 2014). The sand values range from 28.61% to 79.08%. The high sand values within the surface soils according to Mulugeta and Sheleme (2011) could be due to weak aggregate structure of the soils compounded by intensive cultivation. Soil bulk density altered progressively with increased soil depth, according to Shete et al. (2016), contradicting the findings in this case. Yao et al. (2013) also discovered that soil bulk density had very little vertical variation. Because the data were presented differently, it was concluded that significant regional heterogeneities in soil bulk density may arise as a result of intricate soil formation circumstances, ecological processes, and anthropogenic activities.

Bulk density increased down the various PPs, Table 4: Figure 12 and this can be assigned to the sequel of the higher organic carbon contents in the surface soils. Ashenafi et al. (2019) established in their research the lightness of organic matter as compared to mineral fractions and therefore its tendency to improve porosity and hence reduce bulk density. This is in support with the fact that OC was observed to correlate significantly and negatively with bulk density of the soils (−0.40*), as shown in Table 6.

Chemical properties

The soil pH in the surface and subsurface layers of the pedons was assessed as medium to low in this study's field data, according to Landon's rating ratings (Landon, 2014).

Soil acidity descended with corresponding depths across the pedons. This could be due to the fact that the subsurface layers have a higher concentration of basic cations. The greatest pH found in PP5 could be owing to the ions' high solubility, such as Na, Ca, and Mg. The findings support the findings of Ogbodo (2011), who found that spontaneously basic cations can dispense H^+ from exchangeable complexes into soil solution, where it is leached. Changes in pH are caused by the leaching process and the accumulation of ions at specific soil pedons. Strongly acidic soils are likely to have high levels of exchangeable Al and H ions, which might impact plant growth (Schoeneberger et al., 2012)

The pH values were lowest in the upper slope region of a toposequence, showing that pH decreases down the slope, according to Babalola and Akindolire (2011). These observations were in line with the current findings. The presence of acidity on the upper slopes is a sign of extensive chemical weathering and nutrient leaching. Nonetheless, Onweremadu et al. (2008) suggested that high total nitrogen, cation exchange capabilities, and organic matter richness could be a trigger for elevated pH values in the foothills. These findings are consistent with the current findings, as pH values in the toposequence's foothills were high. Exchangeable acidity correlated significantly and negatively with pH (r = -0.54*) and this is an indication that pH is controlled by the leaching of basic cations.

Soil organic carbon (SOC) is vital to the health of natural ecosystems as well as agricultural systems (Lal, 2004). SOC is influenced by topography because of erosion and redistribution of fine soil particles and organic matter across landscapes due to water redistribution, which results in varied leaching infiltration and runoff capabilities (Creed et al., 2013). SOM declined as depth increased in all five (5) pedons, with the highest amounts found in each pedon's surface soils. The findings matched those of Gaudinski et al. (2000), who said that such features are typical of SOC content in damp soils. Previous environmental conditions, in the study area, could also influence SOM content (Janzen, 2005). Wind and water erosive pressures remove and redistribute surface organic and mineral soil constituents, resulting in a decreasing solum from the summit (ridge) to the toe slope (valleys) (Kroetsch, 2004). Overall, the soils were classified as medium in SOM as values obtained were below 2.0% (Federal Ministry of Agriculture and Natural Resources, 1990). They were rated as low in accordance per Landon (1991) who indicates that the soils are vulnerable to water erosion due to the low % concentration of organic carbon. The influence of climatic variables according to Hobley (2015) is eminent mostly in surface soils and diminishes moving down a pedon making site and landuse factors more important in soil organic carbon storage down a pedon. Earlier reports have also indicated that SOC less than 1.16% for tropical soils is an indication of soil degradation involving a highly raised risk of soil erosion (Barrow, 1991).

An indication of this impact could be attributable to TN loss across the pedons (Sheleme and Singh, 2011). Furthermore, site variables such as soil type, texture, and mineralogy were connected as significant determinants in the distribution of soil organic carbon along pedon (Jobbágy and Jackson, 2000). Organic carbon had a significant positive correlation with Av. P (r = 0.76*) and this gives an indication that available P is mostly released from organic matter and this might be due to the easy formation of accessible organophosphate complexes, organic carbon acidulation effect, phosphorus release from organic complexes, and phosphorus reduction fixation by humus as a result of iron and aluminium oxides coating formation. Similar fndings were also reported by Ayele et al. (2013) and Bhat et al. (2017). Different landuse types were detected across the study area, which could have influenced SOM behavior. SOM is determined by land tillage in three ways: periodic disruption of soil structure, integrating plant residues within soil horizons, and changing soil horizons. Land tillage controls determines SOM by threę means i.e. periodic disruption of soil structure, incorporating plant residues within soil horizons and altering soil microclimate (Ozpinar and Ozpinar, 2015). High SOC is also reported to cause an increase in TN and K levels as observed from the results of this study (Wang and Huang, 2001)

Available phosphorus refers to the inorganic form of phosphorus found in soil solution, omitting orthophosphate (Av. P). Adoptive retention of Av. P on colloidal particle surfaces is conceivable. Available P has been shown to decrease along the profiled pits because of increases in clay content (Brady and Weil, 2008a). The difference in organic matter concentration could also explain why surface horizons have a higher Av.P than subsurface horizons.

Cation exchange capacity was highest at the surface soils in comparison to the subsurface soils. The soils' CEC was rather low, and Ca dominated the exchange complex, which was followed by Mg, K, and Na ions. However, as soil depth increased, the amount of exchangeable cations fluctuated, with high and low values, which may be attributable to their leaching from the surface horizon down to the sub-surface, according to observations (Heluf and Wakene, 2006).

The concentrations of the basic cations was dominated by Ca in both surface and subsurface soils. Mg ions however, decreased with increasing depth in PP1 – PP4 and this is in contrast to other studies who revealed increases in Mg concentrations with depth (Behera et al., 2016; Sadiq et al., 2021). This change in trend might have evolved from the very low organic matter contents of the surface soils. In general, the exchangeable bases had lower values and fell within the critical limits for deficiency, implying that fertilization is more likely an option, as indicated by (Obigbesan, 2009). The exchangeable Ca, Mg ratio of the soils ranged from 3.2–2.13 in the summit soil to 2.99–609 in the upper slope, 1.94–2.78 in the middle slope, 3.18–1.11 in the lower slope, and 1.20–0.56 in the toe slope. Some of the soils' exchangeable K, Ca, and Mg were above critical values, while others were below critical values (Landon, 2014). Both K and Na values across and along the various landscape positions fell below 0.6 and 1.0, respectively, and can thus be classified as low (Landon, 2014). CEC values are rated as follows: 5 as very low, 5 - 15 as low, 15 - 25 as medium, 25 - 40 as high, and > 40 as extremely high (Landon, 2014). Per this ratings, according to Brady and Weil (2008b), the CEC may also depend on the nature and number of colloidal particles.

Plants use sodium Na as a partial substitute for potassium in numerous situations. It isn't a necessary nutrient. As a result, its absence or presence in extremely small amounts is usually not harmful to plant nourishment. However, significant amounts of Na, especially when compared to other cations, might have an impact on crops and soil conditions. Fe levels were highest in all profile pits and varied according to slope positions and soil layers. Fe in soil has a critical value of 2.5 mgkg^{-1}, according to Møberg and Esu (1991), which is lower than the Fe content found in this study. Cation Exchange capacity correlated significantly and positively with Ca (r = 0.87*), Mg (0.71*), Na (0.49*), K (0.42*) and with % OC (0.77*) Table 6. This can be attributed to the summative influence of the exchangeable bases on CEC (Sadiq et al., 2021).

Nature and weathering from source rock material are likely to blame for the elevated Fe contents. Zn concentrations increased with progression down the slope. The addition of Zn through plant residues left over from previous cropping practices can be attributed to this buildup. Cu content varied by soil layer inside the profile pits and declined with depth, which might be explained by the build of biomass in the surface layers of soils, resulting in higher organic carbon content in the surface than in the subsurface (Setia and Sharma, 2004). The highest Cu values were found on the top slope, which corresponded to the highest amount of organic carbon, while the lowest values were found on the lower slope. Plant cycling, which is a leading factor, and leaching are two possible causes that could alter vertical distribution and top soil.

The association between phosphorus, SOC and other mineral ions were positively correlated but not significant ($p > 0.05$). This could be related to low Av.P which was more significant in profile pits at the toe of the slope. At the toe and below the pedons, Av.P is easily released from the SOC matrix undergoing mineralization and accumulation. The high Av.P content can also be determined by high percentage of clay fractions as the pedons descend and high leaching effects due to pH variations which causes low binding of minerals. Similarly, Av.P correlated positively to TN and K and the results conform to other reports by (Jiang et al., 2021a).

Other high positive correlation/associations observed were between Ca with Zn (0.790), Av. P (0.873), OC (0.838) and TN (0.510) while showing a high negative correlation with clay (-0.469), EA (0.529) and CEC (-0.872). Fe which was maximum across all profile pits and soil layers displayed high positive correlation with most parameters. Fe positively correlated with Av. P (0.826), OC (0.600), Sand (0.758), CEC (0.704) and EC (0.627) while it showed negative correlations with clay (-0.705), EA (0.599) and BD (0.555).

The observed relationships from the correlation analysis were indicative of the intricate connections among the various soil properties which cannot be observed physically.

Relationship between soils and their physicochemical properties

The results of principal component analysis (Figure 16) and correlation shown in (Table 6) revealed there was both negative and positive correlation between most of the soil parameters measured most influenced by slope positions and gradients along the toposequence. The eigenvalues from the principal components of pH, Ca and Mg which were greater than 1, along PC 1 together could have contributed the maximum variation of 78.1%. Along PC1, maximum positive loadings were observed for Av. P (0.301) however, accounted for only 1.66 % of variation which contributes to the overall 97.3% variation across the study area. PC1 also shows a positive loading factor for sand (0.2722) however negative loading factors for silt (-0.15401) and clay (-0.27156) which contribute to the overall 97.3%.

This could imply that variation in the sand, silt and clay contents are by natural processes. The position of the variables in the multivariate space further confirmed the results of Table 6 analysis and associated significant positive correlation amongst soil exchangeable ions in the study area. Significant positive and negative correlations were identified across the soil properties.

The second principal component explained 18.4% of the total variation with a positive correlation to EA and clay contents while exhibiting a negative correlation with BD. Na, Zn, OC, EA and TN also showed a positive correlation which contributed to the total variation along the axis. The findings were consistent with previous reports by (Sadiq et al., 2021).

Classification of Soils Along the Toposequence

High clay content is likely to increase the soil's capacity to adsorb cations. This gives an indication that clay and silt are easily eroded and leached down the slope than sand. This is in line with Malgwi and Abu (2011), who observed that clay and silt were easily eroded, resulting in higher sand content.

However, sand correlated negatively with CEC, perhaps due to its small surface area and low capacity to hold nutrients, clay however correlated positively with CEC. Silt to clay ratio increased with depth in the summit, shoulder, middle and toe slope. This trend was not so for the foot slope pedon.

Bulk density, or the ratio of soil dry mass to volume, is a critical soil attribute that influences soil water retention, aeration, trafficability, and infiltration rate, and it's also very significant for soil management. Soil mechanical resistance is a measure of the resistance to penetration experienced in the soil and is directly related to soil compaction. The mechanical resistance of the soil rises quickly when the soil dries, and it is used to supplement the data provided by bulk density. Bulk density values in the surface soils ranged from 1.01 in the foot slope to 1.30 g/cm3 in the toe slope, with a mean of 1.15 g/cm3, whereas values in the subsurface soils ranged from 1.04 to 1.83 g/cm3.

The morphological representativeness (Table 9) revealed soil properties at the research site. The surface soil's color ranged from reddish brown (5YR 3/3) to greenish black (5GY 2.5/1) when moist. Soil color ranged from dark reddish brown at the summit, shoulder, and middle slopes to dark grayish brown at the foot slope and greenish black at the toe slope, with prominent hues of 5 and 10 in the surface soils and yellowish red and red to strong brownish yellow in the subsurface soils, with prominent hues of 5 and 10 in the surface soils and yellowish red and red to strong brownish yellow in the subsurface soils. Similarity, reddish and yellowish underlying colors suggest the existence of hematite and goethite as Fe oxides, and consequently ferrugination.

The results demonstrated that soil OM had a significant impact on surface soil color, with the A-blackness horizon's decreasing with depth. Surface horizons with dark colors (values 3) are commonly enriched with OM, which improves the soil in a variety of ways. Subsoil colors on slopes that are not saturated with water are typically reddish and brownish, indicating well-drained and aerated conditions. The presence of iron compounds in various states of oxidation and hydration causes the reddish color (Foth, 1990).

Soil classification

The surface soils of all five pedons, in Table 4 were more or less minimally developed horizons. They were typically thin (10 – 23 cm) and light colored profiles and a very poor structure. The organic carbon content of the pedons' surface horizons ranged between 0.63 and 1.59 percent. As a result, ochric epipedon was found on the surface horizons of all five pedons (Summit, upper, and middle).

All had thick strata (120+) with clay content varying from 24.83 to 56.84 percent in the subsurface with the exception of PP4 and PP5. The clay composition of the first three pedons' subterranean horizons was found to be higher than that of their subsequent surface layers. The subsurface horizons had 15 percent more clay than the horizon above, which had between 30 percent and 57 percent clay, and these clay increments were detected within 20 cm of each other. The horizons' apparent cation exchange capacities ranged from 1.62 to 2.17 cmol/kg. In addition, argillians (faint and conspicuous pedfaces) were seen in the horizons.

As a result of these characteristics, the horizons of the four pedons would be classified as argillic subsurface diagnostic horizons, as indicated by (Buol, 2003). The four pedons were classified as Ultisols based on these characteristics Although there were no indication of major clay increment in the subsurface layers of the toe pedon, there was evidence of color modification with stagnic properties in the foot slope pedon and gleyic properties in the toe slope pedons. In the overlaying horzon, the clay content in the horizons was not considerably greater. However, because the toe slope pedon lacked a tentative diagnostic horizon, it was classed as an entisol (gleyic).

Based on calculations generated, using the region's mean annual and monthly temperature and moisture distributions, the region is characterized by isothermic temperature and ustic moisture regimes (Sempéré, 2003). On the basis of soil moisture regime at the suborder level, PP1, PP2 and PP3 were classed as Ustults. Furthermore, there were no clay drop of 20% or more from the maximum clay concentration and in the absence of any other diagnostic properties, Pit 1 was further grouped as Haplustults at the great group level and a Typic haplustults at the subgroup level under USDA Soil taxanomy which correlates with a lixisol (ferric lixisol) at the WRB classification system. Pit 2 – Rhodustults (due to the presence of a dark surface layer and a reddish argillic horizon of 2.5YR within 100 cm and Typic Rhodustults at great groups which transcend into a chromic lixisol under WRB classification system. Pit 3- Plinthustults (due to the presence of plinthic material within the argillic horizon, then a Typic Plinthusults at the sub group level and further to a plinthic lixisol at the unit level. However, Pit 4 was classified as an Aquult at the sub order level due to the evidence of water table which includes the presence of redoximorphic features (gray and red color pattern). It was further grouped as epiaquult at the subgroup level and to endogleyic fluvisol at the unit level.

PP5 however had poorly formed horizons and hence classified as Entisol at the order level, Aquent at the subgroup level due to the saturation of water close to the surface for long periods of time without oxygen. Aquents are also characterized by the presence of grayish and bluish colours and redoximorphic features, great group as endoaquent due to endosaturation, Aquic endoaquent at the subgroup level which correlates to a gleyic regosol at the unit level. The classification of soils as Ultisols and Entisols clearly demonstrates the influence of topography on soil development.

Spatial Variation of Soil Properties Across Study Area

Descriptive statistics of soil properties at 20 cm depth

The soil characteristics had varying values of descriptive statistics measures thus, according to the data obtained in Table 11. According to Wilding (1985) the coefficient of variation (CV) of soil properties is grouped under three categories low (<15%), moderate (15–35%), and high (>35%). The CV varied from one parameter to the other and ranged between 8 – 206 %. Human influence and natural processes such as agricultural management practices, nature of soil and climate conditions could spearhead the variability pattern of the soil properties. The positive and negative skewness observed for majority of the properties indicates the presence of extreme values (Cooksey, 2020). And this indicates the data on the soil properties did not follow a normal distribution (Cooksey, 2020). Due to this the data on soil properties had to be log transformed. The kurtosis values and suggested the deviation of the data from normality and therefore the transformation of the data to make them normally distributed was necessary prior to geostatistical analysis (Webster and Oliver, 2007).

Relationship among soil properties at depth 20 cm

The Pearson's correlation matrix showed interdependence of the soil properties. From table 12, the negative and significant correlation between sand and CEC according to Blume et al. (2016b) is largely due to the inability of sand to exchange cations due to the lack of electrical charges on the sand surfaces. Moreso, the correlation of clay and CEC was positive and significant and this can be linked to the high tendency of clay to take up and carry cations by adsorption. According to Selmy et al. (2021) the summation of the three soil fractions (sand, silt and clay) equals a constant value of 100 % which implies that they have an inversely proportional relationship with each other. This scenario explains why sand is negatively and significant correlated with silt and clay. Apparently, an increase in one is balanced by a decrease in the and vice versa.

The significant and negative correlation between organic carbon and bulk density gives an indication that an increase in organic matter influences bulk density by decreasing it and hence, the addition of organic materials can be a suggested remedy for high bulk density challenges (Mishra et al., 2020). Their limited dispersion could be attributed to developmental processes such as the loss of dissolved organic and inorganic P, the precipitation of insoluble or physically protected P, the loss of soil bulk, and persistent mineral obstruction.

The researchers found a link between similarly low P concentrations and other factors (Wissuwa et al., 2020)

Spatial distribution of soil properties

The nugget effects were minor and close to zero in Table 14, indicating spatial continuity between surrounding sites; this finding is similar to that of Vieira and Paz Gonzalez (2003) and Jafarian and Kavian (2013), who found that semi-variograms of N and Mg had extremely small nugget effects. This model can calculate the unsampled within a nearby distance of roughly 67.72 meters for pH, 14.05 meters for N, 9.6385 meters for bulk density, 512 meters for Av. P, 305.58 meters for K, 482.01 meters for Zn, 314.59 meters for Ca, and 10.109 meters for Mg. Both intrinsic changes in soil qualities and external variables such as human-induced activities may influence their spatial dependency (Shi et al., 2018).

The maps of soil properties generated by ordinary kriging interpolation are shown in Figure 30-Figure 34. The findings revealed that all of the soil samples differed significantly across the study area. The slope of the semi-variogram was close to zero, and the soil parameters were regarded non-spatially linked, as shown by a high ratio of nuggets (Table 14). When the distribution of soil qualities is moderately or strongly spatially linked, the range of the semi-variogram determines the average extent of these patches. If the ratio was less than 25% or the slope of the semi-variogram was more than zero, it meant that a significant portion of the variance was introduced geographically, showing a substantial spatial dependency of soil attributes. Even if a high nugget:sill ratio was obtained, the unknown spatial dependence of the variable can exist at a lower scale. Similar findings have been reported by others (Wu et al., 2017).

The pH maps show a moderate geographical pattern Table 14 and a distinct patchy distribution throughout the study area (Figure 31). The soil pH in the western half of the study region was lower, whereas the pH in the eastern part of the study area was higher. Soils were often characterized by extensive areas with pH values ranging from 4.3 to 6.8, indicating a mildly acidic nature over the research area (Figure 31). According to Guo et al. (2022), pH can vary as a result of contemporary agricultural practices and the presence of acidic cations, which can lower pH. There was a gradual reduction in Mg from the northwest to the southeast (Figure 31) half of the field throughout the research region. The Mg concentrations in soil samples are highly spatially dependent Table 14. Soils were typically characterized by large areas with concentrations ranging from 0.248 to 7.016 cmol/kg (Figure 31) found almost all over the studied area.

The Zn trend was rather evenly distributed across the research area. The content of Zn in soil samples ranged from 0.571-20.437. The kriging interpolation map for nitrogen (N) demonstrates a high spatial (Table 14) reliance and a consistent distribution pattern throughout the study area (Figure 30). Around the study area, soils were characterized by wide areas of Total N ranging from 0.046 percent to 0.54 percent N (Figure 30). Furthermore, the greater Total N concentration was only discovered in the northeastern region of the sample. The usage or addition of NPK fertilizers may help to alleviate the considerable spatial dependence in Total N levels in various land-use patterns, whereas grassland restoration is commonly supported by planting N-fixing alfalfa (Lu et al., 2021).

The spatial distribution of Av P and K reveals a clear even distribution throughout the study area (Figure 30). The spatial distribution map of Av P moderated spatial continuity, as predicted by autocorrelation analysis (Table 14). In addition, soils were characterized by large areas with accessible phosphorus (Av P) values ranging from 0.568 to 4.669 g/g (Figure 28). Similarly, the kriging map of K indicates a moderate geographical continuity of K, with an increase in the southeast and a reduction in the northwest.

The concentration in the distribution ranged from 0.568 to 4.669 g/g. A significant limit for agricultural productivity was implied by the poor distribution pattern (Lu et al., 2021). Furthermore, geographical characteristics such as terrain, climate, and soil matrix may influence the spatial variability of soil accessible potassium (K) (Huang, 2006). Because of the high and low levels of Av P and Av K, their regional pattern could be influenced by anthropogenic factors like as fertilization.

Calcium (Ca) content was lower on average across about 95 percent of the study region, with higher levels only found in the northeastern half of the study area, while the majority of the study area's center was much lower. Ca's semi-variogram shows considerable geographical correlation (Table 14), implying that a significant portion of the variance is introduced regionally. In addition, soils were typically characterized by large patches with Ca concentrations ranging from 0.066 to 6.7066 cmol/kg (Figure 30). The decreased calcium concentration in this study area could be due to mostly washed-out calcium in the form of carbonates, especially under leaching conditions (Anna et al., 2017).

The bulk density semi-variogram revealed a sparse distribution that was somewhat spatially linked and influenced by both structural and random influences (Table 14). In Figure 31, the bulk densities across the field ranged from 0.796 to 1.589 g/cm3, which was slightly higher than the theoretical expected value of 1.0 g/cm3, indicating that the soils in the research region may be degrading. The nugget impact of bulk densities and depth has been linked in previous investigations. Yang et al. (2016) demonstrated in their paper that bulk densities are more subject to external interferences at upper soil depths, which may limit their spatial dependence.

A substantial spatial dependency can be detected at deeper depths, e.g. 40-100 cm, with a decreased nugget impact, showing that structural elements such as parent material and topography controlled soil bulk densities at various levels. This can be linked to surface soil disturbance caused by human and biological factors, such as crop root intercropping and soil animal activities, especially in agriculturally intensive areas, which can loosen soil and cause the surface soil bulk density to be significantly lower than the subsoil bulk density (Yang et al., 2016).

Clay content was evenly distributed from south to north across the research area. Clay content ranged from 3.566 percent to 41.250 percent. The findings suggest that the percent clay component distribution was impacted by slope position across the research area. Percent clay and sand levels were statistically equivalent. Only the silt fraction, which had a high value in the northern half of the study region, showed significant changes. The percentage of silt fractions ranged from 4.412 to 15.688 percent.

This indicates that the soils in the research area are heavily weathered and thus deficient in weathered able minerals. This could be owing in part to runoff from the neighboring upland, and in part to the soil's low erosion status at this time. This finding did not, however, support the expectation that clay content is often higher near the foot of slopes due to the washing away of clay-rich rocks from higher slopes (Salem et al., 2020). Sand particles, according to Ovalles and Collins (1986), are generally deposited at upper slopes due to their size.

The impacts of intense tillage on geographic variability of soil physical parameters such as particle size, bulk density, soil strength, mean pore size, and saturation hydraulic conductivity were explored by (Tsegaye and Hill, 1998). They found that, with the exception of saturated hydraulic conductivity, all soil physical characteristics were weakly regionally dependent at 6 to 9 cm depth and highly geographically dependent at 27 to 30 cm depth

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

This chapter summarizes the major findings obtained in this research at the various levels of the study. The major outcomes in the field tests and laboratory experiments and analysis are summarized. Recommendations for future research and for interventions have also been proposed. Some challenges that hampered the smooth running of the research were also highlighted.

Conclusion

The results presented in this thesis for the first time provide a detail characterization and description of soil types along a defined toposequence of the study area i.e. UCC Twifo Praso- Wamaso Research Field.

In conclusion, research found that slope location had a considerable impact on soil physicochemical qualities, with the majority of these significant differences occurring between the summit and middle soils, as well as the toe slope of the toposequence. These findings show that soil physicochemical parameters should be explicitly considered when implementing land management approaches, including crop species selection and land usage. Findings of this nature would undoubtedly enlighten stakeholders on the best agricultural species or trees to plant on the property, as well as their population densities, spatial allocation, and other factors.

Future studies focusing on soil physicochemical qualities within various slope aspects and microbial development could be a breakthrough for the introduction of appropriate crops or vegetables suitable for the land, given the impact of habitat factors on growth adaptability. The physico-chemical and biological features of soil could also be used to create soil quality indicators to aid in the rehabilitation of degraded lands. The study's data and findings provide an appropriate foundation for implementing landuse and soil management strategies at the site prior to any crop or vegetation planting program.

Differences in soils encountered along the catena, ultisol and entisol could have come from erosion, translocation, leaching, and deposition of chemicals or soil particles, according to the USDA systems of soil classification along the toposequence within the studied region. The notion that topography does play a role in soil formation is demonstrated by these discrepancies at distinct topographic positions. Hence the null hypothesis that there are no variations in soil types along a toposequence is rejected.

Many important soil quality indicators, such as bulk density, percent carbon, nitrogen, potassium, phosphorus, and others, were altered by various landscape placements, especially at the surface levels. In the midst of continuous cropping or land use, this information is required for proper management and soil amendment procedures. CEC values were found to be notably low across the toposequence's profile pits. This corresponded to the average pH values obtained and very low concentrations of the exchangeable complexes (Mg, Ca, K and Na). Liming and fertilizing at the Wamaso field will be a modest choice to consider in terms of land management because soils with low CEC do not modify their pH buffering capability at a rapid rate. Nonetheless, constant CEC monitoring will detect spontaneous increases that may necessitate soil nutrient management. Because higher soil CEC might lead to relative cation leaching, other factors like drainage will have an impact on soil fertility management.

Assessing spatial variability and recording soil parameters across the study region was a critical first step in implementing precision farming practices in the study area. These maps will be used to quantify spatial variability in soil qualities and offer a foundation for regulating it. The significance is also linked to an understanding of the amount of agricultural inputs that may be required at the site, such as assisting in the reduction of inorganic (fertilizer) inputs to the soil in the form of supplements in order to avoid overburdening the soil, which can lead to pollution and land degradation. The coefficient of variation for all the variables observed was highly different, ranging from 9 % to 208 % across the 20 cm depth of soils examined, according to statistical analysis.

The nugget: sill ratio ranges from 0 percent (Mg) to 58.65 percent (Av.P) in geostatistical analysis of soil properties, indicating that internal (e.g., soil-forming processes) factors were dominant over external (e.g., human activities) factors in determining the observed variations across the field. However, because it was influenced by both internal and external influences, the soil pH, bulk density, K and Av. P had a moderate spatial dependency with a nugget: sill ratio of 25-75 percent.

Other soil characteristics (Total N, Ca, and Mg) displayed a substantial spatial dependency with a nugget: sill ratio of 25%, indicating that these variables were primarily influenced by structural forces. All variables had autocorrelation distances ranging from 10.109 meters (Mg) to 512.29 meters (Av.P), indicating that the sample design was reasonable. Scattering maps produced by kriging interpolation revealed that the analyzed areas were classified by a different trend for Av.P (higher in the north and south) and Ca (lower in the north and south) (higher in northeast and lower distribution in central portion of site). K was (higher in the southeast section of the site), Zn was (sparsely dispersed across the field), bulk density was typically (greater across the field), and pH was (lower in the southeast part of the site) (more highly concentrated towards the northwest). Therefore the null hypothesis that soil properties of the Wamaso research station are not spatially structured is rejected.

For the majority of soil attributes, the kriging interpolation method offered the least interpolation error. It also shows how GIS techniques can be used to interpolate data that hasn't been sampled. These findings can be utilized to offer suggestions for the best agricultural management methods in the area, as well as to enhance soil conditions at the UCC Wamaso Field before large initiatives are implemented.

Recommendations

Based on the results, and findings from this research, the following recommendations for future studies are put forward.

More research along diverse toposequences across the study area is needed to gain a better understanding of physicochemical characterisation and varied soil types.

Seasonal/climate-influenced sampling, as well as long-term monitoring of physicochemical parameters, should be carried out throughout the study. The information gathered will aid in the creation of higher-level spatially referenced maps for the UCC Wamaso study field.

Microbial populations are significant indicators for soil health. Future research across the study area should consider identification of significant microbial operational taxonomic units (OTUs). Knowledge of various microbial populations can help in identifying potential bacteria and fungi which can be engineered for bioremediation purposes in the event of soil nutrient depletion.

The findings of this thesis revealed that some soil properties had very low concentrations while others were moderately high which could have an impact on crop output if their concentrations increased as a result of further fertilizer application. The application of soil amendment materials, such as biochar, to determine absorption and achieve a balance between soil characteristics and nutrients should be a focus of future studies. A study like this may focus on nutrition regulation and release in soils of the field.

Specific studies related to the influence of various soil types on physicochemical properties should be further researched e.g. ultisols under seasonal contrasted climate across the study area.

This research was limited by a clear and detailed land evaluation. A high-level land evaluation procedure across the study area should be studied prior to any future land development.

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APPENDICES

1: Soil Profile Description

SWEDRU SERIES

Profile ID:	UCC/ Pit 1
Soil Name:	Ferric lixisol
Location:	Wamaso, Twifo Praso
Parent Material:	Granite
Rock outcrops:	Nil
Natural vegetation:	Secondary Forest
Land use:	Fallow
Human influence:	Farming
Drainage:	Well drained
Moisture conditions in Soil:	Dry
Soil Appearance:	Dry
Depth of soil:	135 cm
Depth to Groundwater:	Not encountered
Evidence of erosion:	

Evidence of erosion:	Slightly Eroded	
Physiographic position:	Upper slope	
Slope:	3%	
Date:	25/11/2020	
Coordinates:	N 05^{0} 11’ 04.4’’ W 001 29’ 56.8’’	
	Depth	Description
OA	0 -10	▪ Reddish brown (5Yr 3/3), sandy loam, ▪ weak fine granular non – sticky non – plastic, ▪ many very fine many fine few medium roots, ▪ few ant cast and earth worms, ▪ clear and smooth boundary.
AB	10-40	▪ Yellowish red (5Yr 4/5), ▪ weak sub-angular blocky, non – sticky non –plastic, common iron and magnesium dioxide, ▪ few very fine few fine and few medium roots, clear and diffuse boundary ▪ Sandy clay loam, few quartz gravels and stones

Btcs1	40 – 60	▪ Yellowish red (5Yr 5/6), sandy clay loam, ▪ few quartz gravels, medium sub angular ▪ blocky, slightly sticky non – plastic, few ▪ iron and magnesium dioxide, very few fine ▪ few fine and few medium roots, clear and diffuse boundary.
Btcs2	60 – 135	▪ Yellowish red (2.5YR 3/8), clay loam. Sub angular, very firm structure, sticky, 7.5YR 5/8

Profile ID: UCC/PIT 2
Soil Name: Chromic lixisol
Location: Wamaso,
Parent Material: Granite
Rock outcrops: Nil
Natural vegetation: Secondary Forest
Land use: Cocoa
Human influence: Farming
Drainage: well drained
Moisture conditions in Soil: Dry
Soil Appearance: Dry
Depth of soil: 120 cm
Depth to Groundwater: not encountered

Evidence of erosion: Physiographic position: Slope: Date: Coordinates:	Slightly eroded Shoulder Slope 2% 25/11/2020 N 05° 70'70.9'' W 001° 64' 69.9''	
	Depth	Description
Ap	0 – 18	▪ Reddish brown (5YR 3/3), sandy loam, weak fine granular ▪ Structure, non - sticky, non - plastic, few fine medium roots ▪ Few ant casts and worms, very clear and smooth boundary

AB	18 – 52	▪ Red (2.5YR 4/8) sandy clay loam, few quartz gravels and stones ▪ Sub angular blocky structure, non-plastic, non-sticky, very few ▪ Fine to medium roots, clear and diffuse boundary
Btc1	52 – 75	▪ Red (10R 4/8) clay, few quartz gravels, blocky structure, slightly ▪ Plastic and sticky, few medium roots
Btc2	75- 137	▪ Yellowish red (5YR 5/8) clay. Sub angular blocky structure. ▪ Very Massive, plastic and sticky, clear smooth boundary

AKROSO SERIES

Profile ID:	UCC/PIT 4
Soil Name:	
Location:	Wamaso
Parent Material:	Granite
Rock outcrops:	Nil
Natural vegetation:	Secondary Forest
Land use:	Cocoa
Human influence:	Farming
Drainage:	Poorly drained
Moisture conditions in Soil:	Moist
Soil Appearance:	Moist
Depth of soil:	66+ cm
Depth of Groundwater:	66+ cm

Evidence of erosion:	Slightly eroded	
Physiographic position:	Lower Slope	
Slope:	1%	
Date:	25/11/2020	
Coordinates:	N: 05^0 70’74.9’’ W: 001^0 64’ 73.8’	
	Depth	Description
Ap	0 -23	▪ very dark grayish brown (10YR 3/3), fine sandy loam, very fine granular, non-sticky, non-plastic, many very fine medium and course roots, few ant cast, clear smooth boundary ▪ Weak find granular non-sticky ▪ Non-sticky plastic, many very fine

		- Fine few medium roots - Few ant cast and earthworms - Clear and smooth boundary
Btg1	23 – 44	- Brown(10Yr5/8), dark yellowish brown, (10Yr 4/8) faint mottle, sandy clay loam subangular blocky, slightly sticky, non plastic, few very fine roots, clear smooth boundary
Btg2	44 – 66	- Brownish yellow (10Yr 6/8), sandy clay loam, grayish brown (10Yr 5/2) prominent mottle, slightly sticky non – plastic, few weak subangular blocky structure.
C	66+	- Olive yellow (2.5Y 6/8), sandy clay loam

Profile ID:	UCC/PIT 5
Soil Name:	
Location:	Wamaso
Parent Material:	Granite
Rock outcrops:	Nil
Natural vegetation:	Secondary Forest
Land use:	Rice
Human influence:	Farming
Drainage:	Poorly drained
Moisture conditions in Soil:	Moist
Soil Appearance:	Moist
Depth of soil:	78+ cm
Depth of Groundwater:	78+cm
Evidence of erosion:	Nil
Classification:	Entisol (Gleyic Regosol)

Evidence of erosion:	Nill	
Physiographic position:	Toe Slope	
Slope:	1%	
Date:	25/11/2020	
Coordinates:	N 05^0 70'76.6'' W 001^0 64' 74.5''	
	Depth	Description
Oe	0 – 19	- Greenish black (5Gy 2.5/1) sandy loam

		▪ Fine granular structure, not sticky, nonplastic ▪ Medium fine roots, clear smooth boundary
A	19 – 78	▪ Greenish gray (N 5/1) sandy loam, blocky structure ▪ Slightly sticky, slightly plastic, few fine roots
Bw	78+	▪ grayish green (5GY 5/2) sandy loam, blocky structure

2: Soil and Landuse Classification

Table 13: Soil Types and Landuses across Study Area

Sample	Soil Type	Landuse
WMS 01 REF O	Sand	Oil Palm Plantation
	Loamy Sand	
	Sandy Loam	wet Rice Field
	Loamy Sand	rice farm
	Sandy Loam	rice farm
	Sandy Loam	Secondary Forest
	Sandy Clay Loam	Secondary Forest
	Sandy Clay Loam	Secondary Forest with Oil Palm
	Sandy Clay	Down Slope of a mound
	Sandy Clay	Middle of a mound
	Sandy Loam	top of a mound
	Sandy Loam	Secondary Forest
	Sandy Clay Loam	Secondary Forest
	Sandy Loam	Secondary Forest
	Sandy Loam	Secondary Forest
	Sandy Clay Loam	Secondary Forest
	Sandy Clay Loam	
	Sandy Clay Loam	Secondary Forest
	Sandy Clay	Cocoa farm (upper Slope)
	Sandy Clay Loam	Cocoa farm (Middle Slope)
	Sandy Clay Loam	Cocoa farm (bottom Slope)
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm
	Sandy Loam	Cocoa farm
	Loamy Sand	Anthropogenic disturbance (rice farm, burnt field)
	Sandy Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm

Sample	Soil Type	Landuse
	Sandy Clay Loam	Anthropogenic disturbance (presence of a mound)
	Sandy Clay Loam	Anthropogenic disturbance (Cocoa farm)
	Sandy Clay	Cocoa farm
	Sandy Clay Loam	Cocoa farm (top of a mound)
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm (10m away from a Stream)
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm + thicket vegetation
	Sandy Clay Loam	Cocoa farm
	Sandy Clay Loam	after a mound within an Oil Palm farm
	Sandy Loam	Bamboo and Oil Palm
	Sandy Loam	Oil Palm
	Sandy Clay Loam	Oil Palm
	Sandy Clay Loam	Bamboo
	Clay Loam	Bamboo and Oil Palm
WMS 02 REF O	Loamy Sand	bamboo
	Loamy Sand	Crop Land
	Loamy Sand	Oil Palm
	Loamy Sand	Oil Palm
	Loamy Sand	Oil Palm
	Sand	Oil Palm
	Sand	Oil Palm
	Loamy Sand	Cassava, maize and Oil Palm
	Loamy Sand	Cassava, maize and Oil Palm
	Sandy Clay Loam	fallow (2m away from maize and Cassava farm
	Sandy Clay Loam	Secondary Forest with evidence of plinthite beyond 20Cm depth
	Sandy Clay Loam	Secondary Forest (Sparse old rubber Plantation
	Sandy Clay Loam	Oil Palm (with evidence of plinthification)

Sample	Soil Type	Landuse
	Sandy Clay Loam	maize and Cassava farm
	Sandy Clay Loam	before mound
	Sandy Clay Loam	Felled Oil Palm tree and bamboo
	Sandy Clay Loam	Bamboo and Oil Palm
	Sandy Clay Loam	Oil Palm
	Sandy Clay Loam	Oil Palm and rubber
	Sandy Loam	Cocoa farm
	Sandy Clay	Secondary Forest
	Sandy Clay	on a mound
	Sandy Clay Loam	Middle of a mound in a Secondary Forest
	Loamy Sand	thicket vegetation
	Sandy Loam	Cocoa farm
	Sandy Clay Loam	Cocoa farm
1000	Sandy Clay Loam	bamboo + rice farm
WMS 03 REF 0	Clay	Grassland + Cassava
50	Sandy Clay Loam	Grassland
100	Sandy Clay Loam	Plantain + Cassava
104	Sandy Clay	Cassava and Plantain (Presence of a mound)
107		
111	Sandy Clay	Cassava and Plantain
150	Sandy Clay Loam	top of a mound
155	Clay	Middle of a mound
159	Sandy Clay	after a mound
200	Sandy Loam	Cocoa farm
250	Sandy Loam	Thicket
300	Sandy Loam	Cocoa farm + Grass
325	Loamy Sand	boundary of a Stream (Surrounded by Thicket vegetation
350	Sandy Loam	Cocoa farm
375	Sandy Loam	abandoned Cocoa farm
400	Sandy Clay Loam	Secondary Forest
425	Sandy Clay Loam	Secondary Forest with Sparse Cocoa Trees
450	Sandy Clay Loam	Secondary Forest with Sparse Cocoa Trees
500	Sandy Clay Loam	Cocoa farm Intercropped with Pineapple
525	Sandy Clay Loam	Cocoa farm

Sample	Soil Type	Landuse
550	Sandy Clay Loam	Secondary Forest
600	Sandy Loam	Thicket vegetation about 5m away from a Cocoa farm
650	Sandy Clay Loam	Thicket vegetation
679	Sandy Loam	Thicket vegetation
685	Sandy Clay	Cocoa farm
690	Sandy Clay Loam	Cocoa farm
700	Loamy Sand	Cocoa farm
750	Sandy Clay Loam	Cocoa farm
775	Sandy Clay Loam	Cocoa farm
800	Sandy Clay	Cocoa farm
850	Sandy Clay Loam	Cocoa farm
900	Sandy Loam	Thicket
950	Sandy Loam	top of a mound
956	Sandy Loam	Middle of a mound
958	Sandy Clay Loam	After a mound within a Cocoa farm
1000	Loamy Sand	Toe of a mound within a Cocoa farm
1028	Sand	Cocoa farm
wmS 04, ref o	Sandy Clay Loam	Secondary Forest
50	Sandy Clay Loam	Secondary Forest
75	Sandy Clay Loam	Secondary Forest
100	Sandy Clay Loam	Anthropogenic disturbance
130	Sandy Clay	Cocoa and oil palm
140	Sandy Clay	Cocoa farm
150	Sandy Clay	Cocoa farm
160	Sandy Clay	Cocoa farm
165	Sandy Clay	Cocoa farm
172	Sandy Clay	Cocoa farm
188A	Sandy Clay	Cocoa farm (Presence of a mound)
188B	Sandy Clay Loam	Cocoa farm
200	Sandy Clay Loam	Cocoa and Pineapple
236	Sandy Clay Loam	Secondary Forest
245	Sandy Clay Loam	Secondary Forest
255	Sandy Clay Loam	Secondary Forest
265	Sandy Clay Loam	Secondary Forest
272	Sandy Clay	Secondary Forest (Middle of a mound)
275	Sandy Clay	After a mound within a Secondary Forest
282	Sandy Clay Loam	Secondary Forest
285	Sandy Clay Loam	

Sample	Soil Type	Landuse
300	Sandy Loam	Around a Stream
350	Sandy Loam	Swampy area
400	Sandy Loam	Swampy area with Thicket vegetation
450	Loamy Sand	Swampy
475	Loamy Sand	oil palm within a Swampy Secondary Forest
500	Sandy Loam	
525	Loamy Sand	Cowpea and oil palm
550	Loamy Sand	Cowpea, oil palm and Cassava
575	Loamy Sand	Thicket
600	Loamy Sand	Secondary Forest
642	Sandy Loam	Cocoa farm about 4m away from a Stream
655	Sandy Loam	Cocoa farm
700	Sandy Loam	Cocoa farm
750	Sandy Loam	Cocoa farm
800	Sandy Loam	Cocoa farm
WMS 05, Ref 0	Sandy Clay	Thicket
11	Sandy Clay	Thicket
25	Sandy Clay	Thicket
33	Sandy Clay Loam	Thicket
53	Sandy Clay Loam	Thicket
68	Sandy Clay	Thicket
75	Sandy Clay Loam	Thicket
100	Sandy Clay Loam	Thicket
150	Sandy Clay Loam	Thicket
200	Sandy Clay Loam	Thicket
220	Sandy Clay Loam	Thicket
230	Sandy Clay Loam	Thicket
250	Sandy Clay Loam	Cocoa farm
275	Sandy Loam	Cocoa farm
300	Sandy Clay Loam	Cocoa farm
335	Sandy Clay Loam	Cocoa farm

Sample	Soil Type	Landuse
350	Sandy Clay Loam	Cocoa farm
368	Sandy Clay Loam	top of a mound (Secondary Forest)
379	Sandy Clay Loam	Middle of a mound
389	Sandy Clay	after a mound (Secondary Forest)
400	Sandy Clay	Secondary Forest
421	Sandy Clay Loam	Secondary Forest
425	Sandy Clay	Thicket vegetation
428	Sandy Clay Loam	
430	Sandy Clay Loam	Thicket vegetation
458	Sandy Clay Loam	Middle + Plantain
500	Sandy Clay Loam	Middle farm
547	Clay	tomato, pepper, maize and Plantain
553	Sandy Clay	tomato, pepper, maize and Plantain
560	Sandy Clay Loam	
583	Sandy Clay Loam	abandoned Cocoa farm
600	Sandy Clay Loam	Cocoa farm
625	Sandy Clay Loam	Cocoa farm
650	Sandy Clay Loam	Thicket
675	Sandy Loam	Plantain + Middle
700	Sandy Loam	Cocoa farm
720	Sandy Loam	Cocoa farm
740	Sandy Loam	Cocoa farm
758	Loamy Sand	Cocoa farm
wmS 2-1, 1	Sandy Clay Loam	Cocoa and rubber
2	Sandy Clay Loam	rubber farm
3	Sandy Clay	rubber farm (top of a mound)
4	Sandy Loam	rubber farm
5	Sandy Loam	rubber farm
6	Loamy Sand	*Centrosema Sp*
7	Loamy Sand	Middle and oil palm
8	Loamy Sand	*Centrosema* and Middle
9	Loamy Sand	OiL palm and *Centrosema*
10	Sand	*Centrosema Sp*

Sample	Soil Type	Landuse
11	Sandy Loam	rubber farm
12	Sandy Loam	Middle farm
13	Sandy Loam	Middle and oil palm
14	Sandy Clay Loam	Middle farm
15	Sandy Clay Loam	Cocoa and rubber farm
16	Sandy Clay	Cocoa and rubber
17	Sandy Clay Loam	Cocoa farm
18	Sandy Clay Loam	Cocoa and Acheampong Leaves
19	Sandy Clay	Cocoa and oil palm
20	Sandy Loam	Middle farm
wmS3-2, 01	Sandy Clay Loam	maize farm
2	Sand	Rice farm
3	Loamy Sand	*Centrosema*
4	Loamy Sand	Acheampong and Middle
5	Sandy Loam	Cleared area
6	Sandy Clay	Cocoa farm
7	Sandy Clay	oil palm, *Centrosema* and Acheampong
8	Sandy Clay Loam	Thicket vegetation
9	Sandy Clay Loam	Thicket vegetation
10	Sandy Clay Loam	Cocoa farm
11	Sandy Clay Loam	Cocoa farm
12	Sandy Clay Loam	Cocoa farm
13	Loamy Sand	Cocoa farm
14	Sandy Loam	Cocoa farm
15	Sandy Loam	Cocoa farm
16	Sandy Clay Loam	Cocoa farm
17	Loamy Sand	Swamp,
18	Loamy Sand	Cocoa farm
19	Sandy Loam	Cocoa farm
20	Sandy Loam	maize and Middle farm
wmS 4-3, 01	Sandy Clay Loam	Secondary Forest
2	Sandy Clay Loam	Secondary Forest
3	Sandy Clay Loam	Cocoa farm

Sample	Soil Type	Landuse
4	Sandy Clay	Cocoa farm
5	Sandy Loam	Cocoa farm
6	Sandy Loam	Cocoa farm
	Sandy Clay	
7	Loam	Cocoa farm
8	Sandy Loam	Cocoa farm
9	Sandy Loam	Cocoa farm
10	Sandy Loam	Middle and Plantain
11	Sandy Loam	Plantain and Cocoyam
	Sandy Clay	
12	Loam	Cocoa farm
	Sandy Clay	
13	Loam	Cocoa farm
	Sandy Clay	
14	Loam	Cocoa farm
	Sandy Clay	
15	Loam	Cocoa farm
16	Sandy Loam	Cocoa farm
17	Sandy Loam	Cocoa farm near a Swamp
18	Sandy Loam	Cocoa farm
	Sandy Clay	
19	Loam	Cocoa farm
	Sandy Clay	
20	Loam	
	Sandy Clay	
wmS 5-4, 01	Loam	Thicket vegetation
	Sandy Clay	
2	Loam	Thicket
	Sandy Clay	
3	Loam	Thicket
	Sandy Clay	
4	Loam	
	Sandy Clay	
5	Loam	
	Sandy Clay	
6	Loam	
7	Sandy Clay	
	Sandy Clay	
8	Loam	Cocoa farm
9	Sandy Loam	Oil palm
10	Sandy Loam	bamboo, very Close to a Stream
	Sandy Clay	
11	Loam	Oil palm and bamboo
12	Sandy Loam	*Centrosema*
13	Sand	Rice, maize and oil palm
14	Loamy Sand	abandoned rice farm
15	Sand	Middle and maize
16	Loamy Sand	Middle and maize

Sample	Soil Type	Landuse
17	Sandy Clay Loam	Cocoa farm
18	Sandy Clay Loam	Cocoa farm
19	Sandy Clay Loam	Thicket
20	Sandy Clay Loam	Cocoa farm

1: Plates of Attachment

Figure 33: Photos of Sampling and Experimentation

4: Principal Components, Eigenvalues and Loading Factors

Table 14: PCA loading factors of soil variable from profile pits

	Loadings	
	Component 1	Component 2
pH	0.05389	-0.49164
Ca	0.27498	0.19199
Mg	0.20874	-0.13821
Na	0.13762	0.37839
K	0.18606	-0.2396
Fe	0.28397	-0.06809
Cu	0.23733	-0.23098
Zn	0.27592	0.20081
Av. P	0.30162	0.01675
OC	0.25996	0.32815
TN	0.173	0.33126
Sand	0.2722	-0.21371
Silt	-0.15401	-0.01243
Clay	-0.27156	0.24205
EA	-0.23722	0.23525
CEC	0.3014	0.05601
EC	0.27195	0.00299
Bulk Density	-0.17363	-0.15111

5: Principal Components, Eigenvalues and Loading Factors

Table 15: PCA loading scores from transect soil variables

Variable	Loading Scores					
	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
Av. Ph	-0.07	0.0067	0.5729	0.052	-0.0215	0.0407
Av. EC	-0.0671	0.0738	0.0582	0.1559	0.4599	-0.0168
Fe	-0.2521	-0.009	-0.3463	0.3812	0.0687	0.1502
Cu	0.0377	0.2575	-0.0646	-0.3456	0.1624	0.3999
Zn	0.0714	-0.0482	-0.1043	-0.2292	0.6468	-0.0393
Ca	0.187	-0.3195	0.2714	0.098	0.3088	-0.171
Mg	0.1249	0.4439	0.1311	0.0212	0.0477	-0.0962
K	0.0166	0.5402	-0.1107	0.1305	-0.1139	-0.021
Na	-0.1978	0.4455	0.0438	-0.1402	0.167	0.1008
EA	0.1403	-0.0296	-0.5519	0.0505	-0.0473	-0.0627
ECEC	0.2087	0.3043	0.283	0.1337	-0.041	-0.0737
P	-0.4247	0.0084	-0.0199	0.1459	0.3141	0.1524
%OC	0.1697	0.1373	-0.0904	0.422	0.1593	-0.0439
%N	0.1885	-0.0416	0.0421	0.2441	0.2265	0.136
%clay	0.5165	0.0441	-0.0947	0.0154	0.0644	-0.0145
%silt	0.0825	-0.1418	0.1138	0.0921	-0.1053	0.8178
%sand	-0.4945	0.0022	0.0546	-0.0415	-0.0309	-0.207
Bulk Density	0.0672	-0.0135	-0.0924	-0.5649	0.068	-0.001

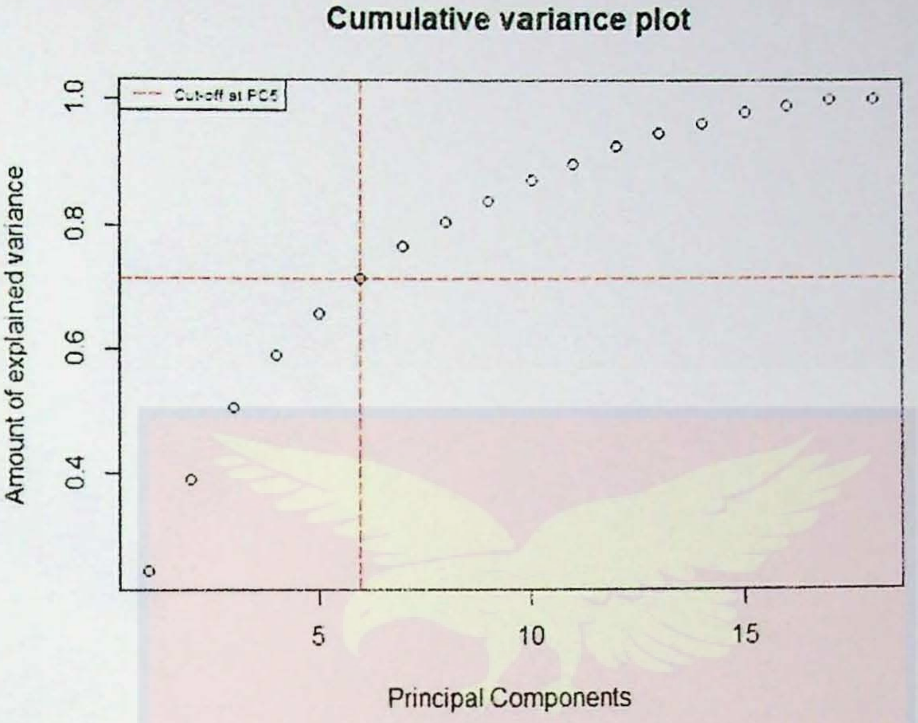

Figure 34: Cumulative Variation Components