VARIABILITY OF SOIL PROPERTIES UNDER FOREST AND TREE PLANTATIONS IN OKOMU FOREST RESERVE, EDO STATE, NIGERIA

BY

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ABSTRACT

Tropical Rainforest (RF) and forest reserves are commonly converted to Oil-Palm (OP) and Rubber Plantations (RP). Variations in soil properties have been studied under different land uses, but studies on the impact of plantations on variability in soil physical and chemical properties is limited. This study analysed soil variability under OP, RP and RF in Okomu Forest Reserve, Edo State, Nigeria.

Plant-soil model provided the framework. Using standard procedure, a 200 m x 300 m plot was established in each plantation type. Within each plot, five transects (300m) were established at 50 m interval. A total of 315 soil samples were collected (OP=105, RP=105 and RF=105) from topsoil (0–15 cm), subsoil (15–30 cm) and deep subsoil (30–60 cm) at each interval. Tree height, diameter-at-breast-height (DBH) and density were measured in ten sub-plots in the upper, middle and lower slope positions. Using standard procedures, soil physical (sand, silt and clay) and chemical properties (pH, organic carbon (SOC), total nitrogen (TN), available phosphorus (P), exchangeable calcium, magnesium, potassium, sodium, aluminum (Al), exchange acidity, effective cation exchange capacity (ECEC), extractable manganese, iron (Fe), copper and zinc) were analysed. Spatial variability in soil properties and vegetation parameters were analysed using descriptive statistics, Multivariate analysis and Geostatistical analysis at $p \leq 0.05$.

Tree height in RF was 16.75 m, OP was 17.21 m, RP was 26.97 m, DHB in RF was 29.97 cm, OP was 154.50 cm and in RP was 60.18 cm. Organic carbon in RF was 2.1%, OP was 1.4%, and RP was 0.8%. Available phosphorus in RF was 8.71 mg/kg, OP was 3.13 mg/kg, and RP was 2.77 mg/kg, while potassium in RF was 0.08 mg/kg, OP was 0.15 mg/kg, and RP was 0.10 mg/kg. Tree height varies significantly with topography in RF (F=5.11) and OP (F=52.34), while variation in DBH was significant in RF (F=1.43). Tree height, DBH and ground elevation were significantly related with pH (r=-0.53, -0.55, 0.53), SOC (r=0.54, 0.54, -0.64), TN (r=0.52, 0.53, -0.59), P (r=0.54, 0.54, -0.55), Al (r= 0.45, 0.51, -0.73), ECEC (r= 0.47, 0.52, -0.75) and Fe (r= 0.46, 0.46, -0.64) in RF respectively. The relationship were not significant in OP and RP. Soil properties variability was similar at different depths in RF (F=0.01), OP (F=1.32) and RP (F=2.09). There was a significant spatial variability of soil properties in topsoil of RF, OP and RP (F=6.17). Significant spatial variability of soil properties were also observed at different slope positions in RF (F=9.94). Spatial variability of soil properties was greater in the topsoil of RP than in OP (F=0.46).

Variability in soil properties under rainforest, oil-palm plantation and rubber plantation was limited to the topsoil and was influenced by position along the slope.

Keywords: Variability of soil properties, Tree plantation, Rainforest in Edo State, Nigeria

Word count: 448

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While walking on this earth, we are nothing in ourselves. Yet God has chosen to use us in
His mighty hand. For the masterplan requires human instruments.
But they must not ever glorify themselves…

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…all the glory must be to the LORD. Only He is worthy of our praise,
no man on earth should give glory to himself
for the glory must be to the LORD – Evie Karlsson

CERTIFICATION

I certify that this work was carried out by Mr. G. O. ENARUVBE in the Department of Geography, University of Ibadan, Nigeria

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DEDICATION

In memory of my father

John Enaruvbe OTUAGOMA

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CHAPTER 1

INTRODUCTION

Background to the Study

Rapid population growth and the quest for social, economic and industrial development have continued to exert increasing pressure on the natural environment, especially the tropical forest, in several ways (Etter et al., 2006; Geissen et al., 2009; Wright, 2005). This pressure has also led to wide spread loss of the tropical forest as a result of increase in demand for firewood, timber and timber products, food, social infrastructure and raw materials. These trends have culminated in several environmental problems in recent decades (Culas, 2007; Islam and Weil, 2000). Tropical deforestation, degradation and land use conversion, particularly from rainforest to large-scale agriculture have been shown to adversely affect soil physical, chemical and biological properties (Celik, 2005; Islam and Weil, 2000; Kizilkaya and Dengiz, 2010).

The increasing recognition of the contributions of the tropical forest to global environmental change and its importance to human sustenance, have resulted in an increased interest in tropical forest research. The focus of much of this research has been on land use and land cover dynamics (Lambin, 1997). The changing structure of the tropical rainforest has implications for the biotic and edaphic components of the environment (Salami, 1998; Wright, 2005). Geist and Lambin (2002), discussed the role of tropical deforestation on the status of climate conditions, biodiversity and net primary production, local-to-global environmental conditions and ecosystem and other valuable functions. Biodiversity and ecosystem loss, soil degradation and fertility decline, and vulnerability of people and places to climate change, economic and social disturbances have also been attributed to tropical deforestation (Houghton, 2005).

The rainforest belt of Nigeria, as in other parts of the tropical environment, has experienced significant changes as a result of the demand for agricultural land, timber harvesting, and urban expansion (Akinyemi, 2013; Balogun et al., 2011; Mengistu and Salami, 2007). FAO

(2000), has shown that about 2.6% of the rainforest is lost annually in Nigeria. The loss of this forest alters the plant-soil equilibrium that exists in the tropical environment (Ekanade, 2007). It has however been observed that the cultivation of tree crops such as cocoa, coffee and oil-palm seems to simulate the features of secondary forest ecosystem by creating soil-plant conditions similar to those which existed in the forest ecosystem in the course of their growing period (Aweto and Obe, 1993; Ekanade, 2007). Empirical evidence suggest that tree species differentially affect soil physical, chemical and biological properties (Awotoye et al., 2011; Geissen et al., 2009; Nzegbule et al., 2013). Similarly, species composition, topography and land use history have been shown to influence soil properties variation in tropical forest ecosystems (Ekanade, 2007; Vitousek and Sanford, 1986).

Most studies on soil properties variation (Adejuwon and Ekanade, 1988; Aweto, 1987; Ichikogu, 2012) are based on the assumption that soil properties are spatially independent and identically distributed (Wang et al., 2012), influenced solely by the factors of soil formation (Jenny, 1994). However, studies have shown that variation exists within soil bodies and landscape units (Cambardella et al., 1994; Scull et al., 2003). Although several studies have examined soil properties variability under various environmental conditions (Adigun et al., 2008; Gallardo, 2003; Kilic et al., 2012; Nkheloane et al., 2012; Schlesinger et al., 1996; Yavitt et al., 2009), the scale, nature and pattern of soil properties variability under tree crop plantations in tropical rainforest soils appear not to have been studied. This study, therefore, intends to analyze and compare the impact of two tree plantations (oil palm and rubber) on soil properties variability in Okomu Forest Reserve, Edo State, Nigeria.

Statement of the research problem

Soil is an important component of the nutrient and water cycle in ecosystems, including forest ecosystems. Therefore a drastic change in rainforest cover not only affects soil properties (Adejuwon and Ekanade, 1988; Aweto, 2001; Isichei and Muoghalu, 1992), but changes in soil properties influence several components of the natural environment including the type of land cover that can be regenerated (Ehrenfeld *et al.*, 2005; Ekanade and Orimoogunje, 2012; Robertson *et al.*, 1988). Apart from climate, parent material, topography and biotic factors (Aweto and Iyamah, 1993; Moore *et al.*, 1993), land use/land cover and vegetation composition are important factors that influence soil properties in an area (Awotoye *et al.*, 2011; Malgwi and Abu, 2011; Salami, 1998).

Tree crop cultivation in the tropical rainforest ecosystem following deforestation has resulted in the modification of environmental conditions of the region (Detwiler, 1986). Deforestation has also been noted as an important contributor to global environmental changes (Ekanade, 2007; Geist and Lambin, 2002), though the rate of deforestation has been observed to vary within and between regions in response to policy and institutional, economic, technological, cultural and population factors (Corlett and Primack, 2008; Geist and Lambin, 2002; Rolfe *et al.*, 2000).

Deforestation in Nigeria has proceeded at a rapid rate, particularly since the introduction of plantation agriculture and plantation forestry because large expanse of land is usually required for plantation agriculture to be viable (Aweto, 2001). The need for a large expanse of land for plantation agriculture has resulted in the clearing of most of the rainforests in the rainforest zone of the country for agricultural activities or replaced with tree crop and exotic species of various types. Apart from exotic tree species such as Gmelina (*Gmelina arborea*), *Pinus caribaea* and teak (*Tectona grandis*) cultivated for timber production and other industrial products, tree crops such as cocoa (*Theobroma cacao*), coffee (*Coffea arabica*), oil-palm (*Elaeis guineensis*), citrus (*citrus spp*), kola (*Cola nitida*) and rubber *(Hevea brasiliensis)* are also commonly grown for commercial purposes.

The conversion of the rainforest to tree crops and exotic tree plantations has been reported to adversely affect the physical, chemical and biological properties of soils (Adejuwon and Ekanade, 1988; Aweto, 2001; Chris-Emenyonu and Onweremadu, 2011; Ekanade, 2007). Until recently the focus of most studies on soil-vegetation relationship have been limited to the spatial variation of soil properties (Burrough *et al.*, 1994) and most studies in the tropical rainforest belt are based on the assumption that soil properties variation are randomly distributed and are therefore independent of each other within a mapping unit. It has however been shown that soil properties exhibit spatial dependency (Iqbal *et al.*, 2005;

McBratney *et al.*, 2003; Nkheloane *et al.*, 2012) with samples collected close to each other being more similar than those far apart.

Tree crop plantations currently occupy a large expanse of deforested land in Nigeria. The impacts of these plantations on soil properties have been assessed by various studies on the assumption that soil properties vary at uniform rate under similar tree species (Aborisade and Aweto, 1990; Iwara and Ogundele, 2013). However, studies have shown that soil properties variation is not uniform over a large area because of the regional distribution of soil types (Gonzalez and Zak, 1994). It is therefore important that the spatial variation and variability of soil properties under tree crop plantations be quantified to provide information on the influence of these plantations on the pattern and scale of heterogeneity of soil properties and hence assist soil scientists, planners and managers in adopting intervention strategies aimed at optimizing resource utilization for attaining sustainable management of soils. In view of the above, this study seeks to provide answers to the following research questions:

i. Do topographic characteristics determine tree density, tree height and diameter-at-breast height in rainforest ecosystem?
ii. Do differences in land use and land cover influence soil properties variability pattern?
iii. Do tree crop plantations significantly alter spatial variability of soil properties in rainforest soils?
iv. What are the effects of oil palm and rubber plantations on spatial variability of soil properties in rainforest soils?

1.3 Aim and objectives

The aim of this research is to characterize the influence of oil palm and rubber plantations on the spatial variability of soil properties in Okomu Forest Reserve, Edo State. The specific objectives are to:

i. determine the spatial pattern of vegetation characteristics under rainforest and tree plantations in Okomu Forest Reserve;

ii. determine the impact of vegetation on the spatial variation of soil properties in rainforest and tree plantations in Okomu Forest Reserve;

iii. characterize the soils under rainforest and tree plantations in Okomu Forest Reserve;

iv. analyze the impact of differences in land use on the spatial variability of soil physical and chemical properties.

1.4 Research hypotheses

i. There is no significant positive relationship between soil properties variation and tree parameters under rainforest and tree plantations.

ii. Differences in spatial variability of soil physical and chemical properties under forest and plantations are not limited to the topsoil layer.

iii. Spatial variability of soil physical and chemical properties is not greater under oil palm plantation than under rubber plantation.

1.5 Significance of the study

Changes in land use/land cover have significant implications for soil fertility and productivity (Agbenin and Adeniyi, 2005; Ehrenfeld *et al.*, 2005; He *et al.*, 2008). Studies show that land use/land cover influences the status of soil fertility, which in turn, influences the type of vegetation that can grow in an area (Clark *et al.*, 1999; Ehrenfeld *et al.*, 2005; Ekanade and Orimoogunje, 2012). However, field-scale variation of plant nutrient can be a limiting factor in tropical rainforest soils (Dobermann *et al.*, 1995).

Though Aweto and Obe (1993) and Ekanade (2007), posited that tree crop plantations tend to simulate rainforest conditions, the degree of simulation seems not to have been quantified under these plantations. The degree of the spatial variability of soil resources and their influence on these plantations is poorly understood. Therefore, comparing the scale and pattern of variability of soil properties under rainforest, rubber and oil palm plantations will provide information necessary to evaluate this hypothesis. Furthermore, analyzing the influence of differences in land use on the spatial variability of soil properties under tree crop plantations is important in providing information on the nature and scale of soil properties variability under plantation agriculture in tropical rainforest soils.

This study intends to examine the influence of land use change and tree plantation agriculture on the spatial pattern of soil properties and soil variability in Okomu Forest Reserve in southern Nigeria. This is important because an effective soil management requires a clear understanding of the distribution pattern of soil properties within the landscape (McBratney *et al.*, 2000). Ecologists, soil scientists, planners, natural resources and forest resources managers require information about the pattern of soil properties variation at the field-scale in other to evaluate the impact of different land use and management practices on soil properties variability and the implications of such variations on soil quality, productivity and management. Information on soil properties variability will also be important in determining site-specific application of farm inputs such as fertilizer, lime and irrigation water in precision agriculture. Furthermore, the information obtained from this study will be useful in evaluating the degree of reliability of data derived from the analysis of composite soil samples under tree crop plantation agriculture (Obalum *et al.*, 2013) and will serve as a major input in the design and analysis of field experiments (Dobermann *et al.*, 1995).

This study will also provide insight into the scale and pattern of soil properties variability under different land uses, particularly in monoculture plantations. It will assist decision-makers to arrive at site-specific decisions, identify and develop management strategies for sustainable soil utilization. Similarly, it will facilitate the development of measures aimed at mitigating the impacts of tree crop plantations on the variation of soil quality and productivity in the rainforest.

1.6 Study area

1.6.1 Location, topography and drainage

This study was conducted in Okomu National Park and the adjoining Okomu oil-palm and Osse rubber plantations located within Okomu Forest Reserve in Edo State, southern Nigeria (Figure 1.1). The area is approximately bound by latitudes 6.08° and 6.30°N and longitudes 5.01° and 5.27°E. Okomu National Park has an area of approximately 202 km^2

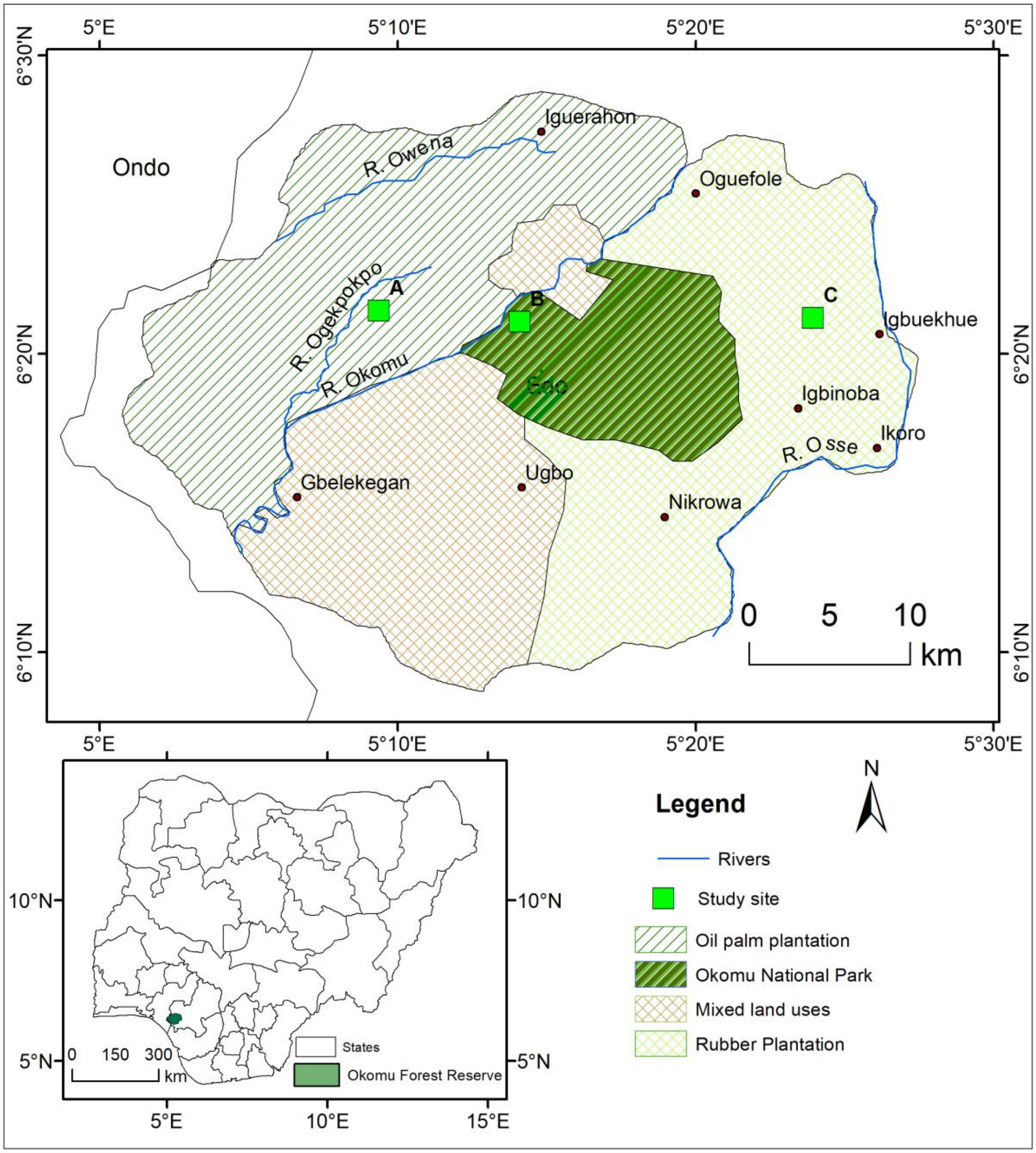


Figure 1.1: The Study Area (Okomu Forest Reserve) in Edo State, Nigeria

(Source: Author's Fieldwork, 2015)

and it is the smallest of Nigeria's seven National Parks. The National Park, Oil palm plantation and rubber plantation are parts of the former 1082 km^2 Okomu Forest Reserve. Much of the reserve is now degraded because of farming activities, illegal timber extraction and other forms of human activities. Ojanuga (2006), classified the area as very humid Lagos-Benin-Asaba lowland zone. This is an area of relatively flat to very gently undulating plain developed on sedimentary rocks and littoral deposits with most parts below 200 m above sea level. Okomu Forest Reserve is located in an area that is gently sloping from north to south. The elevation ranges between 80 m at the northern part to about 40 m above mean sea level in the southern part. Several areas in the Park have no noticeable slopes. The area is drained by River Okomu which flows in a southwest direction into River Siluko which forms the boundary of the area in the west. The eastern boundary is defined by River Osse. There are also a few tributaries of the River Okomu (Akinsorotan *et al.*, 2011).

1.6.2 Climate

Climate data obtained from the Nigerian Metrological Agency (NIMET) for 35 years (1981-2016), shown in Figure 1.2, indicates that there is year-round rainfall which peaks between May and October. The area has a double maximal rainfall pattern with a mean monthly rainfall of about 200 mm. September has the highest rainfall while January accounts for the least rainfall during the year. The driest months are between December and January. The mean monthly temperature is 27°C and the highest temperature occurs between February and March.

1.6.3 Soil and vegetation

The reserve is characterized by acidic sandy loam soil, derived from deep loose deltaic and coastal sediments, sometimes referred to as the Benin Sand. The soils are low in base saturation and have other nutrient related problems such as high exchangeable aluminum, low exchangeable bases and available micronutrients. Exchangeable potassium, magnesium and phosphorus are often required to maintain yields but the soils have to be moderately limed to reduce aluminum toxicity (Aregheore, 2009). The soil in the area were broadly described as Ahiara series by Moss (1957) though a more detailed survey will

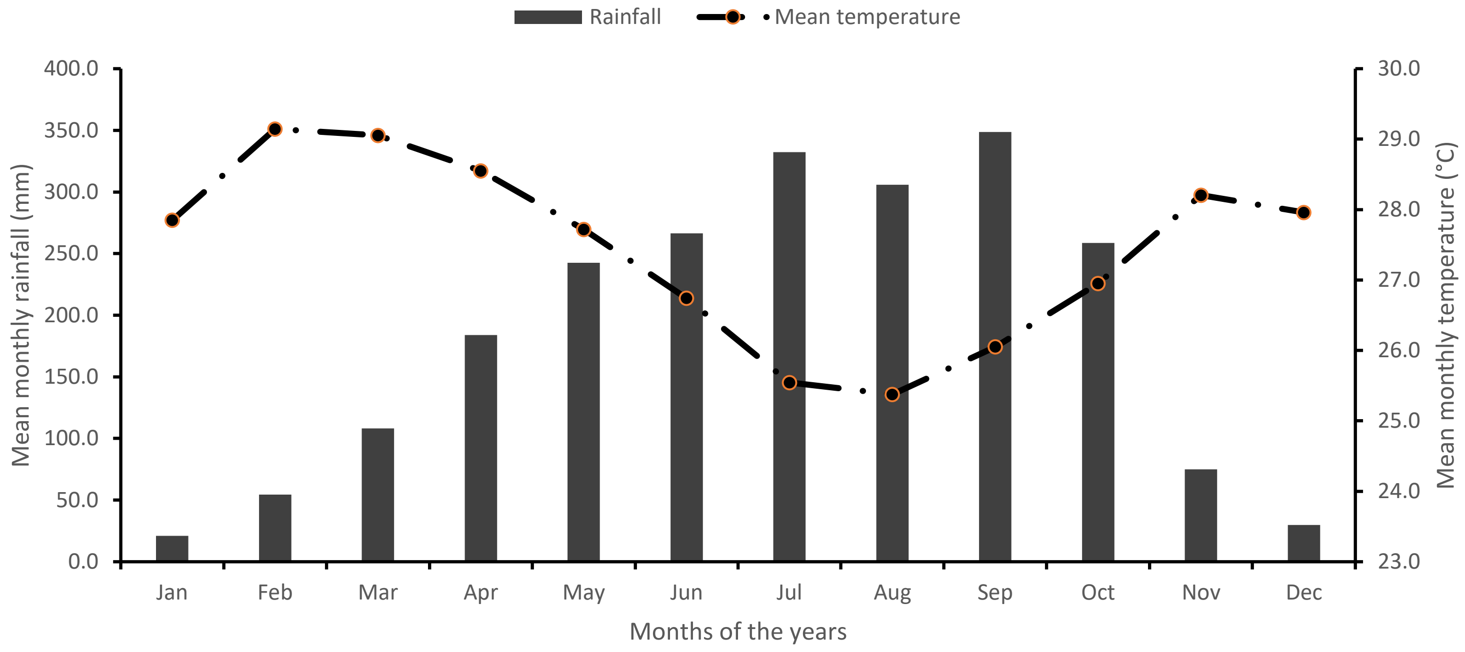


Figure 1.2: Mean monthly rainfall (mm) and temperature (°C) in the study area between 1981–2016

(Source: NIMET Data, 2017)

likely reveal more soil types within the forest reserve. The soil texture is clayey sand and occasionally very clayey. The lower layers vary from brownish-red to dark reddish-brown. They are well drained and the water table is situated well below the limit of the soil solum throughout the year (Aregheore, 2009; Ojanuga, 2006).

Vegetation in the reserve is composed of a close stand of three layers of trees consisting of lower and middle storeys and a discontinuous layers of tall emergent trees. Some tree species in the area include African Mahogany (Khaya ivorensis), Sipo Mahogany (Entandrophragma angolense), Sapele Mahogany (E. cylindricum), Obobo Nofua (Guarea cedrata), and Obobo Nekwi (Guarea thompsonii) though other commercially important tree species exist in the reserve (Ejidike and Okosodo, 2007)**.**

CHAPTER 2

CONCEPTUAL FRAMEWORK AND LITERATURE REVIEW

2.1 Introduction

This chapter discusses the underlying concepts, theories and state of knowledge related to this study. The first section examines the concepts of soil, land use change and land use change models and the plant-soil model. This will provide insight into the nature of land use change and its impacts on the plant-soil system being investigated. It will also elucidate the specific variables to be measured and the methodological approaches employed in variable measurement. The focus of the next section is the review of existing literature on changes in soil properties with specific emphasis on (a) vegetation distribution and soil properties variation, (b) the influence of land use/land cover change on the spatial pattern of soil properties and soil properties variability in tropical soils, and (c) methodological approaches in soil properties variability analysis and modelling.

2.2 Conceptual framework

2.2.1 The concept of soil and soil properties variability

In spite of the recognition of the importance of soil to human sustenance from ancient civilization (Adejuwon and Ekanade, 1988; Jenny, 1994; Scull *et al.*, 2003), attempts at defining the concept of soil has remained difficult (Soil Survey Staff, 1993). Though scientists view soil as a mixture of mineral and organic matter of varying size and composition necessary for plant and microbial growth (Foth, 1990), a generally accepted definition of soil appears to be lacking. This difficulty may stem from the complex and highly variable nature of soil (Oyedele and Tijani, 2010; Scull *et al.*, 2003) and the variety of uses to which it is employed. Oyedele and Tijani (2010), defined soil as a product of the weathering of the parent materials lying over the earth surface which had been influenced by climate and conditioned by biotic and relief over time. Soil has also been described as a mixture of air, water, decaying organic and inorganic matter and living organisms within the surrounding ecosystem (Kizilkaya and Dengiz, 2010; Simonson, 1959). In what is referred to as the “modern concept of soil”, Soil Survey Staff (1993), noted that soil is the collection of natural bodies in the earth’s surface containing living matter and is capable of supporting the growth of plants. Soil is seen as a three-dimensional entity which has length, breadth and depth. Each soil body is composed of a distinct upper limit, fuzzy perimeter and lower boundary (Simonson, 1959; Soil Survey Staff, 1993). Simonson (1959), noted that local differences in the soil continuum are determined by the pattern of individual soil bodies.

The importance of human activities in shaping the soil-forming process is evident in the literature (McBratney *et al.*, 2003; Zhang and McGrath, 2004). There is increasing pressure on the natural environment occasioned by population explosion and demand for socioeconomic development (Etter *et al.*, 2006; Geissen *et al.*, 2009). The environmental consequences of the resulting anthropogenic activities are diverse and enormous. These consequences are culminating in several environmental problems (Culas, 2007) and the modification of soil structure and processes. Soil properties variation at the regional and local scale is the direct consequence of environmental modification arising from deforestation, agricultural expansion and other land uses.

Spatial variability is an inevitable property of all soil types and it directly influences the composition and occurrence, growth and distribution of plant and animal species in the environment (Gallardo, 2003; Lugo, 1997). It is the diversity and configuration of environmental attributes which are often modified by natural and anthropogenic disturbances, global environmental changes such as climate and land use changes, and the interactions that take place between these factors in a geographic region (Fortin *et al.*, 2012). As Douaik *et al.* (2011), observed soil variability is a product of systematic (deterministic) and random (stochastic) environmental processes.

Three approaches - the factor models (Jenny, 1994), the process models (Simonson, 1959) and the energy models (Runge, 1973) - have been applied in accounting for the high variability of soil which illustrates the difficulty encountered in quantifying soil variation and processes (Scull *et al.*, 2003). The factor (Jenny, 1994), model has proved to be the most popular among researchers. The model shows that soil formation is a function of climate, organisms, relief, parent material and time factors. These factors exert important influence on the variation of soil properties and vegetation distribution (Gonzalez and Zak, 1994; Malgwi and Abu, 2011). The factor model has been described using various terms. Krasilnikov *et al.* (2008), for instance, used the term “corpan” while McBratney *et al.* (2000), used the term “clorpt” in describing the model. It has also been termed “environmental correlation” (McKenzie and Austin, 1993; McKenzie and Ryan, 1999).

The spatial variation of soil properties under a variety of conditions has been analyzed in various studies. This has led to the identification of different factor that could result in such variation in time and space. It has however, been noted that the causes of spatial variation of soil properties are scale dependent (Gonzalez and Zak, 1994; Wang *et al.*, 2010). As a result of variability in environmental systems, monitoring and modelling have become inevitable components of environmental planning and management that is required for the sustainable use of soil and other environmental resources (McBratney *et al.*, 2000; Paz-Gonzalez *et al.*, 2000) particularly at the field scale.

2.2.2 Land use/land cover change models

Land cover includes the biotic, abiotic and the human components of the earth’s surface and immediate subsurface (Lambin *et al.*, 2000). Land use on the other hand, is the exploitation of the land cover to meet social, economic, cultural and physical needs of man. Land use/land cover change is one of the most important drivers of environmental change. There are two dimension to land use/land cover change: land cover conversion and land cover modification. Land use/land cover conversion entails the complete replacement of a land cover with a different land cover type. This is a more drastic change than land cover modification which is the alteration of the attributes of the land cover without changing its overall classification. Studies show that the dimensions of land use/land cover change impacts on the biotic and abiotic components of the environment are diverse (Lambin *et al.*, 2003). Land use/land cover change affects the functioning of environmental systems such as the hydrological system, soil properties dynamics, climate conditions and several other components of the natural environment (Cotching *et al.*, 2013; Lambin *et al.*, 2003; Salemi *et al.*, 2013; Taylor *et al.*, 2002).

Rapid changes in land use alter the structure and composition of the natural vegetation. This alteration influences soil forming processes (Jenny, 1994) and can modify the physical and chemical characteristics of the soil. Other factors of soil formation include climate, topography, parent materials and time. The nature and scale at which vegetation varies in space and time is largely controlled by anthropogenic activities. Human activities have resulted in significant changes in land use/land cover globally, particularly since the 1700s (Goldewijk and Ramankutty, 2004). The increasing awareness of the impact of land use/land cover change on global environmental resources has resulted in the development of models aimed at providing better understanding of land use/land cover change pattern and processes. These models are designed to support the analysis of the causes and effects of land use change while providing answers to three fundamental questions – where, when and why – that are relevant to an understanding of land use/land cover change pattern and processes (Lambin *et al.*, 2000). The models also provide insight into land use system functions and assist environmental resources managers in land use planning and allocation, policy formulation and implementation (Angelsen and Kaimowitz, 1999; Verburg *et al.*, 2004).

Land use change models are broadly categorized as descriptive and predictive models. Descriptive models aim at simulating the functioning of land use system and spatially explicit simulation of near future land use patterns. The models attempt to show the processes of land use change as depending on the state of land use pattern in the immediate past. Transition probability model and logistic function model are examples of these set of models (Lambin, 1997). Prescriptive models, however, attempt to determine the optimal land use configurations that will be best in achieving set land use goals and objectives.

These broad groups of models are further subdivided, based on the methods and scale of analysis and sources of data, into three analytical approaches: agent-based approach, systems approach and narrative approach (Angelsen and Kaimowitz, 1999; Lambin *et al.*, 2003; Verburg *et al.*, 2004). The agent-based approach as Lambin *et al.* (2003), noted is rooted in the nature of land use decision-making process by individual members of the society. This approach applies rational economic variables such as background, preferences, household characteristics, gender and class among other determinants in arriving at land use decisions which are usually aimed at profit maximization (Angelsen and Kaimowitz, 1999). Decision makers therefore constantly adjust their choices - based on available information - to accommodate economic, social and environmental constraints so as to improve the benefits accruing to them from available choices. Irwin and Geoghegan (2001), argued that an advantage of focusing on the development of spatially explicit economic models is the usefulness of these models in providing relevant inputs for simulating policy scenarios.

The system approach focuses on the interactions among underlying processes such as organization and institutions of society that operates at various levels to determine land use/land cover change. The approach evaluates the impacts of changes in national or global economic systems on local environmental conditions. It provides important links to macroeconomic variables and policy instruments and the relationship between different sectors of an economy are evaluated (Angelsen and Kaimowitz, 1999; Lambin *et al.*, 2003; Verburg *et al.*, 2004). The influence of the level of economic development and national and international political institutions on land use/land cover change pattern is of significance in contemporary societies. Chen *et al.* (2007), showed that the stage of economic development is an important determinant in the pattern of cultivated land use/land cover changes in Fujian and Taiwan. Clark (2010), developed a land use model based on economic theories to explain the influence of political institutions on the demand for land and land rent. The studies of von Hellermann (2010; 2011), have also highlighted the influence of traditional and political institutions in determining the spatial pattern of deforestation and land use/land cover conversion through the allocation of land for conservation and agriculture.

The narrative approach seeks to provide understanding by in-depth evaluation and interpretation of historical records. The narrative approach tells the land use/land cover story that have influenced the spatial configuration of current land use pattern in a particular locality. It examines all available historical evidence and complexities to reveal the causes of contemporary land use/land cover patterns. The narrative approach is useful for generating scenarios of future land use changes or identify land use patterns aimed at optimizing certain characteristics as demonstrated by Rotmans *et al.* (2000), in Europe.

von Hellermann (2010), also applied the narrative approach in the analysis of the historical events that shaped the land use/land cover configuration of Okomu Forest Reserve in southern Nigeria.

In complex cases, two or more land use/land cover models are integrated in the analysis of land use change patterns and processes. The integration of these models is useful in elucidating factors that cannot be captured when any of the models is used in isolation. For instance, Echeverria *et al.* (2008), examined the impact of forest fragmentation on the current and future spatial configuration of forest habitats at the landscape level in southern Chile and predicted forest habitat pattern between 2010 and 2020 using an integrated approach.

2.2.3 The plant-soil model

Studies indicate that plant-soil interactions play important role in biogeochemical and hydrological dynamics of the natural environment. The plant-soil feedback influences many ecological processes and are also important components of ecological response to changes in local and global environmental conditions (Celik, 2005; Chijioke, 1980; Ehrenfeld *et al.*, 2005; Schlesinger and Pilmanis, 1998). The plant-soil interaction is also linked to other components of the environment such as climate change and water balance (Coughenour and Chen, 1997; Neilson, 1995). Vegetation composition differentially influences soil properties and determines the amount of nutrient build-up (Teka *et al.*, 2015; Walker and Desanker, 2004). It has been observed that vegetation structure and composition influence the type and nature of soil and it determines local-to-global environmental conditions such as weed species abundance, tree height, diameter-at-breast-height and wood volume (Aweto, 1981a, 1985; Ekanade, 2007). Similarly, the nutrient status of soil influences the nature of plant succession in a location (Amorim and Batalha, 2007). The nature of the relationship, however, varies over time and is also influenced by other factors including land use/land cover type, topography and hydrology (Aweto, 1981b; Ekanade and Orimoogunje, 2012; Jirka *et al.*, 2007; Tsui *et al.*, 2004).

Several aspects of the plant-soil interaction such as ecological response to changing environmental conditions, soil nutrient dynamics and the process of non-native species invasion have been studied to elucidate an understanding of the nature and dynamics of the plant-soil interaction processes (Coughenour and Chen, 1997; Kersebaum and Richter, 1991; Levine *et al.*, 2006). It has been shown that the plant-soil system plays important roles in determining vegetation characteristics and distribution pattern over a landscape (Aweto, 1981c). The realization of the interaction between vegetation and soil components of the natural environment has resulted in several studies aimed at providing more understanding of the processes that results from such interactions and the impacts of these interactions on ecosystem functioning (Burke *et al.*, 1999; Chijioke, 1980; Ehrenfeld *et al.*, 2005; Ekanade and Orimoogunje, 2012).

The importance of the plant-soil model in soil-vegetation analysis makes it the most suitable model for this study. This study is therefore based on the plant-soil model as described in the preceding paragraph.

2.3 Literature review

2.3.1 Analysis and estimation of the influence of environmental variables on spatial distribution of vegetation

A cyclical relationship has been noted between soil and vegetation (Ekanade and Orimoogunje, 2012). This relationship is closely linked to the soil forming factors described by Jenny (1994). Soil forming factors are those important factors that have been observed to determine the process of soil formation. These are parent materials, climate, relief, organisms and time. These factors also influence the distribution of soil properties within a landscape (Aweto and Enaruvbe, 2010; Aweto and Iyamah, 1993; Bohlman *et al.*, 2008; Colombo *et al.*, 2015; Jenny, 1994). However, the influence of parent materials, relief and human activities over time are more apparent when soil is studied over a large area (Moore *et al.*, 1993; Soil Survey Staff, 1993). The nature, composition and pattern of soil and vegetation in a landscape are therefore the result of the interactions between these factors (Vitousek and Sanford, 1986). Studies have shown the importance of topography, climate and soil as factors determining the distribution of vegetation (Oliverira-Filho *et al.*, 1989). Soil fertility and human interference are other factors that significantly influence the spatial distribution of tree species (Oliveira-Filho *et al.*, 2001; Oliveira-Filho *et al.*, 1994; Toniato and de Oliveira-Filho, 2004).

Vegetation interaction with other environmental variables such as topography, elevation, landform, parent materials and human activities have been observed to control the pattern and dynamics of soil properties (Burke *et al.,* 1999; White *et al.,* 2009). These interactions modify the impact of vegetation distribution on soil properties and characteristics. Schlesinger *et al.* (1996), examined the spatial pattern of soil nutrients around individual plant species in arid and semi-arid grassland area of the Chihuahua desert, Mexico. They hypothesized that the spatial variability of soil nutrients distribution in desert shrublands are influenced by the size of the dominant individual species. They observed that variation in nitrogen occurred at distances of less than 20 cm in the area. They show that vegetation influences the pattern of spatial autocorrelation. The spatial variability was noted to depend on the mean shrub size and this reflected local nutrients cycling in arid and semi-arid environment. They however failed to investigate the role of depth on the observed pattern of spatial variability of soil properties. Similarly, Jackson and Caldwell (1993), observed that individual perennial plant species influence the pattern of soil properties variability in native sagebrush-steppe site in Utah. They noted that soil organic matter and pH show strong spatial variability at distances of less than 1 m. Aweto and Moleele (2005), observed that despite high clay content in soils under eucalyptus plantation, there was lower levels of soil nutrients under the plantation than in forest soils on an alluvial soil in Botswana. Nzegbule *et al.* (2013), however noted that the fertility status of soils under a 35-years old cashew plantation in southern Nigeria appears to be better enhanced for crop cultivation than an adjacent rainforest.

Isichei and Muoghalu (1992), examined the impact of tree canopy cover on soil properties distribution in a savanna ecosystem in Nigeria. They observed that the nutrient status of soils under tree canopy were significantly higher than in adjacent grassland. They also noted that tree height contributed to the nature of nutrient status in the savanna area as trees with height of 7 m or more had higher nutrient concentration under their canopies. They also reported that there is a relationship between soil texture and soil properties variation.

Onyekwelu *et al.* (2007), however could not establish a relationship between soil properties variation and vegetation diversity in a humid tropical rain forest ecosystem.

The influence of vegetation characteristics and other components of the environment has also been shown to influence soil properties and its characteristics. Topography and vegetation have been observed to jointly influence soil properties distribution and processes in various ecological conditions. These factors are considered important integrating and independent factors in the soil forming process (Gessler *et al.*, 2000; Jenny, 1994; Siqueira *et al.*, 2010). The relief factor gives expression to the interaction of various soil and plant characteristics. The relationship between slope and soil properties variation has been established under a variety of environmental conditions (Moss, 1963; Tsui *et al.*, 2004). This is based on the catena concept which has been most often used for soil properties characterization within landscapes. Catenary soil development occurs in response to the movement of water through and over the landscape as subsurface and overland flow (Moore *et al.*, 1993; Seibert *et al.*, 2007). The changes in soil properties resulting from topography are observed to be linked to slope steepness, length of curvature and relative location within the toposequence (Alijani and Sarmadian, 2014; Aweto and Enaruvbe, 2010; Tsui *et al.*, 2004). These changes are also related to the complex interaction between vegetation and geomorphological processes. Topography influences species distribution and composition which may explain the distribution of soil properties (Aweto and Iyamah, 1993; Colombo *et al.*, 2015; Oliveira-Filho *et al.*, 1994; Seibert *et al.*, 2007), run-off intensity and erosion, drainage, soil depth and soil temperature (Wang *et al.*, 2001) under different environmental conditions. However, studies have shown that soil properties variation are observed in slopes under single tree species which shows the influence of catenary variation on the distribution of soil properties (Aweto and Enaruvbe, 2010)

Vegetation also interacts with landforms in influencing soil properties pattern. The importance of landform on soil properties variation has been highlighted by several workers. For example, Siqueira *et al.* (2010), and Camargo *et al.* (2010), observed the impact of landform in influencing soil properties variability in Sao Paulo, Brazil. Siqueira *et al.* (2010), showed that landform influences the variability of soil properties. They analyzed clay content, organic matter content, water content, aggregate stability, macropores, micropores, total pore volume, saturated soil hydraulic conductivity, soil density, and soil resistance to penetration at 0 - 0.2 m depth. They predicted soil variability based on the nature of landform under orange plantation and noted that soil parameters are significantly influenced by landform variation. They conclude that landform provides an efficient criterion for mapping soil variability. Camargo *et al.* (2010), examined the spatial variability of soil physical properties and their relationship with slope curvature in Alfisol under a sugarcane plantation. They took samples at the intersection of a 10 m by 10 m grid to depths of 0 – 20 cm and 20 cm to 40 cm. The samples were analyzed for bulk density, soil aggregate, porosity, resistance to penetration and moisture. The parameters were subjected to geostatistical, and descriptive statistics, while the differences between mean sample parameters were determined using student's t-test. They observed that apart from aggregates above 2 mm, all soil parameters in the 0 to 20 cm depth were influenced significantly by differences in the characteristics of hill slope curvatures. Similarly, Florinsky *et al.* (2002), showed that topography and slope form are important components of the landscape that must be accounted for when predicting soil properties variability. They noted that in using terrain for the prediction of soil properties, four types of variability - regional, temporal, depth and scale - should be considered in relation to relief and soil. The nature and attributes of landforms influence soil properties and vegetation distribution pattern in a landscape (Camargo *et al.*, 2010; Clark *et al.*, 1999; Siqueira *et al.*, 2010). Studies indicate that soil properties variation is higher in concave slopes than in convex slopes (Camargo *et al.*, 2010; Nizeyimana and Bicki, 1992; Siqueira *et al.*, 2010; Souza *et al.*, 2006).

Relief and elevation characteristics influence vegetation pattern and attributes (Bridge and Johnson, 2000; Siqueira *et al.*, 2010; Vormisto *et al.*, 2004). Vormisto *et al.* (2004), observed that the distribution of palm in the Amazon rainforest was influenced by the complexity of topography. Aweto and Iyamah (1993), however observed no marked variation in vegetation structure along the catena except around a river bank where trees were fewer and shorter along a catena in the swamp forest of southwestern Nigeria. They also noted that tree density was lower near the river bank than in other parts of the slope.

Soil depth influences the impact of vegetation on nutrient characteristics and variation. Ziadat *et al.* (2010), posit that slope steepness and slope curvature are important in influencing the soil depth along a catena in the semi-arid region of Jordan. They observed a systematic relationship between topographic characteristics - slope position, slope steepness and slope curvature - and soil properties variation. Similarly, Alijani and Sarmadian (2014), noted that topographic characteristics such as wetness index and profile curvature were positively correlated with soil carbonate. They observed that soil depth increased with decreasing slope gradient in the Kouhin area, Qazvin Province of Iran. The vertical distribution of soil nutrients is influenced by the nature of soil properties and plant nutrient cycling processes in arid environment. Jobbágy and Jackson (2001), noted that nutrients that are limiting for plants exhibit more shallow vertical distribution than nutrients that are less limiting. They also observed that variation in soil types affect the distribution of soil nutrients in an area. Lu *et al.* (2002), reported similar conclusion in an Amazonian secondary succession forest regrowth in Brazil. They noted that the top 40 cm of soil was more important for plant growth in Alfisols while in Ultisols and Oxisols vegetation growth rate is affected by deeper soil horizons.

Various tools and methods are applied in elucidating information relating to the influence of environmental conditions such as soil nutrients distribution and topography on vegetation distribution. Principally, the purpose of vegetation analysis is to classify and quantify the response of plant communities to ecological gradients and processes that determine the distribution of plants and animal species within an ecosystem (Angers *et al.*, 1999; Corney *et al.*, 2004; Jirka *et al.*, 2007). Researchers have developed various methods that assist scientists in analyzing the interrelationship between species and the environment. These methods include multivariate methods which have gained wide acceptance in geographical and ecological research for the analysis of vegetation and other ecological components of the environment (Attayde and Bozelli, 1998; Aweto, 1981c; Dirnböck *et al.*, 2003).

Canonical Correspondence Analysis (CCA) has particularly enjoyed wide acceptance among ecologists and geographers for ecological gradient analysis. CCA is a multivariate technique that uses linear combination of environmental variables such as soil nutrients concentration to explain species variables such as tree parameters in an ecosystem (Braak and M.Verdonschot, 1995). The technique is able to simultaneously analysis several sets of explanatory and response variables which makes it useful for determining the relationship between environmental components and underlying processes in an ecological community (Angers *et al.*, 1999). CCA is therefore widely used as an ordination technique for analyzing ecological gradients which influence species distribution and response to ecological processes (Jafari *et al.*, 2004). Oliveira-Filho *et al.* (1994), classified the ecological distribution of tree species in a tropical riverine forest in south-eastern Brazil resulting from the effects of soil and topographic gradients using the CCA technique. Also, Angers *et al.* (1999), determined the relative contribution of drainage pattern and environmental factors controlling the structure and pattern of inter- and intra-population genetic diversity among brook charr population in southern Quebec, Canada using CCA technique. Similarly, the effects of landscape scale environmental components on the vegetation composition of British woodlands was examined by Corney *et al.* (2004), using CCA. They were able to determine the relationship that exists between these landscape components and the woodland and provided a baseline against which species dynamics can be assessed at different levels of conservation threat resulting from changes in land use and climate conditions in the area. Ekanade and Orimoogunje (2012), examined the interactions between soil and vegetation variables in the cocoa producing area of south-western Nigeria using CCA. They concluded that while simple relationship exists between soil and vegetation variables, CCA was useful in recognize complex interrelationships which also exist in the cocoa plant community.

2.3.2 Classification of tropical soils

Soil classification is the process of systematically grouping soil individuals into near-homogenous classes in terms of pre-defined objectives (Rossiter, 2007). Soil survey, characterization, classification and mapping provides important information necessary for the evaluation of soils for sustainable agricultural utilization and management (Braimoh, 2002). This has therefore prompted significant research into soil classification at various levels of society. The need to standardize soil classification systems also resulted in the development of standards for soil classification such as those of the United Nations Food and Agricultural Organization (FAO, 2006), United States Department of Agriculture, Soil Survey Staff (Soil Survey Staff, 2014), among several others. However, the development of these soil classification schemes is seen as an indication of different opinions about the major soil forming factors and the criteria to be considered in soil classification (Deckers *et al.*, 2001). These documents have become major sources of information for soil classification around the world.

In Nigeria, several studies have been conducted to classify soils for various purposes. Early studies include those of Doyne *et al.* (1938), Moss (1957), Smyth and Montgomery (1962), Klinkenberg and Higgins (1970) and Murdoch *et al.* (1976). Recent studies on soil characterization and classification have been conducted to evaluate soils for specific purposes especially for agricultural planning and development. For instance, Ogban and Babalola (2009), characterized and classified inland valley bottom soils overlying Basement Complex rock formation for crop production in sub-humid southwestern Nigeria. They classified the soils as Aqic Endoaquepts, Typic Endoaquepts and Aeric Typic Endoaquetps on the basis of variation in depth to water table. In the semi-arid region of northern Nigeria, Sharu *et al.* (2013), identified three soil mapping units on the basis of land forms and surface texture. Using USDA soil taxonomy, they classified the soils as Typic Endoaqualfs, Typic Haplustepts and Lithic Ustorthents which corresponds with Haplic Luvisols, Argic Lixisols and Ruptic Cambisols in the FAO World Reference Base (WRB) system of classification. Chukwu (2013), classified soils in Ikwuano, Abia State in eastern Nigeria, on the basis of toposequence and lithosequence as Ultisols and Alfisols following the USDA soil classification systems and Acrisols and Nitisols using the FAO scheme. They delineated soils in the area into Orlu, Ahiara and Alagba series.

Orimoloye (2011), evaluated soils of southern Nigeria for rubber cultivation and classified the soils in the study area using USDA classification scheme as Ultisol and Inceptisol. The soil series identified are Alagba, Orlu, Kulfo and Ahiara series at Iyanomo and Uyo area while Calabar and Etinan series were identified in Akwete. However, no further analysis was carried out to determine the impacts of rubber plantation on soil properties variability in the areas studied.

Though some studies have been conducted under tree plantations in the rainforest belt of Nigeria, there seems to be limited information on studies conducted under oil palm and rubber plantations for the purpose of examining the impacts of these plantations on the spatial variability of soil properties.

2.3.3 Influence of land use/land cover change on the spatial pattern of soil properties and soil properties variability in tropical soils

Land use/land cover change is recognized as having significant consequences on the global environment. The major contributors to land use/land cover change include deforestation, forest degradation and conversion of forest land to other uses such as large-scale plantation agriculture and monoculture agroforestry (Verburg *et al.*, 2002). These changes have resulted in significant research interest as their impacts on soil, biodiversity, water quality, and climate change are well documented (Akinyemi, 2013; Detwiler, 1986; Khresat *et al.*, 2008). The changes in land use and land cover are also linked to several social and economic consequences such as rural-urban migration and food security issues (Lambin and Meyfroidt, 2010; Matson *et al.*, 1997; Mehdi *et al.*, 2012; Tiwari *et al.*, 2010).

Changes in soil properties because of land use/land cover change have been investigated by numerous workers in different ecological zones and environmental conditions around the world (Geissen *et al.*, 2009; Kidanemariam *et al.*, 2012; Lemenih *et al.*, 2005b; Nyberg *et al.*, 2012). Land use/land cover change affects the spatial and temporal pattern of soil properties. It also determines the capacity of the soil to support agricultural production (Khresat *et al.*, 2008; Lemenih *et al.*, 2005a). Studies indicate that apart from land use/land cover, several other factors including land use history, age of land use/land cover, management practices, soil type, soil depth, parent materials and topography also influence the pattern of soil properties variation in an area (Assefaa and Bork, 2016; Nyberg *et al.*, 2012; Yemefack *et al.*, 2006). The nature, pattern and scale of change observed in soil properties may be influenced by the nature of the parameter of interest - physical, chemical or biological parameters - being examined. These parameters are impacted differently by changes in land use/land cover and the configuration of other components of the natural environment such as parent materials and soil type (Marin-Spiotta *et al.*, 2009; Neill *et al.*, 1997). There are suggestions that soil chemical properties are more variable over short distances than physical properties (Yemefack *et al.*, 2005). Hu *et al.* (2009), for instance, observed no significant different in soil hydraulic properties – soil hydraulic conductivity (*K*) and Gardner α - in soils under different land use/land cover types in Shaanxi province, China. The impact of time on soil properties variation also seems to be determined by the nature of the parameters of interest. However, it is unlikely that soil physical and chemical properties will exhibit significant changes in less than ten years of land use/land cover conversion (Aweto, 1987; Geissen *et al.*, 2009; Seibert *et al.*, 2007).

The nature of change in soil exchangeable cations, anions and other chemical and physical properties because of land use/land cover changes appears to vary with age, soil type and type of vegetal cover (Hartemink, 1997). Bulk density and total porosity increased with increasing length and intensity of cultivation (Igwe, 2001; Lemenih *et al.*, 2005a, 2005b). The changes in bulk density may however, be influenced by length of cultivation and management practices adopted (Aweto, 1985, 1987; Nyberg *et al.*, 2012; Yemefack *et al.*, 2006). Changes in soil carbon and soil organic carbon because of land use/land cover change have attracted significant research interest because of the implications of such changes on the carbon cycle and carbon sequestration (Neill *et al.*, 1997). Total nitrogen and bulk density are other important soil properties that are influenced by land use/land cover changes and have been widely studied (Cotching *et al.*, 2013; Davy and Koen, 2013; Lemenih *et al.*, 2005b; Wilson and Lonergan, 2013). These soil parameters show variation with soil depth, vegetation cover, species composition and chronosequence (Aweto, 1987; Lemenih *et al.*, 2005b). Variations are also observed in exchangeable Ca, K, Mg and available phosphorus under different land use/land cover, soil depth and age (Aweto, 1987; Lemenih *et al.*, 2005b). Tree plantations appear to simulate soil conditions under rainforest and therefore maintain or enhance the soil nutrient status as such plantations mature (Aweto and Obe, 1993; Ekanade, 2007; Montagnini and Sancho, 1990). The level of simulation of forest conditions by plantation agriculture and agroforestry systems may however, depend on other factors such as differences in tree species composition, topographic and relief conditions, parent materials, and age of the plantation (Jenny, 1994).

2.3.4 Methodological approaches in analyzing and modelling soil variability

Accurate measurement of soil properties distribution pattern is required for effective and sustainable soil utilization and management (Douaik *et al.*, 2011; McBratney *et al.*, 2000). These measurements are required to provide information for specific use of soil resources. The goals of many soil survey and characterization have been to evaluate soils for specific uses and identify the major factors that determine the spatial distribution of soil and vegetation on the landscape over time.

A variety of quantitative techniques and methods have been developed to objectively describe, classify and characterize the spatial patterns of soils under various ecological systems and environmental conditions. The development of these methods followed criticism of traditional descriptive soil survey methods, which were qualitative, complex, subjective in nature and in most instances difficult to describe clearly (McBratney *et al.*, 2000; McKenzie and Ryan, 1999). The methods used for quantifying soils are generally classified into three: classical statistical (knowledge-based) methods, geostatistical (data-driven) methods and a combination of classical and geostatistical methods (Heuvelink and Webster, 2001; McBratney *et al.*, 2000; Rossiter, 2005). The choice of a method, however, is usually determined by factors such as the nature of the data, the scale of observation and analysis and the specific goals of the study (Douaik *et al.*, 2011). There are indications that irrespective of the method adopted for the measurement of soil variation in a locality, environmental factors such as climate, topography, vegetation and parent materials are key in determining the pattern of variability. Studies also show that the modelling and estimation of soil properties variability is strongly dependent on sampling techniques and sampling density (Yuan *et al.*, 2013).

2.3.4.1 Classical method

The classical method of soil survey employs the relationship between soil properties and environmental features as the basis for mapping variation. The method is based on Jenny (1994), factors of soil formation. McBratney *et al.* (2000), used the term CLORPT in describing the methods. This method is largely qualitative, complex and subjective as several environmental features may need to be considered in evaluating the nature of soil properties variation in an area. The methods of data collection and processing are based on the scientists' intuition and experience and the outcomes are highly subjective. The approach, described as non-spatial and non-temporal because it ignores spatial and temporal coordinates in many cases (Douaik *et al.*, 2011), is mostly based on bivariate simple linear regression models between environmental variables such as terrain and soil parameters. Multiple polynomial regression models and classical descriptive statistical analysis are also used in some cases for providing insight into the nature and pattern of variation in soil properties in space and time (Hengl *et al.*, 2004). The classical statistical method is commonly used in soil and vegetation analysis (McKenzie and Ryan, 1999; Rodríguez-Lado and Martínez-Cortizas, 2015; Yuan *et al.*, 2013). McBratney *et al.* (2000), argued that this approach combines scientific methods with the scientist's subjective judgments.

Scientists use the classical statistical approach to determine the important factors controlling observed patterns of soil and vegetation distribution and the relationship that exists between soil forming factors. Celik (2005), for instance, compared the status of organic matter and physical properties of soil at two depths (0-10 cm and 10-20 cm) in cultivated lands with an elevation of about 1400 m. They used analysis of variance (ANOVA) to evaluate the difference in organic matter content of soil under cultivated, fragmented forests and pasture lands in Turkey. Similarly, Wang *et al.* (2001), examined variation in soil nutrients in relation to site characteristics such as climate, land use, landscape position in a semi-arid loess plateau of China. They determined the influence of land use and topographic position on soil nutrient variation using ANOVA and concluded that land use and landscape position were important determinants of soil nutrients in the area.

Using simple linear regression, Moore *et al.* (1993), evaluated the relationship between terrain attributes and soil properties. They concluded that the linear regression technique provided information that is useful for enhancing existing soil maps. Gessler *et al.* (2000), also studied the relationship between terrain attributes and soil-landscape parameters using linear regression model. They observed that between 52% and 88% of soil properties variance were explained by terrain variables such as slope and flow accumulation. The use of more extensive environmental variables, digital remote sensing and other ancillary information, such as climate variables, for modelling variation in soil properties is also becoming a common feature. McKenzie and Ryan (1999), used landform and climate variables coupled with linear regression model to generate the spatial prediction of soil properties using digital elevation model with a grid of 25 m resolution. They termed their method "environmental correlation" models. They noted that the model provides spatial predictions that were observed to be superior to conventional soil survey methods. They obtained results which accounted for between 42% and 75% variance in their samples.

Studies have also been conducted in various parts of Nigeria to determine the spatial pattern of soil properties under different environmental conditions based on the CLORPT method. For instance, Aweto and Iyamah (1993), examined the influence of topography on the distribution of swamp forest vegetation. They noted that topography had no significant influence on the variation, structure and composition of vegetation in the swamp forest except in the lower slope segment adjoining the river channel. Olorunlana (2015), studied the spatial variability of soil properties and the important factors determining the pattern of soil properties variability in Akoko region of Ondo State. They subjected their data to descriptive statistics and factor analysis and concluded that spatial variability of soil properties is largely influenced by topography, climate and soil utilization. Textural characteristics, chemical properties and organic matter content were observed to be strong determinants of soil variability pattern in the area. Salami (1998), posited that human activities have significantly affected the structure and complexity of vegetation and the quality of soil in the southwestern part of Nigeria. The impact of differences in management practices is also noted as one of the contributing factors to soil properties variation under different soil types and parent materials. Are *et al.* (2009), examined the effect of slash and burn on soil properties in an Alfisol in southwestern Nigeria. They noted that slash and burn may have a direct and immediate impact on the physical properties of an Alfisols in southwestern Nigeria. Isichei and Muoghalu (1992), observed that tree canopy and height were important factors determining soil properties variation in the savanna region of Nigeria. They also noted that seasonal trends exist in some chemical and physical properties of the soils in the region.

Traditionally, soil scientists used air photograph interpretation in soil mapping and analysis based on the relationship of soil with landforms, parent materials, vegetation and land use (Soil Survey Staff, 1993). Recent advances in remote sensing and other forms of geospatial technologies, such as GIS, have provided new alternatives for soil mapping, analysis and evaluation at local to global scale (Seid *et al.*, 2013) and have resulted in more accurate mapping of soil properties distribution. Zhu *et al.* (2001), for instance, developed a GIS model which they referred to as soil-land inference model (SoLIM) for evaluating soil-landscape relationships based on soil forming environmental conditions. They claim that information derived from the model are of high quality and accuracy compared to the traditional soil survey methods. However, the level of accuracy was observed to depend on the quality of environmental data and knowledge of soil-environment relationship in the area of study. Similarly, McKenzie and Ryan (1999), used an integration of landform and climate variables, with remote sensing data for the prediction of spatial pattern of soil properties in the Bago and Maragle State forests in southeastern Australia. They referred to their model as environmental correlation model. The model accounted for 42%, 78% and 54% of variance present in the samples of profile depth, total phosphorus and total carbon respectively

2.3.4.2 Geostatistical methods

The need for a more precise and quantitative measurement of soil characteristics resulted in the development of methods that will enhance precision in statements made about variation in soil characteristics. The traditional soil survey methods assume that samples collected at locations that are representative of the soil mapping units also represent the unsampled neighbours in the field (Yost *et al.*, 1982). This assumption has been faulted by numerous studies and have resulted in the development of quantitative methods that account for variation of soil properties within landscapes under similar or diverse environmental conditions. The need to account for spatial autocorrelation of soil properties, particularly at local levels prompted the development of the geostatistical methods.

Geostatistical methods are based on the theory of regionalized variable proposed by Matheron (1963), and was further expanded in Matheron (1971). Though the theory was originally proposed for use in the mining industry, it is now applied in the study of the spatial variability of soil properties as a realization of a random function represented by a stochastic model (McBratney *et al.*, 2000). Several studies have discussed the general theory of regionalized variables (Heuvelink and Webster, 2001; Lark, 2012; Oliver *et al.*, 1989) while others have shown its relevance in the spatial variability analysis of soil properties (Burrough *et al.*, 1994; Goovaerts, 1999; Jackson and Caldwell, 1993; McBratney *et al.*, 2000; Minasny and Hartemink, 2011).

Geostatistical analysis is noted as the most robust and commonly applied method for analyzing soil properties distribution at unsampled sites (Ettema and Wardle, 2002) and is now commonly used for soil survey, analysis and modelling. The approach provides a method for determining the spatial variability of soil at local, regional or continental level. It views soil as suites of continuous spatial variables that are spatially dependent on each other. Matheron (1963), stated that a regionalized variable has three distinct characteristics; it is localized as its variation occurs in a mineralized space called a geometrical field; it shows a steady continuity in its spatial variation; and it may show different kinds of anisotropies at certain locations. The kind of anisotropic characteristic displayed, depends on the slope direction or relief pattern. Geostatistical approach encompasses a deterministic component and a stochastic component. The spatial variation in an attribute is expressed by Journel and Huijbregts (1978) in equation 2.1 as:

$$z(\boldsymbol{x}) = \Sigma a_k f_k(x) + \varepsilon(\boldsymbol{x})$$ Equation 2.1

where $\boldsymbol{x}$ is the spatial coordinates of one, two or more dimensions, f_k $\boldsymbol{k} = 0, 1, \ldots$ are functions of the spatial position, a_k are unknown coefficients, and $\varepsilon(\boldsymbol{x})$ is a random component that is itself spatially dependent. The first term on the right hand side of equation 2.1, above is the deterministic component and the second term is the stochastic element. Oliver *et al.* (1989), noted that the stochastic component of the equation is the larger in most instances and is therefore used in representing all variations. The deterministic component can therefore be represented by a constant, μ_v and equation 2.1 becomes:

$$\mathrm{z(x)} = \mu_v + \varepsilon(\mathrm{x})$$ Equation 2.2

where μ_v is the mean and ε (x) is the spatially dependent random residual which has a mean equal to zero and is defined by equation 2.3:

$$\Sigma\,[\varepsilon(\mathrm{x})] = 0$$ Equation 2.3

The variance of the stochastic components is defined by equation 2.4 thus:

$$\mathrm{var}\,[\varepsilon(\mathrm{x}) - \varepsilon\,(\mathrm{x} + \mathrm{h})] = \mathrm{E}\,[\varepsilon(\mathrm{x}) - \{\varepsilon\,(\mathrm{x} + \mathrm{h})\} - \mathrm{s}\ 2] = 2\gamma\,(\mathrm{h})$$ Equation 2.4

where E signifies expectation, and h is a vector, which represent the distance separating two points *x* and *x* + h in both distance and direction. The variance of the stochastic components depends on this distance and the configuration of the sample points and not on the absolute position of *x*. Given a constant mean, equation 2.4 can therefore be written as:

$$\mathrm{var}\,[\mathrm{z}\,(\mathrm{x}) - \mathrm{z}\,(\mathrm{x} + \mathrm{h})] = \mathrm{E}\,[\mathrm{z}\,(\mathrm{x}) - \{\mathrm{z}\,(\mathrm{x} + \mathrm{h})\}\mathrm{x}^2] = 2\gamma\,(\mathrm{h})$$ Equation 2.5

where z is the values of the variables at location $\boldsymbol{x}$. The assumption that the mean and the variances of the differences are both stationary, constitute Matheron's intrinsic hypothesis.

The quantity γ(h) is termed the semi-variogram and as Goovaerts (1999) states, it measures the average dissimilarity between data separated by a vector h. It is defined as half the expected squared difference between two values and it relates the semi-variance to the lag, h (Goovaerts, 1999; Heuvelink and Webster, 2001; Oliver *et al.*, 1989). Spatial variability is manifested in the variogram (Figure 2.1) typically by a monotonic increase from the origin with increasing lag distance until it reaches an upper limit called the "sill" (*n*) at a finite distance called the "range" (*m).* The range defines the limit of spatial autocorrelation. Beyond this point, there is no spatial autocorrelation. Otherwise, the semi-variogram may approach its maximum asymptotically. These two types of bounded variogram are characteristic of second-order stationary processes. For variables with second-order stationary processes, the semi-variance is equal to the auto-covariance of time-series analysis and it is expressed in equation 2.6 as;

$$\mathrm{C}\,(\mathrm{h}) = \mathrm{E}\,[\{\mathrm{z}(x) - \mu\}\,\{\mathrm{z}(x + \mathrm{h}) - \mu\}] \qquad \text{Equation 2.6}$$

Where μ is the mean of the attribute, the semi-variance is represented in equation 2.7 as;

$$\gamma\,(\mathrm{h}) = \mathrm{C}\,(0) - \mathrm{C}\,(\mathrm{h}) \qquad \text{Equation 2.7}$$

where C (0) is the covariance at zero lag, also referred to as the a priori variance of the process. The semi-variogram is an important component for predicting spatial variation using geostatistical techniques. It summarizes spatial variation in the area of interest once the intrinsic hypothesis holds true (Oliver et al., 1989). It is computed as half the average squared difference between the components of data pairs. This is denoted in equation 2.8;

$$\gamma(h) = \frac{1}{2M(h)} \sum_{i=1}^{M(\boldsymbol{h})} \{z(x_i) - z\,(x_i + h)\}^2 \qquad \text{Equation 2.8}$$

where M (h) is the number of pairs of observations separated by the lag h. Semi-variogram modelling using kriging could be univariate, bivariate or multivariate (Oliver *et al.,* 1989).

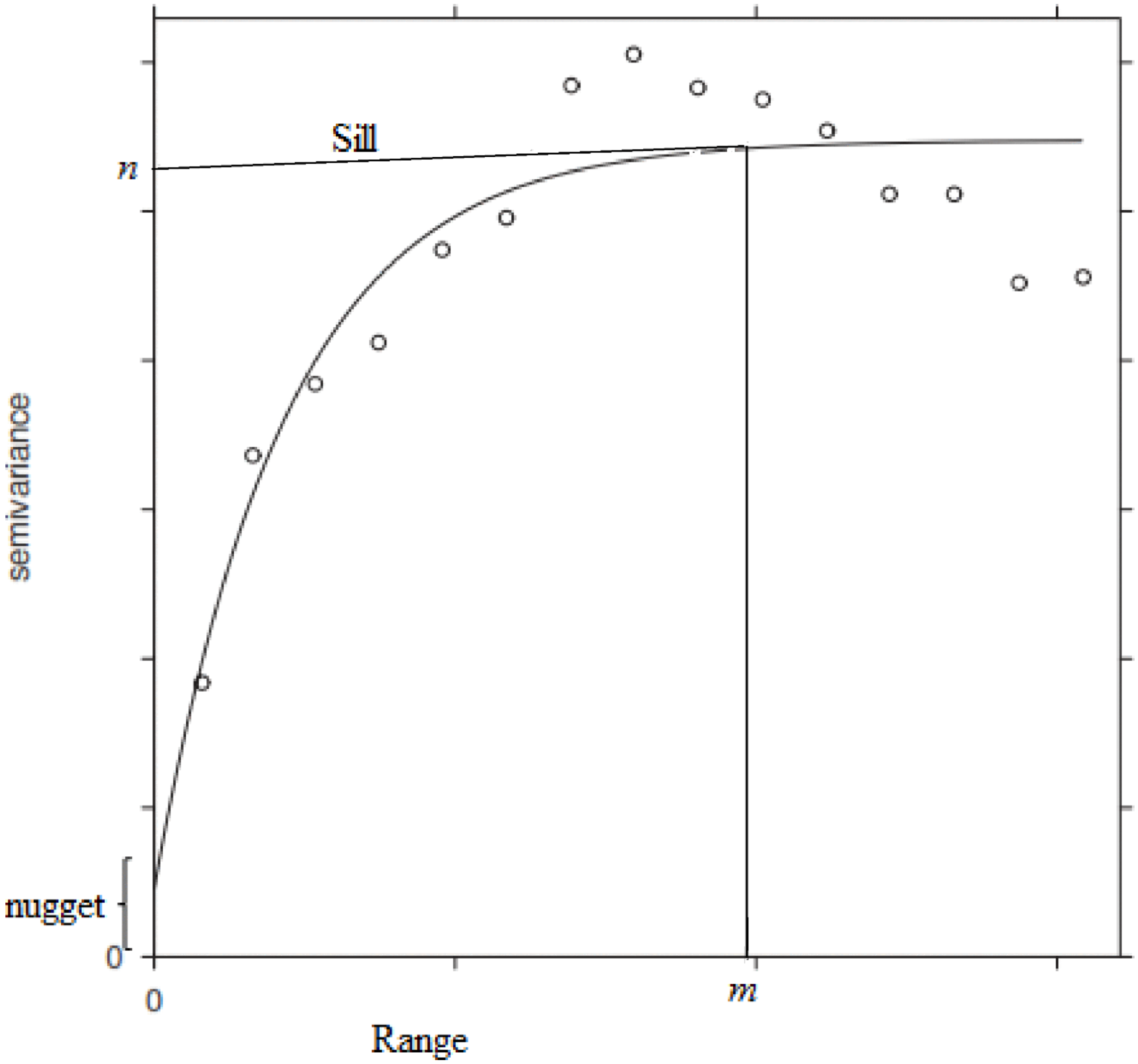


Figure 2.1: The variogram of spatial variability (Source: Author’s Sketch, 2017)

Though researchers agree that the geostatistical approach provides necessary tools for analyzing complex environmental processes operating in the landscape to influence variation in soil properties, it is observed that a combination of the geostatistical approach and knowledge-based approach provide more information about the nature and structure of soil properties variability under different environmental conditions.

2.3.4.3 Hybrid method

The traditional soil survey method is subjective and based on the knowledge and expertise of the soil scientists in relation to environmental variables and the conditions of the locality under investigation. The geostatistical approach, however, emphasizes modelling the error level (residuals) of soil maps which are usually not considered when traditional soil survey methods are considered because of inadequate data. Rossiter (2005), described the deterministic and stochastic components of soil modelling as “explained” and “unexplained” variability. He noted that some of the unexplained variation could however, be because of the inability of the analyst to explain it with current models while other forms of variability may be inherently random in nature. The need to employ available models in explaining the observed pattern of variability in natural systems therefore becomes paramount. This fact, coupled with the increase in the demand for more accurate and quantitative information, and in the improvement in the availability of modern computer technologies for soil analysis and modelling has reduced the difference between pedometrics - the measurement of the degree of uncertainty in soil models resulting from deterministic or stochastic variation, vagueness and lack of knowledge of soil properties and processes - and traditional pedology (Goovaerts, 1999; McBratney *et al.*, 2000). This is because traditional soil survey has become more quantitative over the years leading to increasing level of overlap between pedometrics and pedology (Figure 2.2). The development of the hybrid approach for the determination of soil properties variation is an attempt by scientists to explain variation in soil properties that have not been captured by the knowledge of the soil-formation factors of the CLORPT approach using geostatistical relationships which can improve the prediction of soil variability (Rossiter, 2005). Most contemporary studies on soil properties variation, therefore, use a combination of classical and geostatistical methods.

The combination of CLORPT and geostatistical approaches in the study of soil properties variation has gained much interest among pedologists and environmental scientists in recent decades and has brought about improvement in the ability of scientists to predict the interaction between environmental variables and soil variation (Dobermann *et al.*, 1995). This interest stems from the ability of the hybrid method to combine the advantages of the CLORPT approach and that of geostatistical method in assisting scientists determine the influence of environmental variables on soil properties variations under different conditions (Heuvelink and Webster, 2001). There is a consensus among researchers that the use of the hybrid approach leads to more accurate prediction of soil properties variability and scientists are better able to understand the major factors and processes influencing variation in soil properties from plot-scale to regional levels.

Dobermann *et al.* (1995), analyzed the processes causing spatial variation of soil properties at two depths (0- 15 cm and 15 – 45 cm) on an acid Ultisol in the Philippines using the factorial kriging method. They collected samples in 8 m x 8 m grid and analyzed the samples for pH, P, K, Na, Ca, Mg, and Al. They noted that leaching of acidity along the slope appears to be a general process in the humid tropical environment. They attributed the slope dependent soil variation to amelioration of soil acidity and possible effects of the design of field experiments. They conclude that the combination of Factorial Kriging Analysis (FKA) and knowledge-based techniques offer more insight into the complex processes of soil properties variability at the field scale.

Bocchi *et al.* (2000), examined the spatial variability of soil physical, hydraulic and chemical properties at field scale using factorial kriging method. They noted that soil texture influenced short range variability of soil properties, while long range variability in organic carbon resulted in the heterogeneity of soil water retention capability. They also conclude that combining pedological expert knowledge and geostatistcal techniques improve the ability of farmers to manage soil within the field more efficiently.

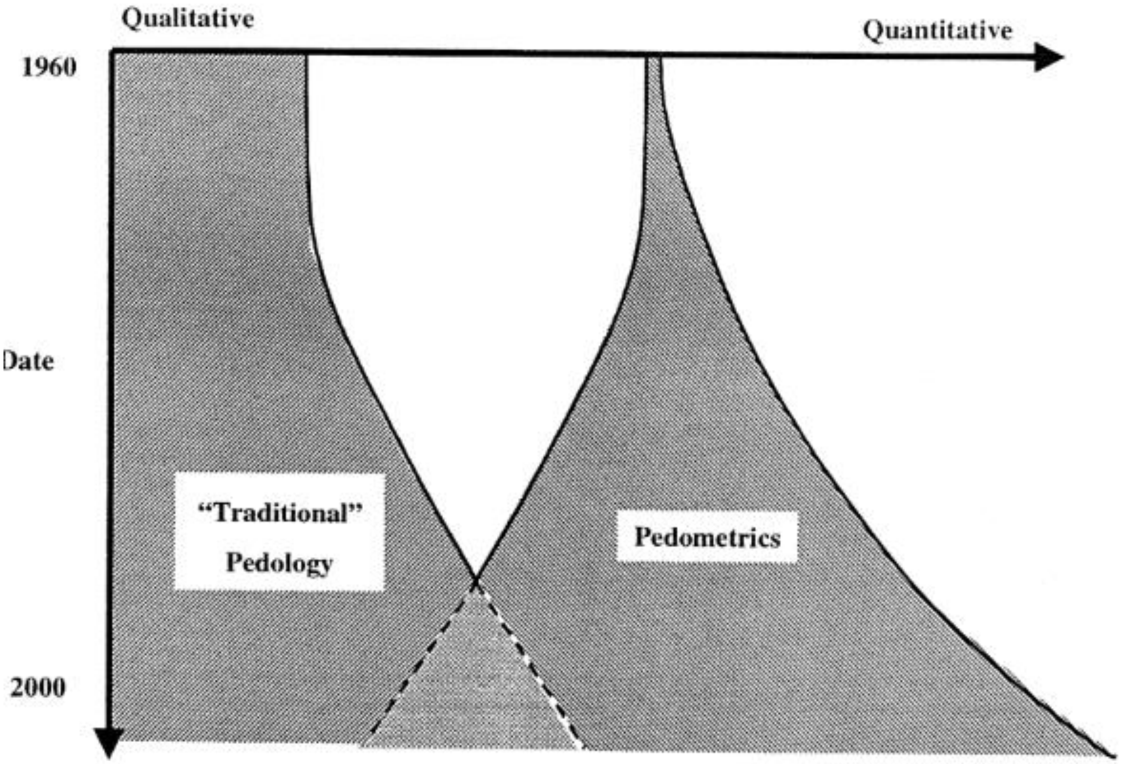


Figure 2.2: A time line of the growth of pedology and pedometrics

Source:(McBratney et al., 2000)

Sun *et al.* (2003), examined the influence of land use alteration on the spatial and temporal pattern of soil quality in the hill region of China using geostatistical method. They collected 105 soil samples from a sampling grid of 100 m x 100 m to a depth of 15 cm in 1985 and 1997 to evaluate the spatial and temporal pattern of soil properties variation in the area. They observed that soil properties showed large variability. The changes in land use was also found to influence the pattern of soil properties variability in the area.

Zhang and McGrath (2004), analyzed the spatio-temporal pattern of soil organic carbon in grassland using the geostatistical methods. They obtained data from soil survey conducted in the same area in 1964 and 1996 in southeastern Ireland. They predicted the values of organic carbon at unsampled points using kriging technique with similar grid system. They determined changes in the two maps derived from the kriging technique using map algebraic function in GIS. They observed that though considerable change was observed between the two maps, the changes were not statistically significant. Topography and geomorphic processes, however, appears to provide better explanation for the changes in the area than land use or cultivation. They conclude that the geostatistical method provides a useful tool for the analysis of spatio-temporal changes in the environmental sciences.

In Cameroun, Yemefack *et al.* (2005), examined the sources of soil properties variation at four levels: regional, local, plot scale and in the laboratory. They collected soil samples at the first three scales in a 2000 km^2 area using different sampling design for each level. They observed that soil properties exhibit spatial variability even at the plot scale, though a regional trend was observed to account for between 30% and 50% of the variation in soil properties. Their results suggest that spatial variability of soil properties at the regional scale was not related to land use, regional trend or environmental factors. It was observed that land use practices significantly influence soil variability pattern at the plot scale. However, plot size determines the level of variability within the plot. They conclude that research should focus on variation at the local scale which they noted, are mostly influenced by land use pattern.

2.3.5 Methods of soil variability model evaluation

The level of accuracy of a soil map determines its quality, reliability and usefulness to land resources planners, managers and land users (Lin *et al.*, 2005; Mueller *et al.*, 2001; Olaniyan and Ogunkunle, 2007). Map scale, sampling density, level of soil diversity in a region, spatial location and specific soil properties influence the accuracy of maps derived from soil surveys (Jafari *et al.*, 2013; Lin *et al.*, 2005). In spite of the importance attached to the accuracy of soil maps, however, many studies on soil modelling fail to assess the accuracy of maps derived from soil surveys (Oyedele and Tijani, 2010; Seid *et al.*, 2013; Yemefack *et al.*, 2006). Hence, very limited attention appears to be given to the assessment of map accuracy in studies relating to soil survey, analysis, modelling and mapping in the literature. This is because scientists assume that the boundaries of mapping units define areas of relatively homogenous soil types (Lin *et al.*, 2005). Studies however, indicate that depending on the nature and interactions between environmental variables such as parent materials, topography and other soil forming processes, variability exists within soil mapping units to varying degrees (Lin *et al.*, 2005; Olaniyan and Ogunkunle, 2007).

The evaluation of the accuracy of information derived from soil modelling and mapping has been carried out using various approaches such as the use of independent data set and field studies, cross validation and the use of remote sensing and GIS methods (Olaniyan and Ogunkunle, 2007; Seid *et al.*, 2013; Veronesi, 2012). Traditional accuracy evaluation entails an assessment of the variance between observed and derived information. In soil mapping this involves the comparison of information observed from field surveys with those shown on soil map to determine the level of map purity (Olaniyan and Ogunkunle, 2007). Map purity, measured in percentage, indicates the level of agreement between ground information and map information. In many cases, soil sampling and analysis is carried out to ascertain the percentage purity. However, recent developments in remote sensing and GIS now makes it possible to quantify map purity using a combination of soil surveys and analysis using GIS for a more efficient and accurate comparison (Lark and Bolam, 1997).

Lin *et al.* (2005), computed the overall purity of mapping unit on the thematic maps of the USA using the area-weighted mean purity approach. Using this approach and two case studies: the purity of soil maps of order I, order II and order IV using GIS; and using a field study involving the collection of 324 soil samples across Minnesota River Basin using nested hierarchical sampling design for the analysis of soil A-horizon thickness, depth to calcium carbonate and surface soil pH values, they investigated the variability of soil map units and soil properties at multiple scales. The first case study results indicate that there was variation in the area-weighted purity to various degree ranging from 24% to as high as 99%. The second study shows that over 50% of the variability of the soil properties examined was at the local scale. They attributed the variability to climate, localized effects of differential infiltration and runoff caused by landscape positions and soil characteristics.

Mueller *et al.* (2001), examined the effect of different sampling intensity and grid interpolation schemes on the accuracy of soil maps derived from field surveys in south central Michigan, USA. They sampled soil using three different approaches: grid-point, grid-cell and simulated soil map unit sampling. They predicted soil quality using kriging, inverse distance weighted (IDW) and nearest neighbour interpolation methods for the different data sets. The map derived from each of the analyses was validated against independent data sets to assess the accuracy of the maps. They observed that soil properties were spatially structured, though kriging prediction were marginal at high sampling intensity and poor at low intensity (between 61- and 100 m grids). In relation to IDW, the accuracy of prediction using kriging interpolation improved with increasing sampling intensity. They conclude that the results obtained from both methods were similar and were generally poor predictors of soil properties variability in the area. Their classification of high and poor intensity appears subjective as no clear criteria are defined for such classification.

Veronesi (2012), mapped soil compaction in a three-dimensional space based on soil depth functions. The steps in the three-step approach included a framework for selecting the best depth function, considers which shape best describes the soil-specific variation by depth and ends with an interpolation of the coefficients of the function across the field. He referred to the approach as the “top-down” method. The accuracy of their results was assessed using the cross-validation accuracy assessment method which involves excluding a percentage of the data and re-evaluating the results obtained. A commonly used approach involves the use of mean prediction error and the root mean square error.

2.3.6 Summary of literature review

The interest generated by studies of the spatial pattern and variability of soil properties stems from the importance of soil as a resource. Soil provides the basis for agricultural production and the sustenance of other environmental resources. The sustainable use of soil resources is key to effective human and environmental development. Though studies have been conducted to characterize and classify soils in various parts of Nigeria, there is limited information on the characterization of the spatial variation of soils under oil palm and rubber plantations in the rainforest ecological zone of Nigeria. Similarly, in spite of numerous studies which show several factors influencing the spatial pattern of soil properties in different ecological conditions, it is evident from the literature that some aspects of the influence of environmental conditions on soil properties variation and variability have not been adequately examined. For instance, apart from Jobbágy and Jackson (2001), who studied the vertical distribution of soil nutrients using global data, most studies focus on the horizontal variation of soil properties and neglect the impact of soil depth and the vertical distribution of soil properties. This has resulted in the dearth of detailed information on the influence of depth on soil properties variability particularly in tropical rainforest ecosystems. Specifically, there appears to be very few studies focusing on the influence of depth and other environmental conditions, variation in tree density and topography on soil properties variability pattern under tree crop plantation agriculture such as oil palm and rubber plantations. Also there are limited studies on the influence of variation in soil types on the distribution of soil properties in rainforest soils.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This chapter outlines the materials and methods adopted in this study. The chapter is divided into three major subheadings. These are data and sources of data, site selection and data collection, and data analysis. Site selection and data collection section is sub-divided into site selection and sampling techniques, vegetation sampling and measurement and soil sampling and profile description method. Data analysis is divided into two sub-sections: laboratory analysis and statistical analysis. Laboratory analysis section details laboratory techniques used for soil analysis. The statistical analysis sub-section discusses statistical techniques adopted for descriptive and geostatistical data analysis.

3.2 Data and sources of data

The data needed for achieving the research aim and the stated objectives include measurement of tree parameters (density, height and diameter-at-breast-height (DBH)), data on soil properties under the different land use/land cover types of interest and data on the landscape characteristics such as elevation and slope. These data were either obtained through field measurement, which was done during fieldwork conducted between December 2014 and February, 2015, or from secondary sources.

3.3 Site selection and data collection

3.3.1 Site selection and sampling technique

The choice of Okomu Forest Reserve for this study was informed by three factors: (1) Okomu National Park is described as one of the largest remaining natural rainforest ecosystem in Nigeria (Anadu and Oates, 1982); (2) Okomu Oil Plc (Okomu oil plantation) and Osse Rubber Estates Nigeria Plc (Osse rubber plantation) are located within the reserve and share boundaries with the National Park making it possible to study the three land use and land cover types in the same vicinity; and (3) several locations within the Forest Reserve have undulating landscape sloping towards River Osse and River Okomu which drain the area. This made it possible to identify slopes which provide suitable settings for examining the impact of environmental (topography and tree density) and anthropogenic (land use/land cover) variables on soil variability in the tropical rainforest ecosystem of Nigeria. A map of the 1,082 km^2 Okomu Forest Reserve was obtained from the research team of Okomu National Park during the reconnaissance field visit. This map was digitized using ArcGIS 10.2 software. The map serves as base map for identifying the locations of the different land use/land cover and other natural and man-made features such as settlements, farmlands and rivers in the Forest Reserve. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery covering the Forest Reserve was obtained from NASA website. The areal extent of the Forest Reserve was extracted from the ASTER image using the digitized base map. The imagery was used to derive the digital elevation model (DEM), topography and slope profile of the forest so as to identify potential study sites under each of the land use/land covers.

On the basis of topography, a 6 hectares (300 m x 200 m) plot (shown schematically in Figure 3.1) with similar elevation were identified under each of the three land use/land cover types. The elevation of the selected sites ranges between approximately 10 m and 50 m above mean sea level for all sites. The slope gradient in the sites range from 5% to about 35%. Site (A) is located within Okomu oil palm plantation (6°23’53” and 6°23’58” N, 5°15’52” and 5°16’01” E). Site (B) which is located in compartment 86 of Okomu National Park, is about 8 km from the closest settlement (6°22’25” and 6°22’33” N, 5°15’42” and 5°15’46” E). Jones (1955), noted that this area is the least disturbed part of the forest. This assertion was confirmed by the forest officers (“rangers”) in charge of guiding the forest against poachers and other intruders. Site (C) is located in (6°24’12” and 6°24’18” N, 5°24’28 and 5°24’33” E) Osse rubber plantation. These sites, shown in Plate 3.1 (Forest), Plate 3.2 (Oil palm plantation) and Plate 3.3 (Rubber plantation), represent the major land use/cover types in the Forest Reserve.

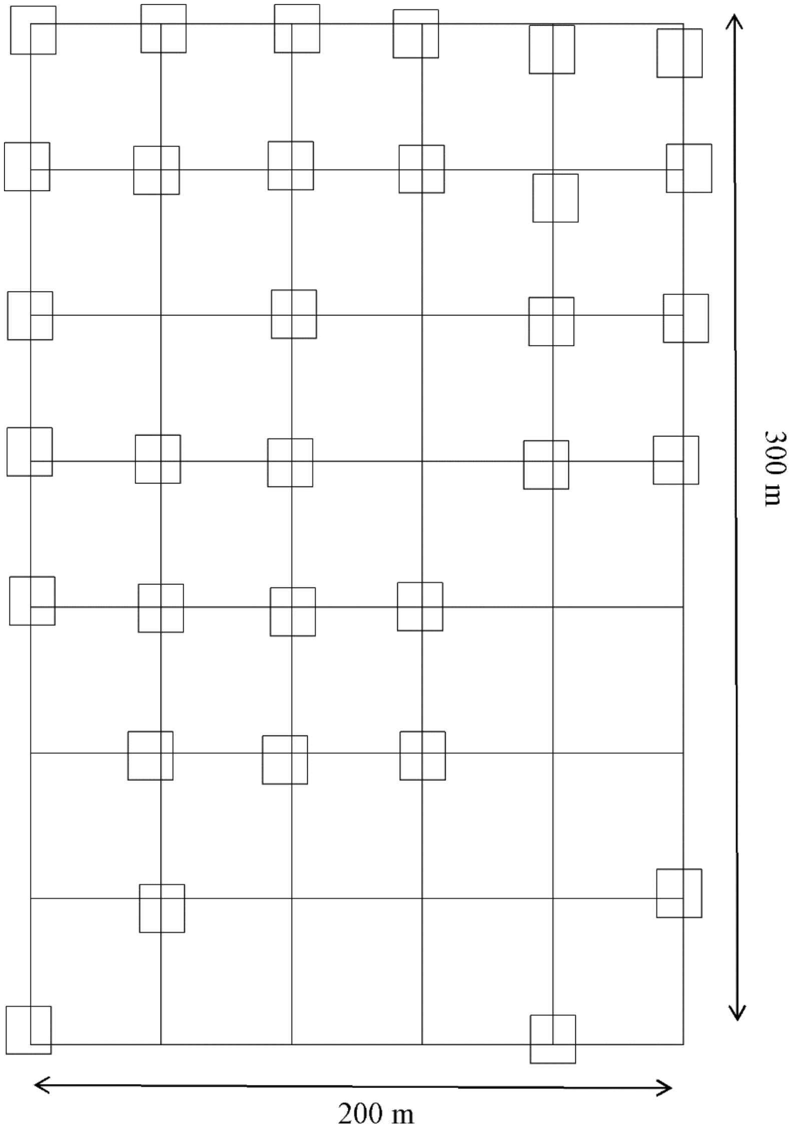


Figure 3.1: Schematic illustration of the research design. Sample points are represented by small squares at grid intersections. Grid Intervals is 50 m, vegetation sampling and measurements was conducted at $5m^2$ in rainforest and $20\ m^2$ in plantations.

(Source: Author’s Sketch, 2017)

Plate 3.1: Cross-sections of the rainforest in Okomu Forest Reserve, Edo State, Nigeria

Plate 3.2: A Section of the Okomu Oil Palm plantation at Okomu Forest Reserve, Edo State, Nigeria. Oil Palm Nursery in front of plantation

Plate 3.3: A section of Osse Rubber Plantation at Okomu Forest Reserve, Edo State, Nigeria

Design-based and model-based sampling approaches (de Gruijter and ter Braak, 1990) are recognized for ecological sampling in the literature. The design-based approach is based on the assumption of a fixed population which posits that samples are identical and independently distributed while the model-based approach assumes that the attributes of samples in a location are random rather than fixed and samples are therefore spatially dependent (Brus and de Gruijter, 1997). In this study, the design-based approach is adopted for vegetation sampling and model-based approach is adopted for soil sampling. Empirical evidence (Diodato and Ceccarelli, 2004; Gonzalez and Zak, 1994; Oyedele and Tijani, 2010), show that sampling interval ranging from a few centimeters to several kilometers are used in studies involving geostatistical modelling of soil properties variation. This appears to suggest that there is no standard sampling interval in the application of geostatistical methods in soil variability modelling. This is further reiterated by Diggle and Ribeiro (2007), who noted that geostatistcal designs are often chosen informally rather than by the use of explicit design criteria. Five parallel, 300 m transects were therefore defined at 50 m intervals from the upper slope to the valley bottom in the plot under each of the land use/cover types.

3.3.1.1 Vegetation sampling and measurement

Because of the high tree density in the rainforest, seven plots measuring 5 m x 5 m (25 m^2) were identified and marked at 50 m interval along each of the five transects under the rainforest ecosystem. Vegetation sampling was conducted in each of these plots that are presentative of most parts of the rainforest in terms of tree density, richness and species abundance. Plot size has been shown to influence the outcome of vegetation analysis (Otypková and Chytry, 2006). However, the homogeneity of the plantations implies that the probability of encountering a new tree species is low as the plantations are regularly cleared of weeds. Therefore, a larger plot size is not likely to alter the outcome of soil-vegetation relationship under the plantations. On this basis, plots of 20 m x 20 m (400 m^2) were marked at 50 m interval along each of the transects under oil palm plantation and rubber plantation for the purpose of measuring tree height and diameter-at-breast height as tree density does not vary under a given plantation. The goal in this study is to ensure that each plot is adequately representative and homogenous enough so that variation in vegetation variables (tree density, tree height, DBH and total species richness) could be related to soil properties and elevation variables (Otypková and Chytry, 2006). Studies show that soil properties exert different effects on vegetation characteristics (Aweto, 1981c). In order to account for the impact of soil physical and chemical properties on vegetation parameters, soil samples were collected from the center of ten subplots at the lower slope, middle slope and upper slope positions where vegetation parameters have been measured (Chen *et al.*, 1997; Solon *et al.*, 2007). All woody plants measuring 2 m and above in height were identified and measured in each plot in the rainforest while the height and diameter-at-breast-height was measured under the rubber and oil palm plantations. Height was estimated with the aid of a 10 m pole (Oliveira-Filho *et al.*, 1994), diameter-at-breast-height (DBH) was measured using a measuring tape at approximately 1.5 m height from the ground surface at the higher end of the slope and the scientific name of each species was recorded.

3.3.1.2 Soil sampling and soil profile description

Seven soil samples were collected at 50 m interval along each transect using a soil auger at depths of 0 -15 cm (topsoil), 15 - 30 cm (subsoil), 30 - 60 cm (deep subsoil). A total of thirty-five (35) samples were collected from each layer and one hundred and five (105) samples per land use/land cover type, were used to determine the physical and chemical properties such as colour (using the Munssel Soil Colour Chart), texture and consistency (using hand feel methods). In order to determine soil mapping units under each of the sites for the purpose of locating soil profile pits, an additional sample was taken at 60 – 90 cm depth in each sample point. A profile pit (180 cm to 200cm deep) was dug at locations where changes in texture, colour or consistency were observed. The coordinates and slope gradient of every soil sample point was recorded. The coordinates were obtained with a handheld GPS receiver at 1 m accuracy level. Slope gradients (%) was determined using hand level attached to a 1 m pole. The pole was place horizontally along the slope and raised until the level is completely horizontal with the slope at the high side. The distance between the horizontal pole and ground is then measured from the lower side of the slope to obtain slope value as a percentage (Soil Survey Staff, 1993).

Each mapping unit was further examined in detail by sinking modal profiles to depths ranging from 180 cm to 200 cm. A total of three representative soil profiles, coinciding with topographic positions - upper, middle and lower slope positions - were dug under each of the different land use types. Profile description was conducted starting at the top and working downwards to identify changes in soil morphological properties. Horizons were identified and marked to distinguish them before description in each profile (Soil Survey Staff, 1993). Soil profile was described and sampled by genetic horizons (Dorji *et al.*, 2014) and soil pedons were sampled at every horizon. Soil samples were placed in a well labeled polythene bag. Samples were air dried at room temperature, ground using a mortar and pistol, then passed through a 2 mm sieve before they were analyzed.

3.4 Data analysis

3.4.1 Laboratory analysis

The soil samples were analyzed using the following standard procedures. Particle size analysis was carried out using the Bouyoucous hydrometer method (Gee and Or, 2002). Soil pH was determined potentiometrically in water and in KCl using soil to distilled water ratio of 1:2.5, while pH in KCl was also determined at a ratio 1:2.5 soil to solution. The readings were taken using the glass electrode (Methler) standardized at pH 7. Organic carbon was determined by the Walkley-Black method (Nelson *et al.*, 1996), total nitrogen by Kjeldahl method (Bremner and Mulvaney, 1982), available Phosphorus was determined by the Bray P1 method (Bray and Kurtz, 1945). Exchangeable bases (Ca, Mg, K, Na) were extracted with IN neutral ammonium acetate (NH_4OAC). Exchangeable Ca and Mg were determined by atomic absorption spectrometer while K and Na were determined by flame photometer. Exchange acidity ($A1^{3+}$, H^{+}) was determined by titration of soil solution with IN KCI (Nelson *et al.*, 1996). Extractable micronutrients, Mn, Zn, Cu and Fe were leached with 0.1N HCl using the method of Wear and Sommer (1948), and were determined on the atomic absorption spectrophotometer. Effective cation exchange capacity (ECEC) was computed by the summation of exchangeable bases (Ca, Mg, K and Na) and exchange acidity (Al and H).

3.4.2 Statistical analysis

The statistical analysis carried out in this study is divided into vegetation analysis and soil analysis. Descriptive and multivariate analysis were done using the Statistical Package for the Social Science (SPSS) software version 22, PAleontological STatistics (PAST) software (Hammer *et al.*, 2001) version 3.08 (2015) and geostatistical analysis was carried out using ArcGIS 10.2.

3.4.2.1 Vegetation analysis

Tree density *(dt)* was calculated on plot basis as the total number of trees in a given plot. Shannon-Weiner index of diversity was computed to determine species diversity and evenness (Onaindia *et al.,* 2004) within sample plots and between topographic positions resulting from differences in elevation, using the following formula in Equation 3.1 below:

$$H' = -\sum_{i=1}^{s} pi * ln(pi) \qquad \text{Equation 3.1}$$

where *pi* is the proportion cover of the *i*th species in a plot and logarithm is calculated with a base of *e*. The Shannon-Weiner Index is based on two assumptions: (1) individuals are randomly sampled from infinitely large population, (2) all individuals from the community are included in the sample. Evenness (E'), which is defined as diversity divided by maximum possible diversity, was computed using Equation 3.2:

$$E' = \frac{\sum_{i=1}^{s} pi * \ln(pi)}{\log s} \qquad \text{Equation 3.2}$$

where *s* is the number of species and logarithm is in base *e* (Armstrong *et al.*, 2011). Species richness (α-diversity) was determined as the difference between Shannon-Weiner Index and evenness.

The relationship between vegetation parameters and environmental variables such as elevation, tree density and soil properties concentration were analyzed using multivariate statistical methods in PAST 3 and SPSS. Data matrices were constructed for vegetation parameters and soil properties. Analysis of variance (ANOVA) was used to compare species richness, evenness and diversity tree density, diameter-at-breast-height and height at different topographic positions to further show the influence of topography on the variation of these tree parameters. Similarly, to evaluate the impact of topography on vegetation diversity, species richness, evenness and diversity were compared on based on topographic position. The relationship between vegetation variables and soil properties at various depths were described using Pearson's product moment correlation analysis in SPSS. The large number of variable involved in this study and the need to ensure that there is no multi-collinearity in the data, necessitated the use of principal component analysis ordination method to extract new set of components from the original data. Variables with loadings ≥0.6 were used for component identification.

Hypothesis one which seeks to determine the relationship between soil properties variation and tree parameters under rainforest was tested using Pearson's product moment correlation analysis. Canonical Correspondence Analysis (CCA) ordination was applied to the data to determine the relationship between environmental (topography and vegetation) variables and soil properties variation at each soil layer.

3.4.2.2 Soil analysis

Soil variability analysis was achieved by subjecting the soil data to two independent analyses: descriptive statistical analysis and geostatistical analysis. Descriptive statistical analysis was carried out on the data in order to understand the nature and properties of the distribution of the data. Mean, standard deviation, kurtosis, skewness and coefficient of variance (CV) were computed for all parameters at all land use/land cover types and at each of the depths. Skewness and kurtosis reveal the peakedness and symmetry of the data. Skewness and kurtosis values above absolute value of two were assumed to indicate noticeable skewness and were therefore log-transformed before they were used for further analysis (George and Mallery, 2014; Stevens *et al.*, 2004). Variability was assessed on the basis of CV where the higher the CV, the more variable the soil parameter. The variability levels were classified as least variable (<15%), moderately variable (15% to 35%) and highly variable (> 35%) (Adigun *et al.*, 2008; Wilding, 1985).

3.4.2.3 Geostatistical analysis and model validation

The geostatistical approach requires using data sets that are normally distributed. Data transformation is therefore necessary where this requirement is not met. The data for each soil parameter were checked for normality on the basis of the kurtosis and skewedness and in cases where a parameter is observed to be skewed (George and Mallery, 2014; Stevens *et al.*, 2004), it was normalized by log-transformation. The spatial variability pattern of soil parameters was evaluated by computing the semivariogram for each soil parameter. The semivariogram expresses the level of spatial variability of a random variable in a sample set. It shows the relationship between the semivariance and the interval between two sample points. It usually has three statistical variables: nugget, sill and range. Semivariance is defined as half the expected squared difference between samples separated by a given distance. The semivariogram model were fitted using exponential model. The model was fitted interactively (Oliver *et al.*, 1989) to minimize the nugget effect on spatial variability in each case while taking the effect of slope into consideration by using anisotropic parameters which accounts for the slope direction and slope angle (Gonzalez and Zak, 1994). Spatial variability was classified, based on the nugget-sill ratio, following Cambardella *et al.* (1994) as strong (< 25%), moderate (25–75%) or weak (>75%). Kriging interpolation technique was used to determine variogram model parameters which were subsequently applied in predicting soil parameters in locations where samples were not collected. The accuracy of the model derived from geostatistical analysis was determined using the jack-knifing or cross-validation method (Singh *et al.*, 2015). In this method, sample values are excluded from the model one at a time and cross-checked with predicted values. Accurate model is indicated by a standardized residual mean error that is close to one (Gaston *et al.*, 2001)

Hypothesis two was tested using analysis of variance to determine differences in spatial variability in soil physical and chemical properties under forest and plantations at various soil depths and ascertain if spatial variability of soil properties under rainforest and tree plantations is not limited to the topsoil layer. While hypothesis three was tested by using one-tailed student’s t-test to compare mean values of the nugget-sill ratio in order to ascertain if soil physical and chemical properties variability is greater under oil palm plantation than under rubber plantation.

CHAPTER 4

SPATIAL PATTERN OF VEGETATION CHARACTERISTICS IN RAINFOREST AND TREE PLANTATIONS IN OKOMU FOREST RESERVE

4.1 Introduction

Though the focus of this study is the spatial variability of soil physical and chemical properties under rainforest and tree plantations, studies have shown that the distribution and composition of vegetation are important determinants that influence the status of soil in an area (Jenny, 1994) . This chapter therefore examines the characteristics of vegetation in the rainforest and tree plantations in Okomu Forest Reserve and the floristic composition of vegetation along a topographic gradient in the rainforest.

4.2 Variation in vegetation characteristics in the rainforest

Table 4.1 and Figure 4.1 (a) – (c) summarize the variation in vegetation characteristics in the rainforest. The table shows that mean tree height is slightly less in the lower slope and middle slope positions than in the upper slope positions (Figure 4.1a). The mean tree height is 15.95 m in the lower slope, 14.69 m in the middle slope and 19.61 m in the upper slope positions. Analysis of variance shows that there is a significant difference ($p < 0.05$) in mean tree height at different elevations. The distribution of mean tree height along the slope may be because of the nature of soil drainage along the slope. The lower slope position is poorly drained and may inhibit tree growth in spite of its higher tree density (Figure 4.1c). This result is similar to findings reported by Aweto and Iyamah (1993), who observed that mean tree height increased with elevation in a swamp forest ecosystem of southwestern Nigeria. de Castilho *et al.* (2006), and Valencia *et al.* (2004), also reported the influence of elevation on the pattern of vegetation distribution in the Amazonia forest. While Valencia *et al.* (2004), observed that topography influenced the species composition and niche-partitioning of eastern Ecuadorian forest of the Amazon, de Castilho *et al.* (2006), in contrast noted that though slope accounted for 14% of above-ground biomass in the Brazilian Amazon rainforest, it did not have a noticeable influence on tree height.

Table 4.1: Summary of vegetation characteristics under rainforest at Okomu Forest Reserve

	Mean tree height (m)	Mean DBH (cm)	Mean tree density/25 m^2 plot
Lower slope	15.94 ± 1.0	33.47 ± 2.5	39.6 ± 4.9
Middle slope	14.69 ± 1.3	27.40 ± 3.3	37.3 ± 4.8
Upper slope	19.61 ± 1.1	29.03 ± 2.0	29.6 ± 3.9
F-ratio	5.11*	1.43*	1.32*

*Significant at 5% level of significance

Source: Data analysis , 2016

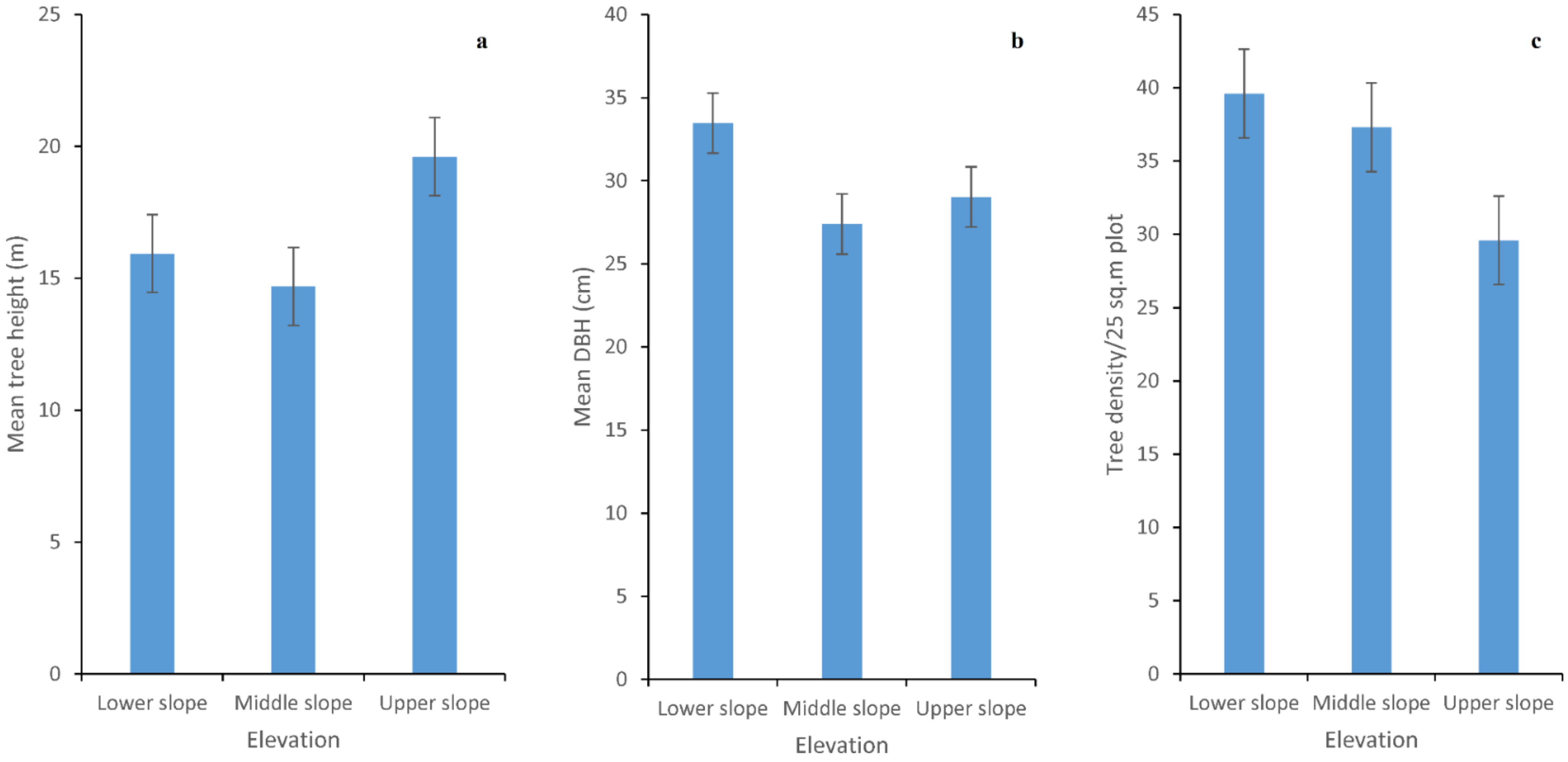


Figure 4.1: Variation of tree characteristics under rainforest (a) mean tree height; (b) mean diameter-at-breast-height; (c) mean tree density at Okomu Forest Reserve

(Source: Data analysis, 2016)

Aiba *et al.* (2004), observed that the impact of topography on three growth varies with tree size.

Mean tree DBH, unlike tree height, is higher at the lower slope position than at the upper slope. The mean DBH in the lower slope is 33.47cm, 27.40 cm in the middle slope position and 29.03 cm in the upper slope position (Figure 4.1b). Analysis of variance also shows that the difference in DBH between the three slope positions is significant at the 5% level of significance. Coomes and Allen (2007), also reported similar findings in a mountainous area in New Zealand. They noted that there was a decline in tree growth with increasing elevation. Berg and Oliveira-Filho (1999), however reported that tree heights and diameters were similar in the lower and middle slopes of tropical montane gallery forest in south-eastern Brazil. Variation in DBH may have been influenced by better nutrient status and moisture conditions which may provide greater potentials to support plant growth at the lower slope position. Tree size distribution has also been observed to be influenced by elevation (Basnet, 1992; Brehm *et al.*, 2003; de Castilho *et al.*, 2006; Valencia *et al.*, 2004).

Mean tree density shows a progressive decrease from the lower slope to the upper slope. Mean tree density per plot at the lower slope is 39.6 trees per 25 square meters, 37.3 trees per square meters in the middle slope position and 29.6 trees per 25 square meters in the upper slope position (Figure 4.1c). Analysis of variance reveals a significant difference in mean tree density among the three slope segments. Early studies (Jones, 1955, 1956) in Okomu forest also reported that there was variation in vegetation characteristics, noting that mean tree density and abundance increased downslope. This variation may be because of variation in soil nutrient and moisture conditions which are also influenced by elevation. Soils in the forest are generally well drained but areas at the valley bottom are slightly moister than the upper slope which may result in better plant growth (Ju-Ying *et al.*, 2008; Vågen *et al.*, 2016; Ziadat *et al.*, 2010). Several studies have shown that elevation and soil moisture influence tree characteristics to varying degree in different ecosystems (Aweto and Iyamah, 1993; Solon *et al.*, 2007). In contrast, Lovett *et al.* (2006), reported that there was a linear trend of increasing stem density with altitude in Ndzungwa mountain National Park, Tanzania.

4.3 Variation in characteristics of trees under plantations in Okomu Forest Reserve

The summary of oil palm parameters is shown in table 4.2 and in figure 4.2 (a) and (b). Table 4.2 shows that mean tree height of oil palm trees is 17.48 m, 16.35 m and 17.64 m in the lower slope, middle slope and upper slope positions respectively. A comparison of mean height of oil palm tree at different topographic positions indicates that there is a significant difference. Vormisto *et al.* (2004), also reported that topography significantly influenced the distribution and characteristics of palm in the Amazonia rainforest.

Table 4.2 also shows the mean diameter-at-breast-height of oil palm trees in the plantation. The table reveals that the mean DBH is 158.31 cm, 151.70 cm and 153.47 cm at the lower, middle and upper slope positions respectively (Figure 4.2). This shows that mean DBH is higher in the lower slope position and least in the middle slope position. Analysis of variance however shows that the difference in DBH is not significant.

Table 4.3 and figure 4.3 summarizes the parameters of rubber trees in Osse rubber plantation and indicates that the mean height of rubber trees is 27.55 m, 26.63 m and 26.74 m respectively in the lower slope, middle slope and upper slope positions. Analysis of variance show that there is no significant difference in mean tree height at different elevation. Mean DBH is 60.70 cm in the lower slope, 59.0 cm in the middle slope and 61.48 cm in the upper slope. There is also no significant difference in the DBH of rubber trees along the slope. These findings are similar to those reported by Coomes and Allen (2007) who observed that tree growth showed a general declined with increasing altitude in a mountainous forest in New Zealand. However, Aweto and Iyamah (1993), reported that mean tree height increased with increasing elevation in a swamp rainforest in southwestern Nigeria.

4.4 Floristic composition and species diversity in Okomu National Park

A total of 1065 trees composed of 338 plant species were sampled in the sampled site. There was an average of 36 trees and 11 species per plot. The most dominant species is

Table 4.2: Summary of oil palm tree parameters in Okomu oil palm plantation

	Mean tree height (m)	Mean DBH (cm)
Lower slope	17.48 ± 2.04	158.31 ± 0.12
Middle slope	16.35 ± 1.35	151.70 ± 0.09
Upper slope	17.64 ± 4.38	153.47 ± 0.07
F-ratio	52.34**	1.39

**Significant at 1% level of significance

(Source: Data analysis, 2016)

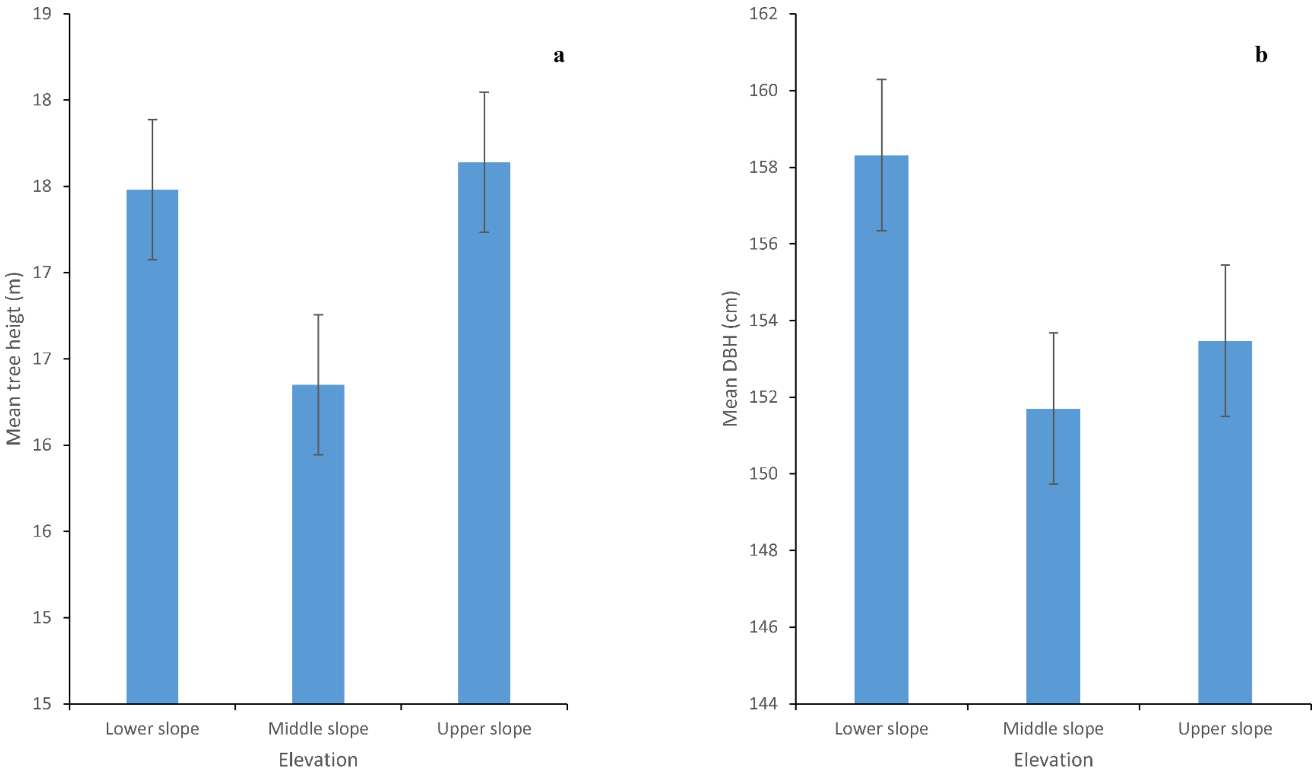


Figure 4.2: Variation of vegetation characteristics under oil palm plantation (a) mean tree height; (b) mean diameter-at-breast height at Okomu Forest Reserve

(Source: Data analysis, 2016)

Table 4.3: Summary of rubber tree parameters in Osse rubber plantation

	Mean tree height (m)	Mean DBH (cm)
Lower slope	27.55 ± 0.64	60.07 ± 1.08
Middle slope	26.63 ± 0.75	59.00 ± 1.56
Upper slope	26.74 ± 0.53	61.48 ± 1.41
F-ratio	0.598	0.832

(Source: Data analysis, 2016)

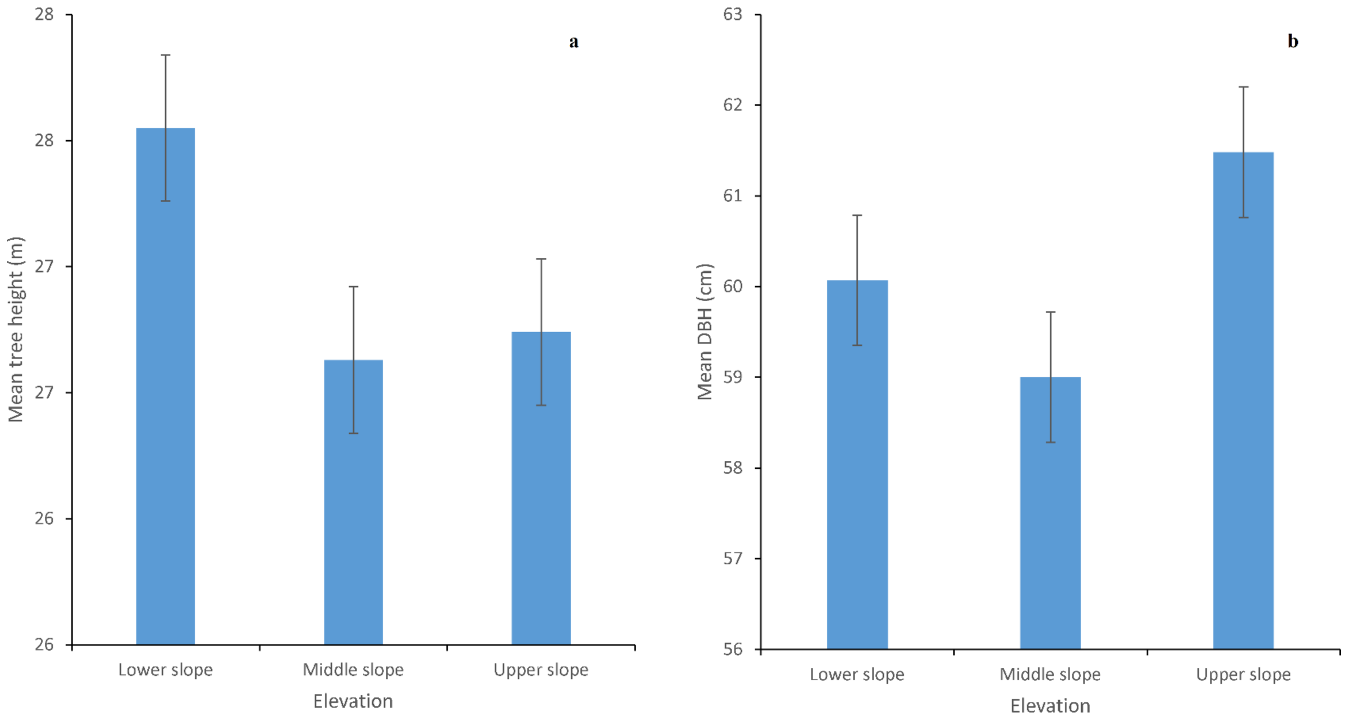


Figure 4.3: Variation of characteristics under rubber plantation (a) mean tree height; (b) mean diameter-at-breast height at Okomu Forest Reserve

(Source: Data analysis, 2016)

Diospyros insculpta (Green Ebony Persimmon) which makes up 10.86% of total trees in the lower slope, *Guarea thompsonii* (Black Guarea) makes up 8.04% of trees in the middle slope while *Afzelia Africana* (African Counterwood), *Ceiba pentandra* (Silk cotton tree) and *Lovoa trichilioides* (African Walnut) each account for 6.44% of trees species in the upper slope.

Table 4.4 shows the species diversity parameters of vegetation in the upper, middle and lower slope positions in Okomu National Park. Table 4.4 shows that mean tree species richness is 3.32 per plot in the lower slope, 3.08 in the middle slope and 2.96 in the upper slope. Analysis of variance shows that there is a significant difference ($p < 0.01$) in species richness between the slope positions. This variation in species diversity may be related to the nature of soil nutrients and moisture conditions. Soils in the upper slope are better drained but the lower slope tend to be higher in nutrient and moisture which may lead to better plant growth (Figure 4.1c). DeMars and Runkle (1992), reported similar findings in Ohio, USA where they observed that species richness and diversity were greatest in the floodplain site and least in the upland. The distribution of forest trees has been observed to be determined by the distribution of soil nutrient along slope gradients (Bridge and Johnson, 2000; John et al., 2007). In contrast however, Lovett et al. (2006), observe that species diversity was higher at high elevation in Ndzungwa mountain National Park, Tanzania. Duivenvoorden (1996), also reported that tree species richness was lower in the lower slope than in a well-drained upper slope in Columbian Amazon rainforest while Oliveira-Filho et al. (1994), observe that there was no significant difference in tree species distribution between river margins in the lower slope and the interior upper slope of tropical riverine forest of south-eastern Brazil. Ensslin et al. (2015), reported that biomass was highest at intermediate slope positions in the rainforest of Kilimanjaro mountains in East Africa. Anthropogenic disturbances are observed to contribute to the pattern of vegetation diversity in the montane zone of southeastern Brazil (Toniato and de Oliveira-Filho, 2004). The differences in vegetation distribution reported in the literature may be because of differences in slope gradients which influenced nutrient distribution, variation in elevation

Table 4.4: Vegetation diversity characteristics in the rainforest at Okomu Forest Reserve

	Lower			Middle			Upper		
Plot	S	H	E	S	H	E	S	H	E
1	2.94	2.91	-0.03	2.89	2.87	-0.02	2.56	2.45	-0.12
2	3.26	3.17	-0.09	2.94	2.88	-0.07	2.71	2.62	-0.09
3	3.33	3.23	-0.1	2.94	2.89	-0.06	2.71	2.61	-0.1
4	3.37	3.24	-0.13	3.04	2.96	-0.09	2.94	2.78	-0.17
5	3.37	3.21	-0.15	3.04	2.98	-0.07	3.00	2.83	-0.16
6	3.37	3.19	-0.18	3.18	3.04	-0.14	3.09	2.94	-0.15
7	3.37	3.2	-0.17	3.18	3.07	-0.11	3.14	3.01	-0.13
8	3.37	3.16	-0.21	3.18	3.07	-0.11	3.14	3.03	-0.11
9	3.40	3.15	-0.25	3.18	3.08	-0.1	3.14	3.02	-0.11
10	3.40	3.14	-0.26	3.18	3.06	-0.12	3.18	3.04	-0.14
x	3.32	3.16	-0.16	3.08	2.99	-0.09	2.96	2.83	-0.13

* S = species richness per plot; H = Shannon diversity index; E = Evenness, x = mean

(Source: Data analysis, 2016)

and vegetation types. Studies in different environmental conditions (Alijani and Sarmadian, 2014; Aweto and Iyamah, 1993; Tsui *et al.*, 2004) have noted the importance of nutrient distribution influenced by slope gradients on the distribution of vegetation characteristics. de Castilho *et al.* (2006), observed that tree size influenced aboveground live biomass concentration along slopes. They reported that small trees of less than 10 cm DBH, were more on slopes while larger trees dominated areas of flat terrain. The contribution of elevation to vegetation distribution in tropical forest ecosystem therefore appears to vary with the nature and structure of the habitat investigated. Hansen *et al.* (2014) and Wolf *et al.* (2012), in separate studies to model aboveground biomass using air-borne lidar images in southeastern United States and Panama respectively, conclude that tree height has a strong influence on species richness. Basnet (1992), showed that slope is an importance factor in the size distribution of trees in the rainforest ecosystem of Puerto Rico.

The mean species diversity is lowest in the upper slope (2.83). It is 2.99 in the middle slope and 3.16 in the lower slope (Table 4.4). The high species diversity in the lower slope position is because of the higher nutrient concentration in the lower slope resulting from nutrient movement due to hydrological flow downslope (Figure 4.1). Also, the moisture condition of the lower slope results in more plant growth. Reed-Dustin *et al.* (2012), stated that Shannon-Wiener's diversity index of 1.7 or higher is considered indicative of high diversity. It therefore shows that Okomu National Park has a high species diversity. Analysis of variance shows that elevation has a significant influence on variation of species diversity ($p < 0.01$) in the forest. Valencia *et al.* (2004), however described the contribution of topography to vegetation species diversity in the Amazon forest of Ecuador as minor. Species evenness is a measure of the equality of species distribution within a habitat. Table 4.4 shows that the mean species evenness in the upper slope is -0.13, -0.09 in the middle slope and -0.16 in the lower slope. This distribution of species is also related to nutrient distribution along the catena (Figure 4.1). Analysis of variance indicates that there is a significant different in species evenness at different topographic positions.

CHAPTER 5

SOIL-VEGETATION RELATIONSHIP UNDER RAINFOREST AND TREE PLANTATIONS IN OKOMU FOREST RESERVE

5.1 Introduction

The dominant role played by climate in the nature of soil characteristics and the composition of vegetation in an area notwithstanding, the soil-plant model shows the relationship between soil and plant which can be described as cyclical in nature. Plant species composition determine the nature and quality of soil properties in an area while soil also influences the nature and type of vegetation that can grow in a locality. This chapter examines the relationship between vegetation variables (tree density, DBH and tree height), topography and soil physical and chemical properties under rainforest and tree plantations in Okomu Forest Reserve.

5.2 Spatial variability of soil physical and chemical properties under rainforest in Okomu Forest Reserve

The results of Canonical Correspondence Analysis (CCA) the rainforest is shown in Figures 5.1, 5.2 and 5.3 for the topsoil, subsoil and deep subsoil layers respectively under rainforest and in Table 5.1. The figures show the first two ordination axes of soil variables relative to vegetation parameters in rainforest. Table 5.1 indicates that the first axis of CCA accounts for 63.86% of variance in soil-vegetation relationship in the rainforest. Figure 5.1 shows the CCA ordination diagram of the topsoil layer. The first axis is characterized principally by effective cation exchange capacity, exchange acidity, organic carbon, total nitrogen and extractable iron which are highly correlated in the lower slope position and negative end of the first axis and pH (KCl) in the upper slope and positive end of the axis. Though to a low level, available phosphorus and exchangeable potassium are also important determinants of vegetation parameters in the lower slope. The upper slope position is characterized by percent sand, pH (H_2O) and extractable copper. The eigenvalue (Table 5.1) of the first axis is 0.04 and Monte Carlo permutation test indicates that topsoil

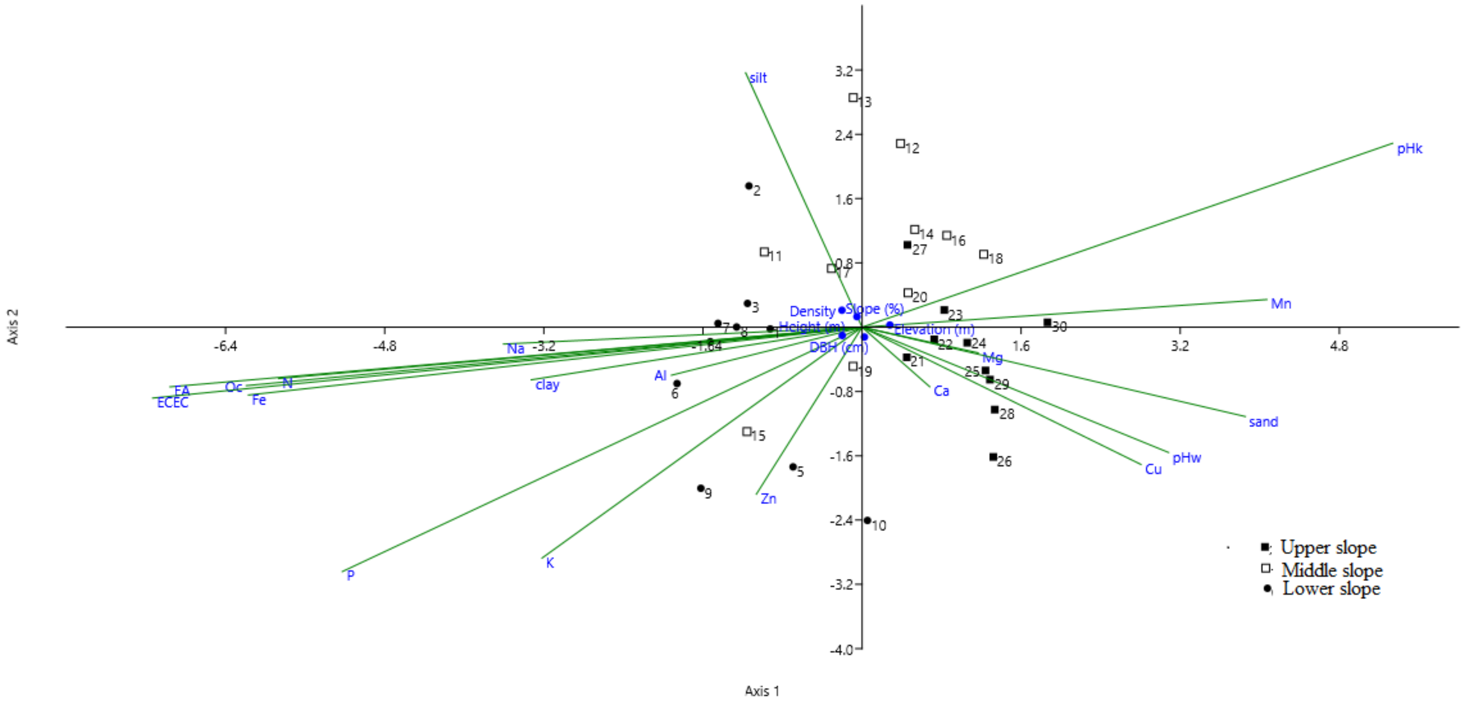


Figure 5.1: Canonical correspondence analysis ordination diagram of topography, vegetation and topsoil variables under rainforest at Okomu Forest Reserve

(Source: Data analysis, 2016)

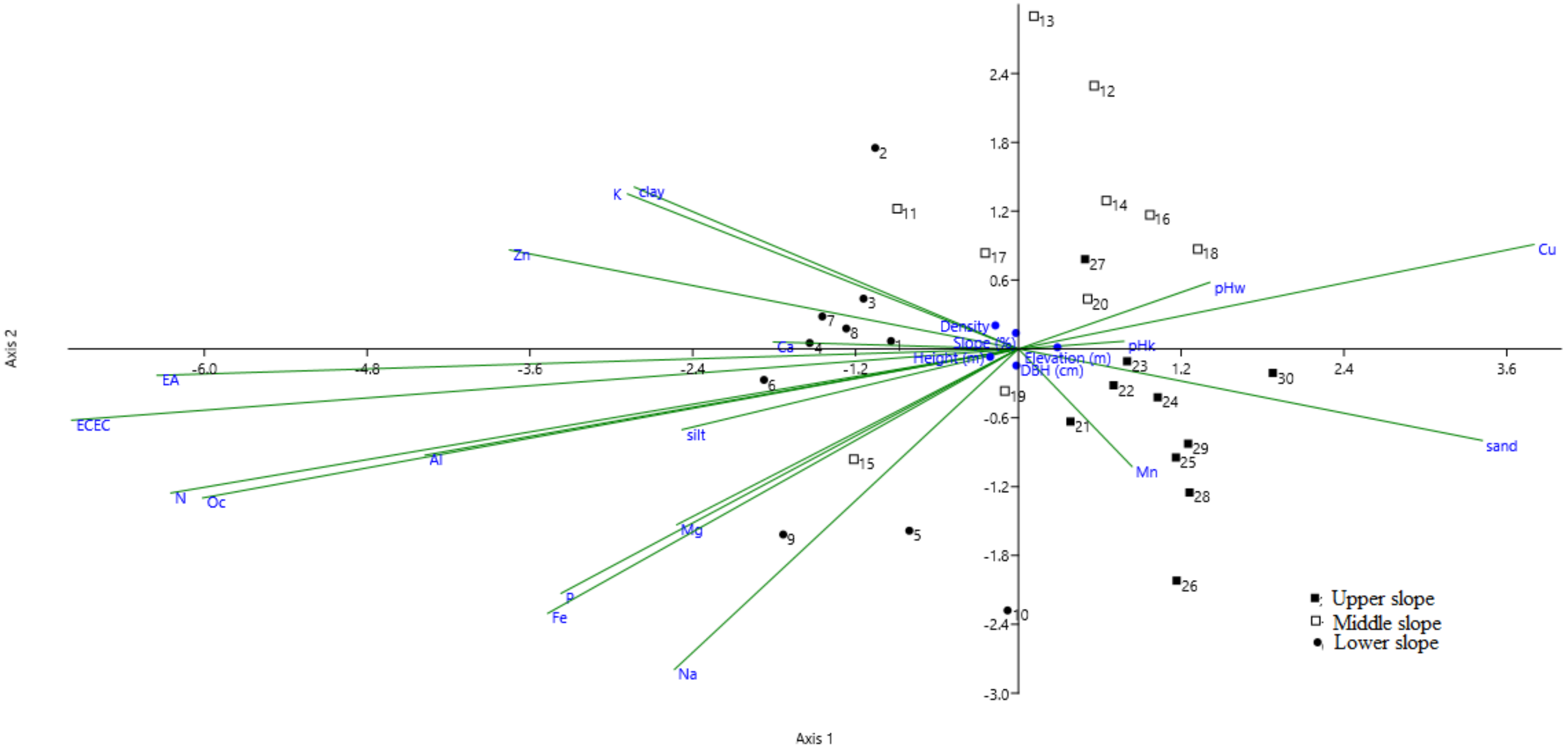


Figure 5.2: Canonical correspondence analysis ordination diagram of topography, vegetation and subsoil variables under rainforest at Okomu Forest Reserve

(Source: Data analysis, 2016)

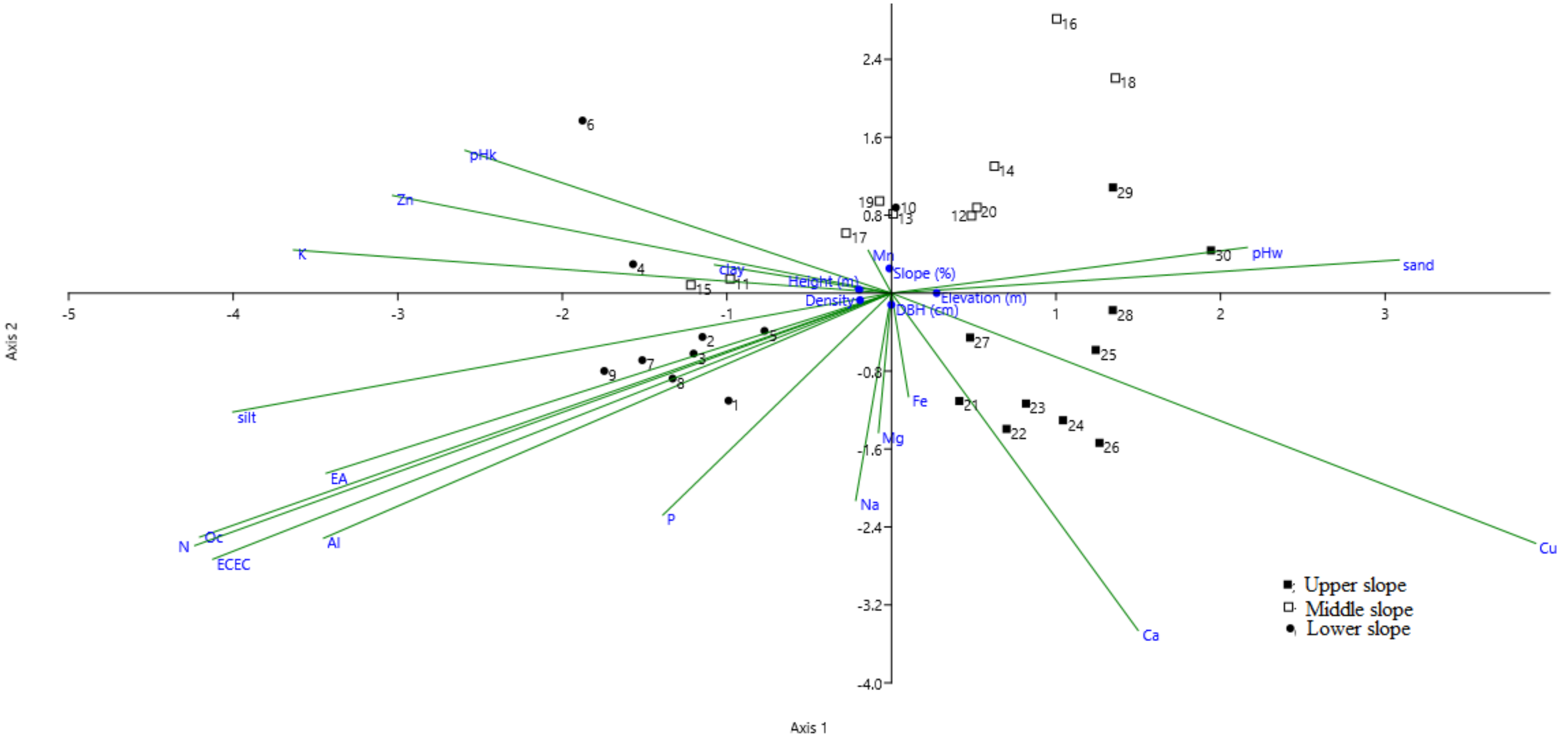


Figure 5.3: Canonical correspondence analysis ordination diagram of topography, vegetation and deep subsoil variables under rainforest at Okomu Forest Reserve

(Source: Data analysis, 2016)

Table 5.1: Summary of canonical correspondence analysis for the first four axes of soil, topography and vegetation variables under rainforest at Okomu Forest Reserve

	Topsoil			subsoil			deep subsoil		
Axis	eigenvalue	% variance	p-value	eigenvalue	% variance	p-value	eigenvalue	% variance	p-value
1	0.004	63.86	0.004	0.034	60.7	0.006	0.037	57.91	0.02
2	0.014	23.31	0.098	0.014	21.21	0.15	0.011	16.57	0.625
3	0.043	6.96	0.976	0.008	12.56	0.133	0.01	16.07	0.004
4	0.004	5.867	0.586	0.004	5.53	0.582	0.006	9.46	0.006

(Source: Data analysis, 2016)

properties in the first axis have a significant ($p < 0.01$) relationship with tree parameters. The second axis shows that silt in the middle slope and extractable copper in the upper slope are determinants of vegetation properties in the topsoil layer. The eigenvalue of the axis is 0.014 and accounts for 23.31% of variance in tree parameters. Monte Carlo permutation test, however, shows that the relationship between soil properties and tree parameters in the second axis of the topsoil is not significant.

The first axis of the subsoil layer (Figure 5.2), is principally defined by effective cation exchange capacity, exchange acidity, total nitrogen and organic carbon in the lower slope position. These nutrients have a strong positive influence on tree growth which is manifested in tree height and DBH. Extractable copper is the main determinant of tree parameters in the middle slope. The first axis accounts for 60.7% of variance and has eigenvalue of 0.034 (Table 5.1). Monte Carlo permutation test shows that soil properties have a significant ($p < 0.01$) relationship with tree parameters. The second axis of the subsoil shows a strong association with most soil properties which are concentrated in the lower and middle slope positions. It accounts for 21.21% with eigenvalue of 0.014. Monte Carlo permutation test show no significant relationship between soil properties and tree parameters.

The first axis of the deep subsoil layer (Figure 5.3), is principally characterized by silt, total nitrogen, organic carbon and effective cation exchange capacity in the lower slope position. In the upper slope, copper is the major determinant of vegetation parameters and exhibits a negative relationship with tree height. The eigenvalue of the first axis of the deep subsoil layer is 0.037. It accounts for 57.91% of variance and Monte Carlo permutation test shows that there is a significant ($p<0.05$) relationship between soil properties and tree parameters. The second axis accounts for 16.57% of variance. It is principally defined by exchangeable calcium and extractable copper in the upper slope position and exchangeable aluminum, available phosphorus and exchangeable sodium in the lower slope. Monte Carlo permutation tests show that there is no significant correlation between soil properties and tree parameters in the deep subsoil layer. The variation in soil properties that are principal determinants of vegetation parameters at different depths of the catena may be attributed to soil processes that redistribute soil nutrients on the basis of topographic gradient and vegetation composition. Similar findings were reported by earlier studies carried out in south-western Nigeria and in the Loess Plateau, Shaanxi Province, China (Adejuwon and Ekanade, 1988; Aweto and Enaruvbe, 2010; Hou and Fu, 2014).

5.3 Influence of topography and tree parameters on the distribution of soil physical and chemical properties under tree plantations in Okomu Forest Reserve

The results of CCA under oil palm plantation is shown in Figures 5.4, 5.5 and 5.6 for the topsoil, subsoil and deep subsoil layers respectively. Figure 5.4 shows that the first canonical axis is principally defined by extractable iron, exchangeable aluminum and effective cation exchange capacity, exchangeable calcium and exchange acidity. The second axis is defined by extractable manganese, extractable zinc, pH and exchangeable sodium. The eigenvalue of the first axis is 0.0036 with variance of 97% while is the eigenvalue for the second axis is 0.00 with variance of 3.0%. Monte Carlo permutation test shows a significant correlation between topsoil variables and vegetation parameters. In the subsoil layer (Figure 5.5), The first axis under oil palm plantation.is principally defined by extractable iron, percent organic carbon, percent nitrogen and available phosphorus. The eigenvalue of the first axis is 0.0034 and a variance of 98.2%. Monte Carlo permutation tests shows a significant correlation at 0.01% level of significance (Table 5.2). The second axis of the subsoil layer under oil palm plantation is defined by extractable manganese, exchangeable magnesium, pH, exchangeable calcium and percent clay. The eigenvalue of the second axis is 0.00 with variance of 1.8%. Monte Carlo permutation test shows no significant correlation in the second canonical axis. The first axis of the deep subsoil layer is defined by extractable iron, percent sand, exchangeable sodium, exchangeable potassium and percent clay. The eigenvalue of the first axis of the deep subsoil layer is 0.0034 with variance of 96.06%. Monte Carlo permutation test shows a significant correlation between soil properties and vegetation parameters in the first axis. The second axis is defined by exchangeable magnesium, extractable copper, pH, and effective cation exchange capacity.

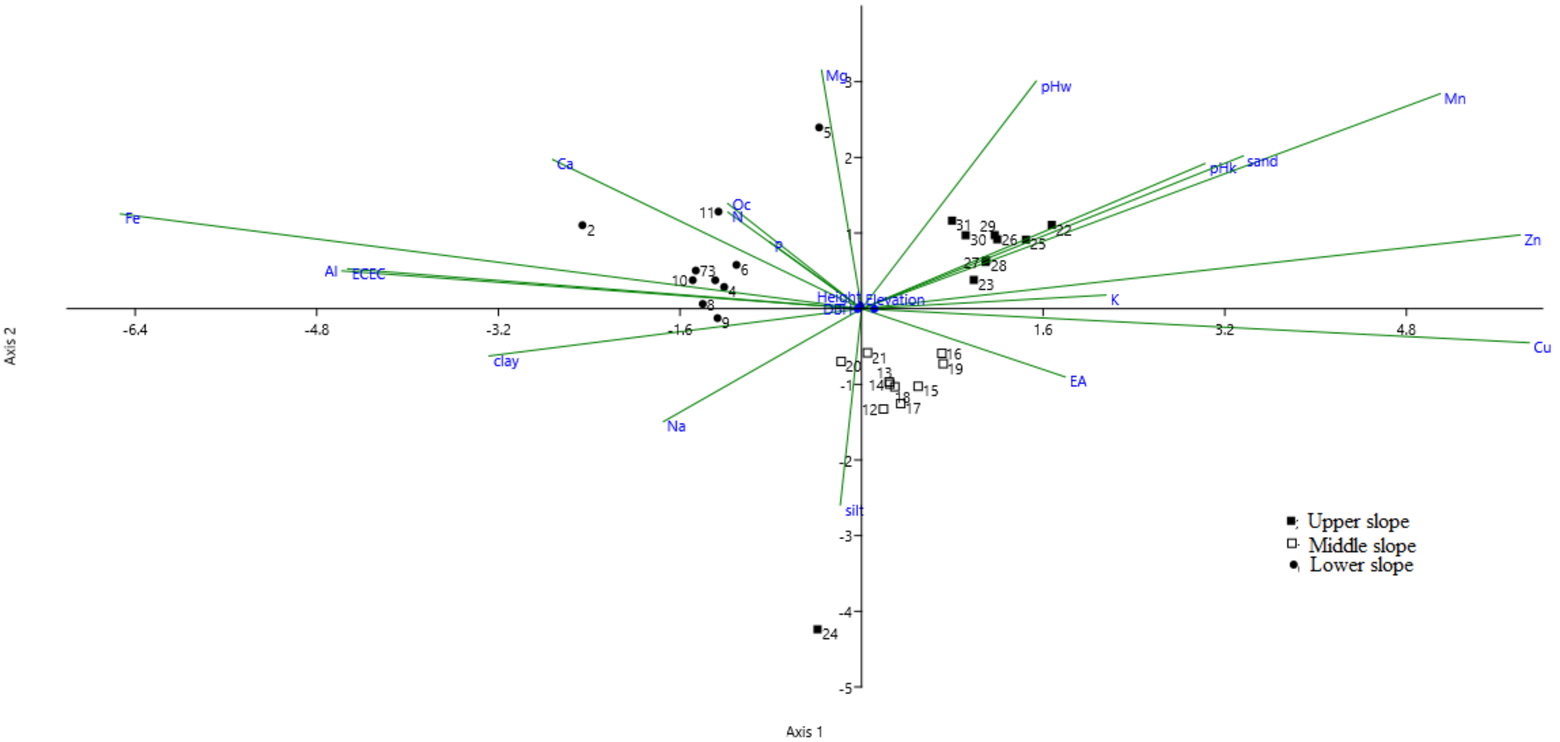


Figure 5.4: Topsoil canonical correspondence analysis ordination diagram of topography, vegetation and soil properties under oil palm plantation at Okomu Forest Reserve

(Source: Data analysis, 2016)

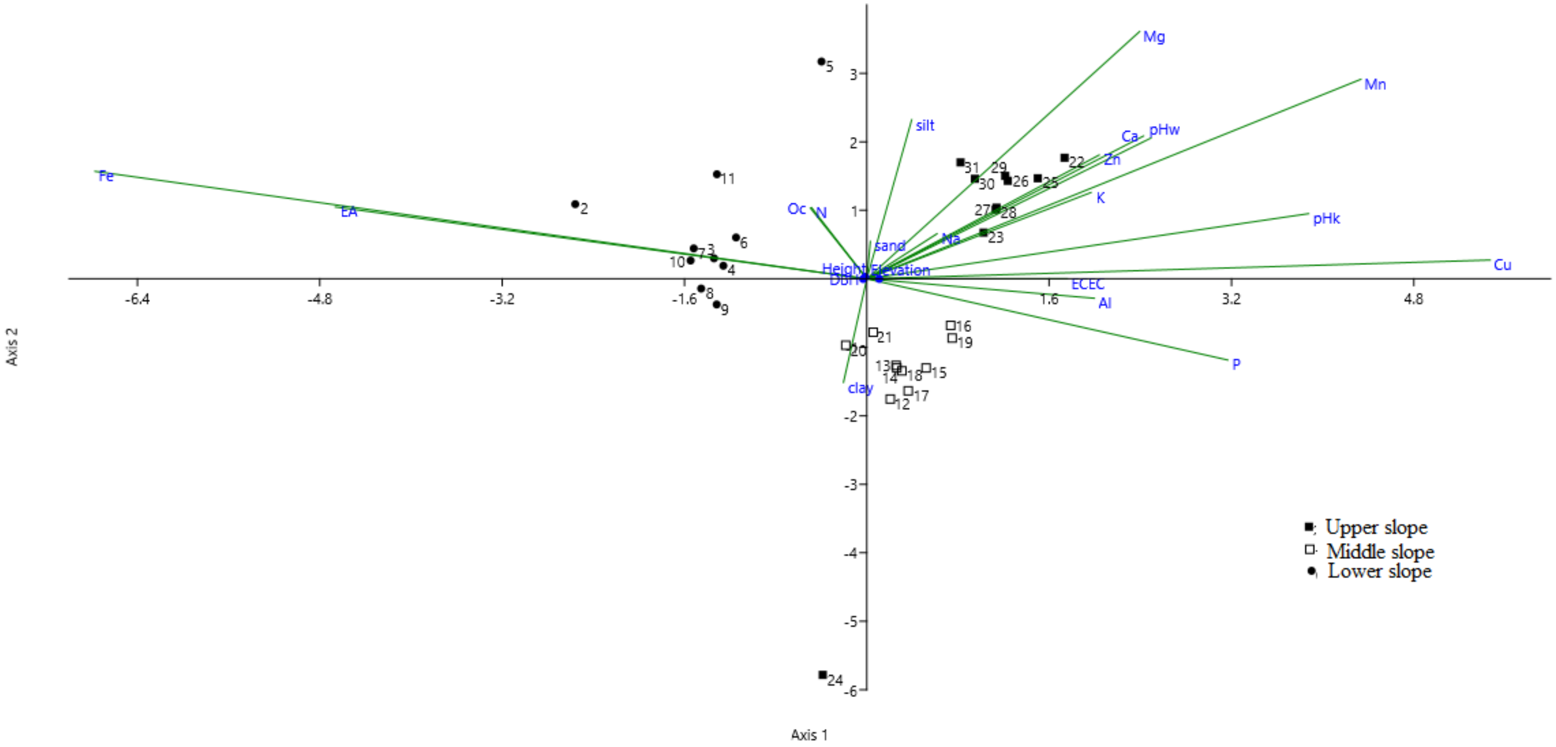


Figure 5.5: Subsoil canonical correspondence analysis ordination diagram of topography, vegetation and soil properties under oil palm plantation at Okomu Forest Reserve

(Source: Data analysis, 2016)

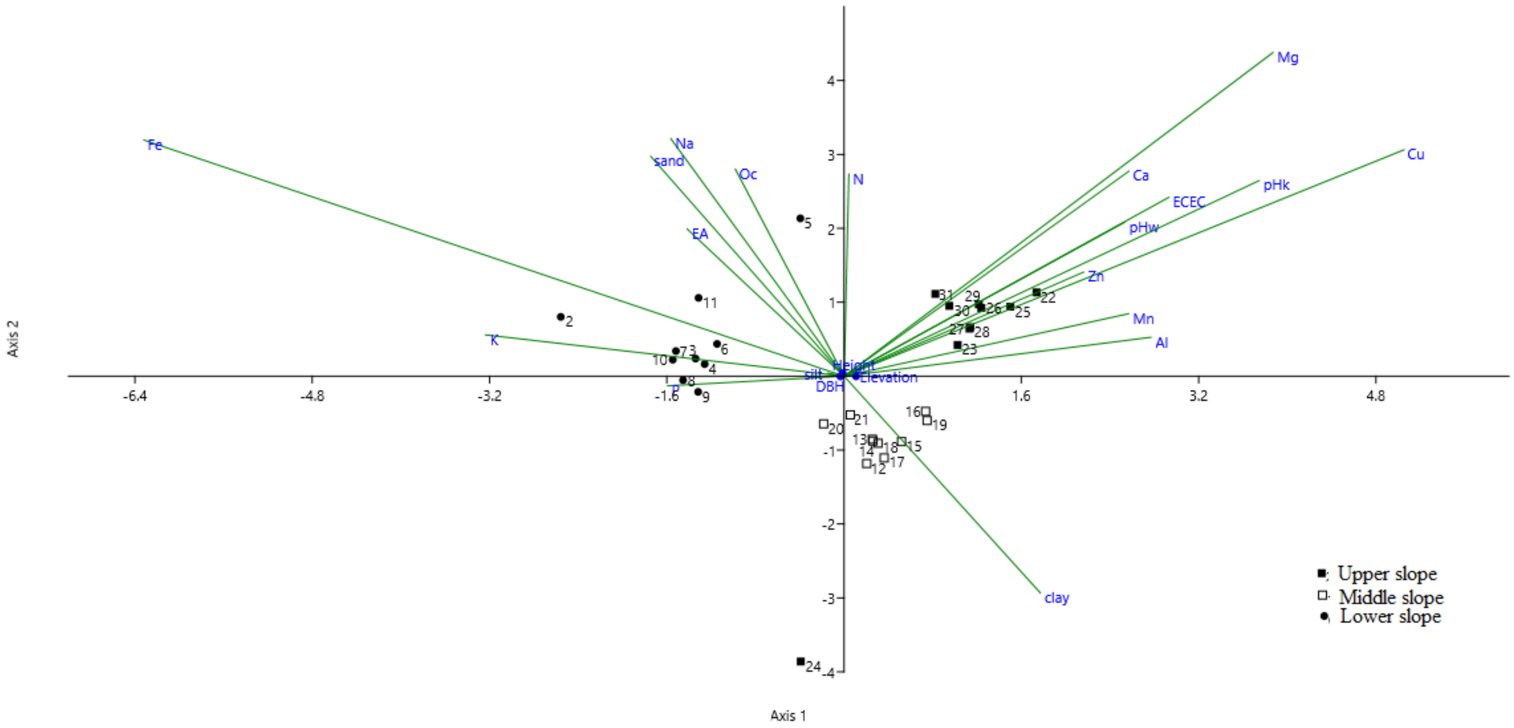


Figure 5.6: Deep subsoil canonical correspondence analysis ordination diagram of topography, vegetation and soil properties under oil palm plantation at Okomu Forest Reserve

(Source: Data analysis, 2016)

Table 5.2: Summary of canonical correspondence analysis for two axes of soil, topography and vegetation variables under oil palm plantation

	Topsoil			subsoil			deep subsoil		
Axis	eigenvalue	% variance	p-value	eigenvalue	% variance	p-value	eigenvalue	% variance	p-value
1	0.0036	96.99	0.001	0.0034	98.20	0.008	0.0034	96.06	0.01
2	0.0001	3.01	0.372	0.0000	1.80	0.920	0.0001	3.94	0.81

(Source: Data analysis, 2016)

The eigenvalue of the second axis is 0.00 with a variance of 3.94%. Monte Carlo permutation test shows no significant correlation.

Figures 5.7, 5.8 and 5.9 show the results of CCA in the topsoil, subsoil and deep subsoil layers under rubber plantation. Figure 5.7 indicates that the first canonical axis in the topsoil layer is principally defined by percent soil organic carbon and extractable copper. Organic carbon shows a strong positive influence on tree height but is negatively correlated with elevation. The second axis is defined mainly by percent total nitrogen and extractable manganese. The eigenvalue of the first axis in the topsoil is 0.0156 with a variance of 96.98%. Monte Carlo permutation tests reveals no significant correlation. The eigenvalue of the second axis is 0.0005 and accounts for 3.46% variance. Monte Carlo permutation test also shows no significant correlation with vegetation parameters (Table 5.3). In the subsoil (Figure 5.8) however, the first axis is defined by exchangeable aluminum, percent organic carbon, exchange acidity, exchangeable calcium and percent clay. The second axis shows extractable iron, silt, sand and pH as the main determinants. Eigenvalue of the first axis of the subsoil is 0.0147 and 0.001 for the second axis. The first axis accounts for 96.83% of variance and shows no significant correlation between soil and vegetation parameters while the second axis accounts for 3.17%. Figure 5.9 shows that extractable iron, pH, extractable manganese and exchangeable calcium are the principal soil properties in the deep subsoil layer that are influencing the growth of rubber. Eigenvalue in the first axis is 0.015 and 0.00 in the second axis. The first axis accounts for 97.3% of variance while the second axis accounts for 2.7% variance. There is no significant correlation between soil properties and vegetation parameters in the deep subsoil layer.

The variation in soil properties relationship at different soil depths under oil palm and rubber plantations may be attributed to the different rate of nutrient immobilization by the two plantations. Studies indicate that the rate of nutrients immobilization varies with differences in vegetation types. Similar results have been reported by studies in soils under agriculture and agroforestry systems (Aweto, 2001; Awotoye *et al.*, 2011; Heuvelink *et al.*, 2013; Were *et al.*, 2016).

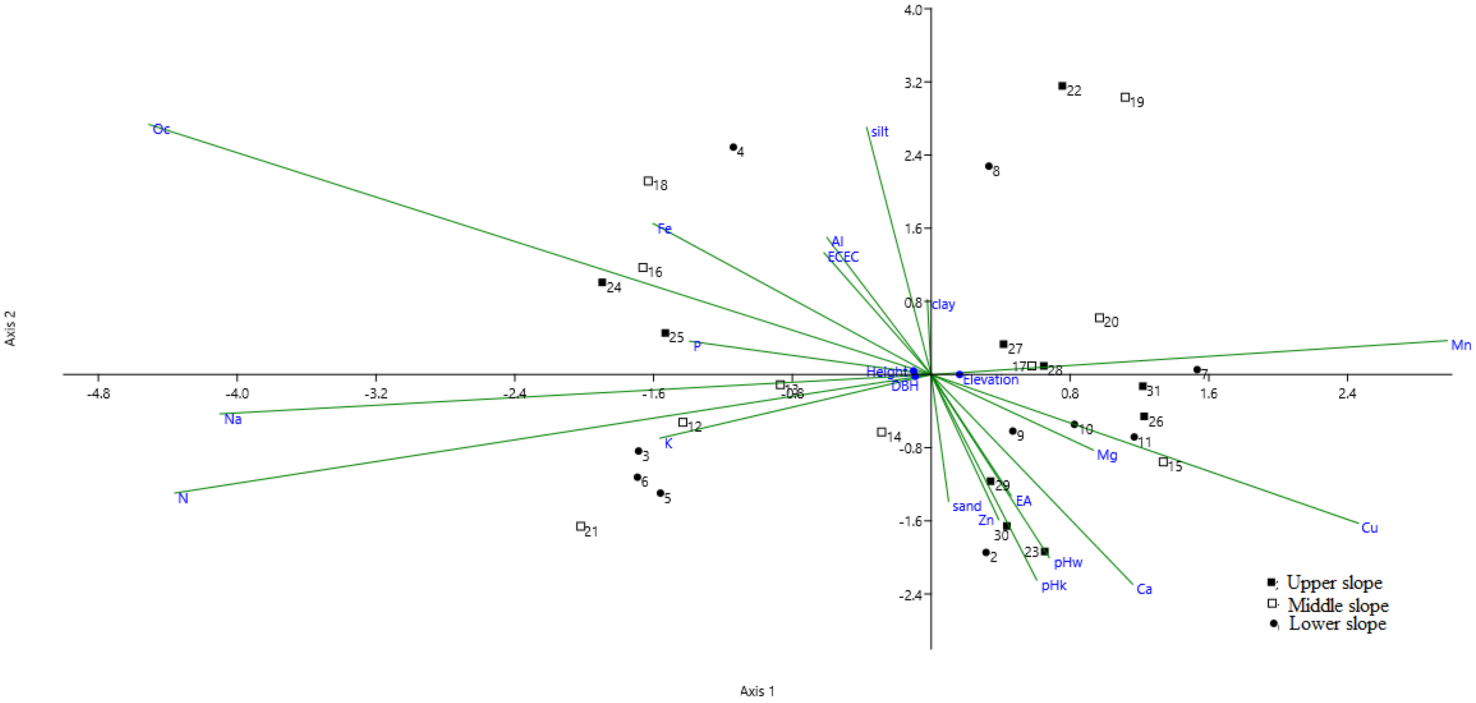


Figure 5.7: Topsoil canonical correspondence analysis ordination diagram of topography, vegetation and soil properties under rubber plantation at Okomu Forest Reserve

(Source: Data analysis, 2016)

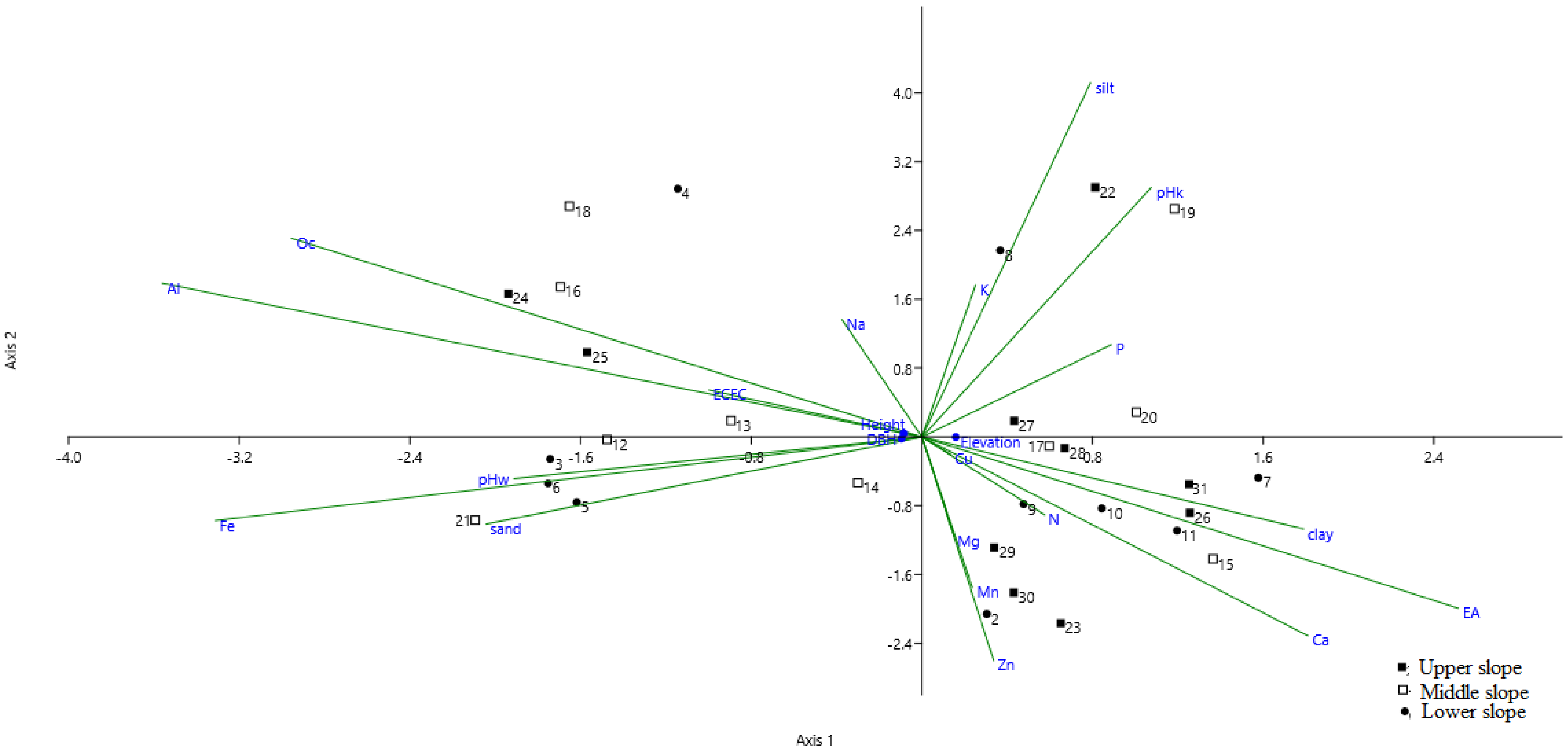


Figure 5.8: Subsoil canonical correspondence analysis ordination diagram of topography, vegetation and soil properties under rubber plantation at Okomu Forest Reserve

(Source: Data analysis, 2016)

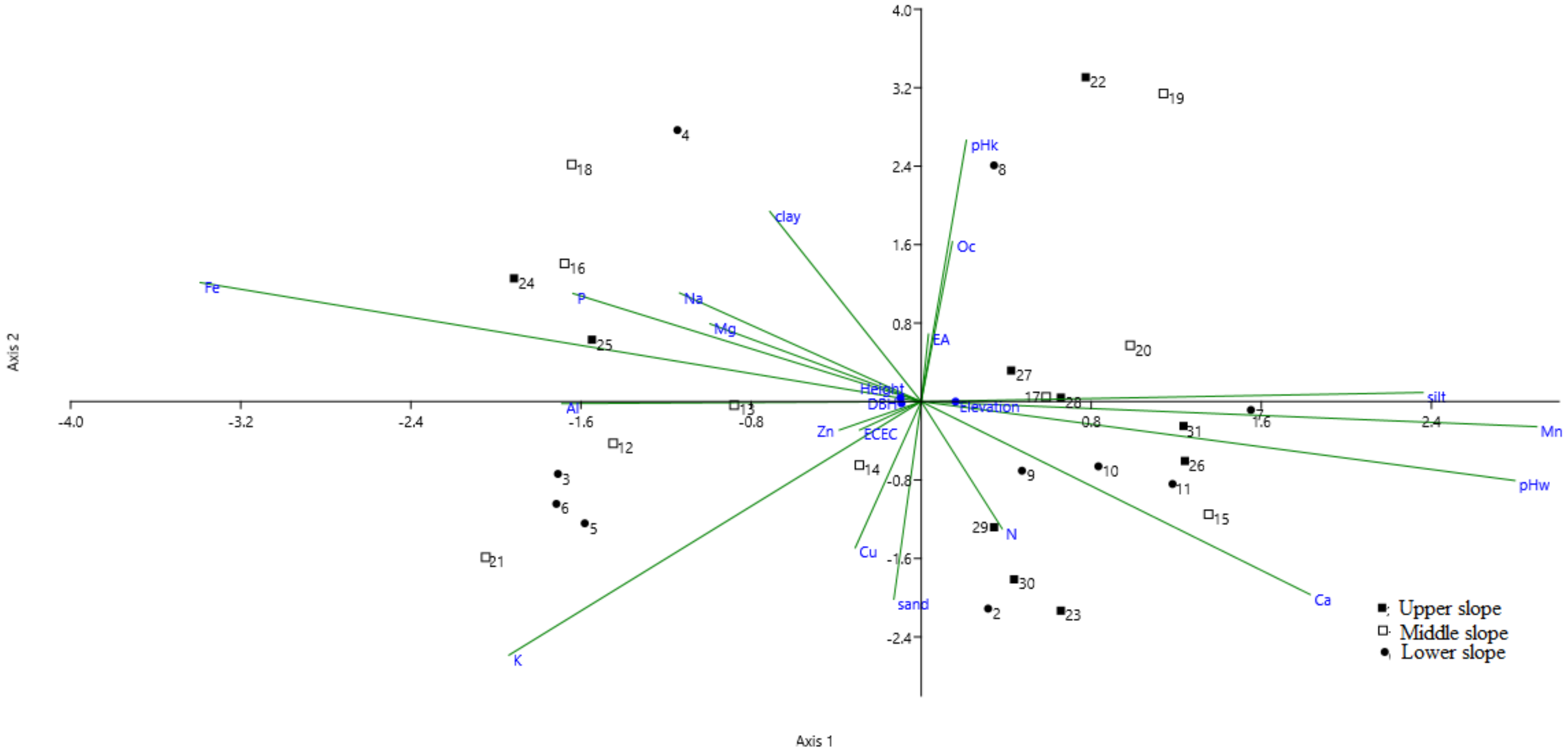


Figure 5.9: Deep subsoil canonical correspondence analysis ordination diagram of topography, vegetation and soil properties under rubber plantation at Okomu Forest Reserve

(Source: Data analysis, 2016)

Table 5.3: Summary of canonical correspondence analysis for the two axes of soil, topography and vegetation variables under rubber plantation

	Topsoil			subsoil			deep subsoil		
Axis	eigenvalue	% variance	p-value	eigenvalue	% variance	p-value	eigenvalue	% variance	p-value
1	0.0156	96.98	0.08	0.0147	96.83	0.18	0.0152	97.3	0.14
2	0.0005	3.46	0.65	0.0005	3.17	0.79	0.0004	2.7	0.87

(Source: Data analysis, 2016)

5.4 Relationship between topography, tree parameters and soil properties variation under rainforest

Tables 5.4, 5.5 and 5.6 show the results of principal components analysis of topsoil, subsoil and deep subsoil layers respectively under the rainforest. Variables with loadings of absolute values of 0.6 and above on each component (bold and underlined) are used for identifying the components. The summary of principal components analysis result of the topsoil layer is shown in table 5.4. The table indicates that the variables of component I in the topsoil layer are total nitrogen, effective cation exchange capacity, exchange acidity, extractable iron, available phosphorus, organic carbon, pH, exchangeable potassium and exchangeable sodium. Component I of the topsoil layer is therefore identified as topsoil fertility status component. Component II is made up of exchangeable calcium, magnesium and manganese. It is identified as calcium, magnesium and manganese status component. The third component is composed of exchangeable aluminum, sand and silt status component. The component is identified as topsoil texture and aluminum status component and the fourth component is composed of extractable copper. It is therefore identified as topsoil copper status component.

Component I of the subsoil layer (Table 5.5) is composed of exchangeable sodium, effective cation exchange capacity, available phosphorus, percent clay mineral, exchange acidity, and percent sand. The component is identified as subsoil nutrient holding capacity status component. The second component is made up of percentage silt, pH and percentage total nitrogen. Component II is identified as subsoil silt, pH and total nitrogen status component. Component III is composed of exchangeable calcium, potassium and iron. The component is termed calcium, potassium and iron status component. Component IV is composed of extractable manganese and exchangeable magnesium and is identified as manganese and magnesium concentration status component. The first principal component of the deep subsoil layer (Table 5.6) comprises of percentage total nitrogen, percentage soil organic carbon, extractable zinc, percent silt and exchangeable potassium. The component is identified as deep subsoil fertility status component. Component II is composed of extractable manganese, extractable copper, exchangeable sodium, exchangeable

Table 5.4: Component loadings of rotated principal components of topsoil variables (loadings with absolute values ≥0.6 in bold and underlined) under rainforest

	Component			
Soil properties	1	2	3	4
Total N (%)	**0.942**	0.128	0.074	-0.010
cmol/kg ECEC	**0.937**	-0.106	0.147	0.097
cmol/kg Ex. Acidity	**0.905**	-0.167	0.248	0.088
mg/kg Fe	**0.899**	-0.054	-0.079	0.153
mg/kg Av. P	**0.864**	0.008	0.002	0.076
Organic C (%)	**0.804**	0.142	-0.141	-0.259
pH (KCl)	**-0.788**	0.078	0.296	0.244
cmol/kg K	**0.753**	0.264	0.219	0.392
pH (H_2O)	**-0.689**	0.343	0.039	0.058
cmol/kg Na	**0.606**	0.429	-0.050	0.343
clay (%)	0.559	-0.510	0.378	0.248
cmol/kg Ca	0.034	**0.939**	-0.092	0.062
cmol/kg Mg	0.177	**0.917**	0.148	0.209
mg/kg Mn	-0.320	**0.734**	0.085	0.029
cmol/kg Al	0.291	-0.008	**-0.673**	-0.064
sand (%)	-0.606	0.272	**-0.665**	-0.074
silt (%)	0.194	0.382	**0.642**	-0.300
mg/kg Cu	-0.096	0.055	-0.018	**0.742**
mg/kg Zn	0.474	0.294	-0.025	0.563

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.5: Component loadings of rotated principal components of subsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under rainforest

	Component			
	1	2	3	4
cmol/kg Na	**<u>0.767</u>**	-0.149	0.007	0.274
cmol/kg ECEC	**<u>0.764</u>**	0.265	0.322	-0.269
mg/kg Av. P	**<u>0.731</u>**	0.302	0.062	0.337
Clay (%)	**<u>0.723</u>**	0.271	-0.052	-0.249
cmol/kg Ex. Acidity	**<u>0.660</u>**	0.224	0.409	-0.426
sand (%)	**<u>-0.613</u>**	-0.586	0.033	0.124
cmol/kg Al	0.446	0.308	-0.387	0.138
mg/kg Zn	0.384	0.047	-0.005	-0.291
silt (%)	0.120	**<u>0.847</u>**	0.017	0.155
pH (KCl)	0.019	**<u>-0.726</u>**	-0.049	0.168
Total N (%)	0.624	**<u>0.667</u>**	-0.031	0.023
Organic C (%)	0.536	0.597	-0.066	-0.014
pH (H_2O)	-0.160	-0.442	-0.149	0.423
cmol/kg Ca	-0.060	-0.014	**<u>0.876</u>**	0.292
cmol/kg K	-0.021	0.270	**<u>0.874</u>**	-0.092
mg/kg Fe	0.411	-0.206	**<u>0.650</u>**	-0.024
mg/kg Mn	0.050	0.053	0.123	**<u>0.831</u>**
cmol/kg Mg	0.534	-0.164	0.208	**<u>0.721</u>**
mg /kg Cu	-0.067	-0.001	-0.028	0.287

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.6: Component loadings of rotated principal components of deep subsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under rainforest

	Component			
	1	2	3	4
Total N (%)	**0.923**	0.055	0.121	0.096
Organic C (%)	**0.851**	0.022	0.137	0.019
mg/kg Zn	**0.762**	0.388	-0.187	0.024
silt (%)	**0.715**	-0.148	-0.491	0.014
cmol/kg K	**0.671**	0.279	0.356	-0.239
mg/kg Mn	0.231	**0.853**	0.151	-0.127
mg/kg Cu	-0.181	**0.761**	-0.036	-0.058
cmol/kg Na	0.111	**0.689**	-0.290	0.270
cmol/kg Mg	0.243	**0.681**	0.391	0.014
cmol/kg Ca	0.150	**0.678**	0.552	-0.002
cmol/kg Al	0.255	0.429	0.191	0.208
pH (KCl)	0.325	-0.043	**-0.791**	-0.117
mg/kg Fe	0.184	0.296	**0.735**	0.036
mg/kg Av. P	0.523	0.312	0.578	0.187
pH (H_2O)	-0.169	0.329	-0.556	0.151
clay (%)	-0.104	-0.077	-0.080	**0.877**
cmol/kg Ex. Acidity	-0.083	0.086	0.198	**0.814**
sand (%)	-0.244	0.140	0.305	**-0.803**
cmol/kg ECEC	0.103	0.392	0.268	0.745

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

and exchangeable calcium. The component is identified as deep subsoil macro- and micro-nutrients status component. Component III is made up of pH and extractable iron. The component is therefore termed deep subsoil pH and iron status component. Component IV is composed of percent clay, exchange acidity, percent sand, effective cation exchange capacity. It is identified as deep subsoil nutrient holding capacity status component.

Table 5.7 shows the summary of the factor loadings of principal components of soil properties under rainforest. The table reveals that the first component of the topsoil layer account for 42.88% of the total variance with eigenvalue of 8.15. The second component accounts for 17.84% and eigenvalue of 3.39. The third and fourth axes has eigenvalue of 1.71 and 1.30 with variance of 8.99% and 6.82% respectively. Table 5.7 also shows that the first two components of the subsoil layer accounts for 31.53% of total variance with eigenvalue of 5.99 while the second component accounts for 13.91% variance with eigenvalue of 2.64. The third and fourth components account for 11.71% and 8.19% and eigenvalue of 2.23 and 1.56 respectively. The eigenvalue of component I of the deep subsoil layer is 5.47. The values of components II, III and IV are 3.11, 2.88 and 2.02 respectively. Components I accounts for 28.79% of variance, component II accounts for 16.34% of total variance while components III and IV each accounts for 15.16% and 10.65% respectively.

The relationship between soil properties and environmental variables (elevation and tree parameters) in soils under rainforest (Okomu National Park) was determined using correlation analysis. Table 5.8 shows the correlation coefficient between environmental variables and topsoil variables. The table indicates that topsoil percent soil organic carbon, percent total nitrogen, available phosphorus, exchangeable aluminum, effective cation exchange capacity and extractable iron have significant positive relationship with tree height. However, topsoil pH (KCl) has a significant negative relationship with tree height. Similar findings were reported by Aweto (1981c), in a secondary forest ecosystem in south-western Nigeria. Aweto (1981c), reported a strong positive relationship between topsoil nutrients, tree size and vegetation cover in a secondary forest in south-western Nigeria.

Table 5.7: Principal components of soil properties, proportion of the total variance explained and eigenvalue at each soil layer under rainforest at Okomu Forest Reserve

	Topsoil		Subsoil		Deep subsoil	
Component	eigenvalue	% variance	eigenvalue	% variance	eigenvalue	% variance
1	8.15	42.88	5.99	31.53	5.47	28.79
2	3.39	17.84	2.64	13.91	3.11	16.34
3	1.71	8.99	2.23	11.71	2.88	15.16
4	1.30	6.82	1.56	8.19	2.02	10.65

(Source: Data analysis, 2016)

Table 5.8: Correlation coefficient between environmental variables and topsoil parameters under rainforest

	Tree height	DBH	Density	Ground elevation
pH (H_2O)	-0.139	-0.244	-0.364*	0.284
pH(KCl)	-0.534**	-0.552**	-0.215	0.531**
% Org. C	0.543**	0.544**	0.284	-0.643**
% Total N	0.516**	0.530**	0.328	-0.589**
mg/kg Av. P	0.540**	0.539**	0.152	-0.547**
cmol/kg Ca	0.099	-0.045	-0.186	0.034
cmol/kg Mg	0.062	-0.048	-0.145	0.104
cmol/kg K	0.34	0.364*	0.022	-0.344
cmol/kg Na	0.297	0.194	0.122	-0.425*
cmol/kg Al	0.453*	0.509**	0.362*	-0.728**
cmol/kg Ex. Acidity	0.098	0.119	0.187	-0.206
cmol/kg ECEC	0.469**	0.519**	0.379*	-0.749**
mg/kg Mn	-0.265	-0.32	-0.293	0.380*
mg/kg Fe	0.461*	0.460*	0.316	-0.640**
mg/kg Cu	-0.057	-0.045	-0.082	0.387*
mg/kg Zn	0.089	0.101	-0.149	-0.186
clay (%)	0.162	0.208	0.113	-0.393*
silt (%)	-0.03	0.033	0.274	-0.072
sand (%)	-0.14	-0.219	-0.26	0.419*

**Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

(Source: Data analysis, 2016)

The relationship between tree height and subsoil properties is shown in Table 5.9. The table shows that subsoil exchangeable aluminum and effective cation exchange capacity have a significant positive relationship with tree height. Similarly, percent soil organic carbon, percent total nitrogen, exchange acidity, extractable iron and percent clay also have a positive relationship with tree height. Table 5.10 shows a weak relationship between soil properties and tree height. The table reveals that only exchange acidity and effective cation exchange capacity have significant positive relationship with tree height. It is observed that pH (H_2O), exchangeable sodium, extractable copper and percent sand exhibit weak negative relationship with tree height.

Table 5.8 also reveals that there is a significant positive relationship between percent soil organic carbon, percent total nitrogen, available phosphorus, exchangeable aluminum and effective cation exchange capacity ($p<0.05$) while exchangeable potassium and extractable iron are also positively related with DBH ($p<0.01$). Topsoil pH(KCl) shows significant negative relationship with DBH. Table 5.9 shows that subsoil exchangeable aluminum shows a significant ($p<0.05$) positive relationship with DBH while effective cation exchange capacity also shows a significant ($p<0.01$) positive relationship with DBH.

Table 5.10 reveals that there is a significant ($p < 0.05$) positive relationship between DBH and deep subsoil exchange acidity and effective cation exchange capacity while exchangeable aluminum also shows a significant ($p <0.01$) positive relationship with DBH. The table also shows that apart pH (H_2O) and percent sand which show negative relationship, there is a positive relationship between deep subsoil properties and DBH. This relationship between DBH and soil properties is however weak and not significant at the 5% level. Significant ($p < 0.01$) positive relationship is observed between tree density and exchange acidity, effective cation exchange capacity while a significant ($p < 0.01$) negative relationship exists between pH (H_2O) and tree density in the topsoil layer. Exchangeable aluminum ($p < 0.05$) and effective cation exchange capacity ($p < 0.01$) also show significant positive relationship with tree density in the subsoil layer. In the deep subsoil layer, exchange acidity and effective cation exchange capacity show significant ($p < 0.01$) positive relationship with tree density.

Table 5.9: Correlation coefficient between environmental variables and subsoil parameters under rainforest

Soil properties	Tree height	DBH	Density	Ground elevation
pH (H_2O)	-0.084	-0.259	-0.29	0.283
pH(KCl)	-0.005	-0.118	-0.359	0.093
% Org. C	0.119	0.161	0.316	-0.482^{**}
% Total N	0.076	0.153	0.302	-0.502^{**}
mg/kg Av. P	-0.082	0.00	0.218	-0.297
cmol/kg Ca	-0.343	-0.292	0.288	0.144
cmol/kg Mg	-0.136	-0.116	0.133	-0.044
cmol/kg K	-0.158	-0.115	0.377^{*}	-0.207
cmol/kg Na	-0.057	0.017	-0.028	-0.101
cmol/kg Al	0.444^{*}	0.481^{**}	0.267	-0.671^{**}
cmol/kg Ex. Acidity	0.081	0.164	0.123	-0.132
cmol/kg ECEC	0.387^{*}	0.446^{*}	0.293	-0.640^{**}
mg/kg Mn	-0.226	-0.166	0.252	0.09
mg/kg Fe	0.13	0.127	0.35	-0.169
mg/kg Cu	-0.248	-0.278	-0.112	0.218
mg/kg Zn	-0.005	-0.095	-0.215	-0.346
clay (%)	0.193	0.26	0.032	-0.430^{*}
silt (%)	-0.126	0.059	0.181	-0.165
sand (%)	-0.108	-0.246	-0.107	0.436^{*}

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

(Source: Data analysis, 2016)

Table 5.10: Correlation coefficient between environmental variables and deep subsoil parameters under rainforest at Okomu Forest Reserve

Soil properties	Tree height	DBH	Density	Ground elevation
pH (H_2O)	-0.244	-0.146	-0.009	0.224
pH(KCl)	0.063	0.104	-0.052	-0.391*
% Org. C	0.22	0.294	0.278	-0.408*
% Total N	0.196	0.294	0.236	-0.436*
mg/kg Av. P	0.069	0.163	0.255	-0.083
cmol/kg Ca	0.003	0.027	-0.131	0.231
cmol/kg Mg	0.093	0.123	-0.136	-0.011
cmol/kg K	0.263	0.262	0.085	-0.401*
cmol/kg Na	-0.05	0.109	0.069	0.006
cmol/kg Al	0.352	0.393*	0.323	-0.241
cmol/kg Ex. Acidity	0.477**	0.588**	0.374*	-0.152
cmol/kg ECEC	0.479**	0.571**	0.397*	-0.25
mg/kg Mn	0.155	0.142	-0.245	-0.017
mg/kg Fe	0.176	0.11	-0.151	0.04
mg/kg Cu	-0.112	-0.074	-0.294	0.475**
mg/kg Zn	0.272	0.317	-0.075	-0.371*
clay (%)	0.068	0.072	0.169	-0.114
silt (%)	0.012	0.182	0.168	-0.508**
sand (%)	-0.072	-0.163	-0.025	0.370*

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

(Source: Data analysis, 2016)

In Table 5.8, percent soil organic carbon, percent total nitrogen, available phosphorus, exchangeable aluminum, effective cation exchange capacity and extractable iron all show strong positive significant ($p < 0.05$) negative relationship with elevation in the topsoil layer. Percent clay and exchangeable sodium show weak significant ($p < 0.01$) negative relationship while pH (KCl), extractable copper and percent sand have significant positive relationship with elevation. In the subsoil layer (Table 5.9), percent soil organic carbon, percent total nitrogen, exchangeable aluminum, and effective cation exchange capacity have significant ($p < 0.05$) negative relationship with elevation while percent sand show significant ($p < 0.01$) positive relationship. Table 5.10 shows that pH (KCl), percent soil organic carbon, percent total nitrogen, exchangeable potassium, extractable zinc and percent silt have significant ($p < 0.01$) negative relationship with elevation. However, extractable copper and percent sand have significant positive relationship with elevation. (Chen *et al.*, 1997), reported a weak negative correlation between organic carbon, nitrogen, and available phosphorus with elevation in a subtropical rainforest of Taiwan. The impact of elevation and erosion processes may have influenced the nature and direction of the relationship between soil properties and topography. Topography has been identified as a major determinant of soil properties and vegetation variation in different environmental conditions (Aweto and Enaruvbe, 2010; Aweto and Iyamah, 1993; Burke *et al.*, 1999; Chen *et al.*, 1997; de Castilho *et al.*, 2006).

5.5 Relationship between topography, tree parameters and soil properties variation under oil palm plantation

Tables 5.11, 5.12 and 5.13 show the component loadings of principal components of topsoil, subsoil and deep subsoil layers under oil palm plantation. The principal components of topsoil variables are shown in Table 5.11. The table indicates that principal component I is composed of pH (KCl), extractable manganese, extractable zinc, pH (H_2O) and extractable iron. Component I is defined as pH and micronutrients status component. Principal component II is made up of exchangeable aluminum, effective cation exchange capacity and extractable copper. The component is identified as nutrient exchange status component. Component III is composed of percent total nitrogen, percent soil organic

Table 5.11: Component loadings of rotated principal components of topsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under oil palm plantation

	Component			
Soil properties	1	2	3	4
pH (KCl)	**<u>0.803</u>**	0.335	-0.255	0.179
mg/kg Mn	**<u>0.787</u>**	-0.167	0.099	-0.055
mg/kg Zn	**<u>0.709</u>**	-0.273	0.112	-0.115
pH (H_2O)	**<u>0.694</u>**	-0.036	0.084	0.182
mg/kg Fe	**<u>-0.637</u>**	0.434	0.307	-0.141
silt (%)	-0.395	-0.234	-0.119	0.372
cmol/kg Al	-0.019	**<u>0.914</u>**	-0.044	0.026
cmol/kg ECEC	-0.035	**<u>0.909</u>**	-0.033	0.056
mg/g Cu	0.255	**<u>-0.605</u>**	-0.087	0.567
cmol/kg Ex. Acidity	-0.362	-0.415	-0.094	-0.263
cmol/kg Ca	-0.136	0.409	0.397	0.354
mg/kg av. P	-0.219	0.315	-0.109	0.058
Total N (%)	-0.032	0.019	**<u>0.957</u>**	0.067
Organic C (%)	-0.024	0.036	**<u>0.956</u>**	0.070
sand (%)	0.419	-0.229	**<u>0.621</u>**	0.324
clay (%)	-0.207	0.357	-0.561	-0.528
cmol/kg Mg	0.007	0.281	0.331	**<u>0.777</u>**
cmol/kg K	0.187	0.128	0.041	**<u>0.753</u>**
cmol/kg Na	-0.519	0.015	0.346	**<u>0.640</u>**

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.12: Component loadings of rotated principal components of subsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under oil palm plantation

	Component			
Soil properties	1	2	3	4
cmol/kg Mg	<u>**0.841**</u>	0.162	0.128	0.155
clay (%	<u>**-0.808**</u>	0.111	-0.218	-0.099
silt (%)	<u>**0.775**</u>	0.112	-0.048	-0.088
cmol/kg Na	<u>**0.636**</u>	0.085	-0.183	0.139
sand (%)	0.549	-0.195	0.289	0.167
mg/kg Mn	0.518	0.188	0.274	0.311
pH (H_2O)	0.457	0.457	0.251	-0.018
cmol/kg Al	0.124	<u>**0.857**</u>	-0.036	-0.078
cmol/kg ECEC	0.160	<u>**0.823**</u>	0.000	-0.095
mg/kg P	-0.245	<u>**0.639**</u>	0.042	0.052
cmol/kg Ex. Acidity	-0.128	-0.592	0.120	-0.359
Total N (%)	0.052	-0.119	<u>**0.897**</u>	0.063
Organic C (%)	0.051	-0.119	<u>**0.896**</u>	0.063
pH (KCl)	0.108	0.447	<u>**0.617**</u>	0.099
cmol/kg Ca	0.471	0.241	0.521	0.133
mg/kg Cu	0.233	0.099	-0.008	<u>**0.820**</u>
mg/kg Fe	0.240	-0.197	-0.101	<u>**-0.774**</u>
mg/kg Zn	0.383	-0.167	0.086	0.523
cmol/kg K	0.245	-0.216	0.179	0.458

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.13: Component loadings of rotated principal components of deep subsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under oil palm plantation

	Component			
Soil properties	1	2	3	4
cmol/kg Ca	**0.840**	0.247	0.085	-0.020
cmol/kg Mg	**0.834**	0.109	-0.158	0.094
pH (KCl)	**0.783**	0.080	0.362	0.215
pH (H_2O)	**0.760**	0.126	-0.119	0.102
mg/kg Cu	**0.710**	-0.051	-0.288	0.277
mg/kg Mn	**0.708**	0.111	0.221	-0.188
clay (%)	-0.256	**-0.854**	0.040	-0.038
sand (%)	0.283	**0.806**	0.168	0.044
cmol/kg Na	0.154	0.540	-0.273	0.101
cmol/kg K	-0.055	0.511	-0.330	-0.458
mg/kg Zn	0.332	-0.510	-0.220	-0.300
Total N (%)	-0.132	-0.067	**0.883**	0.155
Organic C (%)	-0.212	0.072	**0.818**	0.057
silt (%)	-0.054	0.164	-0.524	-0.011
mg/kg Av. P	0.208	0.296	0.365	-0.031
cmol/kg Ex. Acidity	0.152	0.073	0.253	-0.115
cmol/kg Al	0.028	0.197	0.050	**0.910**
cmol/kg ECEC	0.398	0.375	0.023	**0.739**
mg/kg Fe	-0.054	0.459	0.091	-0.587

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

carbon and percent sand. It is identified as soil fertility component while component IV is composed of exchangeable magnesium, exchangeable potassium and exchangeable sodium. The component is identified as soil macronutrients status component.

The first principal component of the subsoil layer under oil palm plantation (Table 5.12) is made up of exchangeable magnesium, percent clay, percent silt and exchangeable sodium. The component is identified as soil texture, magnesium and sodium component. Component II is composed of exchangeable aluminum, effective cation exchange capacity and available phosphorus. The component is defined as soil ECEC, aluminum and phosphorus status component. The constituents of component III are percent soil organic carbon, percent total nitrogen and pH (KCl). The component is identified as subsoil fertility status component. Extractable copper and extractable iron are the constituents of principal component IV of the subsoil layer. The component is identified as subsoil micronutrient status component.

Table 5.13 shows the components loading of deep subsoil layer under oil palm plantation. The first principal component is made up of exchangeable calcium, exchangeable magnesium, pH, extractable copper and extractable manganese. The component is identified as deep subsoil macro- and micro-nutrient status component. Component II is composed of percent clay and percent sand. It is identified as deep subsoil texture status component while component III is composed of percent soil organic carbon and percent total nitrogen which is identified as deep subsoil fertility status component and component IV is made up of exchangeable aluminum and ECEC. Component IV is identified as ECEC status component.

Table 5.14 shows the eigenvalue and variance explained by the first four principal components of soil physical and chemical properties under oil palm plantation. The table shows that the first principal component of the topsoil layer explains 22.26% of total variance with eigenvalue of 4.23. Component II accounts for 20.51% and eigenvalue of 3.90. This indicates that the first two components account for a combined variance of 42.77%. Component III accounts for 14% and component IV accounts for 9.34%. The eigenvalue of component III is 2.79 and component IV has eigenvalue of 1.77. The first

Table 5.14: Principal components of soil properties and the proportion of the total variance explained and eigenvalue at each soil layer under oil palm plantation

	Top-soil		Sub-soil		Deep subsoil	
Component	eigenvalue	% variance	eigenvalue	% variance	eigenvalue	% variance
1	4.23	22.26	4.96	26.09	4.88	25.69
2	3.90	20.51	2.76	14.53	2.66	13.99
3	2.79	14.67	2.08	10.96	2.33	12.25
4	1.77	9.34	1.71	8.99	1.88	9.91

(Source: Data analysis, 2016)

component of the subsoil accounts for 26.09% with eigenvalue of 4.96. The second component of the subsoil layer explains 14.53% of total variance with eigenvalue of 2.76. Component III of subsoil accounts for 10.96% with eigenvalue of 2.08 and 8.99% with eigenvalue of 1.71 for component IV. In the deep subsoil layer, the first component explains 25.69% with eigenvalue of 4.88. The second component accounts for 13.99% of total variance with eigenvalue of 2.66. The third and fourth components explains 12.25% and 9.91% respectively and eigenvalue of 2.33 and 1.88 respectively.

The relationship between soil physical and chemical properties and environmental variables (tree height, tree diameter-at-breast-height and elevation) under oil palm plantation is shown in Table 5.15. The table indicates that except exchangeable copper and percent sand which show negative relationship, the relationship between soil physical and chemical properties and vegetation is weak and not significant. Table 5.16 shows that in the subsoil layer under oil palm plantation, tree height exhibits a weak negative relationship with available phosphorus and percent sand. A significant positive relationship is observed for exchangeable magnesium while other soil physical and chemical properties show weak positive relationship in the subsoil. Available phosphorus and percent sand exhibit weak negative relationship in the subsoil under oil palm plantation. Table 5.17 shows that exchangeable magnesium and exchangeable sodium have a significant positive relationship with tree height in the deep subsoil layer under oil palm plantation.

Diameter-at-breast height exhibits weak significant positive relationship with exchangeable aluminum and effective cation exchange capacity in the topsoil under oil palm plantation (Table 5.15). However, a weak negative relationship is observed for pH, exchangeable calcium and magnesium, extractable manganese, copper, zinc and percent sand. Other soil properties show weak positive relationship with DBH. Several soil properties such as exchangeable aluminum, effective cation exchange capacity, extractable iron and percent clay show significant negative relationship with elevation while extractable manganese, extractable copper and extractable zinc show significant negative relationship with elevation. In the subsoil layer however (Table 5.16), a positive relationship is observed between DBH and percent organic carbon, total nitrogen,

Table 5.15: Correlation coefficient between tree variables and topsoil properties under oil palm plantation

Soil properties	Tree height	DBH	Ground elevation
pH (H_2O)	0.171	-0.220	0.099
pH(KCl)	0.135	-0.230	0.284
% Org. C	0.175	0.034	-0.141
% Total N	0.165	0.037	-0.140
mg/kg Av. P	0.119	0.033	-0.069
cmol/kg Ca	0.342	0.161	-0.265
cmol/kg Mg	0.304	-0.090	-0.071
cmol/kg K	0.039	-0.103	0.224
cmol/kg Na	0.021	0.218	-0.125
cmol/kg Al	0.070	0.045	0.235
cmol/kg Ex. Acidity	0.325	0.396^{*}	-0.376^{*}
cmol/kg ECEC	0.335	0.396^{*}	-0.369^{*}
mg/kg Mn	0.336	-0.264	0.517^{**}
mg/kg Fe	0.072	0.235	-0.694^{**}
mg/kg Cu	-0.037	-0.281	0.596^{**}
mg/kg Zn	0.097	-0.302	0.580^{**}
clay (%)	0.270	0.010	-0.384^{*}
silt (%)	0.067	0.292	0.095
sand (%)	-0.233	-0.168	0.330

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.16: Correlation coefficient between tree variables and subsoil properties under oil palm plantation

Soil properties	Tree height	DBH	Ground elevation
pH (H_2O)	0.150	-0.176	0.229
pH(KCl)	0.119	-0.147	0.411*
% Organic C	0.202	0.056	-0.033
% Total N	0.202	0.056	-0.031
mg/kg Av. P	-0.030	-0.023	0.367*
cmol/kg Ca	0.263	-0.114	0.255
cmol/kg Mg	0.394*	-0.163	0.227
cmol/kg K	0.055	-0.160	0.176
cmol/kg Na	0.188	0.037	0.080
cmol/kg Al	0.054	0.108	-0.496**
cmol/kg Ex. Acidity	0.095	0.009	0.243
cmol/kg ECEC	0.123	0.009	0.217
mg/kg Mn	0.282	-0.238	0.435*
mg/kg Fe	0.358	0.345	-0.683**
mg/kg Cu	0.145	-0.138	0.612**
mg/kg Zn	0.232	-0.091	0.219
clay (%)	0.260	-0.036	-0.050
silt (%)	0.216	-0.098	0.012
sand (%)	-0.195	0.097	0.054

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

exchangeable sodium, exchangeable aluminum, exchange acidity, effective cation exchange capacity, extractable iron and percent sand. While other soil properties in the subsoil layer are negatively correlated with DBH. There is also no significant relationship between soil properties and DBH in the deep subsoil layer (Table 5.17). Available phosphorus, exchangeable potassium, exchangeable sodium, extractable iron and percent sand show positive relationship with DBH while all other soil properties exhibit negative relationship with DBH.

Topsoil pH (KCl), exchangeable potassium, exchangeable aluminum, extractable manganese, extractable copper, extractable zinc, percent silt and percent sand show positive relationship with elevation. A significant positive relationship is observed between elevation and extractable manganese, extractable copper and extractable zinc. However, topsoil exchange acidity, effective cation exchange capacity, extractable iron, and percent clay exhibit significant negative relationship with elevation under oil palm plantation (Table 5.15). The subsoil pH (KCl), available phosphorus, extractable manganese and extractable copper show significant positive relationship with elevation. While significant a negative relationship is observed between elevation and exchangeable aluminum and extractable iron (Table 5.16). In the deep subsoil layer (Table 5.17), significant positive relationship is observed between elevation and pH (KCl), exchangeable magnesium and extractable copper while a significant negative relationship is observed between elevation and extractable iron.

5.6 Relationship between topography, tree parameters and soil properties variation under rubber plantation

Table 5.18, 5.19 and 5.20 show the component loadings of topsoil, subsoil and deep subsoil layers under rubber plantation. The principal component I in the topsoil layer under rubber plantation is characterized by pH, extractable zinc, exchangeable calcium and extractable manganese. The component is identified as topsoil pH, calcium and micronutrients status component. Component II is made up of exchange acidity, exchangeable aluminum, exchangeable potassium and effective cation exchange capacity. Component II is identified as acidity, potassium and cation exchange capacity status component. Component III is

Table 5.17: Correlation coefficient between tree variables and deep subsoil properties under oil palm plantation

Soil properties	Tree height	DBH	Ground elevation
pH (H_2O)	0.084	-0.259	0.204
pH(KCl)	0.321	-0.167	0.391^{*}
% Organic C	0.070	-0.147	-0.171
% Total N	-0.015	-0.236	-0.082
mg/kg Av. P	0.123	0.168	-0.123
cmol/kg Ca	0.305	-0.156	0.252
cmol/kg Mg	0.595^{**}	-0.171	0.413^{*}
cmol/kg K	0.294	0.265	-0.287
cmol/kg Na	0.426^{*}	0.020	-0.165
cmol/kg Al	0.102	-0.065	-0.193
cmol/kg Ex. Acidity	0.050	-0.146	0.285
cmol/kg ECEC	0.292	-0.169	0.299
mg/kg Mn	0.057	-0.136	0.253
mg/kg Fe	0.291	0.154	-0.697^{**}
mg/kg Cu	0.340	-0.275	0.511^{**}
mg/kg Zn	0.082	-0.159	0.202
clay (%)	0.329	-0.016	0.201
silt (%)	-0.059	-0.062	-0.046
sand (%)	0.359	0.041	-0.187

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.18: Component loadings of rotated principal components of topsoil variables (loadings with absolute values ≥0.6 in bold and underlined) under rubber plantation

	Component			
Soil properties	1	2	3	4
pH (H_2O)	**0.928**	-0.047	-0.068	0.166
pH (KCl)	**0.914**	-0.054	0.032	0.187
mg/kg Zn	**0.905**	0.049	-0.038	-0.099
cmol/kg Ca	**0.901**	-0.051	0.003	0.253
mg/kg Mn	**0.657**	0.212	-0.146	-0.109
mg/kg Fe	-0.591	0.074	-0.072	-0.166
cmol/kg Ex. Acidity	0.073	**-0.846**	0.167	0.145
cmol/kg Al	0.211	**0.770**	0.526	-0.019
cmol/kg K	0.033	**0.749**	-0.153	0.352
cmol/kg ECEC	0.248	**0.695**	0.596	0.008
Organic C (%)	-0.094	0.378	-0.021	-0.086
cmol/kg Na	-0.137	0.163	**0.821**	-0.162
mg/kg Av. P	0.295	-0.282	**0.787**	0.189
mg/kg Cu	0.145	0.451	**-0.644**	0.025
silt (%)	-0.241	0.049	0.471	0.241
clay (%)	0.276	0.002	0.093	**0.792**
sand (%)	0.328	-0.009	-0.005	**-0.744**
Total N (%)	0.099	0.146	0.164	**0.700**
cmol/kg Mg	0.029	0.074	0.318	0.574

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.19: Component loadings of rotated principal components of subsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under rubber plantation

Soil properties	Component			
	1	2	3	4
clay (%)	**<u>0.874</u>**	0.057	-0.149	0.116
sand (%)	**<u>0.835</u>**	-0.177	-0.140	-0.061
cmol/kg K	**<u>0.753</u>**	0.079	0.210	-0.003
cmol/kg Ex. Acidity	-0.576	-0.301	0.369	0.144
Total N (%)	0.352	-0.288	-0.116	0.279
cmol/kg Al	0.251	**<u>0.822</u>**	0.274	-0.130
cmol/kg ECEC	0.364	**<u>0.744</u>**	0.133	0.047
cmol/kg Ca	0.501	**<u>-0.732</u>**	0.177	0.303
mg/kg Zn	0.375	-0.592	0.391	0.333
mg/kg Cu	0.202	-0.569	-0.153	0.027
mg/kg Av. P	-0.090	0.175	**<u>0.880</u>**	0.232
cmol/kg Na	0.129	0.070	**<u>0.878</u>**	-0.192
silt (%)	-0.049	0.254	0.572	-0.097
cmol/kg Mg	0.045	-0.017	0.473	-0.097
Organic C (%)	0.061	0.101	0.428	**<u>0.745</u>**
mg/kg Fe	0.256	0.127	0.063	**<u>-0.693</u>**
mg/kg Mn	0.152	-0.296	0.315	**<u>0.642</u>**
pH (KCl)	-0.402	0.449	0.107	0.469
pH (H_2O)	0.068	0.099	-0.363	0.454

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.20: Component loadings of rotated principal components of deep subsoil variables (loadings with absolute values ≥ 0.6 in bold and underlined) under rubber plantation

Soil properties	Component			
	1	2	3	4
clay (%)	**0.917**	-0.069	-0.145	-0.071
sand (%)	**0.899**	0.121	0.104	-0.241
cmol/kg Ex. Acidity	**-0.816**	-0.153	0.140	-0.182
cmol/kg K	0.548	0.325	-0.054	0.172
mg/kg Fe	-0.483	0.322	-0.095	0.061
Organic C (%)	0.063	0.742	0.010	0.088
cmol/kg Na	-0.053	0.727	0.420	-0.243
cmol/kg Al	0.479	**0.639**	-0.187	0.065
cmol/kg ECEC	0.480	**0.604**	-0.234	0.141
mg/kg Av. P	0.162	0.595	0.078	0.019
pH (H_2O)	0.115	-0.545	-0.043	0.366
mg/kg Zn	-0.138	0.493	0.481	-0.307
cmol/kg Ca	0.189	-0.147	**0.859**	-0.210
PH (KCl)	0.048	-0.027	**-0.833**	-0.077
Total N (%)	0.460	0.011	**0.647**	-0.008
mg/kg Mn	-0.287	0.213	0.476	0.216
mg/kg Cu	0.013	-0.028	-0.304	-0.126
silt (%)	0.104	-0.140	0.122	**0.865**
cmol/kg Mg	-0.034	0.075	0.058	**0.859**

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

composed of exchangeable sodium, available phosphorus and extractable copper. It is identified as sodium, phosphorus and copper status component. Component IV is made up of percent clay, percent sand and exchangeable magnesium. The component is defined as topsoil texture and total nitrogen component.

The principal component loadings of the subsoil layer are shown in Table 5.19. The table shows that component I is composed of percent clay, percent sand and exchangeable potassium. The component is identified as subsoil texture and potassium status component. Component II is made up of exchangeable aluminum, effective cation exchange capacity and exchangeable calcium and is identified as subsoil aluminum, ECEC and calcium status component. Component III is composed of available phosphorus and exchangeable sodium. The component is identified as subsoil phosphorus and sodium component. Component IV is composed of percent soil organic carbon, extractable iron and extractable manganese. The component is identified as subsoil carbon, manganese and iron status component.

Table 5.20 shows the components loadings of deep subsoil variables under rubber plantation. The table indicates that the first principal component is composed of percent clay, percent sand and exchange acidity. The component is identified as deep subsoil texture and acidity status component. Component II is composed of exchangeable aluminum and effective cation exchange capacity. The component is identified as deep subsoil exchangeable nutrient capacity status component. Component III is composed of exchangeable calcium, pH and percent total nitrogen. The component is identified as deep subsoil calcium, pH and nitrogen status component. Component IV is made up of percent silt and exchangeable magnesium and is identified as deep subsoil silt and magnesium status component.

The eigenvalues and percent variance of the first four principal components is shown in table 5.21. The table indicates that the first principal component of the topsoil layer accounts for 26.33% of total variance and has eigenvalue of 5.0. Component II accounts for 15.92% with eigenvalue of 3.03 while component III explains 14.33% of total variance with eigenvalue of 2.72. Component IV of the topsoil layer accounts for 10.47% of total

Table 5.21: Principal components of soil properties and the proportion of the total variance explained and eigenvalue at each soil layer under rubber plantation

	Top-soil		Sub-soil		Deep subsoil	
Component	eigenvalue	% variance	eigenvalue	% variance	eigenvalue	% variance
1	5.00	26.33	3.83	20.14	4.31	22.67
2	3.03	15.92	3.59	18.89	2.95	15.53
3	2.72	14.33	2.67	14.07	2.47	12.97
4	1.99	10.47	1.77	9.34	1.89	9.96

(Source: Data analysis, 2016)

variance with eigenvalue of 1.99. The first component of the subsoil layer explains 20.14% of total variance with eigenvalue of 3.83. Component II accounts for 18.89% with eigenvalue of 3.59. component III of the subsoil layer accounts for 14.07% of total variance with eigenvalue of 2.67 while component explains 9.43% of total variance with eigenvalue of 1.77. Component I of the deep subsoil layer explains 22.67% of total variance with eigenvalue of 4.31. Component II accounts for 15.53% of total variance with eigenvalue of 2.95. Component III explains 12.97% of total variance with eigenvalue of 2.47 and component IV of the deep subsoil layer explains 9.96% of total variance with eigenvalue of 1.89.

The relationship between soil physical and chemical properties and vegetation variables under rubber plantation is shown in tables 5.22, 5.23 and 5.24 for the topsoil, subsoil and deep subsoil layers respectively. Tree height under rubber plantation exhibits weak positive relationship with soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, exchangeable sodium, exchange acidity, extractable iron, percent clay and percent silt in the topsoil layer. In the subsoil layer, significant positive relationship is observed between soil pH (H_2O) and rubber tree height. However, soil organic carbon, soil exchangeable macronutrients, extractable iron, extractable copper, extractable zinc, percent clay and percent silt all show negative relationship with rubber tree height in the subsoil layer (Table 5.23). Exchangeable magnesium in the deep subsoil layer, shows a significant positive relationship with rubber tree height. However, soil organic carbon, exchangeable calcium, exchangeable aluminum, extractable manganese, extractable iron, extractable zinc and percent sand have negative relationship with rubber tree height (Table 5.24).

Topsoil organic carbon, extractable manganese, extractable copper and percent clay show weak negative relationship with diameter at breast height of rubber trees (Table 5.22). While all other soil properties in the topsoil layer exhibit positive relationship with DBH. Exchangeable sodium and percent silt in the subsoil layer exhibit significant negative relationship with DBH (Table 5.23) while deep subsoil extractable copper has a significant positive relationship with DBH (Table 5.24).

Table 5.22: Correlation coefficient between tree variables and topsoil properties under rubber plantation

Soil properties	Tree height	DBH	Ground elevation
pH (H_2O)	-0.094	0.126	0.083
pH(KCl)	-0.049	0.195	0.086
% Org. C	0.059	-0.078	-0.487^{**}
% Total N	0.314	0.171	-0.442^{*}
mg/kg Av. P	0.070	0.215	-0.101
cmol/kg Ca	-0.128	0.164	0.136
cmol/kg Mg	-0.067	0.158	0.124
cmol/kg K	0.004	0.111	-0.162
cmol/kg Na	0.148	0.114	-0.430^{*}
cmol/kg Al	-0.151	0.111	0.059
cmol/kg Ex. Acidity	0.287	0.141	-0.016
cmol/kg ECEC	0.281	0.171	-0.013
mg/kg Mn	-0.285	-0.042	0.312
mg/kg Fe	0.440	0.043	-0.144
mg/kg Cu	-0.233	-0.137	0.231
mg/kg Zn	-0.108	0.073	0.047
clay (%)	0.048	-0.227	-0.039
silt (%)	0.276	0.003	-0.009
sand (%)	-0.106	0.227	0.041

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.23: Correlation coefficient between tree variables and subsoil properties under rubber plantation

Soil properties	Tree height	DBH	Ground elevation
pH (H_2O)	0.397*	0.316	-0.143
pH(KCl)	0.300	-0.124	0.132
% Org. C	-0.030	-0.143	-0.358
% Total N	0.200	0.090	0.102
mg/kg Av. P	-0.048	-0.175	0.070
cmol/kg Ca	-0.120	0.116	0.212
cmol/kg Mg	-0.118	-0.009	0.000
cmol/kg K	-0.069	-0.152	0.017
cmol/kg Na	-0.278	-0.367*	-0.123
cmol/kg Al	-0.167	-0.024	0.256
cmol/kg Ex. Acidity	0.134	-0.040	-0.392*
cmol/kg ECEC	0.063	-0.011	-0.112
mg/kg Mn	0.031	0.215	0.080
mg/kg Fe	-0.177	0.218	-0.349
mg/kg Cu	-0.149	-0.075	0.007
mg/kg Zn	-0.060	0.212	0.068
clay (%)	-0.035	0.029	0.201
silt (%)	-0.045	-0.535**	0.000
sand (%)	0.054	0.233	-0.186

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Table 5.24: Correlation coefficient between tree variables and deep subsoil properties under rubber plantation

Soil properties	Tree height	DBH	Ground elevation
pH (H_2O)	.012	-.067	.284
pH(KCl)	.035	-.255	-.011
% Organic C	-.101	-.200	-.024
% Total N	.099	.068	.063
mg/kg Av. P	.231	-.037	-.173
cmol/kg Ca	-.171	.092	.206
cmol/kg Mg	.375*	.103	-.059
cmol/kg K	.023	.121	-.209
cmol/kg Na	.033	-.100	-.136
cmol/kg Al	-.130	-.117	-.015
cmol/kg Ex. Acidity	.089	-.001	-.183
cmol/kg ECEC	-.042	-.047	-.051
mg/kg Mn	-.185	-.080	.313
mg/kg Fe	-.095	-.056	-.392*
mg/kg Cu	.226	.420*	.063
mg/kg Zn	-.189	-.115	-.065
clay (%)	.026	-.060	-.070
silt (%)	.045	-.025	.276
sand (%)	-.043	.070	-.028

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization

(Source: Data analysis, 2016)

Zornoza *et al.* (2007), observed that variation in soil properties disturbance may result in loss of balance which exists between soil properties and vegetation. The variation in relationship between soil properties and vegetation variables under oil palm plantation and rubber plantation may therefore be attributed to the level and frequency of soil disturbances in the plantations. Similarly, Aweto (1985), noted that restoration of soil nutrients in more rapid in the topsoil than in sub-surface layers.

Topsoil percent organic carbon, percent total nitrogen and exchangeable sodium show significant negative relationship with elevation. While exchange acidity has a significant negative relationship with elevation in the subsoil and extractable iron has a significant negative relationship with elevation in the deep subsoil layer.

5.7 Variation in Principal Component Loadings in rainforest and tree plantations in Okomu Forest Reserve

The topsoil in rainforest is majorly determined by the fertility status. The fertility status of soil in rainforest soil accounts for 42% of the variance in soil-vegetation relationship. In contrast, however, soil pH/micronutrients component is more important in soils under tree plantations. Under rubber and oil palm plantations this component accounts for 26% and 22% variance respectively. Topsoil soil texture status also play major roles in soils under rainforest and rubber plantation.

In the subsoil layer, soil texture/potassium component is the most important under the rainforest soil while soil texture/magnesium/sodium component is the important in oil palm plantation. In the rubber plantation, nutrient holding capacity is the most important component and its accounts for 26.1% of the soil variance. This suggests that the texture status of the soil controls the soil-vegetation relationship in rainforest and tree plantation especially in oil palm plantations. Exchangeable sodium status also influences soil properties in rainforest and rubber plantation at the subsoil layer in Okomu Forest Reserve.

In the deep subsoil layer, while soil micronutrient/macronutrients status accounts for the first principal component in oil palm plantation, it is the second component under rainforest soil. Similarly, fertility status influences soil-vegetation relationship in rainforest and oil palm plantation. However, while it is the first principal component in the deep subsoil layer of the rainforest, it is the third principal component in oil palm plantation. Soil texture is important in the deep subsoil layer under rubber plantation as it occupies the first component. In oil palm plantation it is the second component.

It is obvious that soil fertility, texture and macro/micro-nutrient status are very important determinants of the soil variance along catena under rainforest and tree plantations in Okomu Forest Reserve. These variables are capable of influencing the nature of the soil and vegetation in the area. In terms of agricultural productivity, these factors may determine the difference between high yield and poor yield and should therefore be considered during soil management.

CHAPTER 6

VARIATION IN SOIL PROPERTIES UNDER RAINFOREST AND TREE PLANTATIONS IN OKOMU FOREST RESERVE

6.1 Introduction

This chapter characterizes soil physical and chemical properties under rainforest and tree plantations in Okomu Forest Reserve. In the next section, profile pits under rainforest and plantations are described while the impact of plantation agriculture on the spatial and vertical variation of soil physical and chemical properties is the focus of the last section of this chapter.

6.2 Description of soil profile and characterization of soils in Okomu Forest Reserve

6.2.1 Soil profile description and characterization of soil physical properties

Table 6.1 summarizes the physical and morphological properties of soils under rainforest in Okomu Forest Reserve while Plate 6.1 shows the profile pits under rainforest and plantations in Okomu Forest Reserve at the air-dried state. Table 6.1 indicates that soil colour changes with depth from reddish brown (5YR 4/4) at the topsoil to red (2.5YR 4/8) in the upper slope of the rainforest. This suggests an increasing iron content at increasing soil depth. In the middle slope however, the colour range from dark brown (7.5YR 3/3) in the topsoil to reddish yellow (5YR 6/8) colour. The lower slope colour also range from dark brown (7.5YR 3/4) to yellow (10YR 8/8) colour. The soil colour indicates deep and well-drained soil in the upper slope position. However, the middle and lower slope positions are moderate to poorly drained. This difference in soil colour, especially in the lower slope, may be attributed to alluvium deposition (Jones, 1955).

Texturally, the topsoil is mainly sandy but the proportion of sand gradually decreased with depth while clay and silt increase downward. The soil texture in the upper slope is sand in the surface and changes to sandy clay loam at the bottom of the profile. The middle and lower slope section is sandy loam at the surface and sandy clay loam in the subsurface horizons. The soil is generally crumbly in the surface layers but changed to very fine to

Table 6.1: Summary of soil physical properties, particle size distribution and morphological characteristics under rainforest in Okomu Forest Reserve

	Horizon designation	Depth (cm)	Colour (dry)	Clay (%)	Silt (%)	Sand (%)	Tex	cons	stru	mottles	roots	conc	boundary
Upper slope	A1	0-8	5YR4/4	2.6	7.4	90	S	friable	vf,cr	nil	vf,ma	Nil	sm,gr
	A2	8-25	5YR5/6	20	9.4	70.6	SL	friable	co,cr	nil	me, vf	Nil	sm,gr
	B1	25-58	5YR5/6	22	5.4	72.6	SCL	friable	co,cr	nil	co,few	Nil	sm,gr
	B2	58-83	5YR5/8	24	5.4	70.6	SCL	firm	me,sab	nil	f,vf	Nil	sm,gr
	B3	83-159	5YR5/8	26	9.4	64.6	SCL	firm	me,sab	nil	me,vf	Nil	sm,gr
	B4	159-180	2.5YR4/8	26	7.4	66.6	SCL	firm	me,sab	nil	nil	Nil	sm,gr
Middle slope	A1	0-5	7.5YR3/3	12.8	3.4	83.8	LS	firm	vf,cr	nil	f,ma	Nil	wa,cl
	Bt1	5-39	7.5YR6/8	38.8	19.4	41.8	CL	v.fine	m,sab	nil	me,vf	Nil	wa,cl
	B2	39-61	7.5YR6/8	32	3.4	64.6	SCL	v.fine	m,sab	nil	f,vf	few,fe-mn	sm,dif
	B3	61-93	7.5YR6/8	18	7.4	74.6	SL	v.fine	m,sab	nil	nil	co,fe-mn	wa,dif
	Bt2	93-131	5YR6/8	24	3.4	72.6	SCL	v.fine	m,sab	10YR7/8	me,vf	co,fe-mn	sm,dif
	Bc3	131-172	5YR6/8	26	15.4	58.6	SCL	firm	m,sab	10YR7/8	nil	ma,fe-mn	sm,cl
	Bc4	172-190	5YR6/8	22	3.4	74.6	SCL	firm	m,ab	10YR7/8	nil	Nil	nil
Lower slope	A1	0-13	7.5YR3/4	0.6	15.4	84	LS	friable	vf,cr	nil	f,ma	Nil	wa,cl
	Bt1	13-38	7.5YR6/6	42.8	11.4	45.8	SC	friable	m,sab	nil	co,com	Nil	wa,cl
	B1	38-92	10YR7/8	32	9.4	58.6	SCL	friable	m,sab	nil	m,com	Nil	sm,dif
	B2	92-125	10YR7/8	24.8	19.4	55.8	SCL	friable	m,sab	nil	f,few	Nil	sm,cl
	Bt2	125-161	7.5YR7/8	32.8	7.4	59.8	SCL	firm	m,sab	nil	vf,vfe	Nil	sm,cl
	B3	161-180	10YR8/8	26	15.4	58.6	SCL	friable	m,sab	10YR8/4	nil	Nil	nil

Tex = soil texture; LS = loamy sand; SL = sandy loam; SCL = sandy clay loam; cons = consistency; soil stru = soil structure; vf = very fine; pr = prismatic; f= fine; col= columnar; me= medium; pl = platty; sab = sub-angular blocky; ma = many; fe = few; co, com = coarse and common; concs = concretions; sm = smooth; cl = clear; wa= wavy; gr = gradual; dif= diffuse; fe-mn= iron-manganese. (Source: Data analysis, 2017)

(a) Soil Profile pit under rubber plantation

(b) Soil Profile pit under oil palm plantation

(c) Soil profile pit under rainforest

(d) Soil profile pit under rainforest

Plate 6.1: Soil profiles under tree plantations ((a) Typic plinthudults (Alagba series) (b) Plinthic kanhapludults (Ibeshe series) and rainforest ((c) Plinthiaquic paleaquults (Kulfo series) (d) Plinthic kanhapludults (Ibeshe series) in Okomu Forest Reserve Source: (Fieldwork, 2015)

medium sub-angular blocky with depth. Yellow (10YR 7/8) mottles were observed at the subsurface layers of the middle slope and very pale brown (10YR 8/4) at the base of the lower slope profile pits. Plant roots were observed at depths greater than 150 cm in most cases. This can be attributed to the soil depth which makes it easy for plant roots to penetrate deep into the soil. The soil is generally friable to firm in consistency and few iron-manganese concretions are observed in sub-surface horizons of the middle slope. No evidence of human activities such as charcoal is found in the rainforest where the pits show smooth gradual boundaries.

In the oil palm plantation (Table 6.2), soil colour changes from reddish brown (5YR 5/4) at the surface layer of the upper slope to red (2.5YR 4/8) in the sub-surface layer. In the middle slope, soil colour is brown (7.5YR 4/3) at the surface and red (2.5YR 4/8) at the base of the profile pit. The lower slope soil colour is red (2.5YR 4/8) at the surface layer and yellowish red (5YR 5/8) at the sub-surface layer. Generally, sand also decreased from the topsoil to the subsoil under oil palm plantation. The soil texture is loamy soil in the surface and changes to sandy clay loam at the sub-surface horizons. The soil is firm to very firm in terms of consistency and structurally, the soil is massive/angular single grain in the upper slope and sub-angular blocky in the lower slope. Few yellow (10YR 8/8) mottles were observed at the first illuvial B horizon (B1) of the middle slope. A few concretions were also observed in the middle slope while artefacts were observed in the upper slope. Roots could be found at depths of 110 cm in the middle slope and at depths above 150 cm in the upper and lower slopes.

Soil colour under rubber plantation, shown in table 6.2 indicates that soil colour varies from reddish brown (5YR 5/3) in the surface layer to red (2.5YR 4/4) at the base of the soil profile in the upper slope. In the middle slope position, soil colour in the surface horizon is reddish brown (5YR 5/4) and gradually changed to red (2.5YR 4/8) at the base of the profile pit. At the lower slope, the colour changes from reddish grey (5YR 5/2) to yellowish red (5YR 5/8). Proportion of sand particles in the soil slightly increased with depth in the upper slope but decreased with depth in the middle and lower slopes. Soil texture ranges from loamy sand in the surface layer to sandy loam in the sub-surface layer of the upper

Table 6.2: Summary of soil physical properties, particle size distribution and morphological characteristics under rubber plantations in Okomu Forest Reserve

	Horizon designation	Depth (cm)	Colour (air-dry)	Clay (%)	Silt (%)	Sand (%)	tex	cons	soil stru	mottles	roots	concs	artefacts
Upper slope	A1	0-10	5YR5/3	10	1.4	88.6	LS	friable	vf,pr	nil	vf,ma	nil	nil
	A2	10-23	5YR4/6	12	1.4	86.6	LS	friable	f,col	nil	f,fe	nil	nil
	Bt1	23-62	2.5YR4/6	16	1.4	82.6	SL	friable	me,pl	nil	co,com	nil	nil
	B1	62-98	2.5YR4/8	18	1.4	80.6	SL	firm	me,pl	nil	me,fe	nil	charcoal
	B2	98-140	2.5YR4/8	20	1.4	78.6	SL	firm	me,pl	nil	me,fe	nil	charcoal
	B3	140-180	2.5YR4/8	12	5.4	82.6	LS	firm	me,col	nil	co,fe	nil	nil
Middle slope	A1	0-5	5YR5/4	10	1.5	88.5	LS	friable	me,anbl	nil	vf,ma	nil	nil
	A2	5-37	5YR5/6	14	1.4	84.6	LS	friable	f,anbl	nil	me,com	nil	nil
	B1	37-81	5YR5/8	15	1.4	83.6	LS	friable	me,pl	nil	co,pr	nil	charcoal
	B2	81-111	2.5YR5/8	16	1.8	82.2	SL	firm	me,pl	nil	me,vf	nil	charcoal
	Bt1	111-155	2.5YR4/8	20	1.4	78.6	SL	firm	me,col	nil	f,vf	nil	charcoal
	B3	155-190	2.5YR4/8	14	5.8	80.2	LS	firm	co,pl	nil	nil	nil	nil
Lower slope	A1	0-17	5YR5/2	23	1.3	75.7	SCL	friable	vf,pr	nil	vf,ma	nil	nil
	A2	17-40	5YR5/8	26	2.1	71.9	SCL	friable	me,sab	nil	f,fe	nil	nil
	B1	40-74	5YR6/6	13	1.8	85.2	LS	firm	vf,pr	nil	co,com	nil	nil
	B2	74-102	5YR5/8	14	1.2	84.8	LS	firm	f,col	nil	me,fe	nil	nil
	Bt1	102-164	5YR5/8	21	5.3	73.7	SCL	firm	me,pl	nil	me,fe	nil	nil
	B3	164-185	5YR5/8	13	2.5	84.5	LS	firm	me,pl	nil	nil	nil	nil

Tex = soil texture; LS = loamy sand; SL = sandy loam; SCL = sandy clay loam; cons = consistency; soil stru = soil structure; vf = very fine; fve = very few; pr = prismatic; f= fine; col= columnar; me= medium; pl = platty; sab = sub-angular blocky; anbl = Angular blocky; ma = many; fe = few; co = coarse; com = common; concs = concretions; sm = smooth; cl = clear.

Source: (Fieldwork, 2015)

slope. In the middle and lower slope, however, the soil texture ranges between sand clay loam in the surface to loamy sand in the sub-surface layer. Soil consistency was generally firm with no concretions or mottles observed. Boundary form was also clear and smooth. Soils in Okomu Forest Reserve are classified as Ultisols according to the USDA keys to soil taxonomy (Soil Survey Staff, 2014) and Acrisols according to the World reference base (WBS) for soil resources (FAO, 2015). The upper slope and middle positions of rainforest soil are both typic plinthudults. Soil type in the lower slope is typic kandiudults. Soil in the upper slope of rubber plantation is typic paleudults and the middle slope is arenic plinthiaquic paleaquults. The lower slope under rubber plantation is however arenic plinthic kanhapludults. At the series level, the soil in the upper slope positions under rainforest, oil palm and rubber plantations is classified as Alagba series, in the middle slope the soil is kulfo series and in the lower slope position under rainforest the soil is classified as Ngego series while Ibeshe series is observed in the lower slope position under oil palm and rubber plantations respectively.

6.2.2 Characterization of soil chemical properties

Tables 6.3, 6.4 and 6.5 show the summary of soil chemical properties under rainforest, oil palm plantation and rubber plantation respectively. The soil is acidic with pH values ranging between 3.18 and 4.66 in the upper slope soil profile under rainforest, 4.17 and 4.33 in the upper slope profile under oil palm plantation and 3.22 and 3.68 in the upper slope profile under rubber plantation. The pH values generally decrease slightly with increasing soil depth. Soil organic carbon in the surface layer of the upper slope is 0.62% and reduced to 0.4% at the bottom of the profile (Table 6.3). Similarly, total nitrogen and available phosphorus also decrease with increasing soil depth. The value of soil organic carbon also showed slight increase from the crest of the slope to the valley bottom. The value of soil organic carbon is 0.62% in the surface layer of the upper slope, 1.29% in the middle slope and 2.39% in the surface layer of the lower slope.

Aweto and Iyamah (1993), also reported similar findings in the swamp forest catena in south-western Nigeria. Soil exchangeable calcium in the surface horizon in the upper slope is 3.418 cmol/kg and reduced to 0.015 cmol/kg at 159 cm depth. Exchangeable magnesium, potassium and

Table 6.3: Chemical properties of soil profiles under rainforest at Okomu Forest Reserve

Slope position	Horizon	Depth (cm)	$pH(H_2O)$	pH(KCl)	% Oc	% N	mg/kg Av. P	cmol/kg Ca	cmol/kg Mg	cmol/kg K	cmol/kg Na	cmol/kg Acidity	cmol/kg Al	cmol/kg ECEC	mg/kg Mn	mg/kg Fe	mg/kg Cu	mg/kg Zn
Upper	A1	0-8	3.78	3.18	0.623	0.647	29.29	3.418	3.125	0.518	0.878	1.8	2.808	12.547	54.75	247.25	0.93	8.43
	A2	8-25	4.73	3.76	0.388	0.04	5.977	0.021	0.321	0.063	0.6	0.61	2.163	3.778	2.1	25.31	0.53	4.31
	B1	25-58	4.61	3.73	0.032	0.003	2.131	0.01	0.214	0.068	0.478	1.01	1.924	3.704	2	27.84	0.1	4.33
	B2	58-83	5.35	4.04	0.678	0.07	2.452	0.01	0.173	0.066	0.444	0.4	2.884	3.977	2.02	42.22	0.1	4.36
	B3	83-159	3.91	3.29	0.162	0.017	6.858	0.242	0.461	0.124	0.661	0.8	2.881	5.169	3.21	141.03	0.3	4.56
	B4	159-180	5.12	4.66	0.405	0.042	0.518	0.015	0.345	0.049	0.613	0.4	2.601	4.023	3.12	13.35	0.61	3.96
Middle slope	A1	0-5	3.92	3.35	1.292	0.134	8.701	0.077	0.921	0.252	0.557	0.6	2.961	5.368	12.58	235.05	0.61	5.23
	A2	5-39	3.89	3.35	0.646	0.067	3.733	0.025	0.395	0.062	0.526	0.61	2.08	3.698	2.1	181.21	0.3	4.42
	B1	39-61	4.45	3.41	0.754	0.078	1.403	0.028	0.428	0.049	0.661	0.42	2.705	4.291	2.0	140.05	0.74	4.11
	B2	61-93	4.49	3.84	0.549	0.057	2.051	0.021	0.28	0.057	0.578	0.8	2.468	4.204	2.03	87.73	0.41	4.21
	Btc	93-131	4.48	3.99	0.032	0.00	1.971	0.01	0.197	0.078	0.483	0.6	2.163	3.531	1.01	30.21	0.2	4.1
	Bc1	131-172	4.88	3.35	0.552	0.057	0.518	0.015	0.378	0.068	0.713	0.41	1.88	3.464	3.00	14.13	0.6	4.75
	Bc2	172-190	4.64	3.48	0.368	0.038	1.335	0.025	0.345	0.047	0.626	0.4	4.002	5.445	2.11	11.12	0.55	3.82
Lower slope	A1	0-13	4.41	4.02	2.39	0.248	11.104	2.176	2.262	0.367	0.683	0.61	2.411	8.509	70.32	136.38	0.61	5.77
	A2	13-38	3.7	3.5	0.032	0.00	4.855	0.021	0.362	0.106	0.444	0.4	2.881	4.214	4.25	175.23	0.41	4.25
	B1	38-92	4.49	3.35	0.902	0.094	1.403	0.036	0.477	0.072	0.57	1.01	2.602	4.767	2.43	93.69	0.91	4.11
	B2	92-125	4.59	3.52	0.975	0.101	1.811	0.026	0.428	0.063	0.662	0.21	2.604	3.993	3.32	54.75	0.61	4.11
	Bt	125-161	4.7	3.45	0.57	0.059	2.084	0.026	0.395	0.054	0.617	0.22	1.841	3.153	3.00	38.48	0.71	4.22
	B3	161-180	4.86	3.7	0.442	0.046	0.449	0.02	0.304	0.057	0.57	0.41	2.38	3.741	3.1	13.32	0.6	4.35

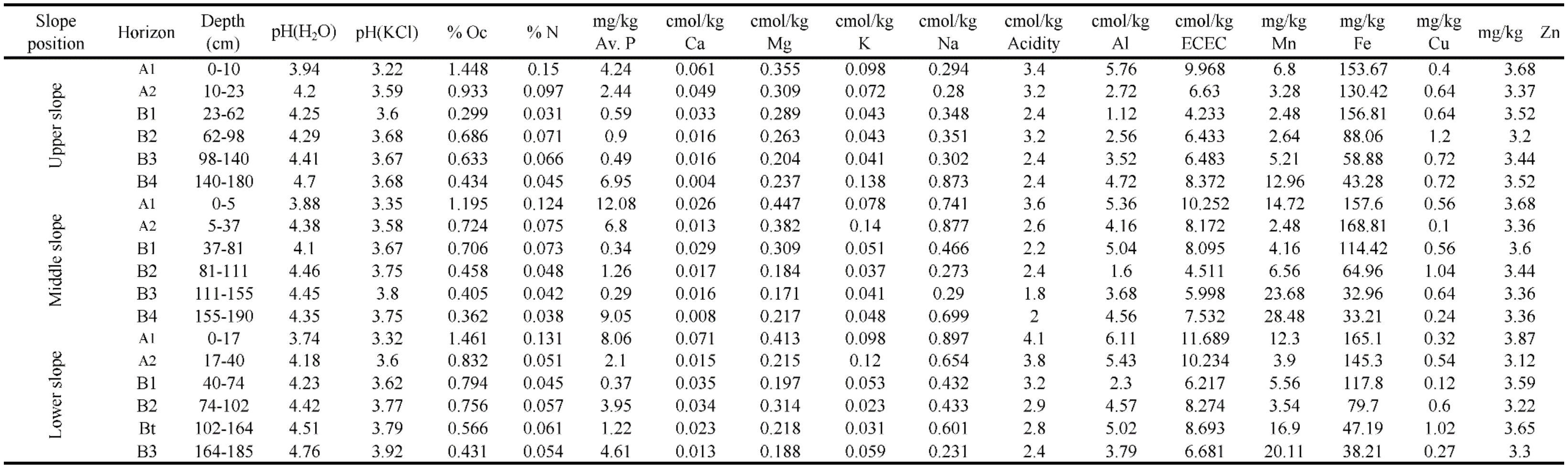
Source: (Fieldwork, 2015)

Table 6.4: Chemical properties of soil profiles under oil palm plantation at Okomu Forest Reserve

Slope position	Horizon	Depth (cm)	pH(H_2O)	pH(KCl)	% Oc	% N	mg/kg Av. P	cmol/kg Ca	cmol/kg Mg	cmol/kg K	cmol/kg Na	cmol/kg Acidity	cmol/kg Al	cmol/kg ECEC	mg/kg Mn	mg/kg Fe	mg/kg Cu	mg/kg Zn
Upper slope	A1	0-18	4.52	4.17	1.69	0.18	2.83	0.23	0.81	0.10	0.61	0.20	1.90	3.86	23.32	70.12	1.02	4.55
	A2	18-42	4.36	3.78	0.29	0.03	2.37	0.05	0.32	0.12	0.49	0.41	1.37	2.75	12.11	52.47	1.42	4.34
	B1	42-69	4.60	4.02	0.49	0.05	2.77	0.05	0.42	0.11	0.54	0.40	1.20	2.71	10.11	49.74	1.22	4.32
	B2	69-115	4.93	4.27	0.88	0.09	1.47	0.18	0.74	0.24	0.58	0.41	2.48	4.63	11.12	30.15	1.32	4.01
	Bt	115-151	4.78	3.95	3.68	0.38	3.81	0.04	0.44	0.22	0.60	0.43	3.21	4.93	4.10	29.65	0.70	4.22
	B3	151-185	5.07	4.33	0.24	0.03	1.13	0.09	0.72	0.32	0.57	0.40	1.94	4.04	3.21	17.48	0.63	3.78
Middle slope	A1	0-20	4.30	3.57	1.84	0.19	2.49	0.07	0.55	0.08	0.61	0.41	2.43	4.14	7.18	140.11	0.82	4.23
	A2	20-37	4.77	3.78	1.51	0.16	1.13	0.05	0.47	0.06	0.57	0.42	1.80	3.37	8.43	79.87	1.21	4.56
	Btc	37-80	4.50	3.76	0.03	0.00	7.10	0.02	0.35	0.08	0.55	0.62	2.88	4.50	3.30	69.65	0.71	4.22
	B1	80-110	4.60	3.58	0.81	0.08	1.20	0.03	0.32	0.05	0.57	0.40	3.84	5.21	4.11	22.26	0.71	5.11
	B2	110-145	4.65	3.54	0.64	0.07	0.59	0.03	0.35	0.05	0.61	0.81	2.58	4.42	3.26	22.23	0.53	3.97
	B3	145-180	4.66	4.03	0.03	0.00	1.89	0.04	0.31	0.07	0.61	0.41	2.88	4.32	2.21	24.61	0.41	4.01
Lower slope	A1	0-20	4.00	3.54	0.90	0.09	7.34	0.03	0.33	0.08	0.53	0.40	3.37	4.72	2.01	30.12	0.30	4.11
	A2	20-46	4.38	3.44	1.45	0.15	2.93	0.02	0.28	0.06	0.43	1.01	1.76	3.56	1.11	291.10	0.50	3.96
	B1	46-75	4.43	3.79	0.36	0.04	2.29	0.03	0.30	0.08	0.62	0.60	2.40	4.02	2.00	84.58	0.30	4.33
	Bt	75-112	4.34	3.71	0.90	0.09	5.10	0.04	0.34	0.07	0.57	0.60	3.45	5.06	2.04	61.24	0.30	4.20
	B2	112-165	4.82	3.70	0.10	0.01	2.85	0.02	0.29	0.06	0.57	0.41	2.08	3.43	1.02	25.63	0.21	3.94
	B3	165-185	4.50	3.47	0.35	0.04	0.45	0.02	0.36	0.07	0.67	0.41	2.17	3.69	2.02	14.78	0.65	4.26

Source: (Fieldwork, 2015)

Table 6.5: Chemical properties of soil profile under rubber plantation



Slope position	Horizon	Depth (cm)	pH(H_2O)	pH(KCl)	% Oc	% N	mg/kg Av. P	cmol/kg Ca	cmol/kg Mg	cmol/kg K	cmol/kg Na	cmol/kg Acidity	cmol/kg Al	cmol/kg ECEC	mg/kg Mn	mg/kg Fe	mg/kg Cu	mg/kg Zn
Upper slope	A1	0-10	3.94	3.22	1.448	0.15	4.24	0.061	0.355	0.098	0.294	3.4	5.76	9.968	6.8	153.67	0.4	3.68
	A2	10-23	4.2	3.59	0.933	0.097	2.44	0.049	0.309	0.072	0.28	3.2	2.72	6.63	3.28	130.42	0.64	3.37
	B1	23-62	4.25	3.6	0.299	0.031	0.59	0.033	0.289	0.043	0.348	2.4	1.12	4.233	2.48	156.81	0.64	3.52
	B2	62-98	4.29	3.68	0.686	0.071	0.9	0.016	0.263	0.043	0.351	3.2	2.56	6.433	2.64	88.06	1.2	3.2
	B3	98-140	4.41	3.67	0.633	0.066	0.49	0.016	0.204	0.041	0.302	2.4	3.52	6.483	5.21	58.88	0.72	3.44
	B4	140-180	4.7	3.68	0.434	0.045	6.95	0.004	0.237	0.138	0.873	2.4	4.72	8.372	12.96	43.28	0.72	3.52
Middle slope	A1	0-5	3.88	3.35	1.195	0.124	12.08	0.026	0.447	0.078	0.741	3.6	5.36	10.252	14.72	157.6	0.56	3.68
	A2	5-37	4.38	3.58	0.724	0.075	6.8	0.013	0.382	0.14	0.877	2.6	4.16	8.172	2.48	168.81	0.1	3.36
	B1	37-81	4.1	3.67	0.706	0.073	0.34	0.029	0.309	0.051	0.466	2.2	5.04	8.095	4.16	114.42	0.56	3.6
	B2	81-111	4.46	3.75	0.458	0.048	1.26	0.017	0.184	0.037	0.273	2.4	1.6	4.511	6.56	64.96	1.04	3.44
	B3	111-155	4.45	3.8	0.405	0.042	0.29	0.016	0.171	0.041	0.29	1.8	3.68	5.998	23.68	32.96	0.64	3.36
	B4	155-190	4.35	3.75	0.362	0.038	9.05	0.008	0.217	0.048	0.699	2	4.56	7.532	28.48	33.21	0.24	3.36
Lower slope	A1	0-17	3.74	3.32	1.461	0.131	8.06	0.071	0.413	0.098	0.897	4.1	6.11	11.689	12.3	165.1	0.32	3.87
	A2	17-40	4.18	3.6	0.832	0.051	2.1	0.015	0.215	0.12	0.654	3.8	5.43	10.234	3.9	145.3	0.54	3.12
	B1	40-74	4.23	3.62	0.794	0.045	0.37	0.035	0.197	0.053	0.432	3.2	2.3	6.217	5.56	117.8	0.12	3.59
	B2	74-102	4.42	3.77	0.756	0.057	3.95	0.034	0.314	0.023	0.433	2.9	4.57	8.274	3.54	79.7	0.6	3.22
	Bt	102-164	4.51	3.79	0.566	0.061	1.22	0.023	0.218	0.031	0.601	2.8	5.02	8.693	16.9	47.19	1.02	3.65
	B3	164-185	4.76	3.92	0.431	0.054	4.61	0.013	0.188	0.059	0.231	2.4	3.79	6.681	20.11	38.21	0.27	3.3

Source: (Fieldwork, 2015)

sodium are 3.125 cmol/kg, 0.518 cmol/kg and 0.878 cmol/kg respectively at the surface horizon. The macronutrients and micronutrients concentration also decreased with increasing soil depth. Akinbola *et al.* (2004) and Lopez-Granados *et al.* (2002), also observed that in general the mean value of soil properties under cultivation decreases with increasing soil depth. Akinbola *et al.* (2004), noted that soil nutrients are generally higher in the surface 0 – 15 cm depth. The high concentration of soil nutrients in the surface soil can also be attributed to accumulation and decay of leaf litter in the surface of the rainforest.

In the oil palm plantation soil (Table 6.4), soil pH is slightly acidic and pH values generally increases with depth. The pH value in the surface layer is 4.17 (KCl) and 4.33 at the bottom of the profile pit (151 – 185 cm) in the upper slope, 3.57 in the surface layer of the middle slope and 3.54 in the surface layer of the lower slope positions. Soil organic carbon in the surface layer of the profile pit under oil palm plantation is 1.69% but reduces to 0.24% at the bottom of the profile pit. In the middle slope position, soil organic carbon in the surface layer of the profile pit is 1.84 and 0.032% at the bottom of the pit.

Organic carbon concentration in the surface layer of the profile pit is 0.9% in the lower slope under oil palm plantation and soil organic carbon is 0.35% at the bottom of the pit. Total nitrogen is 0.176 %, 0.19% and 0.094% in the surface layers of the upper, middle and lower slope positions while available phosphorus is 2.83 mg/kg, 2.49 mg/kg and 7.34 mg/kg in the surface layers of the upper, middle and lower slope positions respectively.

Soil pH under rubber plantation (Table 6.5) is moderately acidic ranging from 3.9 in the surface horizon of the upper slope to 3.88 in the middle slope and 3.74 in the lower slope. The pH value also increases with depth in all the slope positions. Soil organic carbon is 1.45% in the surface horizon of the upper slope, 1.195% in the middle slope and 1.461% in the lower slope. The increase in soil organic carbon downslope may be because of erosion processes which redistribute soil nutrients. Gonzalez and Zak (1994), reported a similar finding in a secondary tropical dry forest in West Indies. Total nitrogen is 0.15% in the surface layer of the upper slope, 0.124% in the middle slope and 0.131% in the lower slope. Soil organic carbon and total nitrogen under rubber plantation decrease with increasing soil depth. Available phosphorus is 4.24 mg/kg in the upper slope surface layer, 12.08 mg/kg in the middle slope and 8.06 mg/kg in the lower slope. Exchangeable cations generally exhibit decreasing concentrations with depth in soils under rubber plantation.

6.3 Variation in soil physical and chemical properties under rainforest and plantations in Okomu Forest Reserve

6.3.1 Variation in soil physical and chemical properties under rainforest

Tables 6.6, 6.7 and 6.8 show classical univariate statistics of topsoil, subsoil and deep subsoil physical and chemical properties respectively under rainforest in Okomu Forest Reserve. The tables show that there is high variability of soil particle size composition in the topsoil. This may be because of topography and slope influence in the area. However, while the variability of silt remains high in the subsoil and deep subsoil layers, clay shows moderate variability in these layers while sand shows low variability in the subsoil and deep subsoil layers.

Soil pH influences the ability of the soil to retain or release plant nutrient. The soil in the rainforest is highly acidic with mean values of 3.27 (KCl) in the topsoil, 3.40 in the subsoil and 3.55 in the deep soil layers. The low pH value of the soil may be attributed to leaching because of the heavy rainfall in the area. Similar findings were reported by Nuga and Akinbola (2011), in the coastal plain soils of humid forest in south-eastern Nigeria and Yousefi and Darvishi (2013), in soils under rainforest in northern Iran. Coefficient of variability indicates that variability of pH is low and does not change much with depth. Soil organic carbon show decreasing value with increasing depth. The values of soil organic carbon in the topsoil, subsoil and deep subsoil layers in forest soil is 2.6%, 2.01% and 1.76%. Sheikh *et al.* (2009), also reported that soil organic carbon decreased with increasing soil depth. Variability of soil organic carbon is moderate in the topsoil (28.41%) and subsoil (32.85%), but high in the deep subsoil soil (38.79%) layer. This shows that soil organic carbon distribution is more homogenous in the surface than in deep subsoil layer. The homogeneity of soil organic carbon at the surface layers may be because of more efficient carbon cycling from the constant addition of organic carbon from decaying forest litter. Dorji *et al.* (2014), reported that soil organic carbon was more homogenously distributed

Table 6.6: Variation of topsoil physical and chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Mean	Standard Error	Standard Deviation	CV (%)	Variability
pH (H_2O)	3.82	0.05	0.3	7.91	Low
pH(KCl)	3.27	0.02	0.15	4.5	Low
% Organic C	2.6	0.12	0.74	28.41	Moderate
% Total N	0.28	0.02	0.1	36.27	High
mg/kg Av. P	10.32	0.55	3.26	31.63	Moderate
cmol/kg Ca	0.02	0.00	0.01	40.8	High
cmol/kg Mg	0.46	0.02	0.11	24.53	Moderate
cmol/kg K	0.09	0.01	0.04	45.35	High
cmol/kg Na	0.32	0.01	0.08	25.44	Moderate
cmol/kg Al	0.44	0.05	0.27	61.18	High
cmol/kg Ex. Acidity	1.06	0.07	0.42	39.48	High
cmol/kg ECEC	2.4	0.1	0.6	24.89	Moderate
mg/kg Mn	7.08	0.65	3.83	54.1	High
mg/kg Fe	260.96	13.34	78.93	30.25	Moderate
mg/kg Cu	0.58	0.03	0.17	29.46	Moderate
mg/kg Zn	1.37	0.18	1.05	76.25	High
clay (%)	19.92	1.24	7.34	36.87	High
silt (%)	5.66	0.7	4.16	73.58	High
sand (%)	74.42	1.39	8.23	11.06	Low

(Source: Data analysis, 2016)

Table 6.7: Variation of subsoil chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Mean	Standard Error	Standard Deviation	CV (%)	Variability
pH (H_2O)	3.92	0.05	0.27	6.83	Low
pH (KCl)	3.4	0.03	0.17	4.97	Low
% Organic C	2.01	0.11	0.66	32.85	Moderate
% Total N	0.22	0.01	0.08	36.86	High
mg/kg Av. P	8.24	0.27	1.57	19.03	Moderate
cmol/kg Ca	0.02	0.00	0.01	66.09	High
cmol/kg Mg	0.37	0.02	0.09	24.96	Moderate
cmol/kg K	0.08	0.01	0.09	123.63	High
cmol/kg Na	0.31	0.01	0.08	25.01	Moderate
cmol/kg Al	3.88	0.19	1.13	29.18	Moderate
cmol/kg Ex. Acidity	1.05	0.05	0.32	30.69	Moderate
cmol/kg ECEC	5.71	0.22	1.31	23.02	Moderate
mg/kg Mn	4.49	0.34	2.03	45.29	High
mg/kg Fe	196.39	10.81	63.93	32.55	Moderate
mg/kg Cu	0.6	0.03	0.17	28.64	Moderate
mg/kg Zn	1	0.1	0.58	57.93	High
clay (%)	23.23	1.22	7.19	30.97	Moderate
silt (%)	5.2	0.72	4.24	81.52	High
sand (%)	71.57	1.53	9.04	12.63	Low

(Source: Data analysis, 2016)

Table 6.8: Variation of deep subsoil physical and chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Mean	Standard Error	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.05	0.04	0.26	6.51	Low
pH (KCl)	3.55	0.04	0.23	6.62	Low
% Organic C	1.76	0.12	0.68	38.79	High
% Total N	0.18	0.01	0.08	45.35	High
mg/kg Av. P	7.56	0.28	1.67	22.07	Moderate
cmol/kg Ca	0.01	0.00	0.01	46.44	High
cmol/kg Mg	0.32	0.02	0.09	28.82	Moderate
cmol/kg K	0.06	0.00	0.03	48.41	High
cmol/kg Na	0.29	0.01	0.08	26.70	Moderate
cmol/kg Al	3.29	0.14	0.85	25.88	Moderate
cmol/kg Ex. Acidity	1.06	0.09	0.50	47.60	High
cmol/kg ECEC	5.03	0.19	1.13	22.44	Moderate
mg/kg Mn	3.57	0.31	1.85	51.87	High
mg/kg Fe	166.45	11.27	66.67	40.06	High
mg/kg Cu	0.61	0.04	0.23	36.89	High
mg/kg Zn	0.90	0.06	0.37	41.70	High
clay (%)	25.14	1.34	7.93	31.53	Moderate
silt (%)	4.68	0.74	4.36	93.14	High
sand (%)	70.18	1.43	8.47	12.08	Low

(Source: Data analysis, 2016)

down the soil profile under agriculture than in rainforest, grassland and shrub land in the mountainous areas of Eastern Himalayas. Variability of total nitrogen and available phosphorus in the soil is high and moderate respectively. Both nutrients did not vary much with soil depth. Soil exchangeable bases (calcium. magnesium, potassium and sodium) show similar trend in all layers of the soil. Apart from sodium which show high variability in the sub-soil, and moderate variability in the other layers, the variability of calcium and potassium is high and variability of magnesium and sodium is moderate in all the layers. Jobbágy and Jackson (2001), also reported that soil nutrients that limit plant growth such as nitrogen and potassium tend to be more concentrated in the surface layer than less limiting nutrients such as sodium. The higher nutrient level in the topsoil may be attributed to more efficient nutrient cycling through litter accumulation and rapid decomposition.

Variability of soil micronutrients was similar in the topsoil and subsoil layers. In these soil layers, manganese and zinc exhibit high variability while the variability of iron and copper is moderate. In the deep subsoil layer, however, all the micronutrients show high variability. Exchange acidity, exchangeable aluminum and effective cation exchange capacity exhibit high variability in the topsoil layer and moderate variability in the subsoil layer. In the deep subsoil layer, exchangeable aluminum shows high variability while exchange acidity and effective cation exchange capacity show moderate variability. Analysis of variance (Table 6.9) shows that the coefficients of variation do not vary significantly with soil depth under rainforest.

6.3.2 Variation in soil physical and chemical properties under tree plantations

Tables 6.10, 6.11 and 6.12 show the physical and chemical properties of soil in the topsoil, subsoil and deep subsoil layers respectively under oil palm plantation. Particle size composition of the soil did not change with depth as variability of clay, silt and sand have moderate, high and low variability respectively in all the layers. Variability of soil pH is low with coefficient of variation ranging from 6.05% in the topsoil, to 8.15% in the subsoil and 6.24% in the deep subsoil. This shows that there is no clear trend in the pattern of change in pH value with depth under oil palm plantation. Soil organic carbon, total nitrogen and available phosphorus show high variability in the topsoil and deep subsoil. However, in the

Table 6.9: Analysis of variance of coefficients of variation of soil properties at different depth under rainforest at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	252.63	2.00	126.32	0.05	0.95	3.17
Within Groups	133416.30	54.00	2470.67			
Total	133668.90	56.00				

(Source: Data analysis, 2016)

Table 6.10: Variation of topsoil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Mean	SE	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.23	0.04	0.21	4.98	Low
pH(KCl)	3.69	0.04	0.22	6.05	Low
% Organic C	1.55	0.13	0.78	50.6	High
% Total N	0.16	0.01	0.08	50.7	High
mg/kg Av.l P	3.67	0.34	2.00	54.5	High
cmol/kg Ca	0.04	0.01	0.03	69.7	High
cmol/kg Mg	0.47	0.02	0.13	28.2	Moderate
cmol/kg K	0.14	0.02	0.09	63.7	High
cmol/kg Na	0.53	0.02	0.10	18.4	Moderate
cmol/kg Al	0.55	0.03	0.18	33.5	Moderate
cmol/kg Ex. Acidity	2.24	0.14	0.86	38.3	High
cmol/kg ECEC	3.97	0.16	0.92	23.2	Moderate
mg/kg Mn	13.5	2.34	13.87	103	High
mg/kg Fe	148.99	8.06	47.66	32	Moderate
mg/kg Cu	0.75	0.04	0.26	34.8	Moderate
mg/kg Zn	4.55	0.09	0.52	11.4	Low
clay (%)	21.16	1.12	6.63	31.3	Moderate
silt (%)	6.23	0.58	3.45	55.4	High
sand (%)	72.61	1.13	6.67	9.19	Low

(Source: Data analysis, 2016)

Table 6.11: Variation of subsoil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Mean	SE	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.35	0.03	0.19	4.33	Low
pH(KCl)	3.68	0.05	0.3	8.15	Low
% Organic C	1.37	0.07	0.43	31.6	Moderate
% Total N	0.14	0.01	0.04	31.6	Moderate
mg/kg Av. P	3.21	0.23	1.36	42.5	High
cmol/kg Ca	0.09	0.04	0.22	232	High
cmol/kg Mg	0.45	0.02	0.11	25.5	Moderate
cmol/kg K	0.17	0.03	0.18	101	High
cmol/kg Na	0.59	0.01	0.08	13.3	Low
cmol/kg Al	0.71	0.1	0.62	86.5	High
cmol/kg Ex. Acidity	1.99	0.11	0.63	31.5	Moderate
cmol/kg ECEC	4.01	0.13	0.77	19.2	Moderate
mg/kg Mn	10.02	2.94	17.37	173	High
mg/kg Fe	145.98	11.3	66.8	45.8	High
mg/kg Cu	0.93	0.07	0.39	41.6	High
mg/kg Zn	4.4	0.05	0.29	6.62	Low
clay (%)	24.35	1.31	7.73	31.8	Moderate
silt (%)	6.47	0.6	3.55	55	High
sand (%)	69.18	1.09	6.42	9.28	Low

(Source: Data analysis, 2016)

Table 6.12: Variation of deep subsoil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Mean	SE	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.52	0.03	0.18	3.99	Low
pH(KCl)	3.68	0.04	0.23	6.24	Low
% Organic C	1.18	0.07	0.44	37.47	High
% Total N	0.12	0.01	0.04	37.8	High
mg/kg Av. P	2.48	0.19	1.15	46.26	High
cmol/kg Ca	0.12	0.05	0.29	244.42	High
cmol/kg Mg	0.41	0.02	0.13	31.37	Moderate
cmol/kg K	0.13	0.02	0.13	105.86	High
cmol/kg Na	0.58	0.01	0.08	13.26	Low
cmol/kg Al	0.52	0.03	0.16	30.54	Moderate
cmol/kg Ex. Acidity	2.16	0.16	0.94	43.57	High
cmol/kg ECEC	3.92	0.18	1.06	27.15	Moderate
mg/kg Mn	6.24	1.22	7.22	115.73	High
mg/kg Fe	86.25	6.98	41.29	47.88	High
mg/kg Cu	0.89	0.06	0.38	43.06	High
mg/kg Zn	4.42	0.05	0.31	7.1	Low
clay (%)	29.33	1.44	8.53	29.1	Moderate
silt (%)	5.6	0.58	3.45	61.54	High
sand (%)	65.07	1.39	8.2	12.6	Low

(Source: Data analysis, 2016)

subsoil layer, variability of organic carbon and nitrogen is moderate while available phosphorus is high. The mean values of these nutrients however, exhibit decreasing levels with depth. The mean values of total nitrogen in the topsoil, subsoil and deep subsoil are less than 0.2% while the CVs are 50.7%, 31.6% and 37.8% respectively. Available phosphorus has mean values that are under 4.0 mg/kg while the CVs are 54.5%, 42.5% and 46.3% for the topsoil, subsoil and deep subsoil layers respectively while the mean values of potassium are 0.14 cmol/kg, 0.17 cmol/kg and 0.13 cmol/kg with CVs of 63.2%, 101% and 105.8% in the topsoil, subsoil and deep subsoil layers respectively. The decrease in total nitrogen, available phosphorus and potassium with depth may be because of the concentration of organic matter in the topsoil layer.

The variability of calcium and potassium exhibit high in variability all the layers with values of 69.7%, 232% and 244.4% and 63.7%, 101% and 105.8% in the topsoil, subsoil and deep subsoil layers respectively while magnesium (28.2%, 25.5% and 31.4%) is consistently moderate. However, variability of sodium is moderate in the topsoil and low in the subsoil and deep subsoil layers. The mean value of calcium increased with depth while magnesium is observed to decrease. Potassium and sodium did not, however, show a clear pattern with depth. Exchangeable aluminum in the soil shows high variability irrespective of soil depth. The mean values of exchangeable aluminum are 0.55 cmol/kg in the topsoil, 0.71 cmol/kg in the subsoil layer and 0.53 cmol/kg while the CVs are 33.5%, 86.5% and 30.5% respectively. Soil exchangeable Acidity exhibit high variability pattern in the topsoil and deep subsoil layers with mean values of 2.24 cmol/kg and 2.16 cmol/kg while the CVs are 38.3% and 43.57% respectively. The mean value of exchange acidity in the subsoil layer is 1.99 cmol/kg and CV of 31.5% with moderate variability. Effective cation exchange capacity has mean values of 3.97 cmol/kg in the topsoil, 4.01 cmol/kg in the subsoil and 3.92 cmol/kg in the deep subsoil layers and corresponding CVs of 23.2%, 19.2% and 27.15%. The variability of ECEC is moderate which is not affected by depth.

The variability of soil micronutrients is similarity at all depths. The variability of exchangeable manganese is high irrespective of soil depth while the variability of iron and copper is moderate in the topsoil layer but high in the subsoil and deep subsoil layers. The variability of zinc (11.4%, 6.6% and 7.1%) is low at all depths. The mean values of exchangeable manganese are 13.5 mg/kg, 10.02 mg/kg and 6.24mg/kg while the CVs are 103%, 173% and 115.7% in the topsoil, subsoil and deep subsoil layers respectively. The mean values of exchangeable iron are 152.16 mg/kg, 146.42 mg/kg and 139.44 mg/kg with CVs of 32%, 45.8% and 47.9% in the topsoil, subsoil and deep subsoil layers respectively.

The variation of the physical and chemical properties in the topsoil, subsoil and deep subsoil layers under rubber plantation is shown in tables 6.13, 6.14 and 6.15 respectively. The tables show that in the topsoil layer, the proportion of sand particles is 83.74%, 83.60% in the subsoil and 82.54% in the deep soil layers. Sand shows a low variability across depth under rubber plantation. This is because the soil is highly sandy in nature and sand is uniformly distributed vertically and spatially across the field. Silt and clay particles show less uniformity in distribution with depth under rubber plantation. Variability of silt is high in all layers while clay is high in the topsoil and subsoil but moderate in the deep subsoil layer. Clay increases from the topsoil layer to the deep subsoil layer (12.59%, 12.69% and 14.35% respectively). The mean value of silt is 3.68%, 3.71% and 3.11% and CV is 37.7%, 62.38% and 49.94% in the topsoil, subsoil and deep subsoil layers respectively.

The soil under rubber plantation is extremely acidic with pH values of 3.61, 3.54 and 3.52 in the topsoil, subsoil and deep subsoil layers respectively. Variability of soil pH is low (12.29%, 2.23% and 3.52%) while the variability of soil organic carbon (26.13%, 22.79% and 27.8%) is moderate. The variability of pH and soil organic carbon is not affected by depth. The mean values of soil organic carbon however, decreases from 1.05% in the topsoil to 0.87% in the subsoil and 0.76% in the deep subsoil layers. The mean values of total nitrogen are 0.12%, 0.14% and 0.11% while the CVs are 73.8%, 113.2% and 102.6% in the topsoil, subsoil and deep subsoil layers respectively. The soil has a moderate to low available phosphorus content with mean values of 6.18 mg/kg, 4.31 mg/kg and 2.77 mg/kg with CV values of 63.6%, 93.41% and 107.79% respectively in the topsoil, subsoil and deep subsoil layers. The mean values of exchangeable potassium are 0.12 cmol/kg in the topsoil and subsoil layers and 0.10 cmol/kg in the deep subsoil layer. The coefficient of variation

Table 6.13: Variation of topsoil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Mean	SE	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.22	0.07	0.42	9.99	Low
pH (KCl)	3.61	0.08	0.44	12.29	Low
% Organic C	1.05	0.05	0.27	26.13	Moderate
% Total N	0.12	0.02	0.09	73.82	High
mg/kg Av. P	6.18	0.56	3.31	53.6	High
cmol/kg Ca	0.06	0.03	0.18	293.3	High
cmol/kg Mg	0.35	0.01	0.06	17.76	Moderate
cmol/kg K	0.12	0.01	0.04	35.36	High
cmol/kg Na	0.53	0.03	0.19	35.01	High
cmol/kg Al	2	0.26	1.52	75.92	High
cmol/kg Ex. Acidity	4.5	0.18	1.04	23.08	Moderate
cmol/kg ECEC	7.57	0.24	1.4	18.49	Moderate
mg/kg Mn	7.47	0.61	3.62	48.42	High
mg/kg Fe	152.16	7.32	43.31	28.46	Moderate
mg/kg Cu	0.65	0.04	0.21	32.8	Moderate
mg/kg Zn	3.67	0.07	0.43	11.62	Low
clay (%)	12.59	0.97	5.72	45.44	High
silt (%)	3.68	0.23	1.39	37.7	High
sand (%)	83.74	0.97	5.72	6.83	Low

(Source: Data analysis, 2016)

Table 6.14: Variation of subsoil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Mean	SE	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.27	0.03	0.19	4.39	Low
pH (KCl)	3.54	0.01	0.08	2.23	Low
% Organic C	0.87	0.03	0.2	22.79	Moderate
% Total N	0.14	0.03	0.16	113.2	High
mg/kg Av. P	4.31	0.68	4.03	93.41	High
cmol/kg Ca	0.06	0.03	0.17	272.5	High
cmol/kg Mg	0.31	0.01	0.06	20.29	Moderate
cmol/kg K	0.12	0.01	0.04	35.91	High
cmol/kg Na	0.52	0.03	0.19	37.11	High
cmol/kg Al	2.6	0.34	2	76.84	High
cmol/kg Ex. Acidity	4.5	0.22	1.29	28.78	Moderate
cmol/kg ECEC	8.12	0.34	2.01	24.81	Moderate
mg/kg Mn	5.37	0.46	2.72	50.59	High
mg/kg Fe	146.43	8.09	47.85	32.68	Moderate
mg/kg Cu	0.6	0.03	0.19	32.7	Moderate
mg/kg Zn	3.51	0.06	0.37	10.57	Low
clay (%)	12.69	0.76	4.51	35.52	High
silt (%)	3.71	0.39	2.32	62.38	High
sand (%)	83.6	0.8	4.71	5.63	Low

(Source: Data analysis, 2016)

Table 6.15: Variation of deep subsoil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Mean	SE	Standard Deviation	CV (%)	Variability
pH (H_2O)	4.32	0.05	0.29	6.66	Low
pH (KCl)	3.52	0.02	0.12	3.52	Low
% Organic C	0.76	0.04	0.21	27.8	Moderate
% Total N	0.11	0.02	0.11	102.2	High
mg/kg Av. P	2.77	0.5	2.98	107.8	High
cmol/kg Ca	0.05	0.02	0.12	245.6	High
cmol/kg Mg	0.29	0.02	0.11	36.65	High
cmol/kg K	0.1	0.01	0.04	38.97	High
cmol/kg Na	0.43	0.04	0.24	56.18	High
cmol/kg Al	2.53	0.31	1.85	73.32	High
cmol/kg Ex. Acidity	3.85	0.24	1.39	36.12	High
cmol/kg ECEC	7.25	0.33	1.94	26.76	Moderate
mg/kg Mn	4.37	0.36	2.14	48.97	High
mg/kg Fe	139.44	7.61	45.03	32.29	Moderate
mg/kg Cu	0.63	0.04	0.21	33.54	Moderate
mg/kg Zn	3.45	0.05	0.32	9.23	Low
clay (%)	14.35	0.81	4.77	33.25	Moderate
silt (%)	3.11	0.26	1.55	49.94	High

(Source: Data analysis, 2016)

indicates high variability in all the soil layers with CV values of 35.36% in the topsoil, 35.91% in the subsoil and 38.97% in the deep subsoil layers. Imogie *et al.* (2012), reported that the use of organic and inorganic fertilizers is a management practice geared at sustainable use of the soil while it also enhances yield per hectare. The use of inorganic fertilizers was confirmed by the farm managers of Osse rubber plantation and Okomu oil plantation[1]. Over three hundred kilograms of inorganic fertilizers particularly nitrogen, phosphorus and potassium are used per hectare of the plantations each year to improve yield and enhance nutrient condition of the soil. The variation in the concentration of total nitrogen, available phosphorus and exchangeable potassium can be attributed to the use of inorganic fertilizers in the plantations. Variability of total nitrogen, available phosphorus and exchangeable potassium in the soil is high in all the soil layers.

Variability of magnesium is moderate in the topsoil and subsoil but high in the deep subsoil layer. However, calcium and sodium have high variability in all the layers. The mean value of magnesium decreases with increasing depth. It is 0.35 cmol/kg in the topsoil, 0.31 cmol/kg in the subsoil and 0.29 cmol/kg in the deep subsoil and the coefficient of variation is 17.76%,20.29% and 36.65% in the topsoil, subsoil and deep subsoil layers respectively. The average value of exchangeable calcium in the soil is 0.06 cmol/kg, 0.06 cmol/kg and 0.05 cmol/kg in the topsoil, subsoil and deep subsoil respectively while sodium also showed negligible reduction in mean value from 0.53 cmol/kg in the topsoil to 0.52 cmol/kg in the subsoil and 0.43 cmol/kg in the deep subsoil layer.

Exchangeable aluminum shows high variability in all layers of soil under rubber plantation. The topsoil mean value of aluminum is 2.0 cmol/kg in the topsoil, 2.6 cmol/kg in the subsoil and 2.53 cmol/kg in the deep subsoil layer with coefficient of variation of 75.92%, 76.84% and 73.32% in the topsoil, subsoil and deep subsoil layers respectively. Exchange acidity in the soil is 4.5 cmol/kg in the topsoil and subsoil. The mean value of exchange acidity is 3.85 cmol/kg in the deep subsoil layer. Variability of exchange acidity is moderate in the topsoil and subsoil but high in the deep subsoil layer. Also, effective cation exchange capacity

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[1] E. A. Eke, farm manager at Osse rubber plantation and G. Ohwevwo, farm manager, Okomu oil PLC

shows moderate variability in all layers of the soil. The mean values of ECEC is 7.57 cmol/kg in the topsoil layer, 8.12 cmol/kg in the subsoil layer and 7.25 cmol/kg in the deep subsoil layer.

Soil micronutrients under rubber plantation show similar pattern of variability across depth. Variability of extractable manganese is high, exchangeable iron and extractable copper are moderate and extractable zinc has a low variability. The mean values of extractable manganese are 7.47 mg/kg, 5.37 mg/kg and 4.37 mg/kg and the CV is 48.42%, 50.59% and 48.97% in the topsoil, subsoil and deep subsoil layers respectively. Exchangeable iron has mean values of 152.16 mg/kg 146.43 mg/kg and 139.44 mg/kg and CV of 28.46%, 32.68% and 32.29% in the topsoil, subsoil and deep subsoil layers respectively. The mean values of extractable copper in the topsoil, subsoil and deep subsoil are 0.65 mg/kg, 0.60 mg/kg and 0.63 mg/kg while CVs are 32.8%, 32.7% and 33.54% respectively. The mean value of extractable zinc is 3.67 mg/kg, 3.51 mg/kg and 3.45 mg/kg and the CV is 11.62% 10.57% and 9.23% in the topsoil, subsoil and deep subsoil layers respectively. The results show that the values of extractable manganese, zinc and exchangeable iron reduced with increasing depth.

In spite of using between 250 and 300 kg of inorganic fertilizers per hectare for enhancing soil fertility in the plantations, table 6.16 shows that with the exception of pH (H_2O), percentage organic carbon, percentage total nitrogen, available phosphorus, exchangeable sodium, iron and percent clay and sand, there is no significant difference in the mean values of soil properties at different soil depths under oil palm plantation. The difference in mean value of soil organic carbon may be because of the litter and delay of palm fronds in the topsoil while leaching may explain the difference in pH (H_2O). The addition of inorganic fertilizers and the subsequent leaching may be responsible for the difference in the mean values of total nitrogen and phosphorus as well as the similarity in the mean value of potassium under oil palm plantation. This results may be an indication of the rapid depletion of nutrient under the plantations. Similarly, table 6.17 shows that except organic carbon, available phosphorus, exchangeable magnesium, iron, extractable manganese and zinc, the mean values of soil physical and chemical properties under rubber plantation are similar at

Table 6.16: Analysis of variance of soil physical and chemical properties at various depths under oil palm plantation at Okomu Forest Reserve

Soil properties	Mean value			p-value
	Topsoil	Subsoil	Deep-subsoil	
pH (H_2O)	4.23	4.35	4.52	0.00**
pH (KCl)	3.69	3.68	3.68	0.99
% Organic C	1.55	1.37	1.18	0.03*
% Total N	0.16	0.14	0.12	0.01**
mg/kg av. P	3.67	3.21	2.48	0.01**
cmol/kg Ca	0.04	0.09	0.12	0.32
cmol/kg Mg	0.47	0.45	0.41	0.19
cmol/kg K	0.14	0.17	0.13	0.34
cmol/kg Na	0.53	0.59	0.58	0.01**
cmol/kg Al	0.55	0.71	0.52	0.08
cmol/kg Ex. Acidity	22.41	19.89	21.97	0.39
cmol/kg ECEC	24.14	21.91	23.73	0.48
mg/kg Mn	13.50	10.02	6.24	0.08
mg/kg Fe	148.99	145.98	86.25	0.00**
mg/kg Cu	0.75	0.93	0.89	0.07
mg/kg Zn	4.55	4.40	4.42	0.21
clay (%)	21.16	24.35	29.33	0.00**
silt (%)	6.23	6.47	5.60	0.56
sand (%)	72.61	69.18	65.07	0.00**

** Significant at 1% level of significance; * Significant at 5% level of significance

(Source: Data analysis, 2016)

Table 6.17: Analysis of variance of soil physical and chemical properties at various depths under rubber plantation at Okomu Forest Reserve

Soil properties	Mean value			p-value
	Topsoil	Subsoil	Deep-subsoil	
pH (H_2O)	4.22	4.27	4.32	0.42
pH (KCl)	3.61	3.54	3.52	0.35
% Organic C	1.05	0.87	0.76	0.00**
% Total N	0.12	0.14	0.11	0.06
mg/kg av. P	6.18	4.32	2.77	0.00**
cmol/kg Ca	0.06	0.06	0.05	0.92
cmol/kg Mg	0.35	0.31	0.29	0.00**
cmol/kg K	0.12	0.12	0.10	0.19
cmol/kg Na	0.53	0.52	0.43	0.10
cmol/kg Al	2.00	2.60	2.53	0.32
cmol/kg Ex. Acidity	45.97	44.18	38.52	0.05*
cmol/kg ECEC	48.23	51.58	51.20	0.74
mg/kg Mn	7.47	5.37	4.37	0.00**
mg/kg Fe	152.16	146.43	139.44	0.5
mg/kg Cu	0.65	0.60	0.63	0.56
mg/kg Zn	3.67	3.51	0.45	0.05*
clay (%)	12.59	12.69	13.35	0.26
silt (%)	3.68	3.71	3.11	0.29
sand (%)	83.74	83.60	82.54	0.56

** Significant at 1% level of significance; * Significant at 5% level of significance

(Source: Data analysis, 2016)

different soil depths. The similarity in soil nutrients at different depths may also be because of high nutrient uptake by the rubber trees.

6.3.3 Impact of plantation agriculture on soil physical and chemical properties in Okomu Forest Reserve.

Table 6.18 shows the mean values and analysis of variance results of soil physical and chemical properties under rainforest, rubber and oil palm plantations. The table shows that apart from exchangeable calcium, which is similar, soil physical and chemical properties vary significantly in the rainforest and tree plantations. It is observed that soil pH is higher under the tree plantations than in rainforest soil. The mean values of pH in the plantation soils is 3.56 under rubber plantation and 3.69 under oil palm plantation while it is 3.41 under the rainforest. The high pH values under the plantations may be because of liming. Soil organic carbon is 2.12%, 0.89% and 1.37% under rainforest, rubber and oil palm plantations respectively. The higher value of organic carbon under oil palm plantation compared with rubber plantation may be because of the slow decay of palm fronds derived from harvesting. In spite of this however, organic carbon is significantly higher under rainforest than in the tree plantations. This result implies that rubber plantation may have a more severe adverse effect on soil carbon than oil palm. Mean value of total nitrogen is 0.23%, 0.12% and 0.14% in rainforest, rubber and oil palm plantations respectively. The significantly lower mean values of total nitrogen under plantation agriculture may be because of rapid nitrogen depletion in the plantations. Studies have shown that most nutrients decline under tree plantations (Aweto, 2001; Aweto and Moleele, 2005) and therefore need to be supplemented to ensure adequate yield and sustainable soil use and management. Available phosphorus is also significantly more under rainforest than in the plantations. The mean values are 8.71 mg/kg under rainforest, 4.42 mg/kg under rubber plantation and 3.12 mg/kg under oil palm plantation. Apart from exchangeable calcium which has higher mean value under rainforest, the exchangeable bases show higher mean values under the plantations. The mean value of calcium is 0.02 cmol/kg, 0.06 cmol/kg and 0.09 cmol/kg under rainforest, rubber and oil palm plantations respectively. Analysis of variance indicates that exchangeable calcium is similar under the rainforest and tree plantations. The values of magnesium are 0.38 cmol/kg

Table 6.18: Analysis of variance for soil physical and chemical properties under rainforest and plantations at Okomu Forest Reserve

	Mean value			p-value
Soil properties	Forest	Rubber	Oil Palm	
pH (H_2O)	3.93	4.27	4.37	0.00*
pH (KCl)	3.41	3.56	3.69	0.00*
% Organic C	2.12	0.89	1.37	0.00*
% Total N	0.23	0.12	0.14	0.00*
mg/kg av. P	8.71	4.42	3.12	0.00*
cmol/kg Ca	0.02	0.06	0.09	0.07
cmol/kg Mg	0.38	0.32	0.44	0.00*
cmol/kg K	0.08	0.11	0.15	0.00*
cmol/kg Na	0.31	0.49	0.57	0.00*
cmol/kg Al	2.54	2.38	0.59	0.00*
cmol/kg Ex. Acidity	1.06	4.28	2.13	0.00*
cmol/kg ECEC	4.38	7.65	3.97	0.00*
mg/kg Mn	5.05	5.74	9.92	0.01*
mg/kg Fe	207.93	146	127.07	0.00*
mg/kg Cu	0.6	0.63	0.86	0.00*
mg/kg Zn	1.09	3.54	4.46	0.00*
clay (%)	22.76	13.2	24.95	0.00*
silt (%)	5.18	3.5	6.1	0.00*
sand (%)	72.06	83.3	68.95	0.00*

* Significant at 1% level of significance

(Source: Data analysis, 2016)

under rainforest, 0.32 cmol/kg under rubber plantation and 0.44 cmol/kg under oil palm plantation. The average values of exchangeable potassium are 0.08 cmol/kg in the rainforest soil, 0.11 cmol/kg in rubber plantation and 0.15 cmol/kg in soil under oil palm plantation. Soil exchangeable aluminum is lower in soil under oil palm plantation than in rainforest and rubber plantation soils. The average value of exchangeable aluminum is 2.54 cmol/kg in rainforest soil, 2.38 cmol/kg in rubber plantation and 0.59 cmol/kg in soil under oil palm plantation. Exchange acidity under rainforest is 1.06 cmol/kg, 4.28 cmol/kg under rubber plantation and 2.13 cmol/kg under oil palm plantation.

Apart from exchangeable iron which show higher mean value in soil under rainforest, soil micronutrients are higher under oil palm plantation than under rainforest and rubber plantation soils. The mean value of manganese in soil under rainforest is 5.05 mg/kg while the values under rubber and oil palm plantations are 5.74 mg/kg and 9.92 mg/kg respectively. The mean values of iron are 207.93 mg/kg, 146.01 mg/kg and 127.07 mg/kg under rainforest, rubber and oil palm plantations respectively. Copper has a mean value of 0.86 mg/kg under oil palm plantation, 0.63 mg/kg in soil under rubber plantation and 0.60mg/kg in soil under rainforest. The value of zinc in soil under rainforest is 1.09 mg/kg, 3.54 mg/kg under rubber plantation and 4.46 mg/kg under oil palm plantation.

The mean clay content of soil under rainforest is 22.76%, while it is 12.21% and 24.95% under rubber and oil palm plantations respectively. The mean values of silt content are 5.18%, 3.50% and 6.10% under rainforest, rubber and oil palm plantations respectively. The soils under rainforest has a mean sand content of 72.06%, while the sand content under rubber and oil palm are 83.29% and 68.95% respectively. The use of inorganic fertilizer, notwithstanding, soil nutrients are significantly lower under the plantations than in the rainforest suggesting that oil palm and rubber plantations immobilize soil nutrients from the soil more than can be naturally replenished.

Inorganic fertilizers are useful for keeping soil nutrients near their natural concentration and therefore enhances the sustainable use of the soil while also improving yield per cultivated hectare of land. Similar findings were reported by Tesfaye *et al.* (2016), who observed that the natural forest stores more soil organic carbon and total nitrogen than plantations and other land uses in the Central highlands of Ethiopia. In the same vein, Aweto and Obe (1993) and Ekanade (2007), reported similar findings in southwestern Nigeria. Studies (Aweto, 1990; Aweto and Moleele, 2005; Montagnini and Sancho, 1990), however indicate that though plantations immobilize nutrients from the soil rapidly, it is better at restoring soil nutrient status in rainforest ecosystem than other land uses.

CHAPTER 7

SPATIAL VARIABILITY OF SOIL PHYSICAL AND CHEMICAL PROPERTIES UNDER RAINFOREST AND TREE PLANTATIONS IN OKOMU FOREST RESERVE

7.1 Introduction

The focus of this chapter is the impact of different land uses on the spatial variability of soil physical and chemical properties under rainforest and tree plantations in Okomu Forest Reserve. The next section of the chapter examines the spatial variability of soil physical and chemical properties under rainforest. The focus of section three is the spatial variability of soil physical and chemical properties under tree plantations (oil palm and rubber plantations). The impact of topography on the spatial variability of soil properties is the focus of section four while section five addresses the difference in spatial variability of soil physical and chemical properties resulting from the conversion of the rainforest to tree plantations. In section six, the spatial distribution of soil physical and chemical properties under rainforest and tree plantations in Okomu Forest Reserve is predicted and mapped using kriging interpolation.

7.2 Spatial variability of soil physical and chemical properties under rainforest

Tables 7.1, 7.2 and 7.3 show the variogram parameters of soil properties under rainforest in the topsoil, subsoil and deep subsoil layers respectively. The tables show the nugget, partial sill, sill, range, nugget-to-sill ratio, lag size, the spatial variability status and cross-validation parameters of each of the soil properties. Apart from the subsoil layer, where clay show moderate spatial variability, soil physical properties under rainforest soil show strong spatial variability pattern. Clay and sand particles in the topsoil show long-range spatial variability. The range of clay, sand and silt particles is 163.6 m, 160.3 m and 65.5 m respectively. Standardized root-mean square value of 0.674 suggests a fair estimation of silt particles in the topsoil. The range of clay, silt and sand particles in the subsoil layer is 81.8 m, 85.1 m and 163.6 m respectively. Cross-validation parameters show that predicted

Table 7.1: Variogram parameters of topsoil physical and chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget / Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.3	0.71	1.011	29.64	82.00	15	0.001	0.14	1.068	M
% Organic C	0.00	1.31	1.309	0.00	218.00	30	-0.022	0.607	1.135	S
% Total N	0.00	1.46	1.464	0.00	220.00	40	-0.002	0.006	1.051	S
mg/kg Av.P	0.00	0.09	0.087	0.00	130.90	20	-0.081	2.201	0.911	S
cmol/kg Ca	0.127	0.05	0.179	70.69	50.00	15	0.00	0.01	0.968	M
cmol/kg Mg	1.032	0	1.032	100	0.00	30	0.00	0.112	0.983	W
cmol/kg K	0.00	0.19	0.19	0.00	229.00	30	-0.001	0.033	1.206	S
cmol/kg Na	0.012	0.07	0.078	15.32	163.00	25	0.00	0.074	1.134	S
cmol/kg Al	1.027	0	1.027	100	0.00	20	0.001	0.415	0.981	W
cmol/kg Ex. Acidity	0.00	0.46	0.459	0.00	210.00	30	0.174	1.17	0.842	S
cmol/kg ECEC	0.00	0.22	0.224	0.00	230.00	30	0.106	1.25	0.749	S
mg/kg Mn	0.217	0.17	0.384	56.61	90.00	20	0.204	3.938	0.875	M
mg/kg Fe	0.00	1.4	1.401	0.00	196.00	30	0.404	61.523	1.056	S
mg/kg Cu	0.00	0.14	0.143	0.00	381.00	5	0.008	0.171	0.752	S
mg/kg Zn	0.112	0.12	0.235	47.63	35,00	10	-0.047	1.026	1.557	M
clay (%)	0.00	1.23	1.226	0.00	163.60	25	-0.237	6.179	1.132	S
silt (%)	0.00	0.71	0.714	0.00	65.50	10	0.404	3.833	0.674	S
sand (%)	0.00	0.02	0.015	0.00	160.30	24.3	0.198	6.624	1.029	S

* P-sill = partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.2 Variogram parameters of subsoil physical and chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget / Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.20	0.89	1.09	17.97	109.10	25.00	0.01	0.153	0.999	S
% Organic C	0.00	1.29	1.29	0.00	196.40	30.00	0.01	0.573	1.086	S
% Total N	0.00	0.11	0.11	0.00	130.90	20.00	0.00	0.057	0.945	S
mg/kg Av. P	0.00	0.03	0.03	0.00	140.20	20.00	-0.06	1.292	0.948	S
cmol/kg Ca	0.11	0.24	0.34	31.31	65.50	15.00	0.00	0.01	1.055	M
cmol/kg Mg	0.68	0.43	1.11	61.65	32.70	15.00	0.00	0.089	0.981	M
cmol/kg K	0.04	0.19	0.23	16.67	32.70	15.00	0.00	0.064	2.17	S
cmol/kg Na	0.01	0.06	0.07	13.34	87.30	10.00	0.00	0.074	0.988	S
cmol/kg Al	0.00	0.93	0.93	0.00	81.80	15.00	-0.01	0.266	0.961	S
cmol/kg Ex. Acidity	0.00	0.12	0.12	0.00	16.36	30.00	0.02	0.825	1.003	S
cmol/kg ECEC	0.00	1.37	1.37	0.00	196.40	30.00	0.00	0.869	0.961	S
mg/kg Mn	0.87	0.15	1.02	85.13	54.50	25.00	-0.04	2.008	1.005	W
mg/kg Fe	0.63	0.39	1.02	61.66	104.70	24.00	-1.14	67.391	1.108	M
mg/kg Cu	0.25	0.76	1.00	24.61	85.10	13.00	-0.01	0.165	1.043	S
mg/kg Zn	0.13	0.02	0.15	85.49	42.00	120.00	-0.15	0.57	1.571	W
clay (%)	0.39	0.81	1.20	32.20	81.80	15.00	-0.29	9.975	0.988	M
silt (%)	0.00	0.60	0.60	0.00	85.10	13.00	-0.17	3.406	0.896	S
sand (%)	0.00	1.13	1.13	0.00	163.60	25.00	0.09	7.717	1.129	S

* P-sill = partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.3: Variogram parameters of deep subsoil physical and chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget / Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.50	0.72	1.22	40.92	52.00	11.00	-0.002	0.225	1.001	M
% Organic C	0.00	0.94	0.94	0.00	63.10	14.00	-0.004	0.56	1.067	S
% Total N	0.00	0.14	0.14	0.00	65.50	12.00	-0.002	0.062	1.008	S
mg/kg Av. P	0.92	0.13	1.04	87.90	76.40	35.00	-0.021	1.687	1.018	W
cmol/kg Ca	0.14	0.13	0.28	51.22	72.00	22.00	0.000	0.006	0.915	M
cmol/kg Mg	0.22	0.95	1.17	18.53	91.60	12.00	0.000	0.024	0.981	S
cmol/kg K	0.00	0.19	0.19	0.00	85.10	13.00	0.000	0.024	0.999	S
cmol/kg Na	0.00	1.05	1.05	0.00	78.50	12.00	-0.003	0.656	0.953	S
cmol/kg Al	0.14	1.23	1.37	10.38	65.50	10.00	0.021	0.487	0.907	S
cmol/kg Ex. Acidity	0.67	0.39	1.06	63.01	70.10	60.00	-0.016	0.819	0.979	M
cmol/kg ECEC	0.15	0.92	1.06	13.83	65.50	10.00	-0.001	1.076	1.000	S
mg/kg Mn	0.07	0.24	0.31	22.26	84.00	11.00	0.098	1.893	0.944	S
mg/kg Fe	0.84	0.30	1.14	74.03	65.50	30.00	1.424	66.398	0.987	M
mg/kg Cu	0.00	1.18	1.18	0.00	144.00	22.00	0.000	0.196	1.107	S
mg/kg Zn	0.00	1.17	1.17	0.00	39.00	12.00	0.101	0.300	0.885	S
clay (%)	0.22	0.81	1.03	21.41	96.00	22.00	-0.219	7.338	1.104	S
silt (%)	0.00	0.68	0.68	0.00	91.60	14.00	0.077	2.23	0.57	S
sand (%)	0.00	1.02	1.02	0.00	114.50	15.00	0.322	7.685	1.198	S

* P-sill = partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

clay and silt distribution are within acceptable limits of accuracy (Chabala *et al.*, 2014; Gaston *et al.*, 2001). Spatial range in the deep subsoil layer is 96 m, 91 m and 114 m for clay, silt and sand respectively. However, the standardized mean square of silt is 0.57 which suggests that silt may have been under-estimated by the model.

Nugget effect accounts for 29.64% of the spatial variance of pH in the topsoil layer of rainforest. Soil pH exhibits moderate spatial variability in the topsoil and deep subsoil layers and strong spatial variability in the subsoil layer. The range of pH is 82 m in the topsoil, 109.1 m in the subsoil and 52 m in the deep subsoil layer. The variation in the spatial variability pattern of soil pH with depth may be attributed to leaching. This is particularly evident from soil profile description (Table 6.1) where the B-horizon show transition and clay accumulation at 93-172 cm depth in the middle and 125-161 cm depth in the lower positions. Soil organic carbon and total nitrogen show strong spatial variability which is not affected by soil depth. Robertson *et al.* (1988), reported contrary findings in a successional plant community. They noted that spatial variability of nitrogen in a successional plant community was strongest in the topsoil layer. This contrast may therefore be related to the difference in vegetation composition. The range of spatial variability is long in the topsoil and subsoil layers, but short in the deep subsoil layer. The range of soil organic carbon is 218 m, 196 m and 63 m in the topsoil, subsoil and deep subsoil layers respectively while total nitrogen exhibit range of 220 m, 130 m and 65 m in the topsoil, subsoil and deep subsoil layers respectively. Gonzalez and Zak (1994), reported a range of 71.2 m in the topsoil layer of dry tropical forest in West Indies. The long spatial range in this study may therefore be attributed to rapid decomposition of litter occasioned by heavy rainfall which may lead to the accumulation of organic matter in the topsoil and mineral nitrification of total nitrogen. The decreasing zone of influence and variability of soil organic carbon and total nitrogen with increasing depth may be related to the decreasing concentration of these soil nutrients with increasing soil depth. Aweto (1985), reported that soil organic carbon and total nitrogen were higher in the topsoil layer than subsoil layer in soils under different types of bush fallow in southwestern Nigeria. The trend exhibited by soil organic carbon and total nitrogen appears to be closely related to soil particle-size distribution. The accumulation of nutrients has been related to the clay mineral content of soils (Aweto and Moleele, 2005). However, Binkley and Hart (1989), also noted that total nitrogen generally decreases with increasing soil depth. They reported shorter range of spatial variability but noted that the pattern of spatial variability of soil nutrients may be affected by the method of assessment. Available phosphorus shows reducing zone of influence with increasing soil depth in soils under rainforest. It shows strong spatial variability and range of 130 m in the topsoil layer, 140.2 m in the subsoil and 76.4 m in the deep subsoil layers. Gonzalez and Zak (1994), reported that the range of available phosphorus in a dry tropical secondary forest was 24 m. This shows that spatial range may be influenced by land use and land cover type and climate variation.

Exchangeable calcium exhibit moderate spatial variability pattern in soil under rainforest. The range of calcium increases with depth from 50 m in the topsoil, 65.5 m in the subsoil to 72 m in the deep subsoil layers. Exchangeable magnesium shows a weak spatial variability in the topsoil, moderate variability in the subsoil and strong spatial variability in the deep subsoil. Exchangeable magnesium exhibit pure nugget effect in the topsoil. This shows randomness in the distribution of exchangeable magnesium in the soil. The range in the subsoil layer is 32.7 m and 91.6 m in the deep subsoil layer. Exchangeable potassium and sodium show strong spatial variability irrespective of soil depth. The spatial range of exchangeable potassium is 229 m in the topsoil, 32.7 m in the subsoil and 85.1 m in the deep subsoil layers. The range of sodium is 163 m in the topsoil, 87.3 m in the subsoil and 78.5 m in the deep subsoil layer.

Exchangeable aluminum exhibits weak spatial variability structure in the topsoil with pure nugget effect. However, it exhibits strong spatial variability in the subsoil and deep subsoil layers with range of 81.8 m in the subsoil and 65.5 m in the deep subsoil layers. Exchange acidity has a strong spatial variability with reducing zone of influence with depth. The range at the topsoil layer is 210 m, 16.36 m in the subsoil and 70.1 m in the deep subsoil layer. Effective cation exchange capacity also exhibits strong and long range spatial variability at all depths. The range of ECEC in the topsoil is 230 m, 196.4 m in the subsoil and 65.5 m in the deep subsoil layer.

Extractable manganese and zinc exhibit moderate spatial variability in the topsoil layer, weak spatial variability in the subsoil layer and strong spatial variability in the deep subsoil layer. Extractable manganese has a range of 90 m in the topsoil, 54.5 m in the subsoil and 84 m in the deep subsoil layers. Extractable iron shows strong spatial variability in the topsoil and moderate spatial variability in the subsoil and deep subsoil layers. The range is 196 m in the topsoil, 104.7 m in the subsoil and 65.5 m in the deep subsoil. The strong long range spatial variability of iron in the topsoil is evident in the red colour of soil in the study area. Extractable copper also exhibits strong spatial variability pattern in all layers of the soil under rainforest. The range is 381 m in the topsoil, 85.1 m in the subsoil and 144 m in the deep subsoil layer.

7.3 Spatial variability of soil physical and chemical properties under tree plantations

7.3.1 Oil palm plantation

Tables 7.4, 7.5 and 7.6 show the variogram parameters of soil physical and chemical properties under oil palm plantation. The tables show that soil particle-size distribution under oil palm plantation exhibit moderate spatial variability in the topsoil. The range of clay is 85.8 m while silt and sand have range of 147.3 m and 58.4 m in the topsoil layer respectively. The relatively short range exhibited by sand particles may have been influenced by catenary differentiation associated with topography and slope. In the subsoil layer, clay and sand particles show strong spatial variability while silt shows moderate spatial variability. The range of clay is 98.2 m in the subsoil while silt and sand have range of 58.6 m and 61.5 m respectively. Silt in the deep subsoil layer shows weak spatial variability while clay and sand exhibit strong spatial variability. The range of sand is 86.1 m, clay 81.8 m while silt show pure nugget effect in the deep subsoil layer. Soil pH in soil under oil palm plantation exhibits moderate spatial variability in the topsoil and deep subsoil layers while it shows strong spatial variability in the subsoil layer. The strong spatial variability in the subsoil layer may be because of nutrient illuviation from the topsoil layer. The range of pH in the topsoil is 87.3 m, 77.6 m in the subsoil and 70 m in the deep subsoil. However, the standardized residual mean error of pH is very low in the topsoil

Table 7.4: Variogram parameters of topsoil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget/ Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.68	0.39	1.07	63.18	87.30	10.00	0.00	0.012	0.003	M
% Organic C	0.94	0.14	1.08	86.82	22.91	70.00	0.00	0.8	0.005	W
% Total N	0.93	0.20	1.13	82.11	35.00	120.00	0.00	0.085	1.028	W
mg/kg Av.P	2.16	3.44	5.59	38.59	261.50	40.00	9.78	12.26	0.18	M
cmol/kg Ca	0.30	0.06	0.36	84.03	98.30	32.00	0.00	0.03	1.1	W
cmol/kg Mg	0.69	0.33	1.02	67.96	120.10	31.00	0.00	0.132	1.04	M
cmol/kg K	0.10	0.08	0.18	55.39	62.60	25.00	0.00	0.089	1.146	M
cmol/kg Na	0.03	0.01	0.04	78.76	98.20	30.00	0.00	0.095	0.959	W
cmol/kg Al	1.06	0.00	1.06	100.00	72.00	29.00	-2.21	8.447	0.954	W
cmol/kg Ex. Acidity	0.05	0.91	0.97	5.48	91.60	21.00	-0.02	0.177	1.102	S
cmol/kg ECEC	1.06	0.00	1.06	100.00	0.00	35.00	-1.23	8.476	0.952	W
mg/kg Mn	0.08	0.63	0.71	10.98	104.70	12.00	-0.42	13.61	1.13	S
mg/kg Fe	0.18	0.64	0.81	21.54	91.60	21.00	-11.30	52.64	1.67	S
mg/kg Cu	0.00	1.24	1.24	0.00	86.10	13.00	-0.01	0.228	0.916	S
mg/kg Zn	0.01	0.01	0.01	50.61	76.40	35.00	-0.01	0.528	1.165	M
clay (%)	0.51	0.55	0.96	53.03	85.80	25.00	-0.14	6.581	1.081	M
silt (%)	0.86	0.34	1.20	71.56	147.30	45.00	0.05	3.484	0.976	M
sand (%)	0.39	0.92	1.31	29.73	58.40	10.00	0.10	6.571	1.012	M

* P-sill= partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.5: Variogram parameters of subsoil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget /Sill (%)	Range (m)	Lag size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.00	0.01	0.01	0.00	77.60	11.80	0.00	0.27	0.999	S
% Organic C	1.03	0.00	1.03	100.00	0.00	32.00	-1.11	0.43	0.986	W
% Total N	1.03	0.00	1.03	100.00	0.00	30.00	-6.79	0.04	0.985	W
mg/kg Av. P	0.35	0.77	1.12	31.43	54.50	25.00	1.10	2.23	0.632	M
cmol/kg Ca	0.22	0.76	0.98	22.46	72.00	11.00	-0.02	0.21	1.156	S
cmol/kg Mg	0.49	0.51	1.00	49.41	80.50	12.00	0.00	0.11	1.015	M
cmol/kg K	0.27	0.22	0.49	54.41	46.30	12.00	-0.01	0.18	1.45	M
cmol/kg Na	0.33	0.79	1.11	29.33	81.80	15.00	0.00	0.75	0.994	M
cmol/kg Al	0.85	0.19	1.04	81.84	104.70	22.00	-0.01	6.41	1.032	W
cmol/kg Ex. Acidity	0.12	0.12	0.24	48.25	104.70	32.00	-0.03	0.63	2.219	M
cmol/kg ECEC	0.85	0.20	1.05	80.93	25.10	23.00	-0.01	6.26	1.027	W
mg/kg Mn	0.00	0.76	0.76	0.00	90.50	11.80	2.03	17.02	2.011	S
mg/kg Fe	0.00	0.22	0.22	0.00	114.80	13.15	3.49	55.98	0.86	S
mg/kg Cu	0.00	1.27	1.27	0.00	104.70	12.00	0.00	0.34	0.86	S
mg/kg Zn	0.00	0.00	0.00	68.01	49.10	15.00	-0.01	0.29	1.04	M
clay (%)	0.08	1.16	1.24	6.39	98.20	15.00	0.11	7.43	1.082	S
silt (%)	0.90	0.34	1.24	72.62	58.60	28.00	0.09	3.62	0.936	M
sand (%)	0.00	0.86	0.86	0.00	61.50	18.78	-4.64	21.77	1.457	S

* P-sill= partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.6: Variogram parameters of deep subsoil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Nugget	P-sill	sill	Nugget /Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.00	0.00	0.00	45.36	70.00	11.00	0.00	0.223	1.021	M
% Organic C	1.00	0.00	1.00	100.00	0.00	12.00	9.96	0.435	1	W
% Total N	0.68	0.47	1.15	59.30	48.00	11.00	0.00	0.044	0.951	M
mg/kg Av. P	0.76	1.18	1.94	39.37	76.50	21.00	2.02	2.618	0.254	M
cmol/kg Ca	0.84	0.64	1.48	56.99	92.10	42.00	-0.04	0.289	2.194	M
cmol/kg Mg	0.02	0.07	0.09	26.49	68.70	21.00	0.00	0.121	1.085	M
cmol/kg K	0.00	0.40	0.40	0.00	84.00	11.00	0.00	0.115	1.08	S
cmol/kg Na	0.96	0.10	1.06	90.89	22.90	21.00	0.00	0.076	0.98	W
cmol/kg Al	0.00	1.46	1.46	0.00	77.60	11.80	0.04	8.831	0.86	S
cmol/kg Ex. Acidity	0.85	0.23	1.08	79.01	61.10	28.00	0.00	0.161	1.006	W
cmol/kg ECEC	0.00	1.44	1.44	0.00	116.40	11.90	0.01	8.917	0.875	S
mg/kg Mn	0.00	0.86	0.86	0.00	108.00	11.00	-0.12	7.42	1.356	S
mg/kg Fe	0.00	1.03	1.03	0.00	90.50	11.80	-0.32	63.873	1.094	S
mg/kg Cu	0.00	0.15	0.15	0.00	100.40	14.00	0.00	0.318	0.94	S
mg/kg Zn	0.64	0.40	1.04	61.63	65.50	30.00	0.01	0.311	1.024	M
clay (%)	0.11	0.96	1.08	10.50	81.80	15.00	-0.12	7.691	1.015	S
silt (%)	0.39	0.00	0.39	100.00	0.00	30.00	0.09	3.399	0.869	W
sand (%)	0.00	1.01	1.01	0.00	86.10	14.00	0.04	6.391	0.904	S

* P-sill= partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

layer which may suggests that the model estimation is inaccurate for this layer. The spatial variability pattern exhibited in the subsoil and deep subsoil layers indicates that pH is relatively homogenous within a zone of 70 m in soils under oil palm plantation. Soil organic carbon in the soil under oil palm plantation exhibits weak spatial variability with a range of 22.91 m in the topsoil. However, the standardized residual mean error is 0.005 which indicates a weak predictive model for spatial variability pattern of soil organic carbon in the topsoil layer. The difficulty in predicting spatial variability pattern of soil organic carbon in the topsoil of oil palm plantation may be attributed to random patterns of variation that cannot be captured at the sampling interval used in this study (Souza *et al.*, 2006). This difficulty also appears to be reflected in the pure nugget effect exhibited in the subsoil and deep subsoil layers. Total nitrogen shows weak spatial pattern in the topsoil subsoil and moderate spatial variability structure in the deep subsoil layer. It shows pure nugget effect in the subsoil while the range is 82.11 m in the topsoil and 48 m in the deep subsoil layer. Similar results have been reported by earlier workers (Binkley and Hart, 1989). Available phosphorus in the soil under oil palm plantation exhibits weak spatial variability irrespective of soil depth. The range in the topsoil is 261 m, while it is 54.5 m and 76.5 m in the subsoil and deep subsoil layers. The long range spatial variability of available phosphorus in the topsoil may be because of the effect of fertilizer application. This results also suggest that oil palm appears to immobilize total nitrogen more rapidly from the soil than rubber. Similarly, soil nutrients available to plants have been observed to reduce through clearing for agricultural purpose and harvesting of produce (Aweto and Ekiugbo, 1994; Detwiler, 1986).

Exchangeable calcium shows weak spatial variability in the topsoil, strong spatial variability in the subsoil and moderate spatial variability in the deep subsoil layer. The range is 98.3 m, 72 m and 92.1 m in the topsoil, subsoil and deep subsoil layers respectively. Exchangeable magnesium exhibits moderate spatial variability at all layers of the soil under oil palm plantation. The spatial range of magnesium is 120 m, 80.5 m and 68.7 m in the topsoil, subsoil and deep subsoil layers respectively. Exchangeable potassium shows moderate spatial variability in the topsoil and subsoil layers and shows strong spatial variability in the deep subsoil layer. The spatial range is 62.6 m in the topsoil, 46.3 m in the subsoil and 84 m in the deep subsoil layer. Exchangeable sodium shows weak spatial variability pattern in the topsoil and deep subsoil layers and moderate spatial variability pattern in the subsoil layer. The range is 98.2 m in the topsoil, 81.8 m in the subsoil and 22.9 m in the deep subsoil layer. Spatial variability of aluminum concentration in soil under oil palm is weak at all layers. The range however, varies with soil depth. The range in the topsoil is 72 m, 104.7 m in the subsoil and 77.6 m in the deep subsoil layer. However, the spatial variability pattern of exchange acidity varies from strong in the topsoil to moderate in the subsoil and weak in the deep subsoil. The range in the topsoil is 91.6 m, 104.7 m in the subsoil and 61.1 m in the deep subsoil layer. The observed high spatial range in the subsoil may be related to leaching from the topsoil layer. The zone of influence of effective cation exchange capacity increased with increasing soil depth. ECEC shows random pattern of distribution and a weak spatial variability in the topsoil layer, 25 m range though with weak spatial variability in the subsoil layer and 116.4 m range and strong spatial variability in the deep subsoil layer. Sampling at multiple intervals may however reveal the spatial variability pattern of ECEC in the topsoil layer of soil under oil palm plantation (Gallardo, 2003).

Extractable manganese, iron and copper exhibit strong spatial variability pattern while zinc shows moderate spatial variability in the soil under oil palm. The variability pattern of these soil nutrients is not affected by soil depth. The range is 104.7 m, 91.6 m, 86.1 m and 76.4 m for extractable manganese, iron, copper and zinc respectively in the topsoil layer. In the subsoil, the range is 90.5 m for manganese, 114.8 m for iron, 104.7 m for copper and 49.1 m for zinc. The range in the deep subsoil is 108 m for manganese, 90.5 m for iron, 100.4 m for copper and 65.5 m for zinc.

7.3.2 Rubber plantation

Variogram parameters of soil physical and chemical properties in the topsoil, subsoil and deep subsoil layers of soil under rubber plantation are shown in tables 7.7, 7.8 and 7.9 respectively. Clay particle distribution exhibits moderate spatial variability in the topsoil and subsoil layers while the spatial variability pattern is strong in the deep subsoil layer.

Table 7.7: Variogram parameters of topsoil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget / Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.00	0.009	0.009	0.00	65.5	20.0	-0.002	0.465	1.538	S
% Organic C	0.00	1.154	1.154	0.00	49.1	5.0	0.006	0.273	0.943	S
% Total N	0.144	0.07	0.214	67.27	43.6	20.0	-0.002	0.091	1.647	M
mg/kg Av.P	0.198	0.142	0.339	58.23	68.7	21.0	0.127	3.298	0.864	M
cmol/kg Ca	0.00	0.631	0.631	0.00	91.0	16.7	-0.02	0.178	4.345	S
cmol/kg Mg	0.681	0.361	1.041	65.37	52.1	21.0	0.00	0.066	1.065	M
cmol/kg K	0.104	0.029	0.133	78.02	65.2	25.0	0.00	0.042	0.967	W
cmol/kg Na	0.027	0.1	0.127	21.65	130.9	15.0	0.003	0.182	1.028	S
cmol/kg Al	0.00	0.111	0.111	0.00	91.7	12.0	0.681	9.985	0.773	S
cmol/kg Ex. Acidity	0.00	1.236	1.236	0.00	117.9	12.0	0.28	1.49	0.549	S
cmol/kg ECEC	0.00	0.082	0.082	0.00	98.2	15.0	0.414	9.481	0.84	S
mg/kg Mn	0.128	1.016	1.144	11.16	98.7	19.0	-0.129	3.324	1.026	S
mg/kg Fe	0.656	0.555	1.211	54.18	51.0	15.0	-1.468	44.764	0.888	M
mg/kg Cu	0.00	1.037	1.037	0.00	83.2	13.0	-0.004	0.191	0.998	S
mg/kg Zn	0.001	0.01	0.01	5.6	81.8	15.0	-0.012	0.404	1.198	S
clay (%)	0.414	0.687	1.101	37.6	68.7	21.0	-0.385	5.32	0.983	M
silt (%)	0.00	1.181	1.181	0.00	114.8	12.0	-0.007	1.316	0.992	S
sand (%)	0.00	1.146	1.146	0.00	90.4	11.8	0.407	5.198	0.978	S

* P-sill= partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.8: Variogram parameters of subsoil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget/ sill	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.42	0.69	1.11	37.89	74.30	29.00	0.00	0.076	1.027	M
% Organic C	0.59	0.48	1.07	55.09	91.60	21.00	0.00	0.197	1.051	M
% Total N	0.00	0.28	0.28	0.00	98.20	15.00	-0.02	0.154	2.505	S
mg/kg Av. P	0.26	0.74	1.00	25.82	91.60	12.00	0.41	3.993	0.676	M
cmol/kg Ca	0.00	0.97	0.97	0.00	104.80	12.00	-0.03	0.153	1.39	S
cmol/kg Mg	0.51	0.51	1.02	49.76	109.10	25.00	0.00	0.066	1.111	M
cmol/kg K	0.14	0.02	0.16	88.51	45.80	21.00	0.00	0.042	0.883	W
cmol/kg Na	0.04	0.16	0.20	20.25	64.70	21.00	0.01	0.188	0.894	S
cmol/kg Al	0.00	0.15	0.15	0.00	91.70	12.00	1.11	12.439	0.796	S
cmol/kg Ex. Acidity	0.96	0.11	1.07	89.84	41.10	30.00	0.27	1.99	0.502	W
cmol/kg ECEC	0.00	1.18	1.18	0.00	78.60	12.00	-0.97	18.191	0.924	S
mg/kg Mn	0.44	0.19	0.63	70.01	101.20	19.00	-0.09	2.688	1.164	M
mg/kg Fe	0.08	0.06	0.14	59.80	68.70	21.00	1.66	47.383	0.858	M
mg/kg Cu	0.41	0.66	1.07	38.54	91.60	21.00	0.00	0.197	1.061	M
mg/kg Zn	0.00	0.01	0.01	0.00	104.80	12.00	-0.01	0.34	1.08	S
clay (%)	0.13	0.09	0.22	60.36	122.20	28.00	0.27	4.744	0.824	M
silt (%)	0.26	0.07	0.33	78.43	87.30	40.00	0.08	2.343	1.038	W
sand (%)	0.27	0.27	0.54	50.09	98.80	21.00	2.31	39.699	0.952	M

* P-sill= partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.9: Variogram parameters of deep subsoil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Nugget	P-sill	Sill	Nugget/ Sill (%)	Range (m)	Lag Size (m)	Mean error	RMS	RMSS	SD
pH (KCl)	0.000	0.001	0.001	7.690	104.700	12.000	0.002	0.114	0.972	S
% Organic C	0.889	0.278	1.167	76.180	36.000	11.000	0.003	0.209	0.938	W
% Total N	0.000	0.268	0.268	0.000	102.200	18.740	-0.008	0.108	1.887	S
mg/kg Av. P	0.086	0.743	0.829	10.340	78.500	12.000	-0.149	2.971	1.225	S
cmol/kg Ca	0.000	0.693	0.693	0.000	78.600	12.000	-0.186	0.115	2.816	S
cmol/kg Mg	0.000	0.098	0.098	0.000	104.800	12.000	-0.004	0.107	1.3	S
cmol/kg K	0.057	0.148	0.205	27.840	91.600	21.000	0.000	0.04	0.973	M
cmol/kg Na	0.355	0.899	1.254	28.310	68.700	21.000	-0.009	0.26	1.327	M
cmol/kg Al	0.116	0.083	0.199	58.160	175.600	23.000	0.308	13.795	0.851	M
cmol/kg Ex. Acidity	0.580	0.569	1.149	50.500	130.900	30.000	0.314	2.049	0.878	M
cmol/kg ECEC	0.352	0.821	1.173	30.000	92.700	17.000	0.145	26.95	0.983	M
mg/kg Mn	0.036	0.151	0.187	19.370	65.800	15.000	-0.001	1.928	0.952	S
mg/kg Fe	0.479	0.730	1.209	39.620	65.500	20.000	0.310	44.616	0.951	M
mg/kg Cu	0.752	0.440	1.192	63.100	45.000	11.000	0.003	0.211	0.927	M
mg/kg Zn	0.076	1.154	1.230	6.190	110.100	21.000	-0.006	0.311	1.142	S
clay (%)	0.000	0.590	0.590	0.000	87.100	16.000	0.336	8.611	1.134	S
silt (%)	0.072	0.202	0.274	26.370	87.300	10.000	0.039	1.566	0.968	M
sand (%)	0.098	0.972	1.070	9.140	78.500	12.000	-0.281	4.424	1.018	S

* P-sill= partial sill; SD = spatial variability; RMS = root-mean square; RMSS = Root-mean square standardized; M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Spatial range of clay is 68.7 m in the topsoil, 122.2 m in the subsoil and 87.1 m in the deep subsoil layers. The long range spatial structure in the subsoil suggests clay illuviation which results in increase spatial range in the subsoil layer. Silt particles show strong spatial variability in the topsoil, moderate spatial variability in the subsoil and weak spatial variability in the deep subsoil layers. Sand in the topsoil and deep subsoil shows strong spatial variability and moderate spatial variability in the subsoil layer. The range in the topsoil layer is 90.4 m, 98.8 m in the subsoil layer and 78.5 m in the deep subsoil layer. The long range spatial variability of sand in the subsoil indicates that percentage of sand is more homogenous in the subsoil layer than in the topsoil and deep subsoil layers. This variation in the pattern of variability of sand particles in the topsoil have implication for soil fertility because clay mineral in the topsoil has less spatial influence and therefore less spatial homogeneity in the topsoil layer.

Soil pH shows strong spatial variability in the topsoil and deep subsoil layers while the spatial variability pattern in the subsoil is moderate. The range of soil pH in the topsoil is 65.5 m, 74.3 m in the subsoil and 104.7 m in the deep subsoil layer. Soil organic carbon exhibits strong spatial variability in the topsoil, moderate spatial variability in the subsoil and weak spatial variability in the deep subsoil layers. The range of soil organic carbon is 49.1 m, 91.6 m and 36 m in the topsoil, subsoil and deep subsoil layers. Total nitrogen exhibits moderate spatial variability pattern in the topsoil layer and strong spatial variability pattern in the subsoil and deep subsoil layers. The range of total nitrogen in the topsoil is 43.6 m, 98.2 m in the subsoil and 102.2 m in the deep subsoil. Yanai *et al.* (2000), reported a strong spatial variability in the top 0 - 15 cm soil in a paddy field. The range of total nitrogen in the field was 19.5 m. Gross *et al.* (1995), also observe shorter range of 16 m in the top 0 – 15 cm of soil under crop cultivation. They noted the possible influence of the composition of vegetation in determining the spatial range of nitrogen in the topsoil. Available phosphorus shows moderate spatial variability in the topsoil and subsoil layer while the spatial variability in the deep subsoil is strong. The range of available phosphorus in the topsoil is 86.7 m, 91.6 m in the subsoil and 78.5 m in the deep subsoil layer. Gonzalez and Zak (1994), reported spatial range of 48.18 m in a dry tropical secondary forest while

Souza *et al.* (2006), observe that available phosphorus show a range of 27.9 m in the top 0 – 20 cm layer and 37.2 m in the 60 – 80 cm layer. They noted that the spatial variability pattern of available phosphorus in the two layers were moderate and argue that the variation in the range may be attributed to management practices in the field. Yanai *et al.* (2000), however, reported a strong spatial variability pattern in a paddy field with a range of 36.9 m in the 0 – 15 cm layer.

Exchangeable calcium exhibits strong spatial variability soil under rubber plantation which is not affected by soil depth. The spatial range in the topsoil is 91 m, 104.8 m in the subsoil and 78.6 m in the deep subsoil layers. Exchangeable magnesium shows moderate spatial variability in the topsoil and subsoil and strong spatial variability in the deep subsoil layer. The range of magnesium is 52.1 m, 109.1 m, and 104.8 m in the topsoil, subsoil and deep subsoil layers respectively. Exchangeable potassium exhibits weak spatial variability in the topsoil and subsoil layer while the spatial variability in the deep subsoil is moderate. The range is 65.2 m in the topsoil, 45.8 m in the subsoil and 91.6 m in the deeps-soil layers. Exchangeable sodium and aluminum show strong spatial variability in the topsoil and subsoil layers while the spatial variability pattern in the deep subsoil layer is moderate. The range of sodium is 130.9 m, 64.7 m and 68.7 m in the topsoil, subsoil and deep subsoil layers respectively while the range of aluminum is 91.7 m in the topsoil and subsoil and 175.6 m in the deep subsoil layer. Yanai *et al.* (2000), reported low spatial range for exchangeable bases in the topsoil layer of a paddy field.

The range of extractable iron which is moderate at all layers of the soil, is 51 m, 68.7 m and 65.5 m in the topsoil, subsoil and deep subsoil layers respectively. Extractable copper exhibits strong spatial variability in the topsoil and moderate spatial variability in the subsoil and deep subsoil layers. The range of extractable copper is 83.2 m, 91.6 m and 45 m in the topsoil, subsoil and deep subsoil layers respectively. Extractable zinc shows strong spatial variability at all layers of the soil under rubber plantation. The range is 81.8 m, 104.8 m and 110.1 m in the topsoil, subsoil and deep subsoil layers respectively.

7.4 Impact of topography on variation and spatial variability of soil properties under rainforest and tree plantations in Okomu forest reserve

7.4.1 Variation in spatial variability of soil properties in the upper, middle and lower slope positions under rainforest

Tables 7.10, 7.11 and 7.12 show the coefficient of variation and the spatial variability parameters of soil properties in the upper slope, middle slope and lower slope positions of topsoil, subsoil and deep subsoil layers respectively under rainforest. Table 7.10 indicates that pH, available phosphorus, extractable copper and percent sand particle exhibit lower variation while exchangeable potassium, exchange acidity, percent clay and silt show a high variation in the upper slope of the topsoil layer. In the middle slope, pH and percent sand particle show low variation and exchangeable calcium, exchange acidity and, extractable zinc and percent silt show high variation. The variation of pH and percent sand is low in the lower slope position while exchangeable calcium, exchangeable potassium, extractable manganese, extractable zinc and percent silt show high variation in the topsoil layer of the lower slope under rainforest.

Apart from exchangeable calcium, exchangeable aluminum and extractable zinc which show moderate spatial variability, the spatial variability of soil properties in the upper slope position of the topsoil layer under the rainforest is strong. In the middle slope position, the spatial variability is also mostly strong while the spatial variability is mostly weak in the lower slope position of the topsoil under the rainforest The spatial range in the upper slope position of the topsoil is longer than in the middle and lower slope positions. For instance, the range of pH in the upper slope position is 205 m while it is randomly distributed in the middle slope and is distributed at a range of 110.7 m in the lower slope position. This suggests that soil physical and chemical properties in the upper slope position of the rainforest are more homogenously distributed than in the middle and lower slope positions. This may be attributed to the movement of water in the surface and subsurface layers of the soil which may remove soil nutrients from the upper slope and deposit it in the lower slope. Studies have shown that many soil properties have higher concentration in the lower

Table 7.10: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under rainforest at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
	CV (%)	Nugget/ Sill (%)	SD	Range (m)	CV (%)	Nugget/ Sill (%)	SD	Range (m)	CV (%)	Nugget/ Sill (%)	SD	Range (m)
pH (KCl)	2.73	0.00	S	205.10	5.47	100.00	W	0.00	3.73	40.00	M	110.70
% Organic C	26.06	3.10	S	182.30	30.76	0.00	S	58.40	17.62	100.00	W	0.00
% Total N	25.95	0.00	S	159.50	30.76	0.00	S	81.80	29.37	100.00	W	0.00
mg/kg Av. P	14.00	0.00	S	91.10	24.71	0.00	S	170.30	28.28	18.85	S	132.90
cmol/kg Ca	27.96	31.54	M	58.80	41.66	100.00	W	0.00	43.79	61.06	M	88.60
cmol/kg Mg	17.67	0.00	S	71.80	26.98	100.00	W	0.00	26.91	67.21	M	110.70
cmol/kg K	35.55	0.00	S	106.60	20.79	100.00	W	0.00	44.13	100.00	W	0.00
cmol/kg Na	25.60	0.00	S	78.30	18.11	0.00	S	140.10	23.40	100.00	W	0.00
cmol/kg Al	32.67	72.32	M	159.50	34.43	0.00	S	162.20	34.50	100.00	W	0.00
cmol/kg Ex. Acidity	44.47	0.00	S	205.10	48.94	8.15	S	201.30	31.83	55.96	M	155.60
cmol/kg ECEC	22.68	0.00	S	175.50	22.43	0.00	S	179.00	27.35	92.48	W	88.60
mg/kg Mn	37.94	0.00	S	104.20	54.90	53.52	M	111.80	55.84	100.00	W	0.00
mg/kg Fe	15.62	0.00	S	182.30	24.70	83.46	W	0.00	22.89	0.00	S	97.20
mg/kg Cu	13.73	0.00	S	88.30	34.57	100.00	W	0.00	32.99	0.00	S	90.00
mg/kg Zn	19.29	47.24	M	45.30	54.11	68.40	M	75.30	83.36	11.16	S	110.70
Clay (%)	44.71	0.00	S	71.40	26.90	0.00	S	94.50	23.84	100.00	W	0.00
Silt (%)	63.34	0.00	S	107.80	95.55	25.92	M	179.00	57.02	0.00	S	75.60
Sand (%)	8.05	0.00	S	159.50	6.19	0.00	S	156.60	11.40	100.00	W	0.00

M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.11: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under rainforest at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/ Sill (%)	SD	Range (m)	CV (%)	Nugget/ Sill (%)	SD	Range (m)	CV (%)	Nugget/ Sill (%)	SD	Range (m)
pH (KCl)	2.38	100.00	W	0.00	3.75	100.00	W	0.00	6.80	42.86	M	68.40
% Organic C	19.30	100.00	W	0.00	22.08	41.46	M	110.60	30.24	0.00	S	107.00
% Total N	19.31	18.98	S	88.80	22.06	39.76	M	111.80	33.77	0.00	S	122.80
mg/kg Av. P	11.85	0.00	S	77.50	13.80	58.33	M	156.60	21.74	13.27	S	199.30
cmol/kg Ca	38.61	100.00	W	0.00	86.17	92.11	W	0.00	39.00	34.69	M	177.10
cmol/kg Mg	19.75	100.00	W	0.00	29.22	100.00	W	0.00	25.57	11.11	S	199.30
cmol/kg K	13.96	23.03	S	70.70	123.94	83.33	W	44.70	35.47	0.00	S	86.40
cmol/kg Na	23.72	100.00	W	0.00	25.92	0.00	S	169.30	23.90	37.99	M	139.60
cmol/kg Al	29.65	0.00	S	155.40	25.70	0.00	S	81.80	18.33	100.00	W	0.00
cmol/kg Ex. Acidity	30.26	28.00	M	124.80	23.83	32.88	M	156.60	31.71	0.00	S	199.30
cmol/kg ECEC	19.22	8.82	S	108.00	18.68	56.16	M	111.80	16.11	0.00	S	85.20
mg/kg Mn	35.94	100.00	W	0.00	52.91	100.00	W	0.00	49.05	56.32	M	88.60
mg/kg Fe	20.60	67.11	M	44.40	31.31	71.90	M	22.40	35.91	100.00	W	0.00
mg/kg Cu	33.84	55.70	M	88.80	25.18	0.00	S	98.60	24.74	46.36	M	88.60
mg/kg Zn	11.77	100.00	W	0.00	31.00	100.00	W	0.00	64.87	0.00	S	98.20
Clay (%)	27.10	100.00	W	0.00	25.43	84.53	W	56.40	28.84	19.38	S	177.10
Silt (%)	60.52	0.00	S	155.40	51.05	46.04	M	87.70	82.03	82.22	W	88.10
Sand (%)	8.04	0.00	S	111.00	7.92	61.90	M	52.10	15.15	60.00	M	88.60

M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

Table 7.12: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under rainforest at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/ Sill (%)	SD	Range (m)	CV (%)	Nugget/ Sill (%)	SD	Range (m)	CV (%)	Nugget/ Sill (%)	SD	Range (m)
pH (KCl)	4.48	40.28	M	46.30	3.19	47.06	M	126.80	8.19	100.00	W	0.00
% Organic C	55.74	0.00	S	135.40	23.42	14.29	S	70.50	31.66	100.00	W	0.00
% Total N	55.61	0.00	S	159.50	23.45	2.69	S	78.10	43.28	100.00	W	0.00
mg/kg Av. P	22.60	100.00	W	0.00	23.62	66.67	M	89.50	21.84	100.00	W	0.00
cmol/kg Ca	33.16	100.00	W	0.00	43.36	10.64	S	95.40	58.17	100.00	W	0.00
cmol/kg Mg	23.03	36.70	M	66.60	31.63	28.87	M	134.20	30.96	39.41	M	132.90
cmol/kg K	32.06	0.00	S	71.40	58.50	0.00	S	81.80	40.58	33.89	M	62.30
cmol/kg Na	27.30	0.00	S	78.80	28.62	53.52	M	179.00	25.16	0.00	S	199.30
cmol/kg Al	22.35	59.91	M	23.40	23.99	30.52	M	111.80	27.37	0.00	S	101.00
cmol/kg Ex. Acidity	38.06	82.19	W	45.60	55.59	0.00	S	90.90	48.62	100.00	W	0.00
cmol/kg ECEC	16.51	64.07	M	68.50	18.16	0.00	S	142.50	26.02	100.00	W	0.00
mg/kg Mn	27.60	52.76	M	48.90	50.39	88.52	W	0.00	69.02	100.00	W	0.00
mg/kg Fe	30.24	100.00	W	0.00	27.92	69.41	M	103.20	54.01	35.35	M	73.40
mg/kg Cu	20.90	32.03	M	45.60	36.24	7.24	S	128.50	37.82	12.28	S	155.00
mg/kg Zn	24.01	0.00	S	182.30	35.16	18.48	S	127.10	49.51	46.45	M	177.10
Clay (%)	50.00	60.29	M	50.20	18.02	100.00	W	0.00	23.35	84.80	W	0.00
Silt (%)	58.45	0.00	S	196.40	39.01	0.00	S	156.60	79.02	0.00	S	136.70
Sand (%)	15.22	30.93	M	57.20	5.06	14.29	S	56.80	9.78	82.98	W	44.30

M = moderate; S = strong; W = weak

(Source: Data analysis, 2016)

slope than in upper slope which influences biomass distribution (Were *et al.*, 2016; Wolf *et al.*, 2012).

Table 7.11 shows that the variation of pH, available phosphorus, exchangeable potassium, extractable zinc and percent sand particles is low while exchangeable calcium, extractable manganese and percent silt exhibit high variation in the upper slope of the subsoil layer. In the middle slope, the variation of pH, available phosphorus, and percent sand particles is low while exchangeable calcium, exchangeable potassium, extractable manganese and percent silt show high variation. The variation in the lower slope indicates that pH is low but exchangeable potassium, extractable manganese, extractable zinc and percent silt show high variation.

The spatial variability pattern of total nitrogen, available phosphorus, exchangeable potassium, exchangeable aluminum, effective cation exchange capacity, percent silt and percent sand particles is strong in the upper slope of the subsoil layer, while other soil properties exhibit weak spatial variability in the middle slope position of the subsoil layer. In the lower slope, pH shows a low variation while exchangeable potassium, extractable manganese, extractable zinc and percent silt show high variation. The spatial variability is generally strong-to-weak in the lower slope position of the subsoil layer. The range of soil properties does not show a clear pattern in the subsoil layer.

In the deep subsoil layer, shown in Table 7.12, the variation of pH is low in all the slope positions, while soil organic carbon, total nitrogen, exchange acidity, percent clay and percent silt show high variation in the upper slope. In the middle slope, exchangeable calcium, exchangeable potassium, exchange acidity, extractable manganese, extractable copper, extractable zinc and percent silt exhibit high variation while percent sand shows low variation. The variation of sand is also low in the lower slope position while the variation of total nitrogen, exchangeable calcium, exchangeable potassium, exchange acidity, extractable manganese, exchangeable micronutrients and percent silt is high.

The spatial variability pattern of soil properties is generally strong to moderate in the upper slope and middle positions of the deep subsoil layer and weak in the lower slope position.

The range of soil properties is also higher in the upper slope than in the middle slope and lower slope positions of the deep subsoil layer.

Table 7.13 shows the result of the analysis of variance of soil properties variation at different slope positions. It indicates that there is no significant difference in spatial variability of soil properties at different slope positions in the rainforest. This shows that though topography influences vegetation distribution and soil properties variation (Alijani and Sarmadian, 2014; Aweto and Enaruvbe, 2010; Bohlman *et al.*, 2008; Burke *et al.*, 1999; de Castilho *et al.*, 2006; Saldana *et al.*, 1998; Wolf *et al.*, 2012), the spatial variation of soil properties is not significantly altered by changes in topography. Sobieraj *et al.* (2002), also observed that hydraulic conductivity showed no significant change with changes in topography in a rainforest catena in Brazil.

Table 7.14 shows the result of analysis of variance for the spatial variability of soil properties in the upper, middle and lower slope positions under the rainforest. The result shows that there is a significant difference in the spatial variability structure of soil properties at different slope positions in the rainforest. This implies that topography influences the spatial variability of soil properties under rainforest. The differences in spatial variability of soil properties at different segments of the slope may be because of the higher concentration of many soil properties in the lower slope than in upper slope. Studies have shown that the uneven distribution of soil properties at different segments along the slope influences the distribution of biomass (Were *et al.*, 2016; Wolf *et al.*, 2012).

7.4.1 Spatial variability of soil properties in the upper, middle and lower slope positions under oil palm plantation

Tables 7.15, 7.16 and 7.17 show the coefficient of variation and the spatial variability parameters of soil properties in the upper slope, middle slope and lower slope positions in the topsoil, subsoil and deep subsoil layers respectively under oil palm plantation. Table 7.15 shows that the variation of soil pH, extractable zinc and percent sand particles is low in all slope positions in the topsoil layer under oil palm plantation. In contrast, the variation of soil organic carbon, total nitrogen, available phosphorus, exchangeable calcium,

Table 7.13: Analysis of variance of the coefficient of variation (CV (%)) of soil properties in the upper, middle and lower slope positions under the rainforest at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	552.35	2	276.18	0.83	0.44084	3.18
Within Groups	16921.56	51	331.80			
Total	17473.91	53				

(Source: Data analysis, 2016)

Table 7.14: Analysis of variance of the spatial variability (nugget/sill (%)) of soil properties in the upper, middle and lower slope positions under the rainforest at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	27656.99	2	13828.49	9.93716	0.000227	3.178799
Within Groups	70971.3	51	1391.594			
Total	98628.29	53				

(Source: Data analysis, 2016)

Table 7.15: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under oil palm plantation at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)
pH(KCl)	6.69	100.00	W	0.00	4.48	0.00	S	152.90	5.39	0.00	S	223.40
% Organic C	52.64	100.00	W	0.00	46.56	39.85	M	80.30	50.38	77.97	W	15.30
% Total N	52.75	100.00	W	0.00	46.23	25.43	M	100.90	50.73	76.23	W	26.29
mg/kg Av. P	64.04	100.00	W	0.00	58.13	100.00	W	0.00	48.32	100.00	W	0.00
cmol/kg Ca	67.12	32.04	M	251.10	38.61	0.21	S	176.10	71.61	35.18	M	166.80
cmol/kg Mg	35.66	81.42	W	50.10	23.79	0.00	S	183.90	24.52	0.00	S	143.30
cmol/kg K	88.25	100.00	W	0.00	33.84	0.00	S	134.80	26.90	11.75	S	131.40
cmol/kg Na	18.32	100.00	W	0.00	16.41	25.51	M	126.90	20.35	89.39	W	135.00
cmol/kg Al	43.63	80.41	W	98.20	34.53	32.54	M	80.30	23.45	100.00	W	0.00
cmol/kg Ex. Acidity	33.54	49.07	M	124.10	24.15	54.43	M	112.60	43.90	0.00	S	257.20
cmol/kg ECEC	31.13	81.19	W	23.90	22.58	24.09	S	73.30	41.17	100.00	W	0.00
mg/kgMn	62.80	0.00	S	157.10	62.31	0.00	S	102.30	60.83	100.00	W	0.00
mg/kg Fe	21.79	71.96	M	191.20	17.59	0.00	S	138.60	25.08	4.27	S	262.90
mg/kg Cu	23.65	90.60	W	47.80	20.79	31.94	M	106.40	41.95	27.61	M	65.72
mg/kg Zn	14.71	100.00	W	0.00	6.64	100.00	W	0.00	6.75	20.15	S	176.50
Clay (%)	30.65	52.58	M	125.20	19.22	58.00	M	97.40	34.87	80.17	W	19.28
Silt (%)	53.07	73.27	M	89.60	64.61	100.00	W	0.00	54.66	100.00	W	0.00
Sand (%)	8.14	100.00	W	0.00	6.98	22.64	S	116.90	10.19	85.16	W	71.70

S = strong; M = Moderate; W = Weak

(Source: Data analysis, 2016)

Table 7.16: Coefficient of variation (CV), spatial variability (SD) and range of subsoil properties in the upper, middle and lower slope positions under oil palm plantation at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)
pH(KCl)	8.92	100.00	W	0.00	6.03	22.45	S	123.21	4.98	84.07	W	167.30
% Organic C	36.67	0.00	S	189.40	19.02	100.00	W	0.00	34.98	100.00	W	0.00
% Total N	36.55	0.00	S	215.20	19.14	100.00	W	0.00	34.89	100.00	W	0.00
mg/kg Av. P	42.08	100.00	W	0.00	42.75	82.57	W	119.40	44.62	0.00	S	262.90
cmol/kg Ca	173.62	57.38	M	73.30	58.72	34.00	M	198.50	86.37	100.00	W	0.00
cmol/kg Mg	23.80	53.90	M	63.10	24.83	100.00	W	0.00	22.65	100.00	W	0.00
cmol/kg K	90.06	0.00	S	78.20	105.92	100.00	W	0.00	104.45	87.94	W	167.30
cmol/kg Na	10.13	100.00	W	0.00	11.91	100.00	W	0.00	16.49	100.00	W	0.00
cmol/kg Al	34.96	36.34	M	220.70	32.52	100.00	W	0.00	99.34	65.81	M	119.50
cmol/kg Ex. Acidity	30.32	27.74	M	167.30	33.85	4.69	S	191.30	31.92	37.06	M	191.20
cmol/kg ECEC	28.44	40.09	M	142.60	30.60	100.00	W	0.00	26.71	85.98	W	167.30
mg/kgMn	105.83	0.00	S	107.50	45.45	72.41	M	71.70	34.77	100.00	W	0.00
mg/kg Fe	33.12	77.36	W	135.80	21.58	0.00	S	127.40	28.12	21.90	S	123.30
mg/kg Cu	28.12	0.00	S	95.60	39.76	56.91	M	88.30	32.01	0.00	S	177.20
mg/kg Zn	7.78	75.65	W	15.80	4.18	70.37	M	143.40	6.87	100.00	W	0.00
Clay (%)	51.86	0.00	S	71.70	20.55	100.00	W	0.00	20.35	91.37	W	143.30
Silt (%)	64.26	100.00	W	0.00	55.84	100.00	W	0.00	49.13	100.00	W	0.00
Sand (%)	13.34	42.75	M	60.70	6.49	100.00	W	0.00	5.62	72.97	M	95.60

S = strong; M = Moderate; W = Weak (Source: Data analysis, 2016)

Table 7.17: Coefficient of variation (CV), spatial variability (SD) and range of deep subsoil properties in the upper, middle and lower slope positions under oil palm plantation at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)
pH(KCl)	7.52	100.00	W	0.00	3.17	27.27	M	87.30	4.79	15.38	S	80.80
% Organic C	27.66	0.00	S	85.30	28.46	100.00	W	0.00	44.18	78.06	W	116.30
% Total N	27.22	7.19	S	108.90	28.56	17.59	S	173.20	47.26	80.58	W	215.50
mg/kg Av. P	69.32	100.00	W	0.00	33.79	100.00	W	0.00	36.66	91.26	W	52.10
cmol/kg Ca	154.62	10.69	S	82.70	89.96	100.00	W	0.00	163.15	3.98	S	191.20
cmol/kg Mg	27.68	0.00	S	104.80	18.08	24.04	S	117.00	16.61	53.57	M	167.30
cmol/kg K	29.63	22.59	S	127.40	45.41	65.37	M	98.20	125.56	24.59	S	85.90
cmol/kg Na	17.28	0.00	S	98.70	12.93	62.96	M	83.60	9.17	94.42	W	143.40
cmol/kg Al	32.47	100.00	W	0.00	18.69	19.94	S	86.40	36.36	100.00	W	0.00
cmol/kg Ex. Acidity	42.89	83.15	W	37.00	38.46	0.00	S	183.90	42.07	81.96	W	63.30
cmol/kg ECEC	39.53	100.00	W	0.00	35.68	19.21	S	85.00	38.86	100.00	W	0.00
mg/kgMn	70.09	35.37	M	143.40	146.89	0.00	S	99.50	106.82	0.00	S	95.60
mg/kg Fe	25.96	74.81	M	215.10	27.15	100.00	W	0.00	32.15	0.00	S	97.70
mg/kg Cu	39.79	0.00	S	131.40	18.10	98.11	W	0.00	20.99	0.00	S	83.60
mg/kg Zn	8.10	100.00	W	0.00	7.38	100.00	W	0.00	5.47	0.00	S	128.20
Clay (%)	31.69	8.47	S	239.00	24.90	37.54	M	119.50	28.35	55.00	M	167.30
Silt (%)	53.12	100.00	W	0.00	78.36	70.41	M	25.10	53.60	100.00	W	0.00
Sand (%)	12.21	0.00	S	183.90	15.33	99.58	W	0.00	10.00	42.74	M	215.10

S = strong; M = Moderate; W = Weak (Source: Data analysis, 2016) exchangeable magnesium, extractable manganese and percent silt is high in all the slope positions in the topsoil layer under oil palm plantation.

The spatial variability of soil properties in the upper slope position of the topsoil and subsoil layers is generally weak. The middle slope position however shows a moderate spatial variability. The weak spatial variability of pH, organic carbon, total nitrogen and available phosphorus in the upper slope resulted in a random distribution of these soil properties. However, in the middle slope position, a range of 152.9 m, 80.3 m and 100.9 m is observed for pH, soil organic carbon and total nitrogen respectively while available phosphorus shows a random distribution. The range of all the macronutrients is above 100 m in the middle and lower slope positions of the topsoil layer though low range is observed in the upper slope position. The range of micronutrients do not however exhibit a clear pattern along the slope segments.

Table 7.16 indicates that the variation of soil organic carbon, total nitrogen, available phosphorus, exchangeable calcium, extractable manganese, percent clay and silt particles show high variation in the upper slope position of the subsoil layer. The variation of pH, exchangeable sodium and percent sand particles is low. In the middle slope, pH, extractable zinc and sand particles exhibit low variation while available phosphorus, exchangeable calcium, exchangeable potassium, extractable manganese and percent silts show high variation in the middle and lower slope positions of the subsoil layer.

The spatial variability of soil organic carbon and total nitrogen, exchangeable potassium and percent clay is strong in the upper slope position but weak in the middle and lower slope positions of the subsoil layer with range of 189.4 m, 215.2 m, 78.2 m and 71.7 m respectively in the upper slope. The range of soil properties is generally longer in the upper slope position than in the middle and lower slope positions of the subsoil layer

Table 7.17 shows that the variation of soil pH and extractable zinc is low in the upper slope, middle slope and lower slope positions in the deep subsoil layer under oil palm plantation. The variation of exchangeable calcium, exchange acidity, effective cation exchange capacity, extractable manganese and percent silt is however high in the upper, middle and lower slope positions of the deep subsoil layers under oil palm plantation. The spatial variability of appears to vary with slope positions in the deep subsoil layer under oil palm plantation. The spatial variability of soil properties in the upper slope is generally strong but weak in the subsoil layer.

Analysis of variance shown in table 7.18 indicates that the difference in variation of soil properties in the upper, middle and lower slope positions is not significant. However, the difference in the spatial variability of soil properties in the upper, middle and lower slope positions in the subsoil layer under oil palm plantation is significant (Table 7.19).

7.4.2 Differences in spatial variability of soil properties in the upper, middle and lower slope positions under rubber plantation

Tables 7.20, 7.21 and 7.22 show the coefficient of variation and the spatial variability parameters of soil properties in the upper slope, middle slope and lower slope positions of topsoil layer, subsoil layer and deep subsoil layer respectively under rubber plantation. Table 7.20 shows that the variation of pH is moderate in the upper slope position of the topsoil layer under rubber plantation but low in the middle and lower slope positions. Percent sand particle show a low variation at all segments of the slope under rubber plantation while the variability of available phosphorus, exchangeable calcium, exchangeable aluminum, extractable manganese and percent silt is high in all segments of the slope.

The spatial variability of soil properties is generally strong in the upper slope, strong to moderate in the middle slope and moderate to weak in the lower slope position. The distribution of pH, soil organic carbon, total nitrogen, extractable manganese and extractable zinc is random in the upper slope position but long in the middle and lower slope positions. For instance, the range of total nitrogen is 208.2 m in the middle slope and 131.2 m in the lower slope. The range of soil properties is generally longer in the upper slope than in the middle and lower slope positions of the topsoil layer under rubber plantation.

Table 7.18: Analysis of variance of coefficient of variation (CV (%)) of soil properties in the upper slope, middle slope and lower slope positions of the topsoil under oil palm plantation at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	727.4125	2	363.71	0.887	0.418	3.18
Within Groups	20918.41	51	410.16			
Total	21645.82	53				

(Source: Data analysis, 2016)

Table 7.19: Analysis of variance of the spatial variability (nugget/sill (%)) of soil properties in the upper slope, middle slope and lower slope positions of the subsoil under oil palm plantation at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	17685.49	2	8842.74	6.95	0.00214	3.18
Within Groups	64876.69	51	1272.092			
Total	82562.18	53				

(Source: Data analysis, 2016)

Table 7.20: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under rubber plantation at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)
pH (KCl)	21.20	100.00	W	0.00	3.39	0.00	S	254.40	2.18	68.61	M	109.40
% Organic C	29.09	100.00	W	0.00	32.10	100.00	W	0.00	21.21	80.64	W	43.20
% Total N	28.82	100.00	W	0.00	106.00	54.63	M	208.20	21.26	37.55	M	131.20
mg/kg Av. P	56.34	0.00	S	80.20	46.56	33.67	M	185.00	44.81	85.59	W	54.30
cmol/kg Ca	231.63	83.68	W	30.80	36.92	31.67	M	94.50	48.82	48.94	M	87.50
cmol/kg Mg	22.45	0.00	S	72.80	22.34	74.17	M	23.10	10.55	57.75	M	131.20
cmol/kg K	46.10	0.00	S	97.80	29.35	39.01	M	114.70	31.54	100.00	W	0.00
cmol/kg Na	31.12	6.94	S	219.30	42.30	59.38	M	161.60	27.75	61.12	M	196.80
cmol/kg Al	71.82	0.00	S	107.20	80.35	0.00	S	203.70	80.34	43.08	M	128.60
cmol/kg Ex. Acidity	17.19	0.00	S	123.50	39.53	0.00	S	146.40	13.79	89.51	W	126.70
cmol/kg ECEC	16.30	0.00	S	130.60	34.51	0.00	S	254.40	11.22	60.93	M	65.60
mg/kg Mn	40.23	100.00	W	0.00	48.64	61.22	M	46.30	52.46	24.46	S	240.30
mg/kg Fe	43.49	0.00	S	197.40	28.99	15.09	S	99.30	16.05	97.05	W	0.00
mg/kg Cu	29.32	0.00	S	116.80	21.72	79.53	W	115.60	42.61	0.00	S	238.80
mg/kg Zn	17.38	100.00	W	0.00	9.70	0.00	S	88.30	4.76	10.14	S	175.00
Clay (%)	48.62	0.00	S	111.80	34.77	0.00	S	165.00	52.30	85.86	W	65.60
Silt (%)	39.90	0.00	S	99.00	38.57	81.00	W	46.30	35.59	100.00	W	0.00
Sand (%)	6.85	0.00	S	86.90	5.59	0.00	S	179.10	7.89	61.54	M	153.10

S= strong; M = moderate; W = Weak

(Source: Data analysis, 2016)

Table 7.21: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under rubber plantation at Okomu Forest Reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)
pH (KCl)	3.44	100.00	W	0.00	1.24	0.00	S	105.80	1.85	100.00	W	0.00
% Organic C	29.64	16.09	S	131.60	26.77	65.36	M	70.50	15.82	82.12	W	65.50
% Total N	143.10	15.34	S	175.40	93.96	0.00	S	180.20	15.74	26.43	M	153.10
mg/kg Av. P	104.71	0.00	S	93.10	95.95	72.13	M	58.80	80.41	72.21	M	218.70
cmol/kg Ca	182.61	100.00	W	0.00	44.27	0.00	S	231.30	45.69	2.09	S	196.80
cmol/kg Mg	20.88	75.05	W	43.90	16.39	62.07	M	108.30	20.85	0.00	S	118.60
cmol/kg K	39.80	91.67	W	109.70	39.81	99.09	W	0.00	32.88	38.67	M	91.80
cmol/kg Na	36.33	72.59	M	87.70	42.73	28.66	M	85.20	35.66	100.00	W	0.00
cmol/kg Al	98.28	30.92	M	97.30	78.47	31.49	M	94.70	64.54	0.00	S	87.00
cmol/kg Ex. Acidity	42.48	100.00	W	0.00	14.65	85.24	W	57.80	27.50	31.36	M	130.80
cmol/kg ECEC	52.56	100.00	W	0.00	12.99	25.45	M	69.10	33.93	0.00	S	117.30
mg/kg Mn	51.50	71.39	M	62.50	39.20	33.81	M	178.30	52.98	0.00	S	196.80
mg/kg Fe	43.33	0.00	S	219.30	30.33	56.54	M	138.00	27.67	100.00	W	0.00
mg/kg Cu	28.62	31.11	M	131.60	38.01	78.80	W	70.40	33.91	100.00	W	0.00
mg/kg Zn	16.51	100.00	W	0.00	5.53	20.00	S	116.00	7.40	5.29	S	238.40
Clay (%)	49.81	19.38	S	153.50	33.34	100.00	W	0.00	27.24	68.01	M	131.20
Silt (%)	49.72	100.00	W	0.00	74.51	100.00	W	0.00	49.53	100.00	W	0.00
Sand (%)	5.45	7.41	S	162.50	6.29	100.00	W	0.00	4.41	40.43	M	69.30

S= strong; M = moderate; W = Weak

(Source: Data analysis, 2016)

Table 7.22: Coefficient of variation (CV), spatial variability (SD) and range of topsoil properties in the upper, middle and lower slope positions under rubber plantation at Okomu forest reserve

	Upper slope				Middle slope				Lower slope			
Soil properties	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)	CV (%)	Nugget/Sill (%)	SD	Range (m)
pH (KCl)	4.87	38.46	M	97.20	2.12	100.00	W	0.00	3.18	16.67	S	150.20
% Organic C	27.73	100.00	W	0.00	36.78	84.67	W	0.00	21.10	72.28	M	63.90
% Total N	117.54	81.94	W	65.80	91.45	54.25	M	138.80	21.14	0.00	S	196.80
mg/kg Av. P	102.81	38.50	M	175.40	54.75	0.00	S	172.30	141.31	62.44	M	101.20
cmol/kg Ca	183.99	100.00	W	0.00	56.35	91.23	W	20.10	44.90	4.90	S	196.80
cmol/kg Mg	21.24	48.74	M	175.40	35.70	12.30	S	81.80	44.60	70.61	M	145.80
cmol/kg K	29.14	78.69	W	36.10	39.28	69.63	M	46.30	43.23	100.00	W	0.00
cmol/kg Na	44.12	39.93	M	109.70	34.68	56.54	M	138.80	66.66	21.89	S	175.00
cmol/kg Al	104.75	100.00	W	0.00	85.17	0.00	S	143.30	50.02	2.01	S	198.60
cmol/kg Ex. Acidity	31.30	59.88	M	87.70	32.74	56.62	M	110.10	42.35	100.00	W	0.00
cmol/kg ECEC	50.65	58.97	M	128.00	53.06	29.00	M	208.20	59.72	0.00	S	96.60
mg/kgMn	34.85	1.29	S	241.20	33.84	0.00	S	95.00	61.33	26.99	M	218.70
mg/kg Fe	37.67	37.88	M	97.60	25.40	17.70	S	138.80	34.22	92.67	W	0.00
mg/kg Cu	26.51	100.00	W	0.00	27.46	100.00	W	0.00	33.61	100.00	W	0.00
mg/kg Zn	9.08	87.14	W	0.00	5.84	75.61	W	69.40	10.09	27.34	M	127.80
Clay (%)	37.01	33.83	M	175.40	29.53	41.32	M	142.20	34.73	0.00	S	104.00
Silt (%)	35.60	100.00	W	0.00	57.14	0.00	S	96.80	47.28	0.00	S	123.90
Sand (%)	5.26	0.00	S	136.80	5.73	68.57	M	161.90	5.88	83.87	W	39.40

S= strong; M = moderate; W = Weak

(Source: Data analysis, 2016)

In the subsoil layer (Table 7.21), soil pH and percent sand particles show low variation. Most of the other soil properties in the subsoil layer exhibit high variation in all segments of the slope. The spatial variability of organic carbon, total nitrogen, available phosphorus, extractable iron, percent clay and percent sand is strong in the upper slope position while exchangeable sodium, exchangeable aluminum, extractable manganese and extractable copper show moderate spatial variability. In the middle slope position, soil pH, total nitrogen, exchangeable calcium and extractable zinc exhibit strong spatial variability while exchangeable potassium, extractable copper, percent clay, percent silt and percent sand show weak spatial variability. The range of soil organic carbon, total nitrogen and available phosphorus is 131.6 m, 175.4 m and 93.1 m respectively in the upper slope position, 70.5 m, 180.2 m and 58.8 m respectively in the middle slope position and 65.5 m, 153.1 m and 218.7 m respectively in the lower slope position.

In the deep subsoil layer (Table 7.22), the variation of pH, extractable zinc and percent sand particles is low in all the segments of the slope. The variation of total nitrogen, available phosphorus, exchangeable calcium, exchangeable sodium, exchangeable aluminum, effective cation exchange capacity, extractable iron, percent clay and percent silt is high in the upper slope. Soil organic carbon, total nitrogen, available phosphorus, exchangeable calcium, exchangeable magnesium and exchangeable potassium show high variation in the middle slope. In the lower slope position, the variation of available phosphorus, exchangeable calcium, exchangeable magnesium, exchangeable potassium, exchangeable sodium, exchangeable aluminum, exchange acidity, effective cation exchange capacity and extractable manganese is high

The spatial variability of total nitrogen, exchangeable calcium, exchangeable potassium, exchangeable aluminum, extractable copper, extractable zinc and percent silt, with range of 65.8 m, 0.00 m, 36.1 m, 0.00 m, 0.00 m, 0.00m, and 0.00 m respectively, in the upper slope position is weak. The range of extractable manganese is 241.2 m and shows a strong spatial variability in the upper slope. In the middle slope, strong spatial variability is observed for available phosphorus, exchangeable magnesium, exchangeable aluminum, extractable manganese, extractable iron and percent sand particles. The range of these soil properties is 172.3 m, 81.8 m, 143.3 m, 95.0 m, 138.8 m and 96.8 m respectively.

Analysis of variance indicates that there is no significant difference in the variation of soil properties at different slope segments in the topsoil layer of soil under rubber plantation (Table 7.23).

7.5 Variation in spatial variability of soil properties under rainforest and plantations

The variogram parameters derived from kriging procedure were used in generating soil properties prediction in unsampled locations within the study sites. Tables 7.24, 7.25 and 7.26 show the spatial variability indicated by the nugget-sill ratio of soil physical and chemical properties in the topsoil, subsoil and deep subsoil layers under rainforest, rubber plantation and oil palm plantation respectively. The results of analysis of variance, shown in Tables 7.27, 7.28 and 7.29 indicate that there is no significant difference in the spatial variability of soil physical and chemical properties at different layers of soils under rainforest and the plantations.

The second hypothesis which states that differences in spatial variability in soil physical and chemical properties under forest and plantations is not limited to the topsoil layer was tested by comparing the spatial variability of soil physical and chemical properties at the topsoil, subsoil and deep subsoil layers of soils under rainforest, rubber and oil palm plantations using analysis of variance. The results indicate that there is a significant difference in the spatial variability of soil physical and chemical properties at the topsoil layer ($p < 0.01$). However, there is no significant difference in the spatial variability of soils physical and chemical properties at the subsoil and deep subsoil layers.

Student’s t-test was used to compare the variation in the spatial variability of soil physical and chemical properties under rainforest and rubber plantation, under rainforest and oil palm plantation and under rubber plantation and oil palm plantation. The results of student’s t-test analysis show that there is no significant difference in the spatial variability

Table 7.23: Analysis of variance of the coefficient of variation (CV (%)) of soil properties in the upper, middle and lower slope positions of the topsoil layer under rubber plantation at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	2065.962	2	1032.981	0.885	0.418	3.18
Within Groups	59487.28	51	1166.417			
Total	61553.25	53				

(Source: Data analysis, 2016)

Table 7.24: Spatial variability (nugget/sill %) of soil physical and chemical properties under rainforest at Okomu Forest Reserve

Soil properties	Topsoil	Subsoil	Deep subsoil
pH (KCl)	29.64	17.97	40.92
% Organic C	0.00	0.00	0.00
% Total N	0.00	0.00	0.00
mg/kg Av. P	0.00	0.00	87.90
cmol/kg Ca	70.69	31.31	51.22
cmol/kg Mg	100.00	61.66	18.53
cmol/kg K	0.00	16.67	0.00
cmol/kg Na	15.32	13.34	0.00
cmol/kg Al	100.00	0.00	10.38
cmol/kg Ex. Acidity	0.00	0.00	63.01
cmol/kg ECEC	0.00	0.00	13.83
mg/kg Mn	56.61	85.13	22.26
mg/kg Fe	0.00	61.66	74.03
mg/kg Cu	0.00	24.61	0.00
mg/kg Zn	47.63	85.49	0.00
clay (%)	0.00	32.20	21.41
silt (%)	0.00	0.00	0.00
sand (%)	0.00	0.00	0.00

(Source: Data analysis, 2016)

Table 7.25: Spatial variability (nugget/sill %) of soil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Soil properties	Topsoil	Subsoil	Deep subsoil
pH (KCl)	0.00	37.89	7.69
% Organic C	0.00	55.09	76.18
% Total N	67.27	0.00	0.00
mg/kg Av. P	58.23	25.82	10.34
cmol/kg Ca	0.00	0.00	0.00
cmol/kg Mg	65.37	49.76	0.00
cmol/kg K	78.02	88.51	27.84
cmol/kg Na	21.65	20.25	28.31
cmol/kg Al	0.00	0.00	58.16
cmol/kg Ex. Acidity	0.00	89.84	50.50
cmol/kg ECEC	0.00	0.00	30.00
mg/kg Mn	11.16	70.01	19.37
mg/kg Fe	54.18	59.80	39.62
mg/kg Cu	0.00	38.54	63.10
mg/kg Zn	5.60	0.00	6.19
clay (%)	37.60	60.36	0.00
silt (%)	0.00	78.43	26.37
sand (%)	0.00	50.09	9.14

(Source: Data analysis, 2016)

Table 7.26: Spatial variability of soil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Soil properties	Topsoil	Subsoil	Deep subsoil
pH (KCl)	63.18	0.00	45.36
% Organic C	86.82	100.00	100.00
% Total N	82.11	100.00	59.30
mg/kg Av. P	38.60	31.43	39.37
cmol/kg Ca	84.03	22.46	56.99
cmol/kg Mg	67.96	49.41	26.50
cmol/kg K	55.40	54.41	0.00
cmol/kg Na	78.76	29.33	90.89
cmol/kg Al	100.00	81.84	0.00
cmol/kg Ex. Acidity	5.48	48.25	79.01
cmol/kg ECEC	100.00	80.93	0.00
mg/kg Mn	10.98	0.00	0.00
mg/kg Fe	21.55	0.00	0.00
mg/kg Cu	0.00	0.00	0.00
mg/kg Zn	50.61	68.01	61.63
clay (%)	53.03	6.39	10.50
silt (%)	71.56	72.62	100.00
sand (%)	29.73	0.00	0.00

(Source: Data analysis, 2016)

Table 7.27: Analysis of variance of spatial variability of soil physical and chemical properties under rainforest at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	19.92	2	9.958	0.0099	0.99	3.1788
Within Groups	51101	51	1001.98			
Total	51121	53				

(Source: Data analysis, 2016)

Table 7.28: Analysis of variance of spatial variability of soil physical and chemical properties under rubber plantation at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	3379	2	1689.57	2.093	0.134	3.179
Within Groups	41176	51	807.374			
Total	44555	53				

(Source: Data analysis, 2016)

Table 7.29: Analysis of variance of spatial variability of soil physical and chemical properties under oil palm plantation at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	3326.5	2	1663.24	1.322	0.276	3.179
Within Groups	64183	51	1258.5			
Total	67510	53				

(Source: Data analysis, 2016)

of soil physical and chemical properties in soils under rainforest and rubber plantation at all the layers. However, while there is no significant difference in soil physical and chemical properties under the subsoil and deep subsoil layers of oil palm plantation and rainforest soils, there is a significant difference ($p < 0.01$) in the spatial variability of topsoil physical and chemical properties under rainforest and oil palm plantation. The difference observed in the spatial variation in the topsoil layer of soils under rainforest and plantation may be attributed to the decomposition of litter from trees which constantly adds nutrient to the topsoil layer (Aweto, 2001; Aweto and Moleele, 2005; Vitousek, 1984; Vitousek and Sanford, 1986). The difference in the spatial variability under rainforest and oil palm plantation could be because of the near absence of leaf litters from oil palm plantation. The major source of nutrient recycling to the soil in oil palm trees is the palm fronds which are pruned during harvesting and are usually laid between the rolls of the palm trees.

The third hypothesis which states that spatial variability of soil physical and chemical properties is greater under oil palm than under rubber plantation was tested using one tailed student’s t-test. The result indicates that spatial variability of soil properties in the topsoil under rubber plantation is greater ($p < 0.01$) than under oil palm plantation. This may be attributed to more efficient organic matter and nutrient recycling in soil under rubber plantation through litter fall. There is however no significant difference in the spatial variability of soil properties at the subsoil and deep subsoil layers in the plantations.

7.6 Spatial distribution of soil physical and chemical properties under rainforest and plantations in Okomu Forest Reserve

The semivariogram parameters derived from geostatistical analysis were used to derive maps showing the predicted spatial distribution of topsoil physical and chemical properties (Figures 7.1 - 7.18) in the study sites. Though there are three soil layers, the prediction was restricted to the topsoil layer because the results shown in tables 7.30, 7.31 and 7.32, show that differences in the spatial variability pattern of soil properties in the forest and plantations is limited to the topsoil layer. Also, the topsoil layer accounts for a large proportion of soil nutrient concentration in the soil.

Table 7.30: Analysis of variance of spatial variability of topsoil physical and chemical properties under rainforest and plantations at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	12918	2	6458.84	6.173	0.004	3.179
Within Groups	53364	51	1046.34			
Total	66281	53				

(Source: Data analysis, 2016)

Table 7.31: Analysis of variance of spatial variability of subsoil physical and chemical properties under rainforest and plantations at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	3450.5	2	1725.25	1.607	0.211	3.179
Within Groups	54758	51	1073.69			
Total	58209	53				

(Source: Data analysis, 2016)

Table 7.32: Analysis of variance of spatial variability of deep subsoil physical and chemical properties under rainforest and plantations at Okomu Forest Reserve

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	2225.7	2	1112.86	1.1741	0.317	3.179
Within Groups	48339	51	947.822			
Total	50565	53				

(Source: Data analysis, 2016)

7.6.1 Predicted distribution pattern of soil physical properties in Okomu Forest Reserve

The predicted distribution of soil physical properties is shown in Figures 7.1, 7.2 and 7.3. Figure 7.1 shows the percentage distribution of sand particles in the topsoil layer. The figure shows that the percent sand particles in the rainforest is mostly above 78% in the middle and lower slope positions. Percentage sand content is high in about half of the plot under rainforest. In contrast, the percentage sand particles in the rubber plantation is generally above 80% and occupies about 90% of the landscape studied. The variability of sand particles is more marked under rainforest and rubber plantation than in the oil palm plantation where it exhibits the least variability.

As with the variability pattern of sand, figure 7.2 shows a more marked variability of silt particles under rainforest while variability under rubber plantation is moderate. The variability of silt under oil palm plantation is negligible. The percent silt in the rainforest is generally above 7% in the upper slope and part of the middle slope while the lower slope has an average of 4% silt composition. The percentage of silt is 5% in the oil palm plantation and 3% in the rubber plantation. The percent clay content of the rainforest reduces from the upper slope downwards. Percent clay is above 25% in the upper slope but is reduced to less than 15% in the middle and lower slope positions. Similarly, the variability of clay is generally more marked under rainforest and moderate under the plantations as depicted in figure 7.3.

7.6.2 Predicted distribution pattern and spatial variability of soil chemical properties in Okomu Forest Reserve

Figures 7.4 – 7.18 show the predicted spatial variability of soil chemical properties in rainforest and plantations in Okomu forest reserve. Figure 7.4 shows the pH values in rainforest, rubber and oil palm plantations. The value of pH is clearly higher in the middle and lower slope positions under the rainforest. In contrast, low values of pH occur in the upper slope in rubber plantation. Variation in pH values is least in oil palm plantation. The

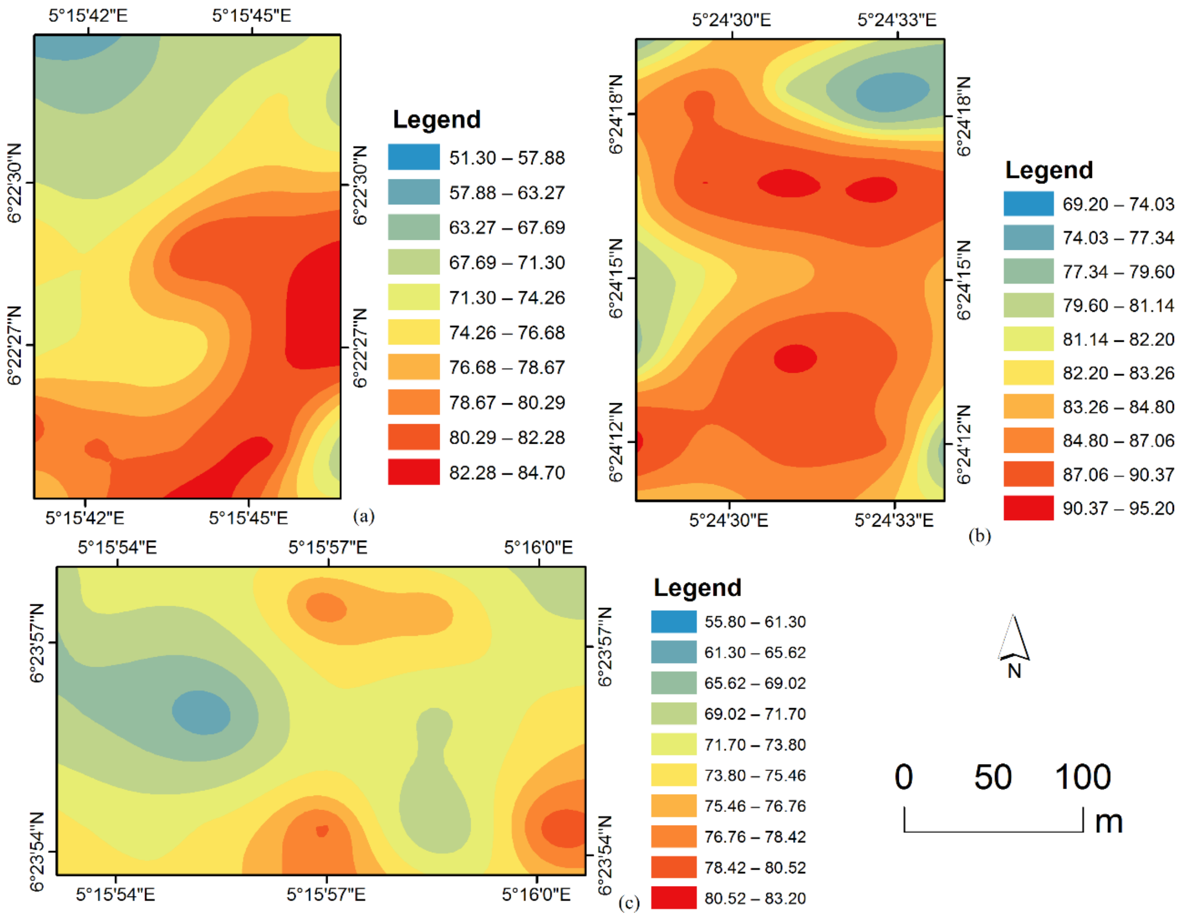

Figure 7.1: Predicted spatial pattern of topsoil % sand content under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

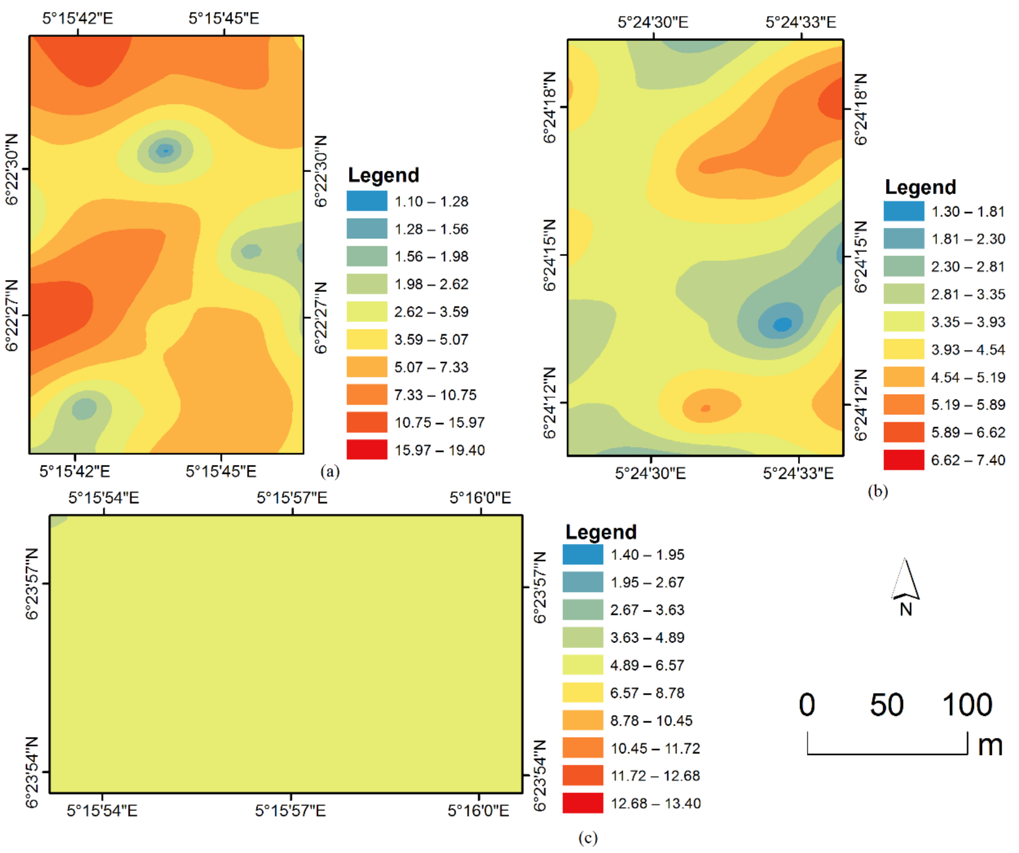

Figure 7.2: Predicted spatial pattern of topsoil % silt content under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve. (Source: Data analysis, 2016)

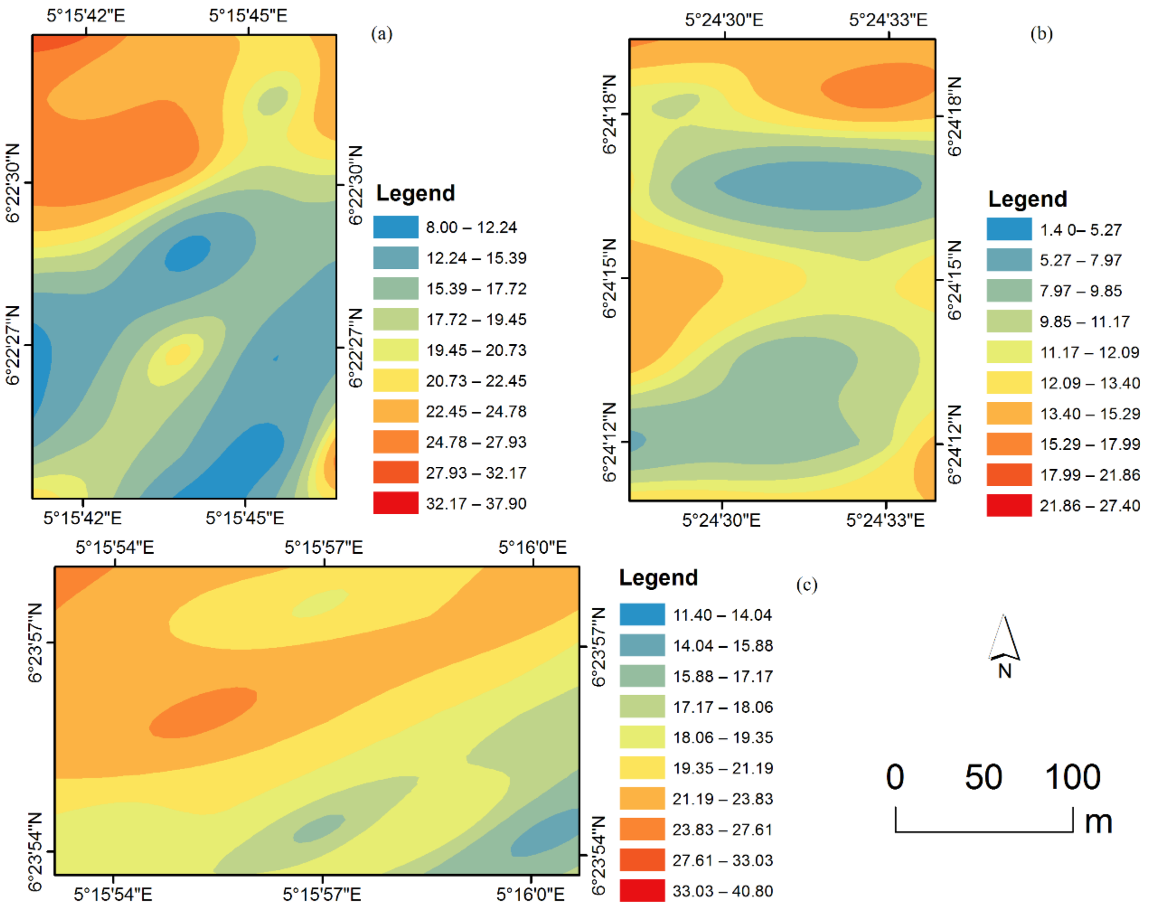

Figure 7.3: Predicted spatial pattern of topsoil % clay content under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

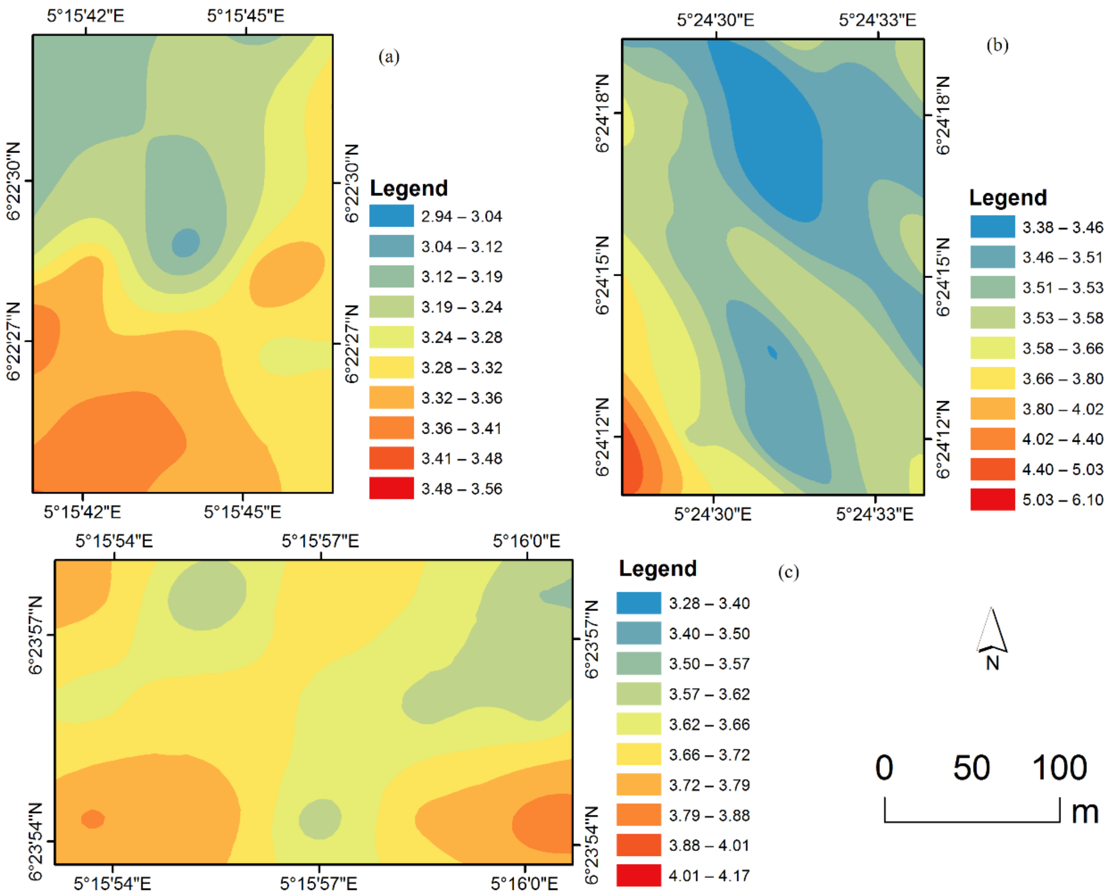

Figure 7.4: Predicted spatial pattern of topsoil pH under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

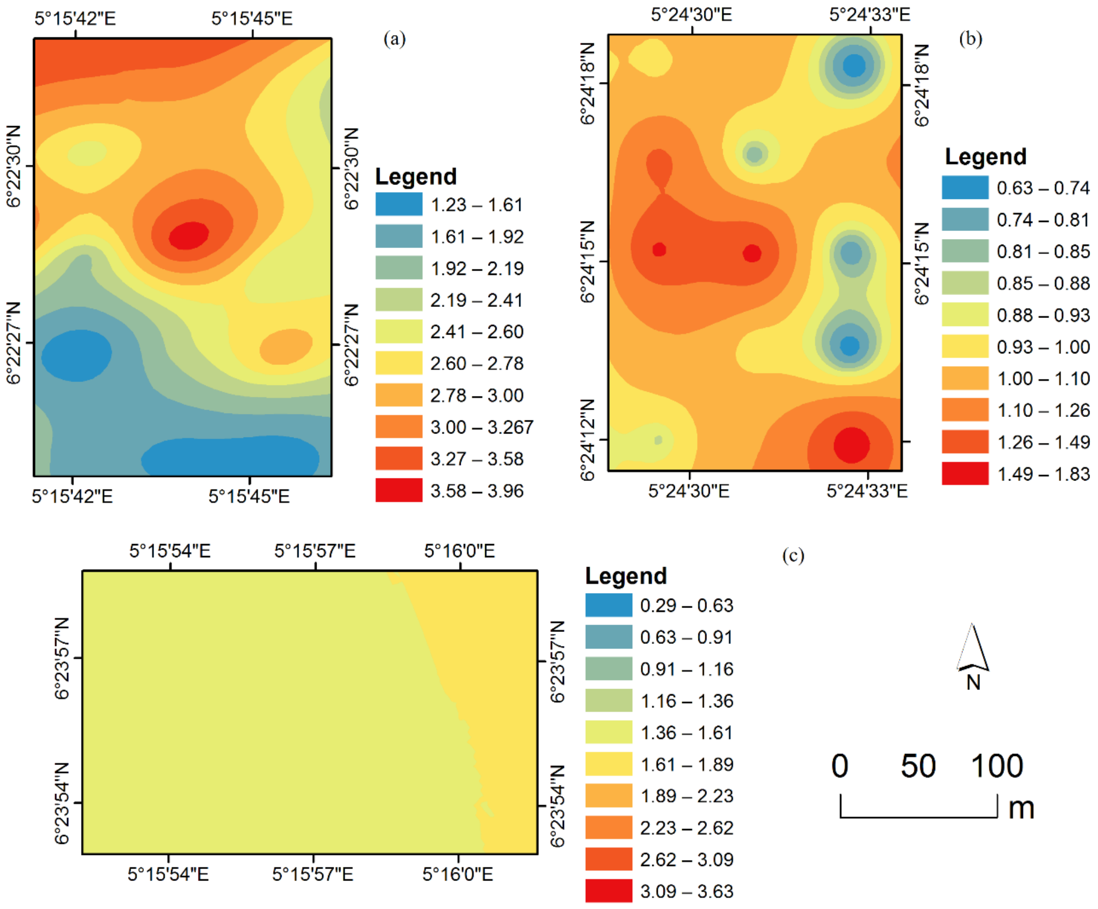

Figure 7.5: Predicted spatial pattern of topsoil % organic carbon under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

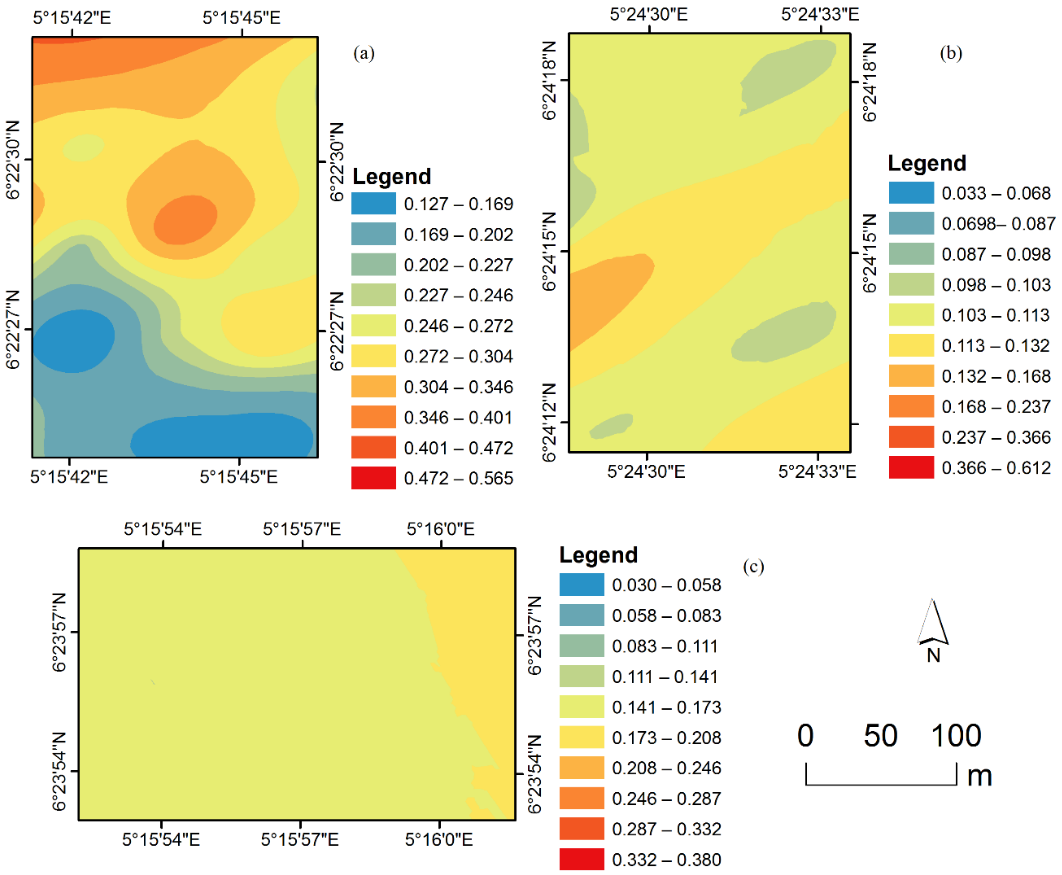

Figure 7.6: Predicted spatial pattern of topsoil % total nitrogen under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

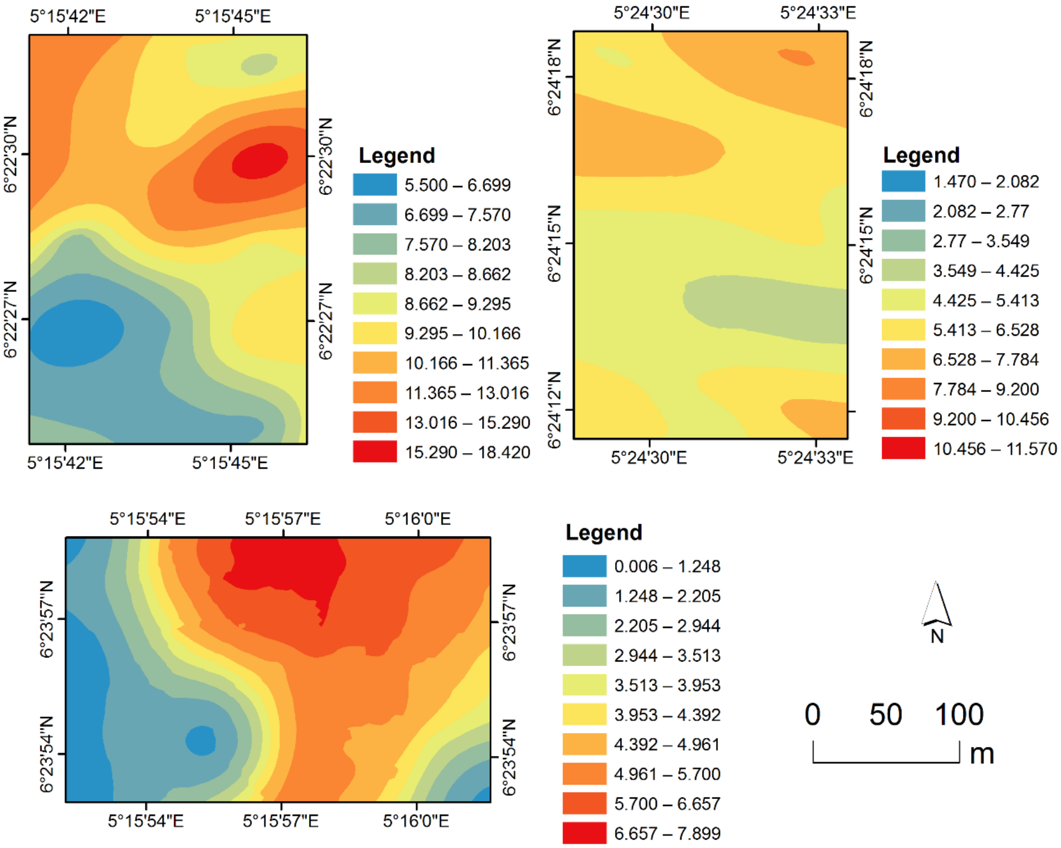

Figure 7.7: Predicted spatial pattern of topsoil available phosphorus (mg/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

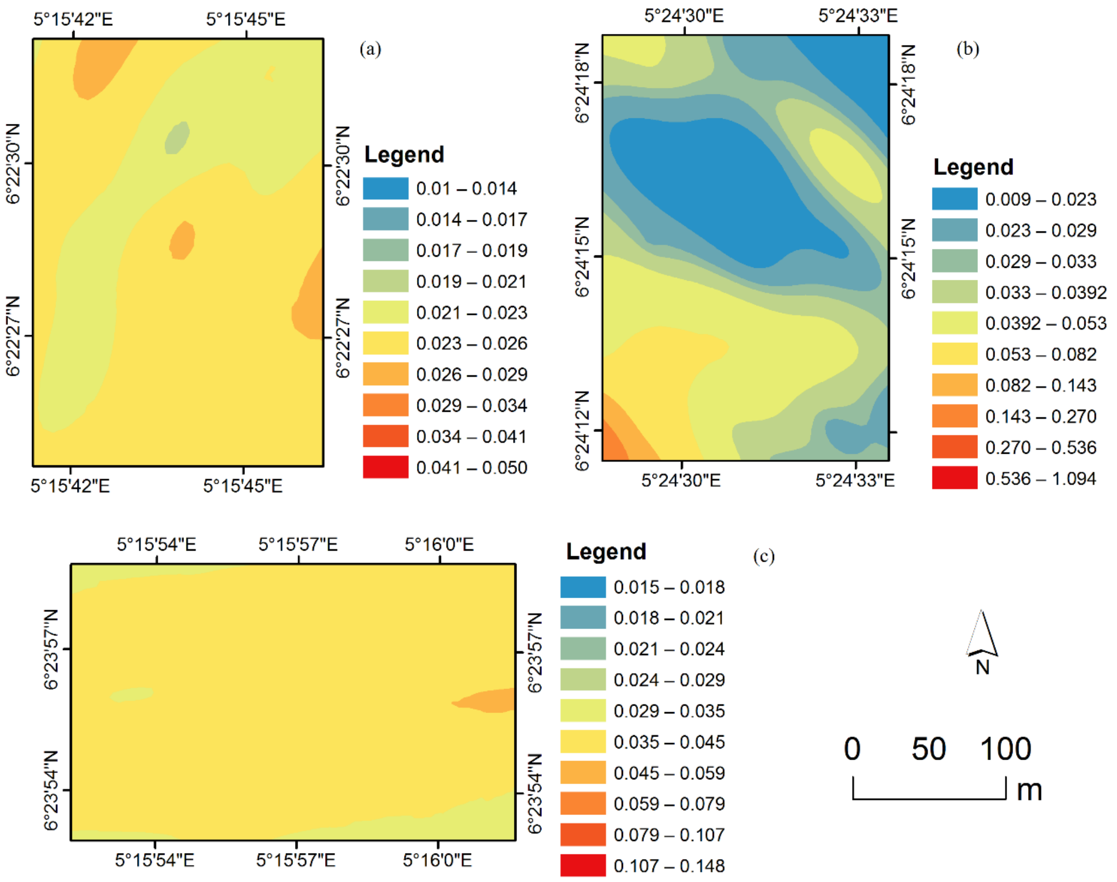

Figure 7.8: Predicted spatial pattern of topsoil exchangeable calcium (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

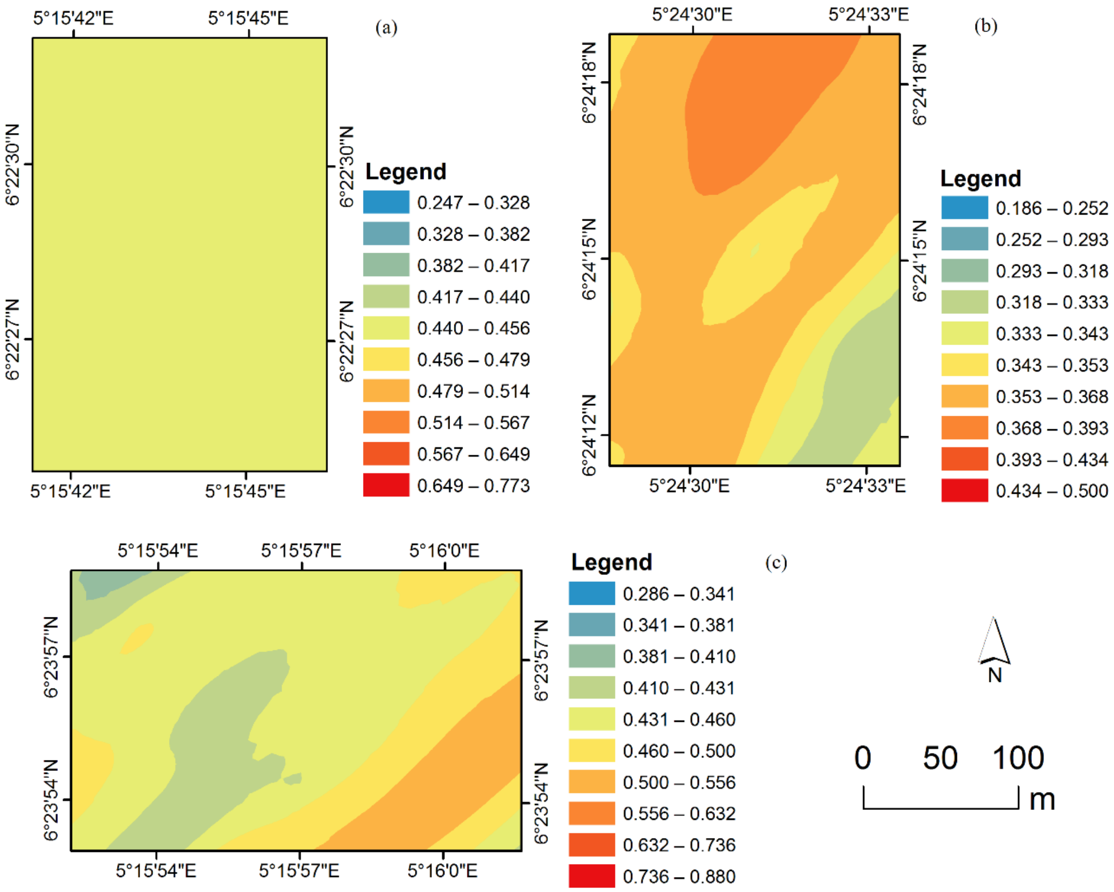

Figure 7.9: Predicted spatial pattern of topsoil exchangeable magnesium (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

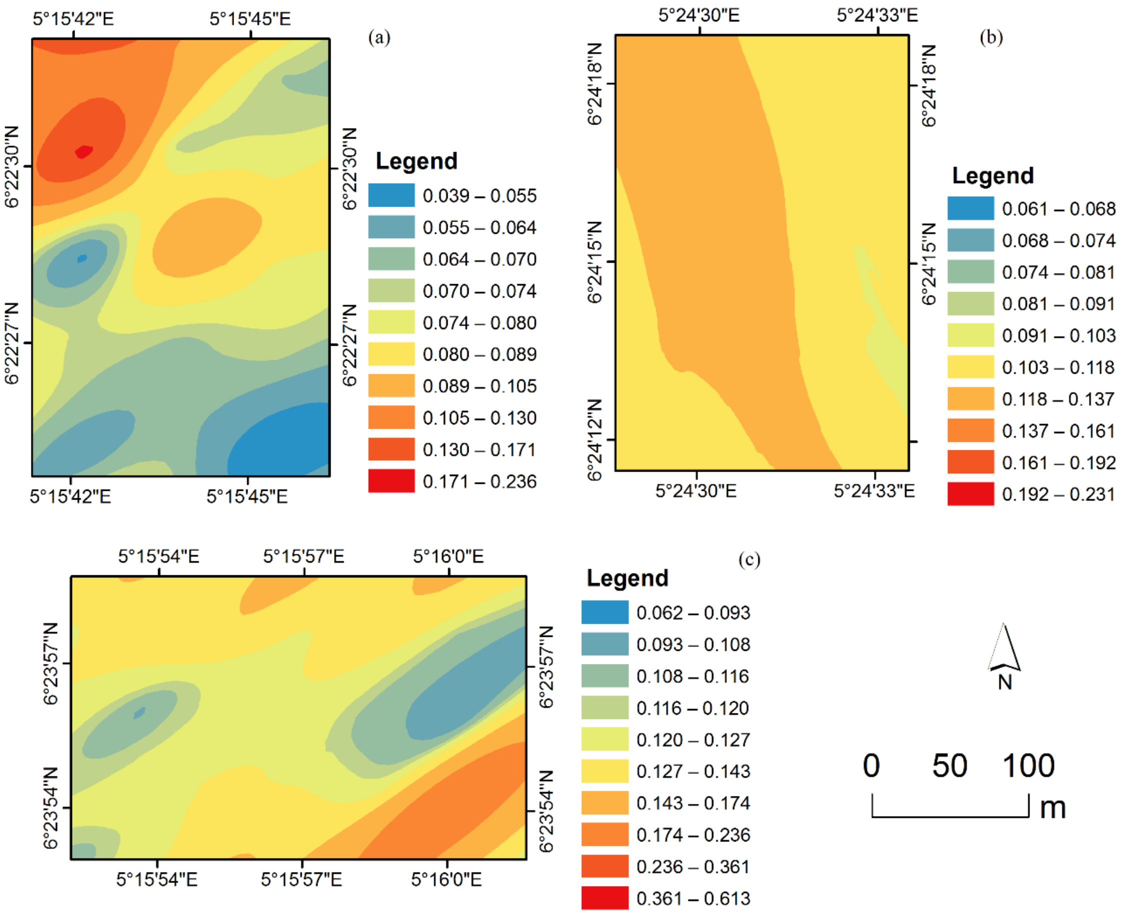

Figure 7.10: Predicted spatial pattern of topsoil exchangeable potassium (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

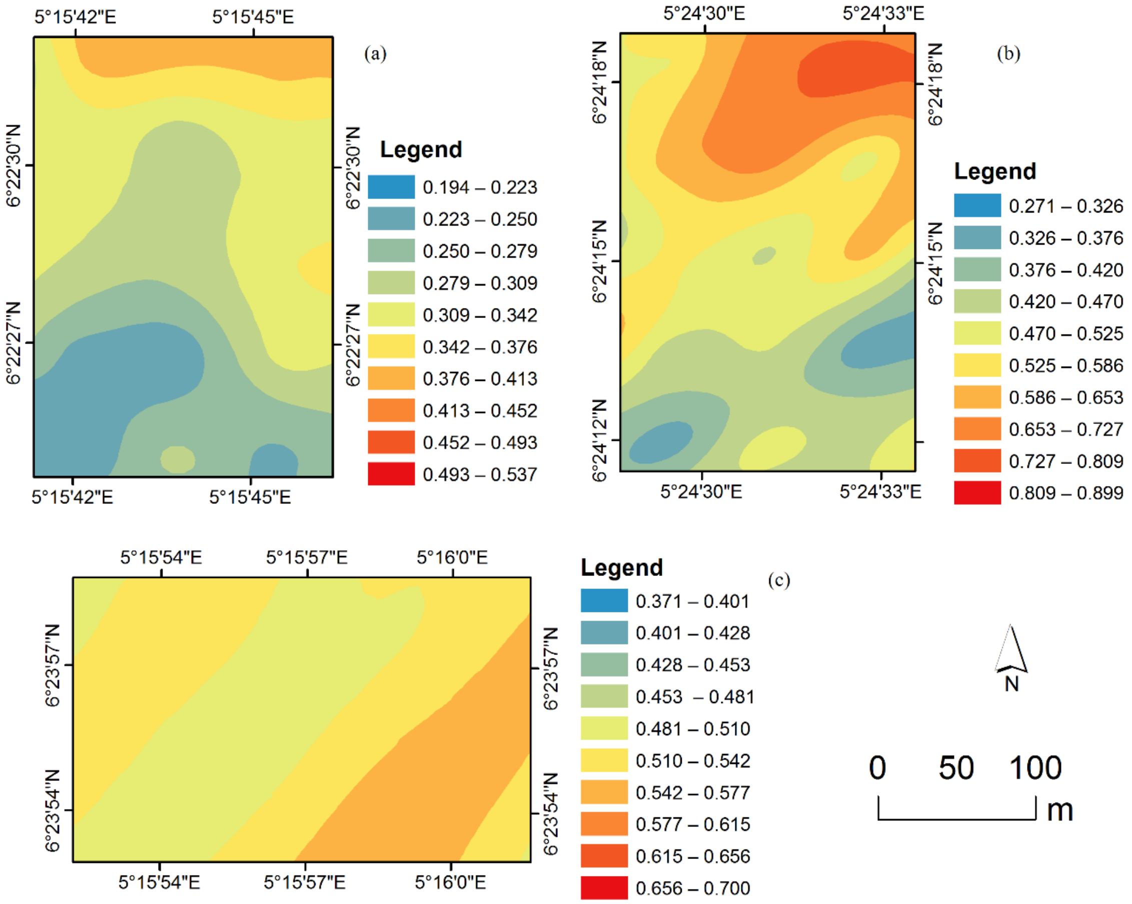

Figure 7.11: Predicted spatial pattern of topsoil exchangeable sodium (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

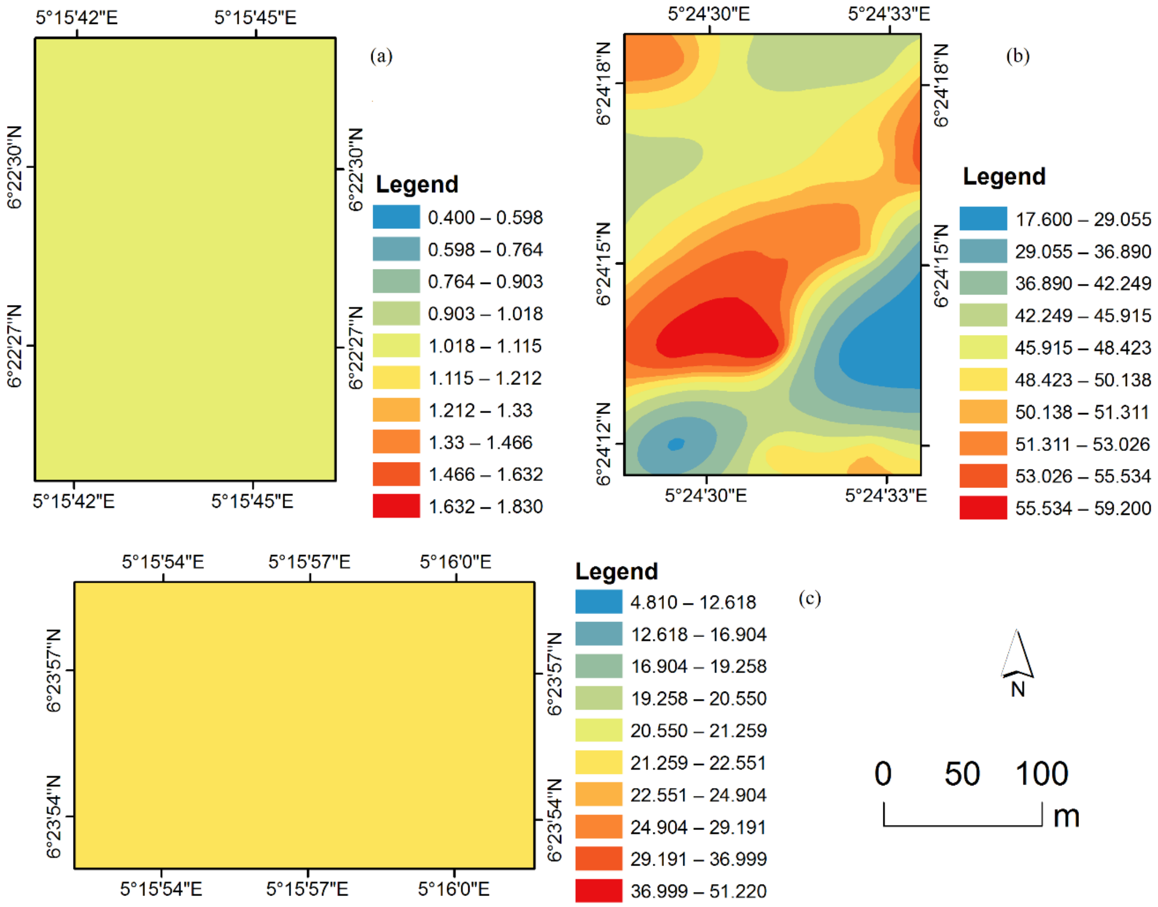

Figure 7.12: Predicted spatial pattern of topsoil exchangeable aluminum (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

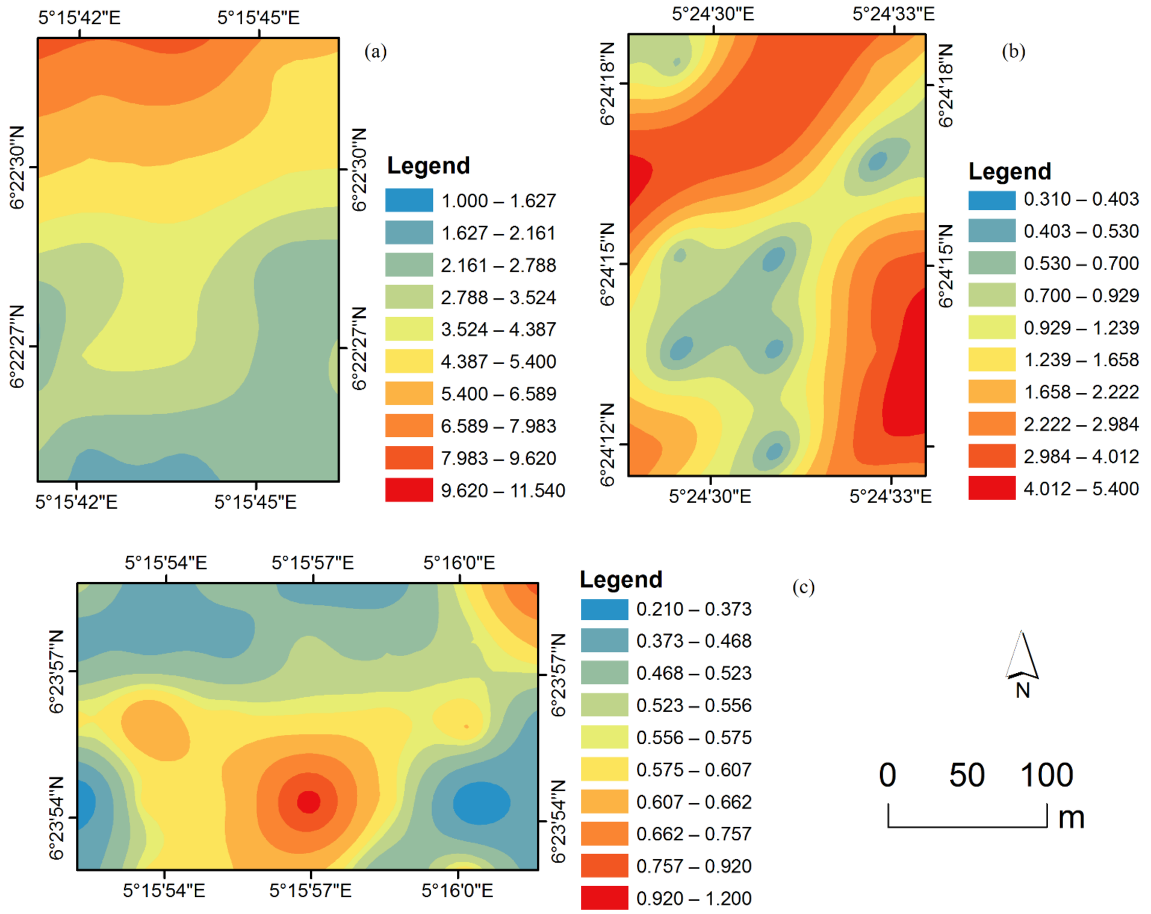

Figure 7.13: Predicted spatial pattern of exchange acidity (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

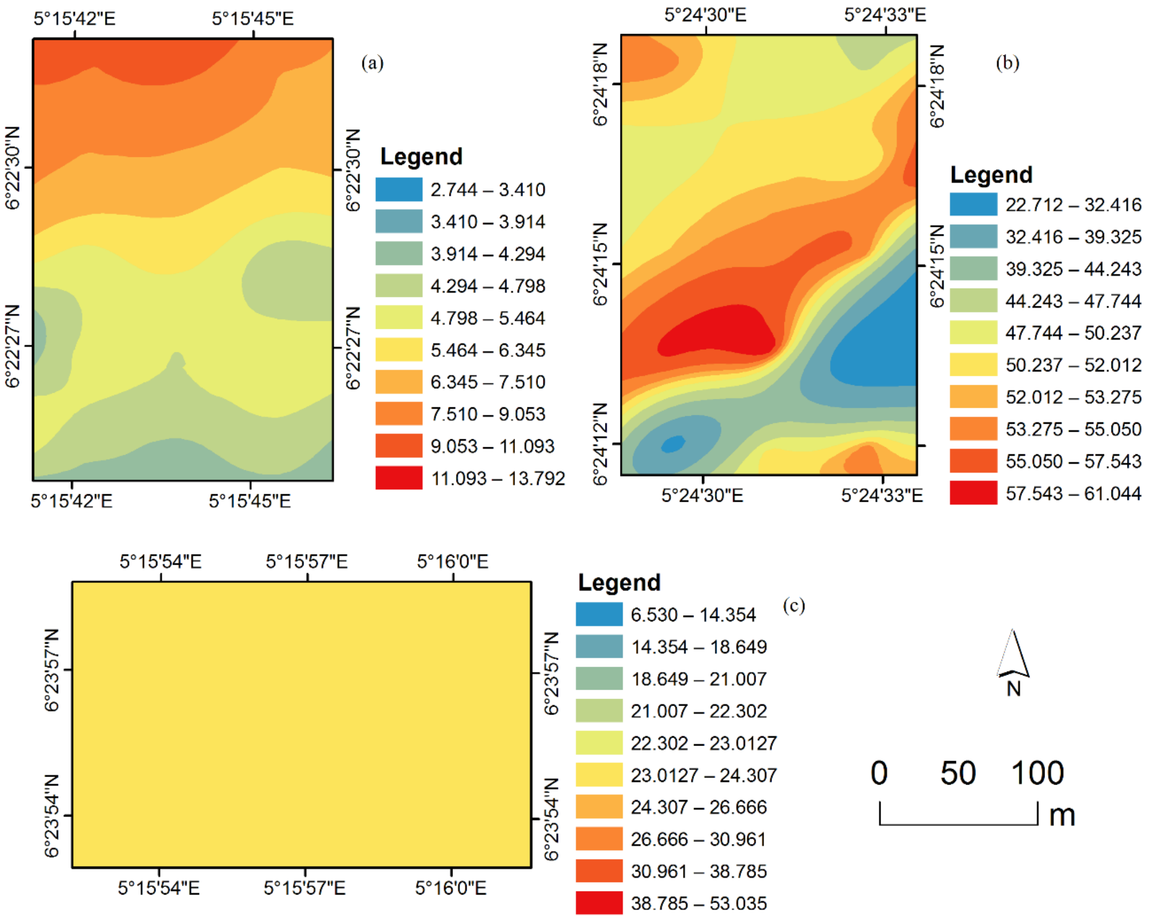

Figure 7.14: Predicted effective cation exchange capacity (cmol/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

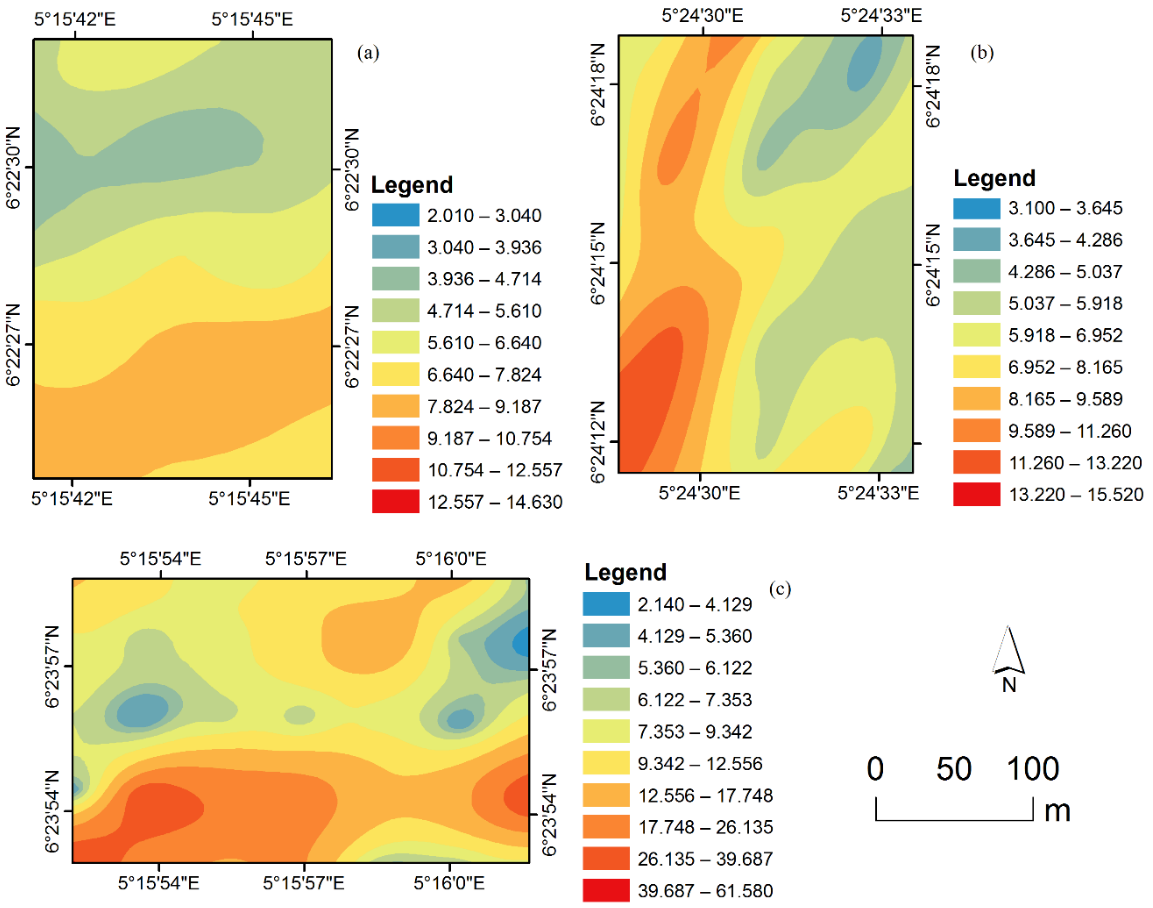

Figure 7.15: Predicted spatial pattern of extractable manganese (mg/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

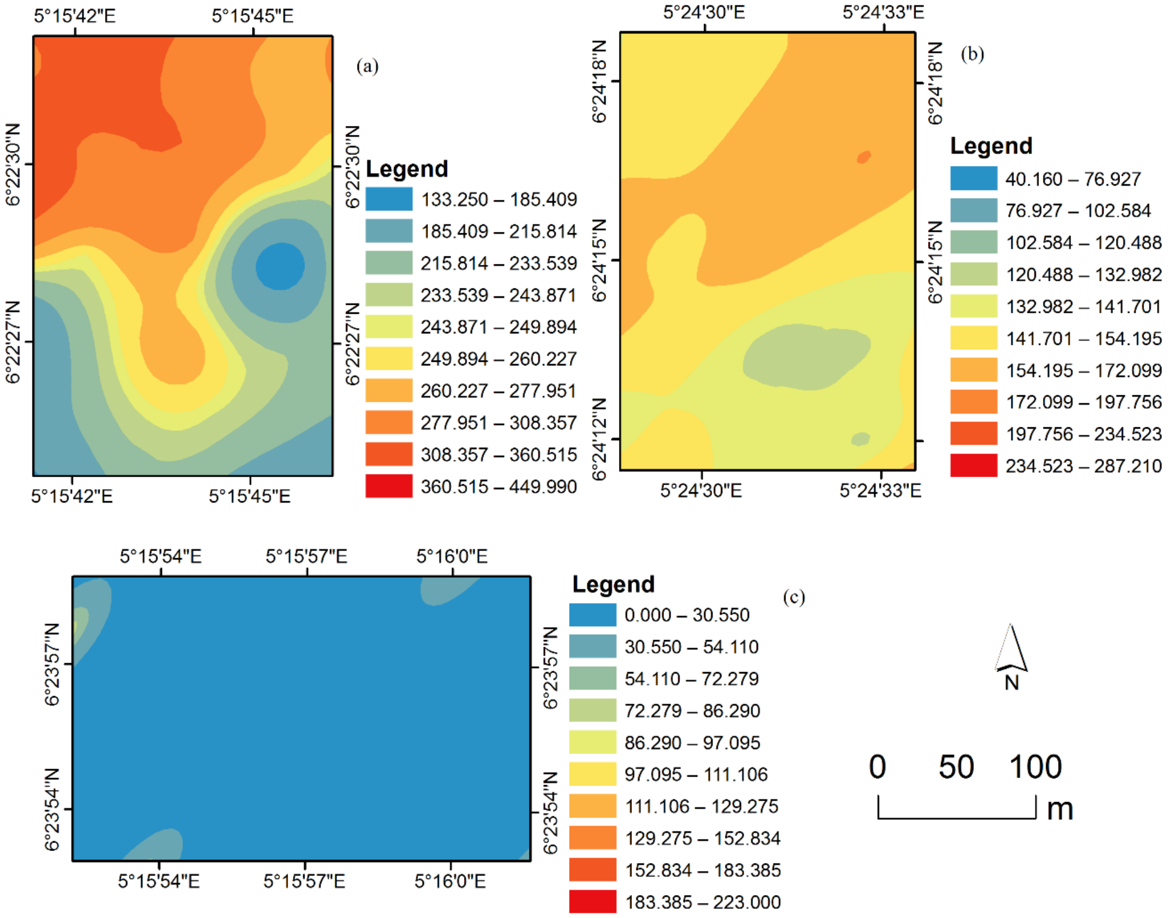

Figure 7.16: Predicted spatial pattern of extractable iron (mg/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

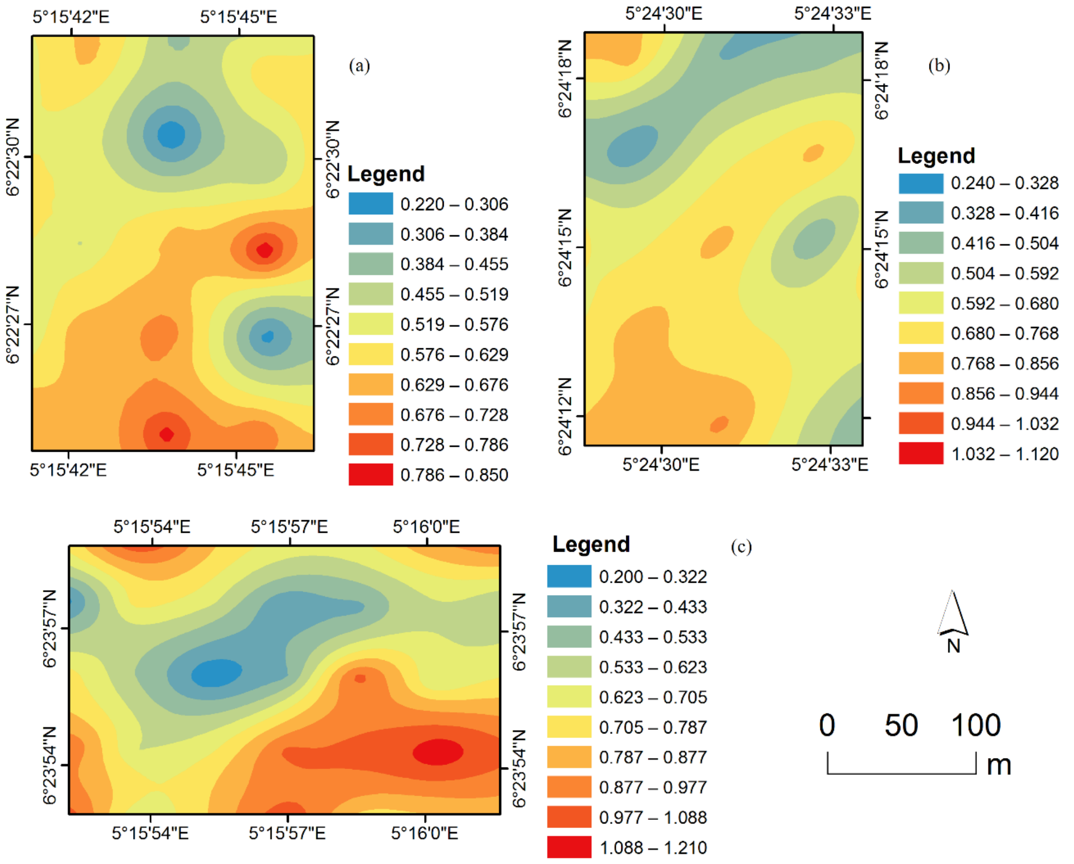

Figure 7.17: Predicted spatial pattern of extractable copper (mg/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

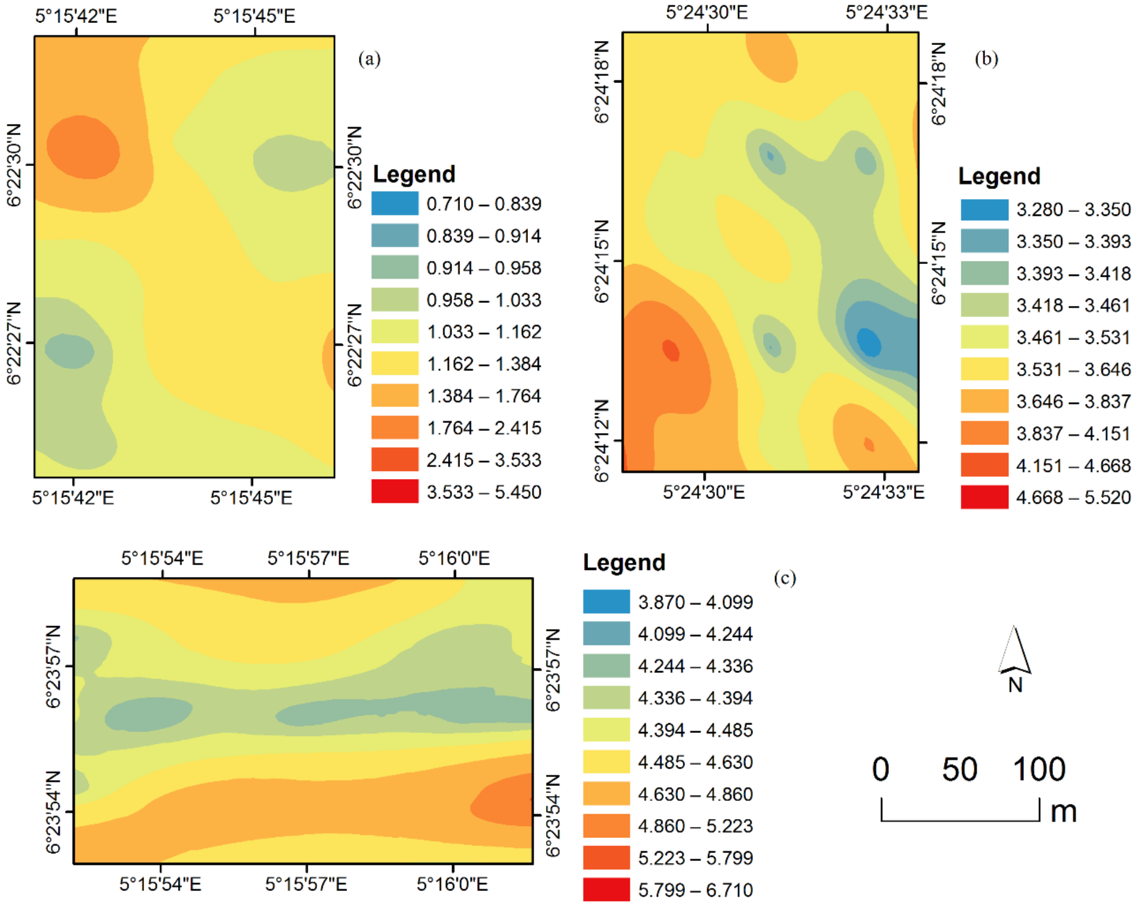

Figure 7.18: Predicted spatial pattern of extractable zinc (mg/kg) under (a) rainforest; (b) rubber plantation; (c) oil palm plantation at Okomu Forest Reserve (Source: Data analysis, 2016)

pH values in the plantations generally range between 3.0 and 4.0 while the values range between 2.0 and 3.5 in the rainforest.

Spatial variability of soil organic carbon in rainforest and rubber plantations is strong while it is low in oil palm plantation soils. Variability of soil organic carbon is marked in the upper slope in rainforest though no clear pattern is observed in rubber plantation. Pockets of strong organic carbon variability exist in the middle and lower slope positions. Low spatial variability of organic carbon exists in oil palm plantation. As with soil organic carbon, total nitrogen shows low spatial variability in the oil palm plantation, low concentration in the lower slope position in rainforest and weak spatial variability in rainforest and rubber plantation.

There is greater spatial variability of available phosphorus under rainforest and oil palm plantation than in rubber plantation. Exchangeable calcium shows low spatial variability in rainforest and oil palm plantation and moderate variability in rubber plantation. A similar pattern is observed for exchangeable magnesium under the rainforest and oil palm plantation. Exchangeable sodium, however, shows a more marked spatial variability in the rainforest than in the plantations. Low spatial variability is observed for exchangeable aluminum in the rainforest and oil palm plantation while a strong variability pattern is shown in rubber plantation.

The spatial variability of exchange acidity is more marked under rubber plantation than in rainforest and oil palm plantation where the spatial variability is moderate. Effective cation exchange capacity exhibits low spatial variability in oil palm plantation and a marked spatial variability in rubber plantation and rainforest. The spatial variability of soil micronutrients is generally strong in the rainforest and plantations. While the variability of extractable iron is marked in the rainforest, it is low under oil palm plantation.

The variation in the pattern of predicted soil physical and chemical properties may be linked to the nature of nutrient recycling in the rainforest and plantations. For instance, the seasonal shedding of rubber leaves is a mechanism of nutrient recycling to the soil as nutrients in the leaves are released into the soil when these leaves are decomposed on the soil surface. Oil palm fronds decay more slowly than forest and rubber leaf litter. Consequently, nutrients are immobilized in oil palm fronds for a longer period than forest and rubber leaf litter. Also, rates of nutrients uptake from the soil and storage in the standing tree biomass vary among rainforest, rubber and oil palm plantations.

The prediction and mapping of nutrient distribution is important in precision agriculture. The use of geostatistical techniques offers an efficient and cost effective method of land assessment for agricultural purposes as it gives an indication of the spatial distribution pattern of soil nutrients in a landscape which can be an important consideration for soil management planning. Areas with low nutrients can then be targeted for more nutrients input than areas with high nutrient values.

CHAPTER 8

SUMMARY AND CONCLUSION

8.1 Summary

The cyclical nature of the interaction between soil and plant is well established and documented in the literature. Consequently, the conversion of the tropical forest to agricultural plantations changes the soil-plant dynamics. Understanding the changes in soil properties variation because of the conversion of tropical forest to large-scale agriculture is of practical importance for sustainable management of soil and other agricultural inputs such as fertilizer and irrigation water.

This study was carried out with the aim of analyzing the influence of tree plantation agriculture on soil properties variability in Okomu Forest Reserve. It also determined the impact of topography on the spatial pattern of tree parameters under rainforest; the impact of topography, tree density, tree height and diameter-at-breast-height on soil properties variation; characterized the soils under rainforest and plantations of oil palm and rubber in Okomu Forest Reserve; and analyzed the impact of differences in land use and topography on the spatial variability of soil physical and chemical properties under rainforest and tree crop plantations.

It was observed that topography has a significant impact on tree height, diameter-at-breast height and tree density in the rainforest. However, while tree height was significantly different among the three slope segments, tree diameter-at-breast height under oil palm plantation is not significantly different at different topographic positions. Under rubber, tree height and diameter-at-breast height did not differ significantly. Tree height, diameter-at-breast height and density under rainforest generally increased downslope. Shannon-Weiner's index of diversity indicates that Okomu Forest Reserve has a high species diversity which is observed to be significantly influenced by elevation.

Canonical correlation analysis shows that topography influences the relationship between soil properties and vegetation parameters at various soil depths. Monte Carlo permutation test shows that first canonical axis, which is defined by ECEC, exchange acidity, organic carbon, total nitrogen and extractable iron, has a significant influence on the soil-vegetation relationship in the topsoil layer under rainforest ecosystem. The first axis of the subsoil layer, defined by ECEC, exchange acidity, total nitrogen and organic carbon, contributed 61% of variance while the second axis of subsoil layer accounted for 21%.

In soils under oil palm plantation, the first canonical axis of the topsoil is defined by extractable iron, exchangeable aluminum, ECEC, calcium and exchange acidity. It accounts for 97% while the second axis, extractable manganese, extractable zinc, pH and exchangeable sodium, accounts for 3%. The first canonical axis of the deep subsoil layer under oil palm plantation is defined by extractable iron, percent sand, exchangeable sodium, potassium and clay and it explains 96% of variance. The first canonical axis of the topsoil layer under rubber plantation, defined by percent soil organic carbon and extractable copper which accounts for 97% of total variance. In the subsoil layer, the first axis is defined by exchangeable aluminum, percent organic carbon, exchange acidity, calcium and clay which explains 97% of total variance while the first axis of deep subsoil layer accounts for 97%. It is defined by extractable iron, pH, extractable manganese and calcium.

Spatial variability is a natural feature of many components of the physical environment. This study has shown that the coefficient of variation and spatial variability of soil properties under rainforest and tree plantations is influenced by slope position, soil depth and land use. In addition, the conversion of the rainforest to plantation agriculture is observed to alter the spatial variability of soil physical and chemical properties especially in the topsoil layer. Specifically, soil organic carbon, total nitrogen, exchange acidity, and effective cation exchange capacity are more homogenous in the rainforest soil than under the tree plantations. The tree plantations therefore increased the heterogeneity of the soil in the tropical rainforest though this is limited to the topsoil layer. It is also shown that soil physical and chemical properties are more homogenous under rubber plantation than under oil palm plantation. The student’s t-test reveals that the spatial variability is greater under rubber plantation than it is under oil palm plantation.

8.2 Conclusion, Recommendations and Policy Implications

The results of this study show that soil physical and chemical properties variation is influenced by topography, soil depth and land use. Okomu Forest Reserve is characterized by high biodiversity, however, its conversion to plantation agriculture may have resulted in the loss of much of its flora and fauna diversity. The conversion of the tropical rainforest to plantation agriculture also has significant impacts on the spatial variability pattern of soil physical and chemical properties.

This study has shown that tropical rainforest conversion and landscape parameters influence the spatial pattern of vegetation parameters and soil physical and chemical properties under rainforest and tree plantations. It also showed that variation in landscape characteristics, soil depth and land use/land cover affect the spatial variability of soil physical and chemical properties under rainforest and tree crop plantations.

The major incentive for large-scale plantation agriculture is economy of scale which is expected to lead to increase productivity. However, the maps of soil properties variability under the different land uses show varying degrees of soil spatial variability. The conversion of the rainforest to tree plantations tend to result in changes in soil properties variability influenced by tree type and topography. Topography and type of tree crop plantation are therefore important considerations when management strategies are adopted for efficient utilization of agricultural input to achieve increase in yield per unit increase in input. This is because soil properties variation within a plantation is capable of compromising the expected gains in production.

Available phosphorus, exchangeable magnesium, potassium, extractable manganese, copper and exchange acidity exhibit moderate to great spatial variability under oil pam plantation. The application of phosphates, magnesium, potassium, manganese and copper fertilizers and liming should therefore be site-specific. The adoption of site-specific management of soil may not only result in increased yield, but can also lead to more sustainable use of soil resources by minimizing the effects of tree crop plantations on soil properties dynamics especially in the topsoil layer.

The conversion of the rainforest to plantation and other agricultural land has been shown to alter the pattern of soil spatial variability. This implies that different soil management practices need to be adopted in soils converted to agriculture and plantation than in the rainforest soils. This is an important consideration if sustainable utilization of soils is desired. The nature of soil spatial variability should be considered during the application of farm inputs such as fertilizer and liming.

In addition, the spatial variability of soil properties is important to soil scientists and researchers interested in soils. Soil sampling design should consider the spatial variability pattern of the soil properties as it has been noted that soil properties do not vary randomly across a large part of the landscape. In particular, the pattern of soil physical and chemical properties in oil palm and rubber plantations has been shown to vary with land use type and management practices. Therefore, in order to manage agricultural soil resources in a sustainable way, attention must be given to the specific soil requirements for tree plantations and the nature of the soil.

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