DETAILED SOIL SURVEY AND SPATIAL VARIABILITY OF SELECTED SOIL PROPERTIES IN UPPER KABETE CAMPUS FIELD, UNIVERSITY OF NAIROBI, KENYA

SAMUEL M. MWENDWA

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE

DEPARTMENT OF LAND RESOURCE MANAGEMENT AND AGRICULTURAL TECHNOLOGY (LARMAT)

FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

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This thesis is my original work and has not been submitted for award of a degree in any other University.

Signed: ……………………… Date: 10/01/2021……………

SAMUEL MWENDWA MUSYOKA

This thesis has been submitted with our approval as University supervisors.

Signed: ……………….. Date: 10/01/2021…………….

PROF. JOSEPH P MBUVI

Department of Land Resource Management and Agricultural Technology (LARMAT).

University of Nairobi.

Signed: ………… Date: 28/01/2021………………

PROF. GEOFFREY KIRONCHI

Department of Land Resource Management and Agricultural Technology (LARMAT).

Signed: ………… Date: 28/01/2021………………

PROF C.K.K GACHENE

Department of Land Resource Management and Agricultural Technology (LARMAT).

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Registration Number: A56/88965/2016
College: College of Agriculture and Veterinary Sciences
Faculty/School/Institute: Faculty of Agriculture
Department: Department of Land Resource Management and Agricultural Technology
Course Name: Master of Science in Soil Science.
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Dedication

For my family, for their love, prayers and support.

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List of abbreviations and acronyms

AAS - Atomic Absorption Spectrophotometer

CEC - Cation Exchange Capacity

CRF - Coffee Research Foundation

FAO - Food and Agriculture Organization

GIS - Geographic Information System

GPS - Global Positioning System

IDW - Inverse Distance Weighted

ITPS - Intergovernmental Technical Panel on Soils

IUSS - International Union of Soil Sciences

Ksat - Saturated hydraulic conductivity

KSS - Kenya Soil Survey

LUTs - Land Utilization Types

NARL - National Agricultural Research Laboratories

PA - Precision Agriculture

RMSE - Root Mean Square Error

SDGs - Sustainable Development Goals

SMU - Soil Mapping Unit

UN - United Nations

UNEP - United Nations Environment Program

USBR - United States Bureau of Reclamation

USDA - United States Department of Agriculture

UTM - Universal Transverse Mercator

WRB - World Reference Base

GENERAL ABSTRACT

The study area exhibits a first-class catena having homogenous parent material and forming a spatial continuum. This study aimed to classify the soils using a geopedological approach which involves a strong relationship between pedology and geomorphology. The area was delineated into Soil Mapping Units (SMUs) through augering into soils defined by different macro-relief. Mapping units were based on slope categories namely 0 to 5%, 5 to 8%, 8 to 16%, 16 to 30% and >30% connoted as flat to gently undulating (AB), undulating (C), rolling (D), moderately steep (E) and steep (F), respectively. Profile pits were dug in the five identified mapping units using Stratified Random Sampling technique. This technique was used because delineation was based on slope categories that acted as stratum within which profile pits were dug. Identified SMUs include UmIr/F, UmIr/E, UxIr/D, UxIr/C and UxIr/AB in the order of decreasing slope gradient. The first entry represents the physiographic unit (Uplands, U), followed by physiographic position (lower middle uplands, m or uplands, undifferentiated levels, x), geology (I), colour (r) and slope class, respectively. Topographic influence on soil properties was presented by Pearson's correlation coefficient (r) with p-value included where the influence was significant. Statistical analysis was done using SPSS software for correlation and descriptive statistics. All the map units were well drained and deep to very deep (>80 cm). The colour of the upper B horizon was predominantly dark reddish brown. The texture of top horizon was clay in UmIr/F and UmIr/E and clay loam to clay, sandy clay loam to clay and loam to clay loam in UxIr/D, UxIr/C and UxIr/AB, respectively, lucidly exposing the influence of topography on the depth of clay illuviation (clay: $r = 0.724$; $p \leq 0.01$). Clay in the top horizons ranged from 24 to 66%. The structure was predominantly subangular blocky throughout the profiles with the top horizon of cultivated areas having predominantly granular structure. Saturated hydraulic conductivity (Ksat) generally decreased with increasing clay content down the profiles and the bulk density ranged from 0.9 to 1.2 gcm^{-3}. Means of soil reaction of top horizons generally slightly decreased with decreasing gradient ($r = 0.231$) having lower values in cultivated areas. Percent organic carbon regularly decreased down the profiles with higher values in uncultivated, steeper areas ($r = 0.521$; $p \leq 0.05$). It ranged from 1.66 to 4.03% in the top horizons. In the top horizon: Total nitrogen was predominantly medium across the study area ranging from 0.2 to 0.56% ($r = 0.185$) and followed the organic carbon trend; Available phosphorus was deficient (<20 ppm) in the study area. Bases were sufficiently to richly supplied while micronutrients were richly supplied. The Cation Exchange Capacity (CEC) was predominantly medium across the profiles ranging from 15 to 27.6 cmol(+)/kg with values increasing slightly with increasing slope (r = 0.320). Based on data collected from description of the profiles and physicochemical data of the soils and according to IUSS Working Group WRB (2014) soil classification legend, the soils were classified as Mollic Nitisols. The findings of this study show that the geopedological approach to soil characterization is valuable in soil management. Spatial variability of soil properties was investigated in a selected farm (Field 3). Selected soil properties varied spatially in the field which indicates the need to blend fertilizers with targeted nutrients. Variable input application is also recommended. Soils of the study area are generally fertile for crop production but application of organic manure is recommended to buffer the acidic soil reaction and to improve nitrogen and phosphorus sources. Organic sources will help in efficient use of these nutrients and also improve soil resilience.

Keywords: First class catena, Soil Mapping Units, Stratified random sampling, Mollic Nitisols, Spatial variability.

CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background information

Soil is a natural system comprising of different forms of matter on the earth surface, occupies space and has horizons distinguishable from the genetic petrography due to the effect of additions, losses, translocation and transformation of energy and matter or the ability to support rooted plants in a natural setup (Soil Survey Staff, 1999). Soil is the natural medium for plant growth whether or not it has discernible horizons (IUSS Working Group WRB, 2006; Soil Survey Staff, 1999). The art of soil survey and classification involves delineation of soils into relatively distinct classes that require comparatively similar management practices (Brevik et al., 2016; Cullum et al., 2017; Minasny and McBratney, 2016). A detailed soil survey involves the use of large scale and elaborate mapping to demarcate the lowest categories. Approximately 15% of the world's population is categorized as food insecure (FAO et al., 2017; FSIN, 2018) therefore there is need for soil characterization, land evaluation (Mwendwa et al., 2019) and precise input application to meet this challenge.

Soil characterization helps to predict the behaviour of different soils and present the results in a language understandable by scientists worldwide (Brevik et al., 2016; Hartemink, 2015). This helps to relate the physicochemical characteristics of the soil at a site to the climate, landscape position, petrography, vegetation, time and human influence and to predict the performance of crops that should planted.

Environmental research requires spatial, high resolution and quantitative data distinguishing variability in the soil profile so as to analyse problems of climate change, desertification and low food productivity. Soil surveys characterise, classify, map and predict possible changes in soil properties under different uses (USDA, 2014). It is a process of determining soil patterns, characterizing and presenting the trend in a way understandable by policy makers for planning. Proper land use planning and knowledge on how soil properties vary in space and time is therefore necessary. This planning requires a good understanding of the environment including soils, climate, geology, geomorphology and the land utilization types to be envisaged (Dent and Young, 1981).

1.2 Statement of the problem

Most of the land in Nairobi area has been engulfed by settlement due to increasing urban population and therefore there is need to map the remaining area in details so as to characterize the soils for crop production. There is need for precise application of agricultural inputs to maximise yields alongside envisaging high value crops where they best fit so as to accrue benefits. Agriculture is the most important economic activity in Kenya (UNEP, 2015) but soil fertility, water shortage, biodiversity loss and climate change pose the greatest challenges to our agriculture (FAO and ITPS, 2015). Taxation on agricultural inputs coupled with deleterious impacts of climate change and pests have led to low productivity due to high cost of inputs and crop failure (Kurukulasuriya et al., 2013). Global organizations like the United Nations have designed Sustainable Development Goals (SDG's) aiming to combat poverty, reduce desertification and curb climate change which are related to the natural environment, agriculture, sequestration of carbon, soil maintenance and biodiversity conservation. The importance of soils in achieving these goals has been highlighted by Keesstra et al. (2016). Specific models have been used to estimate runoff (Borrelli et al., 2016), soil conservation and crop performance. These studies need adequate and high quality data describing the soils and the environment (Brevik et al., 2015) but the problem is lack of coherent, high resolution data on soils in many areas (Sanchez et al., 2009). This study aimed to close that gap.

There is evidence of sub-optimal land use in Kabete as evidenced by rough grazing in the area that could be used for pasture and irrigated using water that flows by gravity from hostels and the kitchen. The use of soil surveys today has been far below their potential partly due to problems of credibility and communication between producers and users of soil reports. Many countries have not devoted significant efforts in research to soil survey exercises; for example, there is limited research effort in Kenya in the subject of soil survey and land evaluation which has led to inappropriate land utilization practices. Soils in Upper Kabete have the same geology and formed under the same climatic conditions but can be differentiated by slope classes into soils having different properties, management requirements and production potential. There is need for knowledge on how soil characteristics vary spatially so as to maximize crop production using optimum inputs.

In this study, spatial variability was based on chemical parameters so that recommendations based on generated management zones could be practical. Chemical parameters entail soil fertility therefore the recommendations would be on how to improve the fertility. Physical properties could be used but some including texture are not easily manipulated. Contents of nitrogen, phosphorus and potassium are seasonal soil properties which are only useful for short term planning but cannot predict the sustainability of the field in long term when used for specific agricultural and engineering purposes. Their use is however required for presentation of soil fertility maps. There is need to take agriculture as a business to ensure less expenditure on agricultural production, sustainability, employment and environmental conservation. This can be done by ensuring that there is benefit from inputs invested in farming. There is need to have a practical training ground for other students who can use the findings of this study for their future research.

1.3 Justification of the study

Knowledge gained from this study will enable more accurate decisions to be applied for specific purposes that would not have been made without point based soil information. The study will also enable more explicit scientific communication and expose the need to classify soils to the scientific world for proper land utilization. It will be useful to other disciplines in determining the best soil condition for a certain activity, choice of working tools, soil water management and nutrient management. The data will be used in land use management, improvement of land utilization and for environmental conservation for example erosion control. Future scientists can identify gaps from this study then design new research ideas using more advanced technologies which is an aspect of capacity building for national development. This research will help to guide investments in land use for the benefit of mankind and to conserve the environment for future generations. Upper Kabete is characterized by heterogeneous physiography therefore there is expectation of differences in soil properties as a function of the non-uniform topography.

Soil mapping will ensure minimum input, maximum output and a sustainable system over many years. This sustainability can be tested over time using indicators including carbon and cation exchange capacity. The resulting document will act as a guide towards achieving vision 2030 and as a foundation for subsequent researchers including soil scientists and agronomists who will be conducting studies to test the influence of topography and other factors of soil genesis on soil properties. Students who will build their foundation on findings of this study could benefit from student assistantship programs to further their studies because this will be a progressive study aimed at improving and working towards feeding the nation. The university will have a reference material in the findings of this study that can be used for training in modern agriculture. This is because the skill on how to practically do soil survey can be applied in subsequent soil surveys. This study will be a reference material in the area of soil survey and soil genesis whereby very few studies on the subject have been done. It will guide future researchers on the concept of soil survey and soil genesis and the approach to undertake it.

1.4 Objectives

1.4.1 Broad objective

To characterize soils of upper Kabete campus as a guide to maximize crop production.

1.4.2 Specific objectives

1. To map, characterize and classify the soils of the study area using a geopedological approach.
2. To evaluate spatial variability of selected soil properties as a guide to precise fertilizer and manure application.

1.5 Research questions

1. How does topography influence soil properties and distribution in a landscape?
2. What is the spatial variability of selected soil properties in the study field?

1.6 Thesis structure and format

This thesis adopts a paper format version having a general abstract, general introduction as chapter one and general literature review as chapter two. Specific objective one appears as chapter three while specific objective two appears as chapter four. Each chapter has conclusions and recommendations. All references are placed at the end just after general conclusions and recommendations.

CHAPTER TWO: GENERAL LITERATURE REVIEW

2.1 Soil Survey

A soil survey entails systematic examination and generation of soil maps of a given area (Dent and Young, 1981) to serve as a means of communication (Hartemink, 2015; Krasilnikov et al., 2010). Soil survey characterizes the soils following standard guidelines, plots boundaries, classifies the soils, stores soil properties data, predicts the suitability for various land utilization types, limitations to production increase and provides knowledge about likely impacts on management practices (Bui, 2004). Soil survey is rooted in scientifically sound principles vividly elucidated by factors of soil genesis and the interaction among landscape features, landforms and soils (Hudson, 1992). This relationship predicts soil patterns in the landscape and the factors of soil formation condition the genetic development of soil profiles. Soil surveys show how soil properties are distributed spatially in an area and presents the variability in maps and reports. Based on the soil characteristics described, it is possible to determine the most appropriate use in terms of agriculture and environmental conservation. The findings of a soil survey help in land use planning. Soil surveys help in the use of the land in ways that are ecologically sound (Soil Survey Staff, 2016). Where land degradation is an issue, findings of a soil survey will be the basis of predicting preventive measures. In long term monitoring of soil characteristics, reviewing previous surveys' work would be of great importance.

A basic classification system for execution and interpretation of soil inventories was proposed by the Soil Survey Staff (1975). This system established class limits of taxonomy and respective quantitative definitions such that a reference soil group could belong to only a single class and marked the end of the use of soil genesis to directly classify soils. Diagnostic horizons and morphological expressions of key genetic processes became the basis for soil classification. Many systems adopted this technique, notably the World Reference Base (WRB) for soil resources (IUSS Working Group, 2014). Soil maps provide detailed spatial data on physico-chemical soil parameters in the different mapping units and horizons. The maps also show the pattern of land use especially when describing the soils in the field. Research has shown that through interpolation, soil functions in any given area can be deduced from the soil characteristics (Calzolari and Filippi, 2016; Lehmann and Stahr, 2010).

In soil classification, morphological features of surface material may be distinct from the underlying parent rock therefore to describe land suitability at these areas, profile pits should be dug to a considerable depth. Another point of concern is the relatively permanent nature characteristic of physical properties, information at temporal scales appears identical. However, this character of physical properties is beneficial since chemical properties change within a short time span and would make soil survey time consuming and very problematic (Hall and Olsen, 1991). Again, some parameters have to satisfy some additional criteria so as to be evaluated easily in the field; for instance, soil consistence can be estimated by the feel method, which is accurate for the purposes of soil classification. However, for hydraulic conductivity and leaching, classical laboratory techniques are most appropriate.

To estimate dynamic properties of soils, data on available inherent soil parameters should be used as a basis. Correlations designated as transfer functions were developed for instance to correlate soil structure and the content of humus with its hydraulic conductivity (Hall and Olsen, 1991). These functions are applied to systematically predict how hydraulic conductivity varies in space in a given area and data modelled to produce interested estimates. Ecosystem services are determined by three key properties of soils including texture, organic matter and mineralogy (Dominati, 2013) which are usually presented in soil reports. These three key properties can be used to deduce other soil characteristics. However, as many parameters as possible are used by researchers as well as information in digital maps in conjunction with other spatial techniques to classify soils over continuous and discontinuous extent.

Spatial variation of soils is not random but rather decreases as distances diminish between sample points in space (Webster, 2000). Natural mapping units result from climate and vegetation acting on parent material with slope exerting a modifying influence over time for pedogenesis to occur (Hudson, 1992). Soils tend to be characteristically similar in different places having similar environmental conditions and this forms the basis for prediction of the locus of different soil types. This is the fundamental principle that makes soil survey exercises practical (Hudson, 1992). The influence of factors of soil formation on soil properties becomes more apparent with increasing scale when small areas are examined in detail (Dematte et al., 2013).

Soil characterization is a comprehensive elucidation of the potential productivity of a given field (Rossiter, 1996). Improved crop production could be achieved through systematic soil survey to evaluate their potential for different alternative uses that are environmentally sound (He et al., 2011; Sathish and Niranjana, 2010). Soil maps provide a key basis for land suitability analysis and despite detailed maps with good resolution being scanty, attempts to overcome this difficulty have been expensive (McKenzie et al., 2000). Map units comprise homogeneous soil and since land characteristics are spatially variable over very fine scales, there is need for detailed soil surveys (Emadi et al., 2008).

Unused good agricultural land is scarce leading to marginally suitable areas being converted into agricultural lands due to increasing demand for food with the increasing population (Van Keulen, 2006). Yields can be improved by increasing production per unit area or by increasing cultivated area with the latter being in real sense impracticable. Different plants require different soil conditions for optimum performance and different rooting depths calls for different soil conditions. Availability of water and nutrients in the soil largely influences crop production (Edwards and Hailu, 2011). The ability of some plant species to succeed in specific environments where other species fail has been studied by many scientists. Soil maps help in evaluating land for suitability of various crops as well as identifying sites for location of structures.

2.2 Types of soil surveys carried in Kenya

2.2.1 Exploratory soil survey

It is done at scales of 1:500000 and 1:1000000 to establish major soil regions for agricultural development and research planning. The composition of the mapping units is done by mapping representative ideas and like areas by interpretation of remote sensing data. The soils are verified by occasional onsite investigation or by traversing. These are not soil surveys in strict sense but generally consist of terrestrial or airborne information of unknown areas. It is comparable to the 5th order soil survey USDA or the exploratory Soil Survey (Sombroek et al.,1982; Mbuvi J.P, personal communication, February 20th, 2018).

2.2.2 Reconnaissance soil survey

This type of survey was used to map the soils of Kisii area under a training exercise in pedology by the Kenya soil survey in 1982 (Wielemaker and Boxem, 1983). It is done at scales of 1:100000 for high and medium potential areas and 1:250000 for low potential areas as a systematic inventory of the soil resources of the whole country for multi-purpose land use planning and pre-investment studies for river basin development emphasizing on soil and water conservation and irrigation purpose. Mapping units include singular soils, their associations as well as their soil complexes as identified within the physiographic units, allowing 30% or less dissimilar soils as inclusions. Inclusions are not named on the map legend but are described in the soil report accompanying the soil map. Use of photo interpretation is the principal work tool. The observation density depends on the soil geography, usefulness of aerial photographs, objectives of the study, familiarity with the survey area and skill of the surveyor. At a scale of 1:100000, one observation for every 100 to 400 ha while at a scale of 1:250000, one observation for every 625 to 2500 ha are suggested (Mbuvi J.P, personal communication, February 20th, 2018). It is comparable to the 3rd and 4th order soil surveys of the USDA and low intensity soil surveys as defined by the FAO (isricu_i00006473_001.08.pdf, n.d.).

2.2.3 Semi-detailed soil survey

It is a grid survey (Mbuvi J.P, personal communication, February 20th, 2018) and was done to map the soils of Kiboko area at a scale of 1:50000 (isricu_i00006473_001.08.pdf," n.d.). It is executed at scales of 1:20000 to 1:50000 to obtain more detailed information than it is possible from smaller scale soil investigation and for single purpose land development for example land management, sugarcane and irrigation development studies. Mapping units include singular kinds of soil, their associations and complexes and their phases, allowing than 20% dissimilar soil as inclusions. Key methodology involves a combination of photo interpretation and field work. Observation density depends on the same variables mentioned under reconnaissance soil survey. The following densities are generally used: At scale 1: 50000, one observation for every 25 to 100 ha and at scale 1: 20000, one observation for every 4 to 20 ha (FAO, 1985; Mbuvi J.P, personal communication, February 20th, 2018). This kind of soil survey is comparable to the reconnaissance soil survey of the USBR and partly comparable to the 2nd and 3rd order soil survey of the USDA and to the medium intensity soil surveys of FAO (isricu_i00006473_001.08.pdf, n.d.). 2nd order level are more detailed compared to 3rd order level surveys. Mapping units in the 2nd order level are identified by field observation and remotely sensed data. The data is intensive and can be used for urban planning and general agriculture. Data for the 3rd order level has less field verification but is more remotely sensed compared to 2nd order levels. It is extensive and can be used for community planning and range development.

2.2.4 Detailed soil survey

An example is the detailed soil survey to map the soils of Kampi ya Mawe at a scale of 1:2500 for agricultural research (isricu_i00006473_001.08.pdf," n.d.). It is done at scales larger than 1:20000 with common final publishing scale being 1:10000 or 1:5000. The key purpose is farm planning, characterization of agricultural research sites or layout of irrigation schemes. The mapping units include singular kind of soil and their phases, allowing less than 10% of dissimilar soils as inclusions which in smaller areas is often indicated by spot symbols (isricu_i00006473_001.08.pdf, n.d.).

2.2.5 Site evaluation

The scale is variable depending on the purpose and it is done purposely for project identification and to diagnose soil-oriented problems for instance poor crop growth. Mapping units include physiographic units embracing major soils of the area, often associations or complexes allowing 30% or less of dissimilar soil as inclusions. Intensive field work is involved and this survey may be published at the same scale as any of the surveys mentioned above. However, the density of observations is usually far below the requirements as defined for semi detailed type of soil surveys (isricu_i00006473_001.08.pdf, n.d.). A good example is mapping of the Yala swamp for irrigation research by the Kenya Soil Survey (isricu_i00006473_001.08.pdf," n.d.).

2.3 Mapping scale

The scale of mapping is very critical in soil surveys. A larger scale leads to increasing details as more observations are made within an area. A study to compare results of different scales was done by Dematte et al. (2013) and found that variations in soil survey scale influenced the final results and land use planning with detailed soil surveys being the most important for decision making in agriculture. This study used a scale of 1:10000.

2.4 Overview of different classification systems

The two major classification systems include the Soil Taxonomy (USDA, 2014) and the IUSS Working Group WRB (Schad, 2017). The WRB is mostly used in Kenya because of the adaptation of its principles to the local conditions. The major difference between the Soil Taxonomy and the WRB system is that in the former, soil moisture regimes are used to define units at all levels. Problems are however encountered when delineating the boundaries of the soil moisture regimes. This problem is avoided when using the WRB system because Xerosols and Yermosols are ignored which is not practical in soil taxonomy as soil moisture regime occurs as a criterion in all levels. Therefore, each soil unit is classified twice in Soil Taxonomy, in the first place assuming the soil moisture regime is ustic and again assuming it is aridic. The particle size classes are predominantly fine-loamy to fine clayey and the soil temperature class for all units is isohyperthermic except for soils at higher altitude, which may be isothermic- case of this study.

2.4.1 Soil taxonomy

This system focuses on quantifiable soil characteristics rather than processes or factors of soil genesis but does not, however, exclude soil genesis. It aims to make characteristics of various soils easier to understand, to vividly expose the relationship among soils and between soils and associated environmental factors and to provide a platform for developing principles of pedogenesis and soil behaviour that have prediction value (Soil Survey Staff, 1975). This system has six categories in order of decreasing rank and increasing number of differentia namely Order, Suborder, Great group, subgroup, family and series. There are 12 orders differentiated by the presence or absence of diagnostic horizons, features marked in the soil or differences in the degree and kind of dominant set of soil forming processes (USDA, 2014).

2.4.2 The World Reference Base (WRB)

Taxonomic units in World Reference Base for soil resources are defined in terms of measurable and observable diagnostic horizons which are the basic identifiers in soil classification alongside diagnostic properties and materials (IUSS Working Group WRB, 2014). Selection of diagnostic properties and materials factors in their relationship with the factors and processes of soil genesis with more emphasis put on diagnostic features that are of importance for soil management. Background understanding of processes of soil genesis contributes to proper soil characterization but these processes are not in strict sense used as differentiating criteria.

Climate parameters are not applied in soil classification but are used for interpretation purposes. Soil classification is therefore not subordinated to availability of climatic data meaning that the name of a reference soil group remains valid despite change in global or local climate. The WRB system is comprehensive enough such that it accommodates national soil classification systems whereby soil description reflects variations in soil characteristics occurring vertically and laterally in the landscape. Traditionally used terms or terms that can be introduced with ease into the current language are retained in the nomenclature used to distinguish soil groups and defined precisely so as to avoid confusion that may occur when names with different connotation are used (Soil and Reports, 2014). This is the reason why the WRB was adopted in this study. The system has 32 major soil types.

2.5 Soil Sampling

Soil sampling is an important component of soil mapping as it determines the accuracy and cost of the mapping (Brungard and Boettinger, 2010). De Gruijter and Brus (2006) systematically elucidated the methods of spatial sampling and classified them into design-based sampling for instance stratified random sampling and model-based sampling for example geostatistical sampling. Various soil sampling techniques have been developed with the aim of obtaining the highest soil mapping performance with the least number of soil samples. The key goal of soil sampling is to accurately characterize the nutrient status of the soil in the cheapest way possible (Dinkins and Jones, 2008). To map spatial variability, sample locations are geo-referenced using a GPS to allow correlation of soil test results with spatial details of the soil sample.

An important issue is the operational challenge of the sampling methods because indoor design of sampling points is practically different from real field sampling. Kidd et al. (2015) stated that sampling predetermined coordinates is often difficult and time consuming because potential access constraints may prevent sampling at desired locations. These constraints include steep terrain, land use, land disputes and road blocks.

2.5.1 Stratified Random Sampling

The sampling location is spatially subset into different strata typically geographic information features including slope gradient, land cover type, slope aspect, landform and parent material. Random sampling is applied to each stratum for instance randomly establishing profile pits based on slope percentage classes. It is assumed that these strata are strongly related to the target soil features. Sampling regions may be set equally or in proportion to the area if the target feature is rare or easily observable, respectively (Kuhn and Johnson, 2013). Stratified random sampling is accurate and economical depending on the suitability of the defined strata which is again dependent on adequate prior knowledge of the target soil parameters.

2.5.2 Grid-point soil sampling scheme

It is mostly applied in precision agriculture and in investigating spatial variability within fields whereby soil samples are collected in predetermined grids. This scheme divides the field into cells and soil samples are taken from the intersections of the cells (Mallarino and Wittry, 2004). Pattern schemes in grid sampling include random composite, regular systematic point and systematic unaligned point (Franzen, 2011). Augering is done at cell intersections which are geo-referenced using Global Positioning System (GPS). Five to ten soil samples are taken from each point within the cell intersection within a circle of radius 3 meters from the point of intersection and composited (Crozier and Heiniger, 1998; Rehm et al., 2002). An interpolation method like spline, IDW or kriging can be used to develop a more continuous surface map representing both sampled and unsampled areas (Chang et al., 1999).

Grid sampling scheme compromises randomization to some extent; the first selected point is usually random, but subsequent points are basically pre-determined. However, it provides reliable nutrient information if the selected points are close enough to allow spatial dependence. Developing a standard recommendation for grid distance is impracticable because of the varying sampling requirements of different areas based on situations on the ground. For accurate estimates, the point samples should be small enough such that the data collected is spatially related to one another (Lauzon et al., 2005). This method has been widely used based on negotiations of cost rather than the significance of the information to be generated (Lauzon et al., 2005).

2.6 Digital soil mapping

A soil map transmits information about the spatial distribution of soil attributes graphically (Yaalon, 1989). Digital soil mapping is widely used to map soil characteristics (Arrouays et al., 2014) so that the maps can be produced accurately for sustainable land resource management. It allows the usage of minimum datasets in soil surveys and saves a lot on costs of these surveys. It revives the relationships between obtained soil characteristics and spatially auxiliary data that represent the five factors of soil formation and uses Geographic Information Systems (GIS) to enhance the accuracy of soil maps. Digital maps may not be more accurate than conventional ones but it is expected that they have a quantitative estimate of uncertainty therefore the sampling effort should be expended to achieve this. Digital soil mapping creates and populates spatial soil information systems by numerical models inferring the spatial and temporal variations of soil types and soil properties from soil observation and knowledge from related environmental variables (Lagacherie and McBratney, 2007).

2.7 Spatial variability of soil properties

Spatial variability of soil parameters is very paramount in the explanation of the influence of the factors of soil genesis and also the influence land use on soils. It permits the use of different tracks of land for different purposes and is the central concept in soil mapping. Franzluebbers and Hons (1996) explained the significance of spatial variability of soil attributes by comparing the distribution of plant available nutrients under conventional and no tillage farming systems. They stressed the importance of having soil information as a guide to soil management. Several studies have highlighted the importance of measuring spatial variation of soil properties, most of which have used geostatistical indexes (Appel et al., 2018; Santos et al., 2018; Amaral and Della, 2019; Leroux and Tisseyre, 2019). Spatial variability has been highly documented (Bouma and Bregt, 1989) and exhaustively appears in many review articles (Jury, 1986). Spatial variability is the key to any soil study including leaching, crop management and assessment of soil quality.

Soil heterogeneity has influence on leaching of contaminants to ground waters (Van der Zee and Van Riemsdijk, 1987). This non-uniformity is usually demonstrated by how hydraulic conductivity varies (Jury, 1986). Models that assume a field has parallel non-interacting columns of soil can explain macro-scale non uniformity (Leij, 1996). In late 1960's, soil scientists begun to systematically study soil variability. Their studies evolved independently and soil variation was seen as an inconvenience that reduced reliability of a map. Today soil variability is seen as a key attribute of soils and has been a subject of an enormous research effort (Burrough, 1993). The term 'Pedometrics' was coined in 1992 to describe the quantitative study of variation of field soils. Systematic variation is a change in properties of soil owing to the effect of the five factors of pedogenesis (Jenny, 1941). Spatial variability within fields is the basis for a point-based input application system.

A detailed survey covering part of the former Kenya Agricultural Research Institute (KARI) was done by Kathumo (2007) aiming to characterize spatial variability of the soil properties, to determine the relationship between spatial variability of soil fertility and their determining factors and to evaluate Grid-point versus Grid-cell soil sampling schemes for precision farming. Some of the results showed that phosphorus and percentage clay content were highly variable while total nitrogen was least variable. Present land use, vegetation cover and soil texture were the major factors influencing soil phosphorus, total nitrogen and soil pH distributions in the study area respectively, all being significant at $p<0.05$. It was recommended that soil management decisions should be based on the developed soil management zones for precision agriculture (Kathumo, 2007).

Each point in the field has unique physical and chemical attributes. Characteristics including texture, structure, moisture, nutrient availability, organic matter and presence of vegetation vary across fields (Batchelor et al., 1997). Understanding soil variability is key to management decisions in order to maximize benefits in cells across a field (Batchelor et al., 1997). Spatial variability compromises soil testing since mixing soils to make a composite creates a sample that is not representative of either area. Bouma et al. (1996) suggested the reasons as relief and crusting which cause significant redistribution of water, termites which enrich the soil insitu, effect of vegetation, aspect and geomorphology (Gaze et al., 1997).

Other than the five factors of soil formation, management history is also crucial in determining the productivity of a given soil (McBratney et al., 2003). Field operations including fertilization, tillage and manure application are also sources of variability at various scales of distance (Mallarino, 1998). High variability for soil reaction and nutrients is usually observed in farms (Cahn et al., 1994; Mallarino, 1996) and is related to soil types and not effect of fertilization or application of liming materials (Franzen and Peck, 1995; Mallarino, 1996). Farms where fertilizer application has been done by banding or where manure has been applied in large quantities show huge localized nutrient variability (Mallarino, 1996).

Soil physical properties which are reliable for long term land use planning should be studied carefully (Birkas et al., 2008) to help in the choice of farm implements and timing of operations based on the condition of the soil. Mapping spatial variation of soil characteristics helps in understanding the mechanism of change of processes temporally and spatially (Pereira and Ubeda, 2010). Variability in soil bulk density has been studied and documented (Barik et al., 2014; Bogunovic et al., 2014) and variation in soil moisture content has also been researched on (Brocca et al., 2007; Iqbal et al., 2005).

Accurate prediction of soil variability requires close sampling densities but this is expensive (Franzen and Peck, 1995; Wollenhaupt et al., 1994). Taking soil samples usually follow pre-determined zones of management such as soil types (Anderson-Cook et al., 1999), physiography (Franzen et al., 1998) or systematic layouts (Anderson-Cook et al., 1999; Franzen and Peck, 1995). Soil variability results majorly from complex interactions among topography, geology and climate coupled with land use (Liu et al., 2015). Soils therefore exhibit marked spatial variability at macro and micro-scale (Shukla et al., 2016). Spatial variability of soil maps guide in correct management of soil nutrients (Brevik et al., 2015) and helps to understand the pattern of spatial variability which is the combined effect of chemical, physical and biological processes occurring at different spatiotemporal scales coupled with anthropogenic activities (Goovaerts, 1998). Spatial variability of soil characteristics is assessed effectively by geostatistical techniques (Emadi et al., 2016; Moosavi and Sepaskhah, 2012; Moradi et al., 2016; Shahabi et al., 2016,). Variation in soil properties could be due to adoption of different soil management practices including variable fertilizer application (Behera et al., 2016).

2.8 Precision Agriculture

Developments in computing techniques and remote sensing technology provide opportunities for more data-driven applications in farm management, an approach referred to as precision agriculture (Wolfert et al., 2017). Remote sensing and GIS helps to manage in-field variability, a technology known as precision agriculture (Bramley, 2009; Robertson et al., 2012) that uses information tools including the GPS (Aubert et al., 2012; Llewellyn and Ouzman 2014). Big data is the extraction of insights and data over a large area that is previously technically and economically infeasible (Sonka, 2015). To realize the benefits of this technology requires enabling institutional, technical and social environment. This technology requires high skill, competent interpretation and judgement therefore posing a challenging adoption scenario (Robertson et al., 2012).

Data on spatial variability of soil attributes can improve the efficiency of farm operations by applying exactly what the crops need and saving on the excess. Research has shown that precise application of farm inputs increase profits (Shockley et al., 2011; Smith et al., 2013) and ensures water quality by controlling pollution. According to Schieffer and Dillon (2015), knowledge on spatial variability contributes to environmental conservation and increases agricultural productivity using lesser inputs. Cotton producers in the Southern United States have adopted this technology (Lambert et al., 2015; Paxton et al., 2010; Walton et al., 2010; Watcharaanantapong et al., 2014) and studies have been done on factors affecting adoption mapping spatial variability of soil properties in other countries (Robertson et al., 2012). Spatial variability studies have also been carried out in Africa, Kenya and even in Kabete area (Kandagor, 2015).

2.9 Effect of relief on soil properties

Topography influences soil properties due to the process of eluviation-illuviation of soil materials. It is one of the fundamental factors of soil genesis and its influence on soil properties has been widely studied (Dai and Huang, 2006; Huang et al., 2015; Li et al., 2017). Pedons on a landscape are functionally and taxonomically distinct due to the influence of topography and also other factors of soil genesis (Esu et al., 2008). Lateral and vertical flow paths of water within the soil results in re-distribution of materials (Bailey et al., 2014). Slope position is a key factor determining the distribution of soil properties in any given landscape. Soils of the study area are formed under the same geology that is Nairobi trachyte of Tertiary age (Saggerson, 1991) but can be delineated using slope classes into mapping units having different properties and requiring different management. It forms a first-class catena which is a sequence of soils derived from similar parent material and occurring under similar climate but characteristically distinct due to variation in relief and drainage (Komisarek, 2000).

To establish the effect of relief on soil properties, this survey followed Dokuchaev's hypothesis (Florinsky, 2012) which states that the state of soil in any given environment is defined by climate, vegetation, parent material, topography and time. Where all state factors are the same, the soil is homogeneous but where any of these factors change, the soil also changes. This concept was echoed by Hartemink and Bockheim (2013). Topography can accelerate or retard the effect of climate on soils by influencing the chemical, morphological and physical characteristics of the soil, same parent material notwithstanding (Esu et al., 2008). These characteristically heterogeneous edaphic properties in different slope classes are reflective of variable degrees of addition, loss, translocation and transformation of physical, chemical and biotic elements of the profile (Buol et al., 2011). Research has shown that a slight change in slope can result to significant variability in soil attributes (Uehera et al., 1985). Soils on rolling segments of a landscape exhibit remarkable spatial variation in properties because of lateral movement of water across the profile (Bailey et al., 2014; Jankowski, 2013).

Topography conditions the incontrovertible concept of geological sorting along a toposequence due to hydrological velocity on a slope whereby coarser particles preferentially accumulate on steeper slopes while finer particles are carried further downslope before deposition (Glasmann et al., 1980). Manning et al. (2001) explained the difference in soils along a slope as a function of variable sedimentation rates due to the effect of water movement downslope, which is controlled by topography. Processes occurring on soils in summit positions along a slope have influence on soils in lower slope segments of the same slope system (Hons, 2004).

Geometrical dimensions of a slope at any given segment can be convex, concave or linear. Increasing gradient downslope results to a convex vertical curvature whereas decreasing gradient along the slope results to concave vertical curvature. Convex orientations favour runoff especially when the slopes are steep (Schaetzl, 2013). In most cases, there is usually a change in soil type when the curvature changes from convex to concave in vertical orientations along the slope. Upper slopes, generally convex, are predominantly erosional and exhibit significant correlations between slope percentage and soil properties. Lower slopes, mostly concave, are predominantly depositional and show greater variability in soil attributes (Anderson and Burt, 1978; Park et al., 2001).

Slope affects moisture distribution which in turn affects vegetation patterns and profile development. The slope gradient, elevation, aspect and curvature quantify the influence of topography on vegetation distribution (Laamrani et al., 2014). The slope gradient controls flow velocity on soil surface (Liu et al., 2015). The altitudinal zonality of a soil is determined by elevation (Pabst et al., 2013). Aspect conditions the direction of water flow, intensity of evaporation and insolation (Moore et al., 1991). Surface curvature influences gravitational water movement and its accumulation in landscapes.

Topography has a significant impact on moisture-vegetation relationship which is the central dogma in ecohydrology. Slope gradient is directly proportional to the rate of runoff and is inversely proportional to the amount of water percolating through the soil. Increasing gradient leads to a parabolic decrease in the depth of clay accumulation zone within the profile (Manning et al., 2001). This is due to decreased translocation of clay down the profile due to decreased amount of water available for leaching. Subsurface flow of water in the soil is basically lateral whereby vertical flow is hindered by formation of water restrictive horizons down the pedon (Mcdaniel et al., 2008). Lateral flow of soil materials has been documented (Bourgault et al., 2015; Gannon et al., 2014; Gannon et al., 2017; Gillin et al., 2015). The rate of transmission of the soil materials is a function of the saturated hydraulic conductivity of the soil (Brooks et al., 2004). Hydrologic flow in soils is anisotropic which is conditioned by differences in size and shape of soil particles.

One approach to a detailed soil inventory is based on geopedological approach suggested by Zinck (2016) which entails strong relationship between pedology and geomorphology. In this approach, soil properties are attributed of the influence of slope. It is a mapping technique whereby the soil attributes are associated to the influence of the landscape, for example the influence of slope on soil properties. It assumes that vegetation patterns are indicative of soil boundaries and that grid soil sampling technique can be used to predict soil properties in unvisited sites. Geomorphology helps to explain the relationship between soil properties and physiography which involves differences in soil properties as a function of variation in relief (Zinck, 2016).

Soil organic carbon is a master variable that determines the chemical, biological and physical conditions of the soil (Brevik, 2012; FAO, 2015; Singh and Ryan, 2015). The stability of organic matter is influenced by living and non-living factors (Mligo, 2015) which are moderated by topography (Sollins et al., 1996). Baldock and Nelson (2000) suggested that relief and aspect influence climate and soil characteristics and hence are responsible for the distribution of organic carbon in the soils. The rate of organic matter decomposition decreases with temperature which is characteristic of high elevations where more litter is produced and organic carbon accumulates. This acts as sink for excess CO_2 in the atmosphere which is sequestered as soil organic carbon (Banwart et al., 2015). This study - investigated the influence of slope on soil properties while also factoring other soil forming factors.

2.10 Background studies in Upper Kabete Campus field

Irrigation suitability assessment was done by Michieka (1977) on soils of valley bottoms of Kabete veterinary laboratories aiming to find whether the soil and water were suitable for irrigation of lucern, napier and alfafa. They were found to be suitable. A study to evaluate and map soil erosion susceptibility in a small part of the study area was conducted (Gachene, 1989) combining grid soil survey with slope gradient map. The effect of rainfall intensity and distribution and also the stability of the soil against rainfall intensity were measured and it was observed that areas with greatest erosion had slope gradients of 30 percent or more. The need for a reliable procedure to map soil erosion was recommended. It was a test of usefulness of field observations to supplement measurement of erosion susceptibility. This study was continued in 2015 to assess the susceptibility of different cropping systems to erosion by use of runoff plots in a nearby site (Nyawade, 2015).

Soil hydraulic properties were determined by Karuku et al. (2012) to determine its influence on water relations for environmental, agricultural, ecological and engineering purposes. Saturated hydraulic conductivity (Ksat) was high in the surface than subsurface horizons. It was also higher in vertical than horizontal direction except for Bt1 and Bt2 horizons where horizontal ksat exceeded the vertical ksat. This phenomenon was attributed to activities of fauna creating tunnels in the soil layer. Decrease in ksat with depth was attributed to decreasing organic matter and increasing clay content. The compaction of soil reduced macro to intermediate pores and with micropores remaining constant, that led to lower hydraulic conductivity (Karuku et al., 2012). Soils of the study area were classified as Humic Nitisols (Siderius, 1976).

CHAPTER THREE

A GEOPEDOLOGICAL APPROACH TO SOIL MAPPING AND CLASSIFICATION IN UPPER KABETE CAMPUS FIELD, UNIVERSITY OF NAIROBI, KENYA

3.1 Abstract

Background. The study area exhibits a first-class catena having homogenous parent material and forming a spatial continuum. Functionally and taxonomically distinct soils result from differences in drainage and lateral movement of materials in the soil. Aim. This study aimed to classify the soils using a geopedological approach which involves a strong relationship between pedology and geomorphology. Methodology. The area was delineated into Soil Mapping Units (SMUs) through augering into soils defined by different macro-relief. Mapping units were demarcated according to slope categories namely 0 to 5%, 5 to 8%, 8 to 16%, 16 to 30% and >30% connoted as flat to gently undulating (AB), undulating (C), rolling (D), moderately steep (E) and steep (F), respectively. Profile pits were dug in the five identified mapping units using Stratified Random Sampling technique. Identified SMUs include UmIr/F, UmIr/E, UxIr/D, UxIr/C and UxIr/AB in the order of decreasing slope gradient. A soil map with a legend describing the mapping units was produced using a scale of 1:10000. Topographic influence on soil properties was presented by Pearson's correlation coefficient (r) with p-value included where the influence was significant. Statistical analysis was done using SPSS 25th edition and MS Excel. Results. All the mapping units were well drained and deep to very deep (>80 cm). The colour of the upper B horizon was predominantly dark reddish brown. The texture of top horizon was clay in UmIr/F and UmIr/E and is clay loam to clay, sandy clay loam to clay and loam to clay loam in UxIr/D, UxIr/C and UxIr/AB respectively, lucidly exposing the influence of topography on the depth of clay illuviation (clay: $r = 0.724$; $p \leq 0.01$). The structure was predominantly subangular blocky throughout the profiles with the top horizon of cultivated areas having predominantly granular structure. Saturated hydraulic conductivity (Ksat) generally decreased with increasing clay content down the profiles and the bulk density ranged from 0.9 to 1.2gcm^{-3}. Means of soil reaction of top horizons generally slightly decreased with decreasing gradient ($r = 0.231$) having lower values in cultivated areas. Percent organic carbon regularly decreased down the profiles with higher values in uncultivated, steeper areas ($r = 0.521$; $p \leq 0.05$). In the top horizon: Total nitrogen was predominantly medium across the study area ranging from 0.2 to 0.56% ($r = 0.185$) and followed the organic carbon trend; Available phosphorus was deficient (<20 ppm) in the study area. Bases ranged from sufficient to rich while micronutrients (Iron, Zinc, Manganese and Copper) were richly supplied. The cation exchange capacity (CEC) was predominantly medium across the profiles ranging from 15 to 27.6 cmol(+)/kg with values increasing slightly with increasing slope ($r = 0.320$). Based on data collected from description of the profiles and physicochemical data of the soils and according to IUSS Working Group WRB (2014) soil classification legend, the soils were classified as Mollic Nitisols. Implications. The soils are generally fertile for crop production but organic manure is recommended to buffer the acidic soil reaction, improve nitrogen and phosphorus sources. Precise input application is encouraged.

Keywords: First class catena; Soil Mapping Units; Stratified Random Sampling; Soil classification.

3.2 Introduction

Soil characterization helps to relate the physicochemical properties of the soil to the climate, landscape position, petrography, vegetation, time and human influence and to predict the performance of crops should they be planted in the soils. Environmental research requires global, spatial, high resolution and quantitative data that distinguish soil variability to a higher precision. The rationale behind this study is that most of the land in Nairobi region has been engulfed by settlement due to increasing urban population therefore there is need to map the remaining area in detail so as to characterize the soils.

To establish the effect of relief on soil properties, this study was guided by the Dokuchaev's hypothesis which relates soil characteristics to the influence of factors of soil formation. Topography can accelerate or retard the effect of climate on soils as it influences the chemical, morphological and physical characteristics of the soil, same parent material notwithstanding (Esu et al., 2008). These characteristically heterogeneous edaphic properties in different slope classes are reflective of variable degrees of addition, loss, translocation and transformation of physical, chemical and biotic elements of the profile (Buol et al., 2011). Research has shown that a slight change in slope can result to significant variability in soil attributes (Lawal et al., 2013). Soils on rolling segments of a landscape exhibit remarkable spatial variation in properties because of lateral movement of water across the profile (Bailey et al., 2014; Jankowski, 2013).

Topography conditions geological sorting along a toposequence whereby due to hydrological velocity on a slope, coarser particles preferentially accumulate on steeper slopes whilst finer particles are carried further downslope before deposition (Glasmann et al., 1980). Processes occurring on soils in summit positions along a slope have influence on soils in lower slope segments of the same slope system (Miller and Schaetzl, 2015). The shape of a slope at any given segment can be convex, concave or linear. Increasing gradient downslope results to a convex vertical curvature; decreasing gradient along the slope results to concave vertical curvature. Convex orientations favour runoff especially when the slopes are steep (Schaetzl, 2013). In most cases, there is usually a change in soil type when the curvature changes from convex to concave in vertical orientations along the slope. When contour lines are curved, horizontal curvatures result. Upper slopes that are generally convex, are predominantly erosional and exhibit significant correlations between slope percentage and soil properties. Lower slopes that are mostly concave, are predominantly depositional and show greater variability in soil attributes (Park et al., 2001).

Slope affects moisture distribution which in turn affects vegetation patterns and profile development. The slope gradient, elevation, aspect and curvature quantify the influence of topography on vegetation distribution (Laamrani et al., 2014). The slope gradient controls flow velocity on soil surface (Liu et al., 2015). The altitudinal zonality of a soil is determined by elevation (Pabst et al., 2013). Slope aspect conditions the direction of water flow, intensity of evaporation and insolation (Moore et al., 1991). Surface curvature influences gravitational water movement and its accumulation in landscapes.

One approach to a detailed soil inventory is based on geopedological approach suggested by Zinck et al. (2016) that is, using the geomorphological aspect to improve the soil inventory. It assumes that vegetation patterns are indicative of soil boundaries and that grid soil sampling technique can be used to predict soil properties in unvisited sites. Geomorphology helps to explain the relationship between soil properties and physiography; differences in soil properties as a function of variation in relief (Zinck et al., 2016).

Spatial variability of soil parameters is very paramount in the explanation of the influence of the factors of soil genesis. It can also be used to explain the influence of land uses in soils and permits the use of different tracks of land for different purposes. Soil heterogeneity is the central concept in soil mapping. Franzluebbers and Hons (1996) explained the significance of spatial variability of soil attributes by comparing the distribution of plant available nutrients under conventional and no tillage farming systems. They stressed the importance of having soil information as a guide to soil management. Spatial variability has been highly documented and exhaustively appears in many review articles (Jury, 1986). The term 'Pedometrics' was coined in 1992 to describe the quantitative study of variation of field soils. Systematic variation is a change in properties of soil owing to the effect of the five factors of pedogenesis (Jenny, 1941) and is the basis for a point-based input application system.

Each point in the field has unique physical and chemical attributes and characteristics including texture, structure, moisture, nutrient availability, organic matter and presence of vegetation vary across fields (Batchelor et al., 1997). Understanding soil variability is the key to management decisions in order to maximize benefits in cells across a field (Batchelor et al., 1997). Spatial variability compromises soil testing since mixing soils to make a composite creates a sample that is not representative of either area. Bouma et al. (1996) suggested the reasons as relief and crusting which cause significant redistribution of water, termites which enrich the soil insitu, effect of vegetation, aspect and geomorphology (Gaze et al., 1997). Soil variability results mainly from complex interactions among the factors of soil genesis at different spatiotemporal scales coupled with land use (Behera et al., 2016; Liu et al., 2015). Soils therefore exhibit marked spatial variability at macro and micro-scale (Shukla et al., 2016). Spatial variability of soil characteristics is assessed effectively by geostatistical techniques (Emadi et al., 2016; Moosavi and Sepaskhah, 2012; Moradi et al., 2016; Shahabi et al., 2016) and helps in correct management of soil nutrients (Brevik et al., 2015). The objective of this study was to characterize the soils based on a geopedological approach and recommend on proper soil management.

3.3 Materials and methods

3.3.1 Description of the study site

This research was done in Upper Kabete Campus field, University of Nairobi (Figure 3.1) covering an area of 168.63 ha. The site lies within longitude 247653, latitude 9861440 and at an altitude of 1876 meters above sea level (masl) measured in Universal Transverse Mercator, UTM (36.732280°E, -1.252590°S, 1876 masl). The site is part of the Loresho Ridge which is an upland characterized by slopes ranging from 0 to 32% according to figure 3.1 and 3.2 (Mwendwa et al., 2019). It falls under Agro Climatic Zone III (Sombroek et al., 1982). Rainfall is bimodal in distribution where long rains start in March or April and end in June; short rains start in October and end in December. The climate is typically sub-humid (Jatzold and Kutsch, 1982) while the geology comprises the Kabete grey-green porphyritic trachyte of middle division of Tertiary age (Mathu and Mwea, 2014; Onyancha et al., 2011; Saggerson, 1991) overlying the Nairobi trachyte and Kirichwa valley tuffs. These rocks are overlain elsewhere by the Limuru-Karura trachytes and are equivalent in age to the Ruiru dam trachyte. Upper Kabete Campus area was ideal for estimation of the influence of topography on soil properties due to its heterogeneous physiography. Field work was done from September 2017 to August 2018.

3.3.2 Soil survey procedure

This study was a detailed survey carried out at a scale of 1:10000 meant to characterize the soils of the study site. Mapping was based on terrain analysis and soil profiles taking into account physical and chemical properties using the geopedological approach. This principle is consistent with principles outlined by Dent and Young (1981). The main purpose of this survey was to characterize the soils using a geopedological approach. The study area was pre-visited to determine the study area boundary, unique zones for instance due to variation in vegetation, rocks and this formed the baseline information. One hundred and sixty-four (164) augerhole observations were made to a depth of 100 cm or upon hitting a rock to identify the SMUs. No soil samples were collected for laboratory analysis from the auger holes. Coordinates and slope percentages were taken using a Garmin Etrex Global Positioning System (GPS) and a Suunto clinometer, respectively. An augerhole description form was filled including among others, slope percentage and position, land use data, depth, colour, texture, consistence, mottling and concretions. These auger points were used to delineate the study area into Soil Mapping Units (SMUs) based on slope classes (Figure 3.1). These slope class delineations were the strata within which soil profiles were dug, described and sampled for chemical and physical analysis. The following map (Figure 3.1) was produced using detailed interpolation procedures in Arcview GIS 3.3 software.

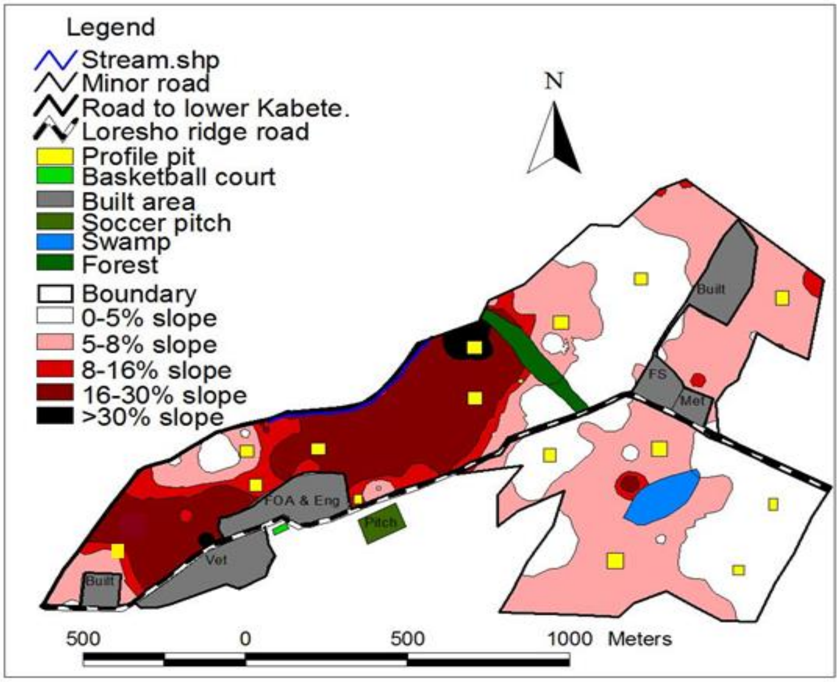

Figure 3. 1: Study area map showing slope categories and location of profiles

The slopes: 0 to 5%, 5 to 8%, 8 to 16%, 16 to 30% and >30% were connoted as flat to gently undulating (AB), undulating (C), rolling (D), moderately steep (E) and steep (F), respectively. Location of the profiles was based on Stratified Random Sampling scheme. The slope classes were the strata where profile pits were dug randomly in each stratum, the number of profiles dictated by the size of the stratum. There were 4 profiles for 0 to 5 % slope, 5 profiles for 5 to 8%, 4 profiles for 8 to 16%, 2 profiles for 16 to 30% and 1 profile for >30% slope. Stratified Random Sampling was selected to capture key population characteristics and to produce sample characteristics that are proportional to the overall population. Stratification was meant to ensure a smaller error of estimation and greater precision. Profile pits were described according to criteria elucidated in the

IUSS Working Group WRB (2014), taking into account environmental and morphological characteristics. General information was recorded including coordinates, land use and geology whereby information on geology was based on secondary data. Profile pits measured 2 meters in length, soil allowing depth and 1 meter in width, with stairs on one width side where core rings for saturated hydraulic conductivity and bulk density were also taken. Core samples were collected for physical analysis (Ksat and bulk density) using 100 cubic centimeter rings in triplicate per horizon and core rings were taken according to the natural horizons. Profile codes were attached to the degree sheet of the study area (148/4). Profile pits were opened across the SMUs with UmIr/F having one profile (profile 7), UmIr/E having two profiles (profiles 5 and 6), UxIr/D having four profiles (profiles 1, 2, 4 and 14, UxIr/C having five profiles (profiles 3, 8, 9, 11 and 13) and UxIr/AB having four profiles (profile 10, 12, 15 and 16). Horizons were identified using the Munsell soil colour charts, geological hammer, knife and morphological characteristics. Profile description included: Horizon designation, depth and boundary, colour, structure, cutans, pores, texture and stoniness, consistence and concretions. For chemical analysis, 1 kilogram of disturbed sample was collected from each identified horizon.

3.3.3 Soil analysis

Soil reaction was measured with a glass electrode pH meter (Baillie et al., 1990; Ingram, 1994). Total organic carbon (C), available phosphorus (P) and total nitrogen (N) were determined using the Walkley-Black method as lucidly exposed by Nelson and Sommers (1996), Molybdenum Blue technique (Mehlich et al., 1962) and Kjeldahl steam distillation (Black et al., 1965), respectively. Base saturation and CEC were determined according to Bremner (1996) which involves leaching with 1N NH_4OAC and 1N KCl solution then analysing the leachates. Exchangeable potassium (K) and exchangeable sodium (Na) were measured using a flame photometer while exchangeable calcium (Ca) and exchangeable magnesium (Mg) were analysed using the Atomic Absorption Spectrophotometer (AAS) at element specific spectral signatures. Available manganese (Mn), available zinc (Zn), available copper (Cu) and available iron (Fe) were analysed in the AAS machine from the available P extract after the P aliquot had been taken. Soil textural components were determined using the hydrometer (Bouyoucos) method as elucidated by Glendon and Doni (2002). Saturated hydraulic conductivity (Ksat) was determined according to Reynolds and Elrick (2002) and the same sample used for determining bulk density (Grossman and Reinsch, 2002).

3.3.4 Generation of the soil map

Kriging interpolator was used because it scientifically assumes that the distance between sample spots shows spatial correlation and that closer points are more related compared to widely spaced points. It gives the best linear unbiased prediction of intermediate values and is able to estimate the variance at each point hence the spatial accuracy of the interpolation can be judged. It is the most appropriate tool for measuring spatial dependence by examining the semivariogram and it gave real results true to the reality in the field. Sample points were loaded in ArcMap 10.1 and spatial analyst expanded in the Arc toolbox, interpolation selected and kriging tool chosen. The points were selected as input and one of the soil parameters put in the Z value field. The raster surface to be generated was named in the Output surface raster field. Ordinary kriging method was chosen as interpolation method and circular as semivariogram model for all the soil parameters and slope percentages. Other models were not tested as the circular model was deemed sufficient based on the objective of this study. The cell size was specified and the processing extent set as study area boundary shapefile in the environments section. The generated surface was clipped using the study area boundary shapefile and classified using ratings in differentiating criteria using reclassify tool. It was then vectorised and classified to obtain polygons then given a name and colour. The soil mapping units map was further digitized and a legend was generated.

3.3.5 Statistical analysis

SPSS was used to generate the Pearson's correlation coefficient (r) for soil properties against slope categories and also to generate summary statistics.

3.3.6 Soils and soil classification

A study to evaluate and map erosion susceptibility in an area partly covering the study site was done by Gachene (1989). The study identified different soil types including Humic Nitisols, Humic Cambisols, Lithic Leptosols and Dystric Fluvisols, with Humic Nitisols being the dominant soils.

The IUSS Working Group WRB (2014) classification legend was used in this study. The FAO-UNESCO is the system used in Kenya by the Kenya Soil Survey (KSS) for soil classification. Van de Weg and Mbuvi (1975) also used the system to characterize the soils of the Kindaruma area.

The general principles include the classification of soils based on soil properties defined in terms of diagnostic horizons, properties and materials, which to the greatest extent possible are measurable and observable in the field. The selection of diagnostic characteristics took into account their relationship with soil forming processes. In this study, diagnostic features were selected that are of significance to soil management.

The first step in classification was to look at the clay distribution to determine whether there was an argic B horizon or not. The clay distribution was used as a way to guide narrowing down in the classification. A nitic B horizon was found in all profiles as characterised by moderately to strongly developed nutty structure with many ped surfaces. Distinguishing properties included the clay distribution, CEC, base saturation, presence of cutans and organic carbon distribution. If the percent soil organic carbon showed close values between the top and the immediate underlying horizon, that showed a transition horizon for example presence of AB horizon. Similar horizon colours was also indicative of horizon transition. Diagnostic horizons, properties and materials were described as per their diagnostic criteria and field identification.

3.3.7 Construction of the soil mapping units: Systematics and nomenclature

The broadest category of the mapping code was based on physiography (Uplands). This land type was sub-classed by the parent material on which the soils are developed (geology). The other major component of the legend was the slope class. Each mapping unit on the soil map was indicated by a code for which this code system was used in the legend. The first entry represents the physiographic unit (Uplands, U), followed by physiographic position (lower middle uplands, m or uplands, undifferentiated levels, x), geology (I) for intermediate igneous rocks, colour (r) for red and slope class, respectively (Table 3.1). Slope codes included AB, C, D, E and F (Figure 3.2).. Drainage - the speed and extent of removal of water from the soil used class 4 (well drained). Texture and other characteristics including cutans, concretions and consistence were described according to Miscellaneous Soil Paper No. M24 of 1987 - Manual for soil survey and land evaluation by The Kenya Soil Survey Staff (isricu_i00011434_002.04 (1).pdf. n.d.). The soil colour was described using the Munsell soil colour charts (Munsell, 1975). The moist colour of the upper B horizon is given in the legend and colour of the whole B is given in the report. The B horizon was described to a depth of 100 cm. Table 3.1 presents the soil mapping units and slope categories.

Table 3. 1: Soil mapping units and slope categories used

Mapping code	Definition	Slope code	Gradient (%)	Description
U	Uplands	AB	0-5	Flat to gently undulating
m	middle lower-level upland	C	5-8	Undulating
x	uplands, undifferentiated levels	D	8-16	Rolling
I	Intermediate igneous rock	E	16-30	Moderately steep
r	red soil	F	>30	Steep

3.3.8 Differentiating criteria for soil properties

Differentia used for the legend, description of soil mapping units and soil fertility aspects were adopted from Booker Tropical Soil Manual (Landon, 2014) and also from Metson (1961).

3.4 Results and discussion

3.4.1 Diagnostic horizons and properties of the studied soils

A nitic B horizon, mollic A horizon and a base saturation >50% by NH_4OAC were identified through observation and laboratory analysis across all SMUs (Table 3.2 to 3.17; Appendix 1 and 2).

3.4.2 Soil classification

All profile pits had variable degrees of shiny faces in the subsoil horizons indicating the presence of nitic properties and qualifying for nitic horizon as well. Various soil mapping units identified during the field study are presented in Figure 3.2. A nitic B horizon was the key feature of the subsurface. The nitic horizon had less than 20 percent relative change in clay content over 15 cm to layers immediately above and below; 30 percent or more clay; a silt to clay ratio less than 0.40; moderate to strong subangular blocky structure breaking to flat-edged or nut shaped elements with shiny ped faces attributed to clay illuviation and a thickness of 30 cm or more. These are properties of Nitisols according to IUSS Working Group WRB (2014).

The mollic horizon was a thick, dark coloured surface horizon caused by the accumulation of organic matter (Appendix 1). It had a base saturation by 1M NH_4OAC, pH 7 of ≥ 50% on a weighted average throughout the entire thickness of the horizon and a soil structure that was not both massive and hard or very hard when dry and a moist colour value of ≤ 3 and chroma of ≤ 3 (IUSS Working Group WRB, 2014). It had moderate to high content of organic matter. In this study, soil organic matter content ranged from 2.86 to 6.93% (1.66*1.72 to 4.03*1.72). On average, the mollic horizon was 20 cm thick with predominantly dark reddish brown (2.5 YR 3/3) colours when moist (Table 3.3 to 3.22; Appendix 1).

In the study area, only Nitisols were identified as influenced by climate and geology of the study site (IUSS Working Group WRB, 2014). The soils had a predominantly diffuse, smooth boundary between A and B horizons and having nitic properties. Only Mollic Nitisols were found because of the occurrence of a mollic A horizon. Weathering in these soils is moderate to high but the soils are highly productive under appropriate management (IUSS Working Group WRB, 2014). The section under forest, swamp and rocky areas were mapped separately and are indicated in the map.

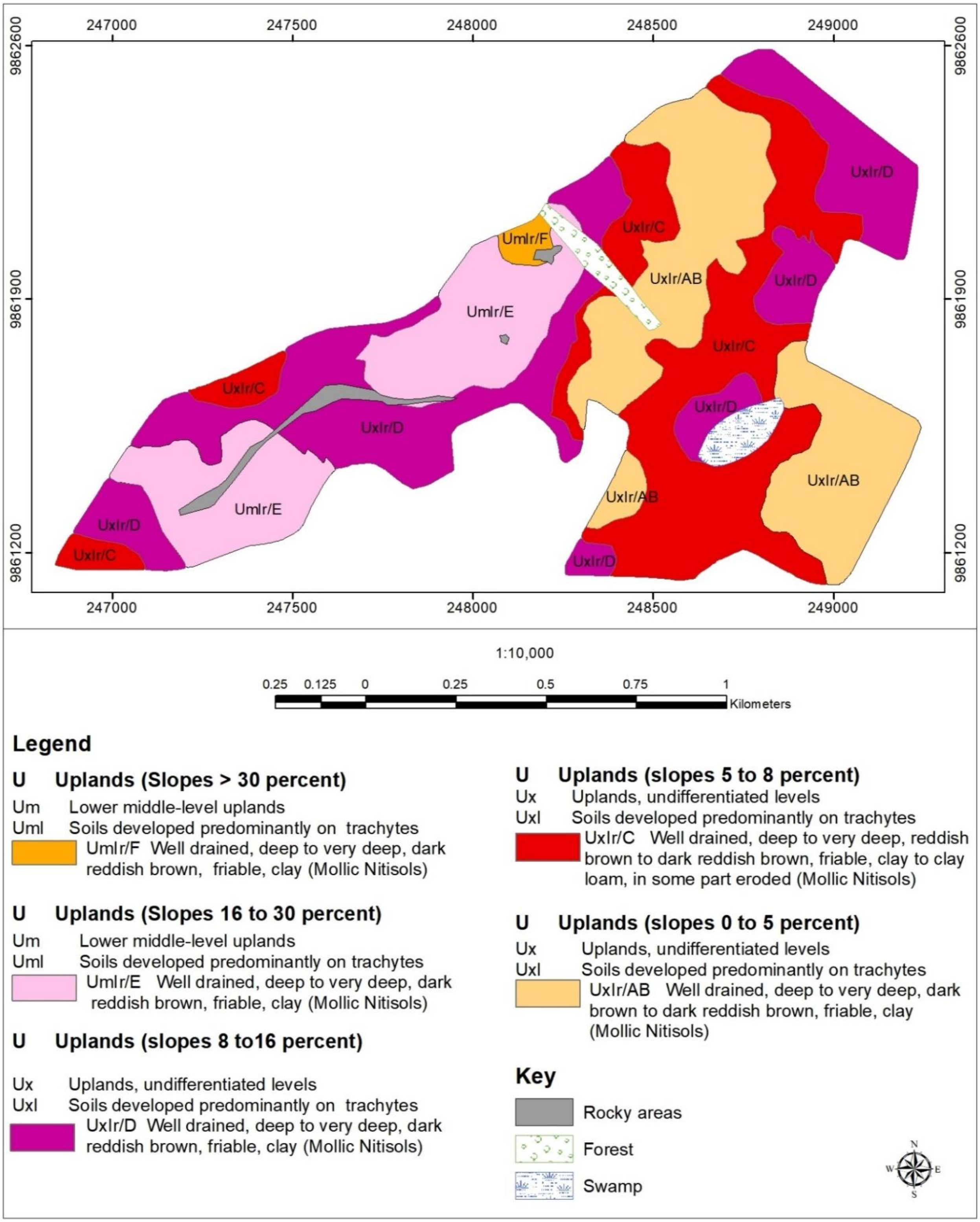

Figure 3. 2: Soil Map of Upper Kabete Campus Area

3.5 Mapping units

All the identified mapping units were physiographically uplands except in the area mapped as swamp. Uplands concern erosional surfaces and surfaces of former accumulation, undergoing erosional processes of degradation of slight to moderate intensity (isricu_i00011434_002.04 (1).pdf. n.d.).

U Uplands

Um Lower-middle level uplands; UI Soils developed predominantly on trachytes (1.64 ha).

3.5.1 UmIr/F

Soils developed from intermediate igneous intrusive rocks. They occur in Um-lower middle-level upland slope position having steep macro-relief (>30%). Ground water level is always very deep. The soils are well drained and deep to very deep. The moist colour of the B horizon ranges from weak red (10R 4/4) to dark reddish brown (2.5YR 3/3); the texture is clay throughout the horizons; the structure is weak to moderate, fine subangular blocky; soil consistence is slightly hard to hard when dry, friable when moist, slightly sticky to very sticky and slightly plastic to plastic when wet; having few, patchy to many, broken cutans in the subsurface horizons; having very few to common, fine pores; there are common pieces of weathering rock in the sub horizon; having few, fine, live roots; having very few to few, fine, spherical and irregular iron and manganese concretions; having gradual and diffuse, smooth boundary transitions.

The soil reaction is slightly acid (6.1) in top horizon, slightly acid to neutral in the sub horizons (6.4 to 6.8) and is strongly acid in the bottom horizon (5.1); the soils are non-saline with electrical conductivity (EC) in dS/m values of 0.1 throughout the horizons. Percent organic carbon (%OC) is adequate in the top horizon (2.95%), but low to moderate in the subsoil ranging from 0.23 to 1.82 %. Percent nitrogen (%N) is medium in the top soil (0.19 to 0.39%) and low in the subsoil (0.03 to 0.12%). The cation exchange capacity (CEC) in cmol(+)/kg is predominantly medium throughout the profile (14 to 22). Base saturation is high in all samples (61 to 92%). The profile is located at the border of a thick, rocky bush and cultivated area. The soils classify as Mollic Nitisols (Table 3.2). Main land use is cultivation of maize and beans. Included in this mapping unit is a segment having rock outcrops inside a bushy area having few tall eucalyptus trees and constituting less than 10% of the unit. The summary statistics for this mapping unit is presented in appendix 4(a).

Table 3. 2: Selected physical and chemical data for profile No. 148/4-7

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-14	22	14	64	C	6.1	0.1	2.95	0.39	22	92
AB	14-39	24	10	66	C	6.4	0.1	1.82	0.19	17	81
Bt1	39-63	22	10	68	C	6.7	0.1	1.20	0.12	18	91
Bt2	63-97	20	10	70	C	6.8	0.1	0.81	0.08	17	61
Bt3	97-163+	18	8	74	C	5.1	0.1	0.23	0.03	14	88

Legend: Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Where: TC=Textural Class.

The reddish colour of the soil (Appendix 1) can be attributed to presence of iron compounds at various states of oxidation, an observation consistent with findings of Foth (2003) who attributed reddish colour of soils to presence of iron compounds. The development of subangular blocky structure especially in the sub-horizons can be attributed to decreasing levels of organic matter, increasing clay content and reduction in abundance of plant roots in the subsoil. These results are in accordance to findings of Dengiz et al. (2013) and Lelago and Buraka (2019) who attributed angular soil structure to increasing clay content. Changes in consistence down the profiles in the study area can be attributed to differences in contents of organic matter and clay content. Horizon boundaries showed a slight change ranging between gradual to diffuse which are characteristic of Nitisols. The IUSS Working Group WRB (2006) and IUSS Working Group WRB (2014) explains Nitisols as having gradual and diffuse horizon boundaries.

The profile representing this mapping unit (Table 3.2) had the thinnest top horizon attributable to soil truncation by runoff along its steep topography. Former erosional processes on the steep slope may have continued for longer period on steep than on gentle slopes, delaying re-establishment of floral species therefore resulting to thinner solum. This finding is in agreement with the observation of Schaetzl (2013) who found relatively thin top soils on steep slopes. Liu et al. (2015) also elucidated that there is increased flow velocity on sloping terrains compared to gentle slopes that can lead to soil erosion. The silt-clay ratio of <0.4 throughout the profile can be attributed to clay translocation and accumulation in the subsurface horizon, an observation consistent with

IUSS Working Group WRB (2014) which describes a silt-clay ratio of < 0.4 in the subsurface as indicative of a nitic property. It ranges from 0.1 to 0.2 with the higher values (0.2) in top soils attributable to clay translocation down the profile (eluviation-illuviation) leaving coarser silt particles on the top soils. The same observation was noted by Wanjogu and Mbuvi (1993) who attributed higher values of silt-clay ratio on top soils to clay neoformation generated by renucleation of SiO_2, CaO and MgO rather than clay translocation down the profile by lessivage. This phenomenon can also be attributed to greater destruction of the silt fraction into finer colloidal particles in upper horizons and subsequent translocation to bottom horizons. The clay texture in the horizons including the top horizon lucidly exposes the influence of topography on the depth of clay illuviation which shows lesser clay translocation on steeper areas. The higher clay content in the bottom horizon despite the steep gradient and increasing cutans down the profile can be attributed to eluviation-illuviation process, an observation consistent with Buol et al. (2011) who observed increasing cutanic faces with soil depth and attributed it to clay translocation. The IUSS Working Group WRB (2014) also attributes cutans to argilluviation process. These observations of increasing clay content with depth are in accordance with the findings of Sekhar et al. (2014) who attributed the observation to insitu synthesis of secondary clays and weathering of primary minerals in the B horizon. A strip of rocky area overlain a weathered rock could be a function of differential weathering along a toposequence arising due to variable moisture regimes as influenced by slope. Flat areas with good drainage accelerate profile development therefore the steep gradient could have retarded weathering. This fact explains the rudic properties of within this mapping unit which lies on the steepest slope category and has been mapped separately.

The slightly acidic pH in the top horizons and slightly acid to neutral pH in the sub horizons can be attributed to leaching of basic cations. Vegetation coupled with runoff control measures could have slowed down runoff resulting to considerable leaching of bases despite the steep slope. This finding is consistent to observations of Wei et al. (2014) who found that shrubs are important in reducing runoff. The water table is very deep and salinity is not a limitation to crop production. Relatively lower organic carbon values compared to UmIr/E (Table 3.3 and 3.4) can be attributed to runoff on the steep topography due to sediment transport. This finding was also observed by Schwanghart and Jarmer (2011) who found lesser organic carbon on steepest slopes. The range is however adequate for crop production with occasional nutrient replenishment and control of runoff. Results of this study show higher organic matter in the top horizon that can be attributed to organic inputs and root systems in the rhizosphere. Browaldh (1995) and Pillon (2000) observed the same trend of decreasing content of percent organic carbon with depth and attributed it to more organic matter and faunal activities in the top soil. It can also be attributed to addition of aboveground biomass especially from litter to the soil surface, indicative that vegetation increases carbon stocks in the soil. Burle et al. (2005) observed the same trend of decreasing organic carbon with depth and attributed it to addition of biomass to the surface.

Percent nitrogen decreased regularly down the profile in the same trend of percent carbon indicating the role of C in binding N in soils (r = 0.9868, n = 5). This observation is in accordance to findings of Lelago and Buraka (2019) who also documented a positive correlation between total carbon and total nitrogen in the soil. Medium CEC and high base saturation indicate a favourable resource for plant nutrition. The medium CEC can be explained by adequate organic matter of the soils. The CEC values are lower than those observed by Karuku et al. (2012) which can be attributed to some degree of soil degradation and more detailed soil observation in this study. The high base saturation reflects dominance of non-acid cations in the exchange sites and limited nutrient uptake in the site. This position requires adequate erosion control measures including cover cropping, terracing and cultivation along contours to prevent detachment, transportation and deposition of soil particles to the nearby stream downslope.

Available phosphorus is deficient (<20 ppm) in all mapping units having a negative relationship with slope (r = -0.195). Micronutrients are richly supplied in the study area whereby iron (r = -0.210), copper (r = 0.007), manganese (r = -0.367) and zinc (r = -0.367) with ‘r’ representing their correlation with slope. Bases are sufficient to rich and correlate with slope whereby calcium is rich in UmIr/F and UxIr/D but sufficient to rich in UxIr/AB, UxIr/C and UmIr/E (r = 0.344); magnesium is rich in UmIr/F, UmIr/E and UxIr/D but sufficient to rich in UxIr/C and UxIr/AB (r = 0.695; $p \leq 0.01$); potassium is rich in UmIr/F and UxIr/D but sufficient to rich in the other map units (r = -0.293). The sample population for the regression was that of the top horizons (n =16). This information has been summarized in appendix 2.

U Uplands

Um Lower-middle level uplands; UI Soils developed predominantly on trachytes (31 ha).

3.5.2 UmIr/E

Soils developed from intermediate igneous intrusive rocks. They occur in Um-lower middle-level upland slope position having moderately steep macro-relief (16 to 30%). Ground water level is always very deep. The soils are well drained and deep to very deep. The moist colour of the B horizon ranges from dark reddish brown (2.5YR 3/4) to reddish brown (2.5YR 4/4); the texture is clay throughout the profiles; the structure is moderate, thin to medium subangular blocky in the top horizons and weak, fine to medium subangular blocky in sub horizons; the consistence is slightly hard to very hard when dry, loose to friable when moist, sticky and slightly plastic when wet in the top horizons; slightly hard to hard when dry, friable when moist, sticky to very sticky and plastic to very plastic when wet in the sub horizons. There are few, patchy to many, broken cutans; having very few to few, fine pores; very few to common, fine, medium and coarse, live roots; having very few to few, fine and medium, spherical and irregular Iron and Manganese concretions; having diffuse and smooth boundary transitions.

Soil reaction is quite variable ranging from strongly acid to slightly acid (5.3 to 6.1) in profile 148/4-5 and slightly acid to neutral (6.2 to 7.1) in profile 148/4-6. The soils are non-saline with EC (dS/m) ranging from 0.1 to 0.2. Percent organic carbon (%OC) is adequate to rich in the top horizons (2.33 to 4.03%) but low to adequate in the subsoil ranging from 0.70 to 1.40%. Percent nitrogen (%N) is medium (0.28 to 0.49%) in the top soil and is predominantly low in the subsoil (below 0.2%). The CEC (cmol(+)/kg) in this mapping unit is predominantly medium throughout the profiles while the base saturation is high. The soils classify as Mollic Nitisols (Table 3.3 and 3.4). This mapping unit is a bushy land with rough grazing activity. Included is a small segment of rock outcrops constituting less than 10% of the unit. The summary statistics for this mapping unit is presented in appendix 4(b).

Table 3. 3: Selected physical and chemical data for profile No. 148/4-5

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
A	0-16	26	8	66	C	5.6	0.2	3.18	0.35	16	90
Bt1	16-38	24	8	68	C	5.9	0.1	1.40	0.14	18	91
Bt2	38-66	22	10	68	C	6.1	0.1	1.16	0.11	13	87
Bt3	66-89	22	8	70	C	5.7	0.1	0.93	0.09	14	81
Bt4	89-140+	18	10	72	C	5.3	0.1	0.70	0.07	15	80

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 4: Selected physical and chemical data for profile No. 148/4-6

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
A	0-33	30	22	48	C	6.2	0.1	4.03	0.49	28	94
AB	33-53	24	24	52	C	6.2	0.1	2.33	0.28	24	93
Bt1	53-84	24	22	54	C	6.5	0.2	1.36	0.18	22	93
Bt2	84-111	22	24	54	C	6.9	0.1	1.24	0.15	18	91
Bt3	111-140+	18	18	64	C	7.1	0.1	0.97	0.11	15	90

Legend: Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Where: TC=Textural Class.

Increasing clay with depth can be attributed to greater clay translocation under the bush canopies. This observation of eluviation-illuviation process is consistent with Buol et al. (2011) and Sekhar et al. (2014) who found increase in clay content with depth and attributed it to clay accumulation in lower horizons of a soil profile. The structure is subangular blocky throughout the profiles because there is no cultivation that could have otherwise caused structural breakdown by fracture and could also be due to the influence of soil genesis on profile development by ferrugination process involving clay translocation. This observation is consistent with findings of Dengiz et al. (2013) and Lelago and Buraka (2019) who attributed the soil structure to clay translocation. Increasing quantity and grade of cutans down the profiles is indicative of a nitic property. These results are consistent with those of Lelago and Buraka (2019) and Sekhar et al. (2014) who observed increasing clay content with soil depth. It could also be due to drying of water from the surface of peds leaving a shiny, waxy lustered surface, a possibility suggested by Brewer (1960). Cutans could lead to locking away of nutrients and lateral movement of materials dissolved in water. This possibility was also suggested by Bosch et al. (1994) and Gillin et al. (2015). It occurs when nutrients are unable to penetrate the cutanic matrix to lower depths resulting to lateral redistribution of water and dissolved materials. The few concretions indicate a good drainage condition.

Organic carbon was higher in top horizons compared to the sub horizons which can be attributed to organic inputs to the soil. It could also be due to root decay and/or addition of aboveground biomass to the soil surface. Lelago and Buraka (2019) also observed the same trend and attributed it to decreasing organic matter and decreasing decomposition with depth. Percentage nitrogen follows the organic carbon trend strongly correlating positively (r = 0.9987). There is need for proper nitrogen management should this area be cultivated to prevent nitrogen depletion through leaching in this well drained environment and to increase crop productivity. Medium CEC reflects moderate ability of the soil to hold cations against leaching. The high base saturation reflects dominance of non-acid cations and soil genesis from a parent material rich in basic cations.

U Uplands

Ux   Uplands, undifferentiated levels; UI Soils developed predominantly on trachytes (49.8 ha).

3.5.3 UxIr/D

Soils developed from intermediate igneous intrusive rocks having a rolling macro-relief (8 to 16%) and occurring in various slope positions. Ground water level is always very deep and the soils are well drained and deep to very deep. The moist colour of the B horizon ranges from dark red (2.5YR 3/6) to dark reddish brown (2.5YR 3/4). The structure is moderate, thin to medium granular and subangular blocky in top horizons; moderate, thin to medium subangular blocky in sub horizons; the soil consistence is slightly hard to hard when dry, loose to friable when moist, sticky to very sticky and slightly plastic to plastic when wet in top horizons; slightly hard to very hard when dry, friable when moist, sticky to very sticky and plastic to very plastic when wet in the sub horizons. There are few, patchy to many, broken argillans; having very few to common, fine pores; having krotovina (10cm diameter) in profile 148/4-2 in the Bt3 horizon; having few, fine, live and dead roots; having very few to few, fine and medium, spherical and irregular ferromanganese concretions; having diffuse and smooth boundary transitions.

The soil reaction is quite variable ranging from very strongly acid to neutral (4.9 to 6.7) in the sub horizon and medium to slightly acid in top horizons (5.7 to 6.4); the soils are non-saline with electrical conductivity (EC) in dS/m ranging from trace to 0.2. Percent organic carbon (%OC) is adequate in the top horizons (2.25 to 3.80%) and it ranges from low to adequate (0.41 to 2.75%) in the sub horizons. Percent nitrogen (%N) is low to medium in both top and in the sub-horizon ranging from 0.04 to 0.42%. The CEC in cmol(+)/kg is predominantly medium throughout the profiles. The base saturation is high in all samples. Two of the profiles are in bushy area, one under grassland and one under coffee plantation (Tables 3.5 to 3.8). The soils are classified as Mollic Nitisols. Included is a small segment of rock outcrops covering less than 10% of the unit. The summary statistics for this mapping unit is presented in appendix 4(c).

Table 3. 5: Physical and chemical data for profile No.148/4-2

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
A	0-23	31	30	39	CL	6.2	0.1	3.45	0.39	23	91
Bt1	23-50	32	26	42	C	6.5	0.1	1.94	0.19	22	88
Bt2	50-73	36	18	46	C	6.7	0.1	1.35	0.15	18	86
Bt3	73-105	41	10	49	C	6.4	0.1	0.62	0.06	16	79
Bt4	105-152+	43	8	49	C	5.6	TR	0.50	0.05	13	55

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 6: Physical and chemical data for profile No.148/4-14

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-15	45	27	28	CL	5.7	0.1	2.55	0.20	20	70
Bt1	15-40	39	15	46	C	6.2	0.1	1.16	0.12	17	90
Bt2	40-60	35	13	52	C	6.2	0.1	0.90	0.09	12	87
Bt3	60-100	37	9	54	C	5.9	TR	0.64	0.07	19	68
Bt4	100-125+	39	7	54	C	4.9	0.1	0.41	0.04	5.4	72

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 7: Physical and chemical data for profile No.148/4-4

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
A	0-27	32	22	46	C	6.4	0.1	3.80	0.42	27	93
AB	27-38	30	20	50	C	5.9	0.1	3.37	0.36	22	87
Bt1	38-62	28	22	50	C	6.1	0.1	2.75	0.31	26	92
Bt2	62-92	28	20	52	C	6.5	0.1	1.51	0.18	21	90
Bt3	92-120+	26	20	54	C	6.7	0.1	1.09	0.14	17	89

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 8: Physical and chemical data for profile No.148/4-1

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
A	0-16	40	8	52	C	5.7	0.2	3.68	0.36	23	73
AB	16-35	32	14	54	C	5.9	0.1	2.25	0.30	22	60
Bt1	35-64	30	12	56	C	6.0	0.1	1.94	0.19	16	87
Bt2	64-91	28	16	56	C	6.2	0.1	0.85	0.11	14	75
Bt3	91-140+	28	12	60	C	5.1	TR	0.81	0.08	12	51

Legend: Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Where: TC=Textural Class.

Increase in clay content down the profiles is indicative of presence of a nitic B horizon. Increasing clay down the profiles 148/4-2 and 148/4-14 indicates sufficient clay translocation despite the rolling topography due to slowing of water velocity by buildings on the upper side of the profile and litter, respectively. This observation is backed up by findings of Wei et al. (2014) who found that physical barriers can prevent runoff. The structure of profile 148/4-1 and 148/4-4 which are uncultivated is subangular blocky throughout the horizons attributable to non-cultivation as anthropogenic edaphic disturbance can lead to structural breakdown. These results are consistent with those of Lelago and Buraka (2019) who attributed angular blocky structure to increasing clay content.

Higher organic matter content was observed in the uncultivated area compared to cultivated area indicative of the importance of vegetation in maintenance of soil carbon. There was higher organic matter content in the top horizons of all the profiles attributed to organic inputs to the soil surface. Similar results were observed by Browaldh (1995) and Burle et al. (2005) who attributed the observation to lesser organic content in the lower horizons. Lower values of percent carbon and nitrogen in cultivated areas can be attributed to continuous cultivation and plant uptake leading to nutrient depletion. This finding is in accordance to observations of Paz-Ferreiro and Fu (2016) and Willy et al. (2019) who documented that continuous cultivation deteriorates soil quality. Constant levels of organic carbon and dark chroma down the profile in 148/4-4 are attributable to vegetation of the area whose effects override those of genetic processes of additions, losses, translocation and transformation of materials within the profile. With the dominant vegetation being grass, fibrous root decay at depth in addition to litterfall to the surface could have increased the organic matter content. This is in accordance with findings of Chalise et al. (2018) who noted that vegetation and plant litter combined with minimum soil disturbance in a grassland environment can prevent erosion and lead to organic accumulation. Higher percent nitrogen in the top soils show the influence of carbon on nitrogen concentrations indicating that most of the nitrogen in unfertilized fields is supplied by the organic matter (r = 0.9850). These observations are in accordance to those of Amalu (1997) and Lelago and Buraka (2019) who found a positive correlation between carbon and nitrogen in the soil. Medium CEC reflects moderate ability of the soil to hold bases against leaching. The high base saturation reflects dominance of non-acid cations (especially calcium) in the exchange sites and soil genesis from a parent material rich in basic cations.

U Uplands

Ux Uplands, undifferentiated levels, UI Soils developed predominantly on trachytes (46.1 ha).

3.5.4 UxIr/C

Soils developed from intermediate igneous intrusive rocks. They have undulating macro-relief (5 to 8%) and occur at different upland levels. Ground water level is always very deep. The soils are well drained and deep to very deep. The moist colour of the B horizon ranges from red (2.5YR 4/6) to dark reddish brown (2.5YR 3/3); the texture is predominantly clay across the profiles. The structure is weak to moderate, fine to medium granular and subangular blocky in the top horizons; weak to moderate, thin to medium subangular blocky in sub horizons; the consistence is slightly hard to hard when dry, friable when moist, sticky to very sticky and plastic to very plastic when wet in the top horizons; hard to very hard when dry, friable when moist, sticky to very sticky and slightly plastic to very plastic when wet in sub horizons; having few, patchy to many, broken argillans; there are very few to common fine pores; having very few to common, fine and medium, live and dead roots concentrated in the top and middle horizons; there are few, fine, spherical and irregular ferromanganese concretions across the profiles except for bottom horizons of profile 148/4-3 (uncultivated) where there is abundant, medium Fe-Mn concretions; having gradual and diffuse, smooth boundary transitions.

The soil reaction is medium acid to neutral (5.9 to 6.6) in the uncultivated area and strongly acid to slightly acid (5.4 to 6.2) in the cultivated area topsoil. It is neutral (6.7 to 6.8) in uncultivated and strongly acid to neutral (5.0 to 6.7) in the cultivated sub horizons. The soils are non-saline with electrical conductivity (EC) in dS/m ranging from trace to 0.3. Percent organic carbon (%OC) is adequate in the uncultivated area (2.17 to 3.95%) and moderate to adequate in the cultivated area (1.80 to 3.30%) top horizons, while it is low to moderate in both uncultivated and cultivated areas sub soil (0.50 to 1.63 and 0.26 to 1.28%), respectively. Percent nitrogen (%N) is medium to high (0.24 to 0.56%) in uncultivated area and low to high (0.18 to 0.56%) in cultivated areas topsoil and low in both and uncultivated and cultivated areas sub soil (0.05 to 0.17 and 0.03 to 0.15%), respectively. The CEC in cmol(+)/kg is predominantly medium throughout the profiles. Base saturation is high in all samples. Most of the area is used for farming. The soils were classified as Mollic Nitisols (Tables 3.9 to 3.13). The summary statistics for this mapping unit is presented in appendix 4(d).

Table 3. 9: Physical and chemical data for profile No.148/4-3

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
A	0-21	32	22	46	C	5.9	0.2	3.95	0.56	26	68
AB	21-45	30	20	50	C	6.6	0.1	2.17	0.24	22	91
Bt1	45-70	34	12	54	C	6.7	0.1	1.63	0.17	20	90
Bt2	70-95	32	14	54	C	6.7	0.1	0.62	0.06	17	88
Bt3	95-133+	38	16	46	C	6.8	0.1	0.50	0.05	17	88

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 10: Physical and chemical data for profile No.148/4-8

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-17	47	23	30	SCL	5.9	0.2	3.14	0.34	21	92
Bt1	17-38	39	19	42	C	5.1	0.1	0.97	0.11	18	91
Bt2	38-63	35	11	54	C	5.8	0.1	0.78	0.09	14	89
Bt3	63-100	33	7	60	C	5.7	TR	0.58	0.06	14	89
Bt4	100-141+	25	13	62	C	5.0	TR	0.54	0.05	13	88

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 11: Physical and chemical data for profile No.148/4-9

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-21	51	27	24	SCL	5.4	0.3	3.30	0.32	24	52
Bt1	21-50	41	25	34	CL	6.2	0.2	1.28	0.15	21	93
Bt2	50-70	37	11	52	C	6.1	0.1	1.09	0.14	16	91
Bt3	70-92	39	11	50	C	6.4	0.1	0.93	0.11	16	91
Bt4	92-120+	39	7	54	C	5.1	TR	0.74	0.08	13	90

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 12: Physical and chemical data for profile No.148/4-11

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-25	30	30	40	CL	5.7	0.1	2.51	0.56	23	94
Bt1	25-50	28	24	48	C	6.5	0.1	0.89	0.11	16	91
Bt2	50-74	24	22	54	C	6.7	0.1	0.50	0.06	16	91
Bt3	74-103	24	8	68	C	6.3	0.1	0.39	0.04	15	90
Bt4	103-125+	22	9	69	C	5.8	0.1	0.27	0.03	14	90

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 13: Physical and chemical data for profile No.148/4-13

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-15	30	16	54	C	6.2	TR	1.99	0.25	19	92
AB	15-38	26	18	56	C	5.9	0.1	1.80	0.18	19	83
Bt1	38-61	24	18	58	C	5.8	0.1	0.45	0.05	12	88
Bt2	61-80	24	16	60	C	5.5	TR	0.41	0.04	11	87
Bt3	80-134+	22	16	62	C	5.1	TR	0.26	0.03	11	87

Legend: Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Where: TC=Textural Class.

Predominantly increasing clay content with depth is indicative of sufficient clay translocation in undulating topography. This observation is in accordance with IUSS Working Group WRB (2006) and IUSS Working Group WRB (2014). In profile 148/4-11, there is evidence of erosion which is supported by low nutrient availability in chemical data. Low chemical values of eroded soils were also observed in upland soils in a study in Northwest Vietnam (Clemens et al., 2010; Wezel et al., 2002) whereby fertile soils were found on less eroded zones. The influence of erosion on soil nutrients was also reported by Garcia-Diaz et al. (2017) and Li et al. (2016) who found that erosion decreases the thickness of the soil layer most useful to plant growth and also reduces soil fertility. Geological sorting might have played a role too in transporting clay down the landscape, a fact demonstrated by the clay loam texture in the top horizon. Geological sorting along a slope indicates that coarser soil particles are likely to be found in higher slope positions with finer particles transported further downslope (case of profile 148/4-11). This process was also suggested by Glassman et al. (1980). The variation in the type of structure (granular and subangular blocky) is reflective of clay destruction in the top horizon through cultivation except for profile148/4-3 which is located in the bush where the structure is subangular blocky throughout the profile. For example, addition of organic inputs in the soil could have lightened the texture therefore influencing the structure. This observation is in consistence with that of Lelago and Buraka (2019) who documented that the soil structure could be dictated by the amounts of organic matter and clay content.

Increasing quantity and grade of cutans down the profiles indicate a possible locking away of nutrients and possible lateral flow of soil materials whereby much of the soil material could be isolated from the activity of plant roots affecting plant growth. Lateral flow of soil materials was also documented by Gannon et al. (2014). Topography strongly influences drainage along a landscape therefore influences the formation of concretions which are materials formed by local concentration of compounds that irreversibly react to alternating processes of oxidation and reduction. They are few in this mapping unit due to good drainage except in profile 148/4-3 which is positioned at lower-level upland where they are many in the bottom horizon. Concretions could have settled as sand during texture analysis using the Bouyoucos method as they are not digested by hydrogen peroxide. It may overestimate sand and explains increasing plasticity even when the texture is coarser than clay.

The lower pH values in the cultivated area can be attributed to use of acidifying fertilizers which is in accordance to findings of Bolan and Hedley (2003) who attributed soil acidification to use of acidic fertilizers. In profile 148/4-8, it can be attributed to good drainage and more leaching corresponding to greater clay translocation near the forest. The higher percent carbon and nitrogen in the uncultivated areas can be attributed the influence of organisms on soil fertility due to increasing soil cover. Higher percent nitrogen in the top soils shows the influence of carbon on nitrogen concentrations (r = 0.9819). These observations are in accordance to those of Amalu (1997) and Lelago and Buraka (2019) who found a positive correlation between carbon and nitrogen in the soil. Higher carbon and nitrogen percentage in profile 148/4-3 is due to convergence and heterogeneous accumulation of organic rich materials in the area of deposition. The medium CEC reflects moderate ability of the soil to hold cations against leaching and the high base saturation reflects soil development from a parent material rich in basic cations. This mapping unit has a high potential for crop production with good agricultural practices including precise input application, land suitability evaluation, control of erosion, returning of crop residue, application of well decomposed manure, legume inoculation, weeding, pest and disease control.

Uplands

Ux Uplands, undifferentiated levels, UI Soils developed predominantly on trachytes (40.1 ha).

3.5.5 UxIr/AB

Soils developed from intermediate igneous intrusive rocks. They have a flat to gently undulating macro-relief (0 to 5%) and occur at different upland levels. Ground water level is always very deep. The soils are well drained and deep to very deep. The moist colour of the B horizon is dark brown (7.5YR 3/3) to dark reddish brown (2.5YR 3/3); the texture is clay loam to clay in the top horizons and sandy clay to clay in the sub horizons; the structure is weak to moderate, thin to medium granular and subangular blocky in top horizons; moderate, thin to medium subangular blocky in sub horizons; the soil consistence is soft to hard when dry, loose to friable when moist, slightly sticky to very sticky and slightly plastic to plastic when wet in top horizons; hard to very hard when dry, friable when moist, sticky to very sticky and slightly plastic to very plastic when wet in sub horizons; there are few, patchy to many, broken clay cutans; having few, fine to common, fine pores; having few, fine, live roots; there are few to many, fine, spherical and irregular ferromanganese concretions with exception of profile 148/4-10 where there are many, fine, spherical and irregular Fe-Mn concretions; having gradual and diffuse, smooth boundary transitions.

The soil reaction is quite variable where in profile 148/4-16 is very strongly acid to medium acid (4.4 to 5.9) whilst in the other profiles it ranges from very strongly acid to neutral (4.9 to 6.9). The soils are non-saline and non-sodic with electrical conductivity (EC) in dS/m ranging from trace to 0.2. Percent organic carbon (%OC) is moderate to adequate in the top horizons ranging from 1.24 to 2.73% but low to moderate in the subsoil ranging from 0.08 to 1.76%. Percent nitrogen (%N) is medium in the top soil (0.21 to 0.31%) and is low in the subsoil ranging from 0.01 to 0.20%. The CEC soil in cmol(+)/kg is predominantly medium throughout the profiles. Base saturation is high in all samples. This mapping unit is used for farming with 2 profiles positioned in coffee plantation. All the soils classify as Mollic Nitisols (Tables 3.14 to 3.17). The summary statistics for this mapping unit is presented in appendix 4(e).

Table 3. 14: Physical and chemical data for profile No.148/4-10

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-16	36	32	32	CL	6.3	0.2	2.05	0.22	16	91
AB	16-38	36	26	38	CL	6.6	0.1	2.13	0.27	26	95
Bt1	38-72	42	18	40	C	6.6	0.1	1.51	0.18	19	93
Bt2	72-93	38	14	48	C	6.6	0.1	0.66	0.07	18	70
Btc	93-123+	46	14	40	SC	6.7	0.1	0.50	0.05	21	87

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 15: Physical and chemical data for profile No.148/4-16

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-25	44	24	32	CL	5.5	TR	2.40	0.24	20	93
AB	25-51	46	12	42	C	5.6	0.1	2.10	0.22	18	92
Bt1	51-74	38	10	52	C	5.9	TR	1.09	0.11	18	92
Bt2	74-97	38	10	52	C	4.4	0.1	0.52	0.06	18	90
Bt3	97-123+	38	2	60	C	5.5	0.1	0.41	0.04	14	89

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 16: Physical and chemical data for profile No.148/4-15

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-18	28	34	38	L	5.6	0.1	2.73	0.31	20	70
AB	18-45	28	30	42	C	6.4	TR	2.51	0.29	23	94
Bt1	45-79	30	22	48	C	6.8	TR	1.76	0.20	22	93
Bt2	79-114	32	16	52	C	6.9	0.1	0.86	0.11	15	90
Bt3	114-138+	28	14	58	C	6.6	0.1	0.82	0.08	14	89

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Table 3. 17: Physical and chemical data for profile No.148/4-12

Horizon designation	Depth(cm)	Sand (%)	Silt (%)	Clay (%)	TC	pH	EC (dS/m)	%OC	% N	CEC (cmol(+)/kg)	BS%
Ap	0-18	35	40	25	L	5.8	0.1	1.66	0.22	18	78
AB	18-32	41	32	27	L	5.9	0.1	1.24	0.21	21	72
Bt1	32-56	33	20	47	C	6.4	0.1	0.62	0.06	16	91
Bt2	56-82	35	16	49	C	6.3	0.1	0.23	0.03	14	90
Bt3	82-136+	24	18	58	C	4.9	0.1	0.08	0.01	16	53

Legend: Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols.

Where: TC=Textural Class.

Increasing clay trend down the profiles is indicative of sufficient clay translocation on level to gently undulating topography. This observation is consistent with findings of Lelago and Buraka (2019) who also attributed increasing clay translocation down the profile to eluviation-illuviation process. The variation in the type of structure is reflective of clay destruction in the top horizon through cultivation and by root penetration. Lelago and Buraka (2019) also attributed structural variation to changes in contents of clay content and organic matter. Increasing plasticity down the profiles can be attributed to increasing clay with depth. This is also leading to more cutanic surfaces with depth suggesting possible locking away of vertical nutrient flow and a possibility of lateral flow. This suggestion is supported by Bosch et al. (1994), Brewer (1960) and Gillin et al. (2015) who suggested the possibility of lateral flow in soils. The stable subangular blocky structure of moderate grade throughout the horizons can be attributed to cementation by iron compounds, clay translocation and its redistribution. The sandy clay texture in the bottom horizon of profile 148/4-10 can be attributed to the abundant concretions which might have settled alongside sand in the water column during texture analysis. These concretions could be less than 2mm in diameter therefore able to pass through the sieve as part of the sample.

Lower pH values in profile 148/4-16 could be attributed to more leaching under the coffee canopies compared to other profiles in the same slope category. It can also be due to the process of decomposition of weeds which could have released organic acids. The soils are therefore not limited to crop production by effects of salinity. Higher organic matter on top horizon is attributed to organic inputs and litterfall coupled with good aeration that could have led to organic decomposition therefore increasing the organic carbon in the soil. Decreasing trend down the horizon was also observed by Browaldh (1995) who attributed it to decreasing faunal activities.

The irregular trend of percent carbon in profile 148/4-10 can be attributed to non-uniform deposition in the flat to gently undulating, concave orientation. It could also be due to admixturing of A and B horizons as a result of cultivation. There was higher percent nitrogen in the top horizons compared to bottom horizons because most of the nitrogen in unfertilized fields is supplied by the organic matter content (r = 0.9892). Lelago and Buraka (2019) found a positive correlation between the contents of carbon and nitrogen in the soil and concluded that most of the nitrogen in the soil is bound by carbon. Medium CEC reflects moderate ability of the soil to hold cations against leaching. The high base saturation reflects dominance of non-acid cations in the exchange sites and soils originating from a parent material rich in basic cations.

3.6 Physical properties: Saturated hydraulic conductivity (ksat), bulk density (ρb) and porosity

The Ksat in this study generally decreases with depth in all profiles due to decreasing organic matter content, presence of more uniform soil material and decreased anisotropy with depth (Table 3.18). This observation is consistent with findings of Chakraborty et al. (2010) who attributed decreasing Ksat to decreasing organic matter and increasing clay content. Compaction of the soil could have reduced macro to intermediate pores and with micro pores remaining constant, the ksat decreased with depth. This finding has been observed in the same area and elsewhere (Karuku et al., 2014; Libohova et al., 2018).

Under ideal circumstances, high ksat equates low bulk density but texture and presence of cutanic surfaces can condition a display of disparity to this generalization. Other factors that could have resulted to similar bulk densities showing variable ksat as shown by profile 8, 15 and 16 include presence of faunal channels which increases the amount of water percolation, presence of roots and stones within the sample that could have blocked some pores. This finding is a replication of observations by Karuku et al. (2012 and 2014) who found bulk densities of a profile ranging from 1 to 1.1 Mgm^{-3} and the ksat (cmhr^{-1}) ranging from 0.4 to 6.0. Presence of cutans in the study area suggests some degree of lateral movement and on greater scale some restriction to root penetration. This is consistent with principles explained by Brewer (1960) about lateral movement in presence of cutans which has also been documented by Bourgault et al. (2015). Results of this study show that argillans have the greatest influence on ksat across all slope categories. Cutans on walls of voids and surface of peds could have prevented the bulk of the soil material from allowing free water movement resulting to low ksat.

Analysis shows that the bulk density decreases with decreasing slope and increases with increasing slope ($r = 0.303$) reflective of a possibility of detachment of lighter top soils from steeper areas, their transportation and deposition on more gentle slopes. Profile 148/4-5, 148/4-6 and 148/4-7 on moderately steep and steep topography respectively, are all in the rapid saturated hydraulic conductivity class with bulk densities of 1.1 gcm^{-1}. The rapid conductivity despite considerably high bulk densities can be attributed to good drainage conditioned by topography. Profile 148/4-1, 148/4-2, 148/4-4, and 148/4-14 on 8 to 16% slope are in rapid, moderately rapid, moderately rapid and rapid class, respectively, with bulk densities of 1.0, 1.2, 1.1 and 1.0 gcm^{-3}, respectively. Compaction due to grazing in profile 148/4-4 could have reduced the ksat to moderately rapid due to reduction of large pores to intermediate pores therefore reducing water percolation. This observation is consistent with findings by Karuku et al. (2012) who attributed low ksat to soil compaction. The rapid class in profile 148/4-1 and 148/4-14 can be attributed to good drainage and cultivation, respectively. Profile 148/4-3, 148/4-8, 148/4-9, 148/4-11 and 148/4- 13 on 5 to 8% slope are in moderately rapid, moderate, moderate, rapid, and very rapid classes respectively with bulk densities of 1.1, 0.9, 1.1, 1.1 and 1.0 gcm^{-3}, respectively.

The top horizons of profile 148/4-10, 148/4-12, 148/4-15 and 148/4-16 on 0 to 5% slope category were in the moderate, very rapid and rapid classes respectively with bulk densities ranging from 1.2, 1.1, 0.9 and 0.9 gcm^{-3}, respectively. Profile 148/4-10 and 148/4-12 had lower ksat values which were attributed to deposition of fine silt blocking pores and compaction by tractor cultivation, respectively. They also have higher bulk densities and lower porosity values compared to profile 148/4-15 and 148/4-16 that could have restricted hydraulic conductivity and reduced soil aeration. Increased litter from coffee canopies where profile 148/4-15 and 148/4-16 are positioned could have improved the soil structure facilitating water movement and aeration.

Table 3. 18: Physical properties

Prof	Map unit	Depth	Sand	Silt	Clay	SCR	TC	Ksat	Class	BD	Por
	UmIr/F										
148/4-7	Mollic Nitisols	0-14	22	14	64	0.2	C	9.2	R	1.1	58
	UmIr/E										
148/4-5	Mollic Nitisols	0-16	26	8	66	0.1	C	8.7	R	1.1	58
148/4-6	Mollic Nitisols	0-33	30	22	48	0.5	C	8.5	R	1.1	58
	UxIr/D										
148/4-1	Mollic Nitisols	0-16	40	8	52	0.2	C	11.1	R	1	64
148/4-2	Mollic Nitisols	0-23	31	30	39	0.8	CL	6.1	MR	1.3	53
148/4-4	Mollic Nitisols	0-27	32	22	46	0.5	C	6.1	MR	1.1	60
148/4-14	Mollic Nitisols	0-15	45	27	28	1	CL	8	R	1	62
	UxIr/C										
148/4-3	Mollic Nitisols	0-21	32	22	46	0.5	C	7.9	MR	1.1	59
148/4-8	Mollic Nitisols	0-17	47	23	30	0.8	SCL	5.2	M	0.9	66
148/4-9	Mollic Nitisols	0-21	51	27	24	1.1	SCL	5.8	M	1.1	60
148/4-11	Mollic Nitisols	0-25	30	30	40	0.8	CL	8.2	R	1.1	60
148/4-13	Mollic Nitisols	0-15	30	16	54	0.3	C	16.5	VR	1	64
	UxIr/AB										
148/4-10	Mollic Nitisols	0-16	36	32	32	1	CL	3.6	M	1.2	53
148/4-12	Mollic Nitisols	0-18	35	40	25	1.6	L	3.6	M	1.1	58
148/4-15	Mollic Nitisols	0-18	28	34	38	0.9	L	16.5	VR	0.8	69
148/4-16	Mollic Nitisols	0-25	44	24	32	0.8	CL	10.9	R	0.9	66

Legend: SCR-Silt Clay Ratio, TC- texture class, BD- bulk density (g/cm^3), Ksat units= cmhr^{-1}, Por- percent porosity, R= Rapid, MR= Moderately Rapid, M= Moderate, VR= Very Rapid

3.7 Conclusions

Soils of the study area were classified as Mollic Nitisols. They are well drained and deep to very deep indicating that drainage and depth are not limitations to production. There is need to apply manure to the soils as it plays a vital role in buffering the soil reaction, maintaining high organic matter and indirectly maintaining nitrogen sources. Continuous cultivation without adequate replenishment of soil nutrients should be avoided. The soils have good physical and hydrologic properties for crop production. The decreasing saturated hydraulic conductivity with depth is attributable to increasing clay content with depth. The rapid ksat values in steeper slopes reflects better drainage than in gentle slopes. Aspects like physical barriers for example bushes and rocks slowing the velocity of water movement resulting to clay translocation in upslope convex positions are observed in this study. The effect of clay cutans on leaching and probable lateral flow lines is also accentuated as shown by more acidic soil reaction in bottom horizon of some profiles. The impact of erosion on soil quality is lucidly exposed by the low fertility parameters in profile 148/4-11. There is need to control erosion in soils so as to maintain high soil and water quality. Of the major elements, phosphorus is the most deficient which can be attributed to soil genesis from a P-deficient parent material and also the predominantly acidic soil reaction that could have resulted to fixing of P sources making it unavailable for plant uptake. There is therefore need for phosphorus replenishment in the soil. Soil characterization should be used to understand the soil properties and their potential in different parts of the field.

CHAPTER FOUR

ASSESSING SPATIAL VARIABILITY OF SELECTED SOIL PROPERTIES IN UPPER KABETE CAMPUS FARM, UNIVERSITY OF NAIROBI, KENYA

4.1 Abstract

This study aimed to evaluate spatial variability of selected soil parameters as a guide to precise fertilizer application. The study area was delineated into Soil Mapping Units (SMUs) defined by different macro-relief. A farm designated as Field 3 which is under Arabica coffee within one of the SMUs was selected for a more detailed soil observation at a scale of 1:5000. Soil samples were taken at depths of 0 to 15 and 15 to 30 cm across 20 sample locations in grids and selected properties analysed in the laboratory. Inverse Distance Weighted (IDW) interpolation method was used to estimate the accuracy of interpolation through cross-validation of the top soil parameters. In 0 to 15 cm depth, the pH varied from 5.1 to 6.0 with a mean of 5.6 while in 15 to 30 cm it varied from 5.1 to 6.3 with a mean of 5.8 showing low variability of 5.1% and 5.8%, respectively. Organic carbon ranged from 2.12 to 3.18% with a mean of 2.75% in 0 to 15 cm and 1.82 to 3.07% with a mean of 2.40% in 15 to 30 cm, indicating low variability of 10.4% and 12.7%, respectively. Percent nitrogen in 0 to 15 cm ranged from 0.23 to 0.38% with a mean of 0.32% and 0.21 to 0.35% with a mean of 0.29% in 15 to 30cm, indicating low variability of 14.5% and 17.6%, respectively. Phosphorus was deficient in both depths and shows moderate variability of 36.2% and 42.3% in 0 to 15 and 15 to 30 cm, respectively. Potassium was predominantly rich in both upper and lower depths showing low and moderate variability (21.7% and 28.9%), respectively. Calcium and Magnesium ranged from sufficient to rich and show moderate and low variability in top and bottom depths, respectively. All micronutrients were sufficient in the soil. The soils were classified as Mollic Nitisols. Results show that soil parameters varied spatially within the field therefore there is need for variable input application depending on the levels of these elements and purchasing of fertilizer blends that are suitable for nutrient deficiencies. Precision agriculture is highly recommended in the field to capitalize on soil heterogeneity.

Keywords: Spatial variability, Mollic Nitisols, Variable input application, Precision Agriculture, Soil heterogeneity

4.2 Introduction

Agriculture is the most important economic activity in Kenya and also specifically in the study area (Bauer, 2014) but low soil fertility, lack of detailed soil information, taxation on agricultural inputs, deleterious impacts of climate change and pests pose a challenge to our agriculture. Land degradation can greatly undermine agricultural production if there is no proper input management (Mugendi et al., 2007).

Sustainable Development Goals (SDGs) of the United Nation are aimed to combat poverty, reduce desertification, curb climate change and ensure global prosperity which are related to the natural environment and agriculture (World Dev. Rep. 2008, 2007). The importance of soils in achieving these goals has been highlighted by Keesstra et al. (2016). Soil maps may lead to better understanding of existing nutrient limitations thus allowing easy maintenance of soil fertility through precision agriculture. The major cause of differences in yield or response to inputs is a function of spatial differences within the field. Basso et al. (2011) and Muschietti-Piana et al. (2018) recommended that variable input application in fields has the ability to increase yields and reduce environmental impact.

Spatial variability of soil parameters is paramount in the explanation of the influence of the factors of soil genesis and land use on soils. It permits the use of different tracks of land for different purposes and is the central concept in soil mapping. Franzluebbers and Hons (1996) compared the distribution of available nutrients under different farming systems and stressed the importance of having soil information as a guide to soil management. Soil management decisions should be based on soil management zones for precision agriculture (Kathumo, 2007). Management zones delineate farms on basis of soil attributes to guide fertilizer application (Fridgen et al., 2004).

Other than the factors of soil genesis, management history is also crucial in determining the productivity of a given soil (McBratney et al., 2003; Pendleton and Jenny, 1945). Soil variability results mainly from complex interactions among topography, geology and climate coupled with land use (Behera et al., 2016; Liu et al., 2015) therefore soils exhibit marked spatial variability at macro and micro-scale (Shukla et al., 2016). Field operations including fertilization, tillage and manure application are also sources of variability at various scales of distance and time (Kathumo, 2007) therefore awareness of this heterogeneity for sustainable agricultural production and increasing profitability is paramount.

Spatial variability is the combined effect of chemical, physical and biological processes occurring at different spatiotemporal scales coupled with anthropogenic activities (Goovaerts, 1998). It can help to correct nutrient deficiencies (Brevik and Miller, 2015) and to determine production constraints related to soil fertility. Spatial variability of soils can also act as a guide in suggesting variable remedial measures for optimum production and appropriate land use practises sustainable in the long run (Hălbac-Cotoară-Zamfir et al., 2019; Punday et al., 2018). Spatial variability of soil properties is assessed effectively by geostatistical techniques (Emadi et al., 2016; Liu et al., 2014; Moosavi and Sepaskhah, 2012; Moradi et al., 2016; Shahabi et al., 2016) which can explain the extent of soil variability. Soil heterogeneity has been studied under different management systems (Sanjib Kumar Behera and Shukla, 2015). Spatio-statistical tools predict the values for unsampled locations by factoring in the geographical association between sampled and projected points and reducing variance of assessment error and costs (Sanjib Kumar Behera and Shukla, 2015).

Developments in computing techniques and remote sensing technology provide opportunities for more data-driven applications in farm management. This approach is referred to as smart farming (Wolfert et al., 2017) or precision agriculture. Remote sensing and GIS helps to manage in-field variability, a technology known as precision agriculture (Robertson et al., 2012) that uses information tools including the Global Positioning System; GPS (Aubert et al., 2012; Llewellyn and Ouzman, 2014). This technology requires an enabling institutional, technical and social environment, high skill, competent interpretation and judgement therefore posing a challenging adoption scenario.

Precision Agriculture (PA) technology has undisputable benefits in agriculture as it can improve the efficiency of farm operations by applying exactly what the crops require and saving on the excess (Eastwood et al., 2017; Smith et al., 2013). It can improve water quality and conserve the environment (Lundström and Lindblom, 2016). Recognition of field variation enables the application of variable rate treatments with fine degrees of precision than it would be without point based soil information (Lindblom et al., 2017), therefore representing a paradigm shift in farm practises. PA technology considers a field as a heterogenous entity eligible for selective treatment (Aubert et al., 2012). Spatial variability for PA studies have been done in many parts of the world using different approaches (Castaldi et al., 2017; Morari et al., 2018; Kandagor, 2015).

Increasing population has been shown to decline agricultural productivity (Muyanga and Jayne, 2014) therefore there is need to utilize the remaining land appropriately for maximum agricultural production. The key objective of this study was to evaluate spatial variability in the study area so as to guide decisions on input application. This was driven by the existence of within-field variability in nearby fields (Kandagor, 2015) and other parts of the world. It was also motivated by the potential for better crop productivity with knowledge on point-based soil information.

4.3 Materials and methods

4.3.1 Description of the study site

This study was done in a selected farm (Figure 4.1; 5.87 ha) in upper Kabete campus field, University of Nairobi within a larger study area (168.63 ha). The farm (Field 3) lies within 248599 longitude, latitude 9861349 latitude and 1842 altitude – UTM (Mwendwa et al., 2019) or 36.741longitude, -1.253 latitude and 1842 masl. More information about the study site is as described in section 3.3.1.

4.3.2 Soil sampling

The key goal of soil sampling was to accurately characterize the nutrient status of the soil. Sample locations in Field 3 were geo-referenced using a GPS to allow correlation of soil test results with spatial details of the soil sample (Figure 4.1). Samples were collected at 0 to 15 and 15 to 30 cm depths in twenty (20) sampling points across the farm at a distance of approximately 50 meters from one observation to the other in grids.

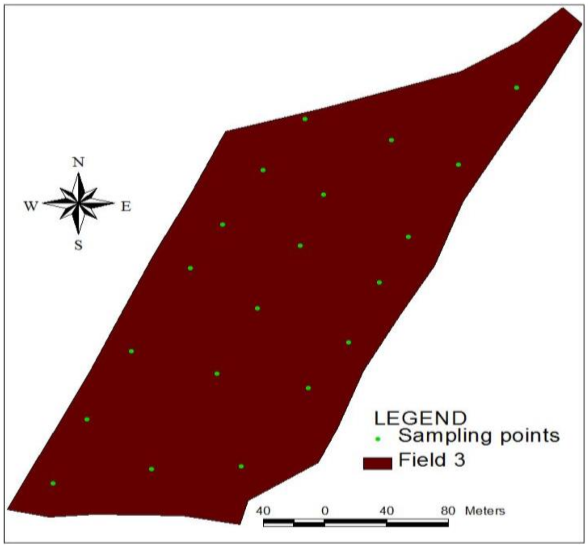

Figure 4. 1: Field 3 showing sample points

4.3.3 Soil analysis and differentiating criteria

Sample preparations and analysis is as described in section 3.3.3 while the differentiating criteria is as explained in section 3.3.8. Base cations were expressed in cmol(+)kg^{-1} while micronutrients in ppm.

4.3.4 Generation of spatial variability maps

The Inverse Distance Weighted (IDW) procedure was used to generate soil variability maps. Maps for micronutrients were not presented in this study because there were no management zones required as the elements are sufficiently supplied in the soil and also because this study was approached from a management point of view. Maps showing a single zone were also not presented.

4.3.5 Cross-validation of the IDW procedure

Since IDW interpolation was used, a semivariogram was not fitted. This is because Kriging interpolation capable of fitting a semivariogram requires at least 30 data points. The root mean square error (RMSE) was calculated to evaluate the accuracy of the interpolation method. The following formula was used to calculate the RMSE of the model.

$$\mathrm{RMSE} = \frac{\sqrt{\sum_{i=1}^{N}(0i - Si)^2}}{N}$$

Where, O_i is the observed value, S_i is the predicted value and N is the number of samples

4.3.6 Statistical analysis

Descriptive statistics was done using SPSS to obtain the coefficient of variation (%cv). Guidelines used to classify the coefficient of variation (%cv) were: cv < 25% = low, cv = 25 to 50% = moderate, cv > 50% = high variation. Other parameters including the mean, median, standard error, standard deviation, sample variance, kurtosis, skewness, range, minimum and maximum were also generated.

4.3.7 Soil classification

The larger area within which this study was done involved digging of soil profiles, horizon description, soil sampling and analysis and a detailed characterization of the soils, with Soil Mapping Units (SMUs) based on slope categories. The IUSS Working Group WRB, 2014 (Schad, 2017) was used in soil classification as the larger area within which this study was done involved detailed soil survey and classification.

4.4 Results and discussions

4.4.1 Diagnostic horizons and properties

Diagnostic horizons and properties is as described in section 3.4.1 and 3.4.2. The soils were classified as Mollic Nitisols.

4.4.2 Cross-validation

The IDW method was cross-validated at each sampling location by comparing approximated values with actual values (Table 4.1). The RMSE was small (<0.5) for pH, organic carbon, nitrogen, potassium and sodium indicating that the interpolation model was an adequate representation of the spatial properties of the soil. It demonstrated a lack of logical bias for forecast spatial distribution therefore the projected maps of the soil properties and the results were consistent (Figure 4.2 to 4.6). Values for phosphorus, magnesium, calcium and micronutrients indicate a moderate prediction quality of the interpolation method.

Table 4. 1: Cross-validation results from IDW of 0 to 15 cm depth

Soil Property	RMSE
Soil pH	0.260
Organic Carbon (%)	0.319
Nitrogen (%)	0.058
Phosphorous (ppm)	4.485
Potassium (cmol(+)/kg)	0.485
Sodium (cmol(+)/kg)	0.086
Magnesium (cmol(+)/kg)	0.561
Calcium (cmol(+)/kg)	2.664
Iron (ppm)	13.824
Copper (ppm)	2.731
Manganese (ppm)	23.391
Zinc (ppm)	7.795

4.4.3 Descriptive statistics

The coefficient of variation (cv%) was used to express the extent of spatial variability of the soil properties (Appendix 4f and g). Soil reaction showed the lowest variability (5.1% and 5.8%) in 0 to 15 and 15 to 30 cm, respectively. This indicates that the soil reaction is similar over a large area and therefore a wide sampling range would be appropriate for soil pH studies in the area. The values of skewness and kurtosis were near zero indicating that the data distribution did not deviate largely from the normal distribution. The standard deviation was used to indicate the shape of distribution in relation to the mean. Most of the values in this study are near zero indicating that the data values are concentrated around the mean. The standard error was used to indicate the reliability of the mean whereby a small SE was interpreted as a more accurate reflection of the actual population mean. Most of the values in this study are near zero indicating an accurate representation of the actual population mean. The maximum and minimum values indicate no evidence of outliers, deviating by slight margins from the mean.

4.4.4 Soil pH

It determines nutrient availability and the rate of microbial reactions (Yan et al., 2019). The pH varied from strongly acid to medium acid (5.1 to 6.0) with a mean of 5.6 and strongly acid to slightly acid (5.1 to 6.3) with a mean of 5.8 in 0 to15 and 15 to 30 cm, respectively (Figure 4.2). It shows low variability of 5.1 and 5.8% in top and subsoil, respectively. In the 0 to 15cm depth, strongly acid covers an area of 2.03 ha while medium acid covers an area of 3.84 ha while in 15 to 30 cm depth, slightly acid covers 0.60 ha, medium acid 4.58 ha and strongly acid 0.69 ha. The acidic pH of the soil can be attributed to leaching of basic cations under humid conditions (Jatzold and Kutsch, 1982) which is demonstrated by higher pH values in 15 to 30 cm depth. In a similar study in Nepal, Panday et al. (2018) attributed moderately acidic soil reaction to leaching of major cations.. Predominantly acidic pH can also be attributed to incessant uptake of cations by coffee feeder roots in the upper depth and this observation is consistent with findings of (Khadka et al., 2017) who found variable pH in a single farm in Dhanusha, Nepal. The pH range is favourable for the growth of Arabica coffee as it is known to grow in soil conditions ranging from acidic to neutral (pH 4 to 7). This is in accordance with Version, (2008) who documented acidic soil reaction as appropriate for optimal coffee production.

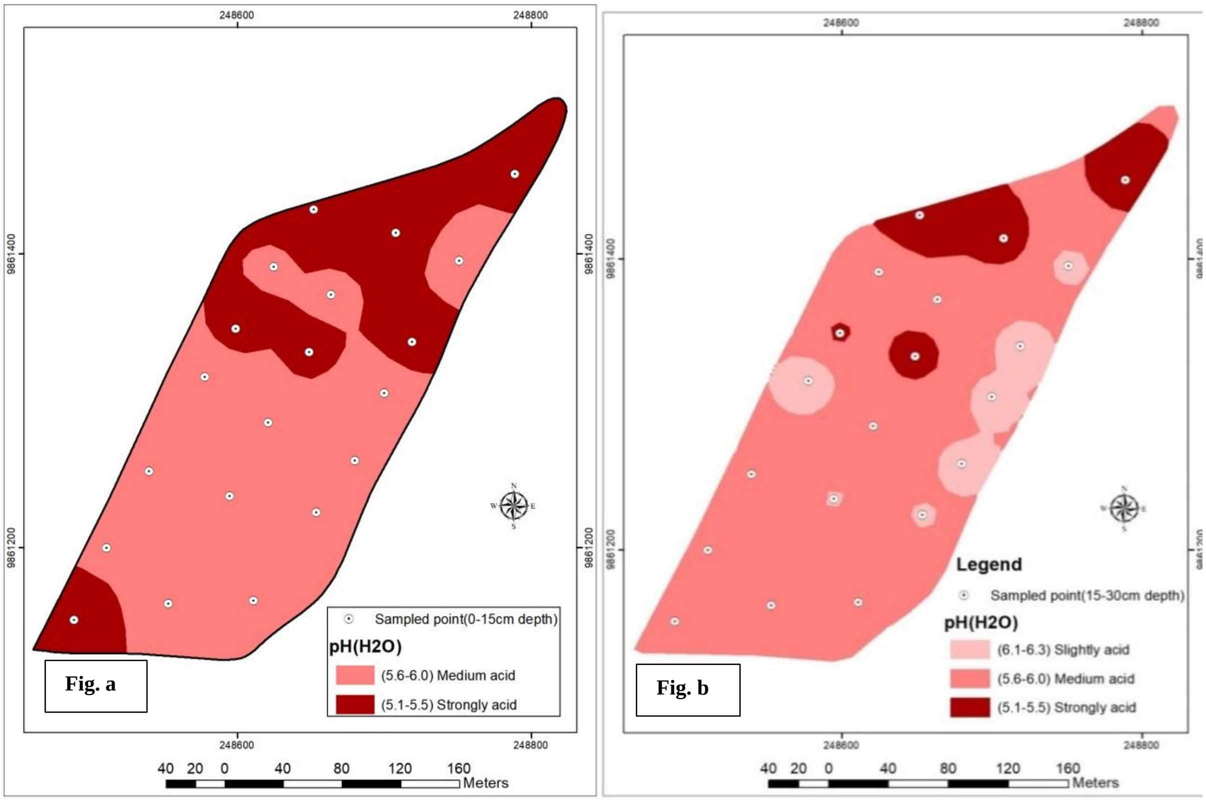

Figure 4. 2: Spatial distribution of pH: a) 0 to 15 cm; b) 15 to 30 cm

4.4.5 Percent Organic Carbon (%OC)

It is the precursor to organic matter and plays a crucial role in maintaining the soil structure and binding nitrogen thus improving infiltration and plant uptake, respectively. The correlation coefficient (r) for carbon and nitrogen is 0.2 and 0.3 in 0 to 15 and 15 to 30 cm, respectively (Appendix 3a and b). This observation is consistent with findings of Cheng et al. (2016) and Lelago and Buraka (2019) who found that organic carbon is essential for nitrogen availability. Organic carbon ranges from 2.12 to 3.18% with a mean of 2.75% and 1.82 to 3.07% with a mean of 2.40% showing adequate and moderate to adequate status in 0 to 15 and 15 to 30 cm, respectively (Figure 4.3). Both depths show low variability (10.4 and 12.7%), respectively. In 15 to 30 cm depth, organic carbon was moderate in 0.15 ha and adequate in 5.72 ha. Higher organic matter content in top horizon can be attributed to more litter on the surface, an observation consistent with findings of (Browaldh, 1995) who attributed higher organic matter in top horizons to more litter. In terms of coffee production, these values are rated as low (Table 4.2) therefore 3 to 5 tonnes/ha of well-decomposed animal manure should be added per year to improve nutrient supply.

Table 4. 2: Soil critical ratings for total carbon and total nitrogen

Rating	Total Carbon (%)	Total Nitrogen (%)
Very high	>20	>1.0
High	10 - 20	0.6 -1.0
Medium	4 - 10	0.3 - 0.6
Low	2 - 4	0.1 - 0.3
Very low	< 2	< 0.1

Source: NARI (n.d)

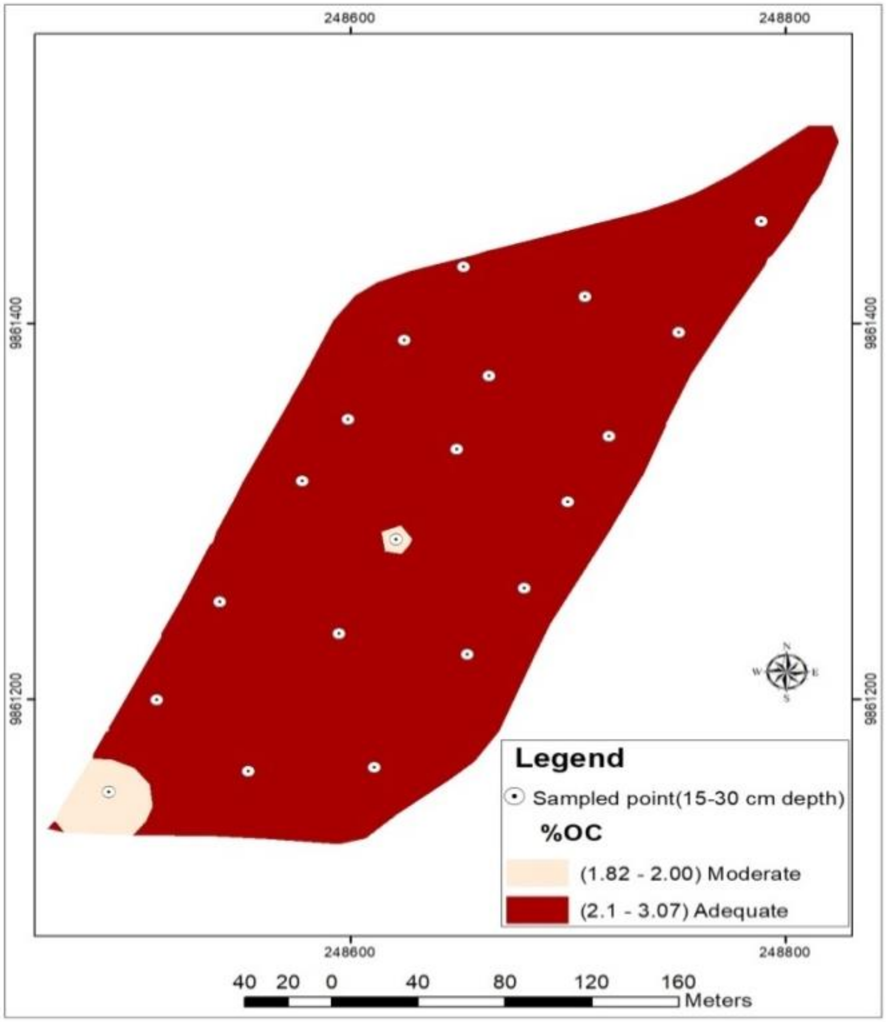

Figure 4. 3: Spatial distribution of %OC in 15 to 30 cm

4.4.6 Total Nitrogen (%N)

It is vital for vegetative development and most frequently deficient in soils across the world (Ullah et al., 2010). In 0 to 15 cm, it ranges from 0.23 to 0.38% with a mean of 0.32%. In 15 to 30 cm, percent nitrogen ranges from 0.21 to 0.35% with a mean of 0.29%. All samples are in medium category. Both depths show low variability (14.5% and 17.6%), respectively. These values are relatively lower than the critical levels (0.3 to 0.6%) for optimal coffee production as recommended by The Coffee Research Foundation (CRF). The decline in percent nitrogen levels can be attributed to continuous cultivation without nutrient replenishment especially manure. This is consistent to findings of Willy et al. (2019) who attributed declining soil nitrogen to continuous cultivation. Application of NPK fertilizer at the rate of 250 grams per coffee tree biannually is recommended after soil analysis and establishing the N content level.

4.4.7 Available phosphorus (P)

It is important in metabolism and transformation of energy in plants (Rai et al., 2011) and plays a vital role in coffee in developing the bearing branches. Phosphorus is deficient in the studied farm having a mean of 10.65 and 10.31 ppm and showing moderate variability (36.2 and 42.3%) in 0 to 15 and 15 to 30 cm, respectively. These values were below the critical level (20 to 100 ppm) for coffee production as per the CRF recommendations. Phosphorus deficiency can be attributed to its attachment to sediments and subsequent transportation through erosion and also the acidic pH of the soils that could have led to P fixation. This observation is consistent with findings of Bakhshandeh et al. (2014) in Lahijan, Iran who attributed P deficiency to fixation in acidic soil reaction. It could also be due to soil development from a phosphorus-deficient parent material, an observation consistent with findings of Porder and Ramachandran (2013) who found that parent materials had a great influence on the amount of phosphorus in the soil. Erosion could also have played part in the phosphorus deficiency in the studied soil. Application of 3 to 5 tonnes/ha of well-decomposed animal manure is recommended. Manure would increase the number of colloids with low phosphate fixation in the like of organic matter.

4.4.8 Exchangeable Potassium (K)

Potassium is vital for maintenance of physiological processes, protein synthesis and maintaining plant water balance (Sumithra et al., 2013). In 0 to 15 cm, K varies from 1.5 to 3.0 cmol(+)kg^{-1} with a mean of 2.19 cmol(+)kg^{-1} indicating rich supply and showing low variability (21.7%). In 15 to 30 cm, K ranges from sufficient to rich (0.6 to 2.4 cmol(+)kg^{-1}) with a mean of 1.74 cmol(+)kg^{-1} and shows moderate variability of 28.9% (Figure 4). In 15 to 30 cm depth, sufficient covers 1.09 ha while rich covers an area of 4.78 ha. These observations indicate adequate status of potassium enough for coffee nutrition based on K values between 0.4 to 2.0 cmol(+)kg^{-1} which are the recommended rates for optimal coffee production. Higher values in the top depth could be a function of minimal K loss from the soil. These soils were derived from volcanic activities hence rich in K and that could that could have led to the adequate K in the soils.

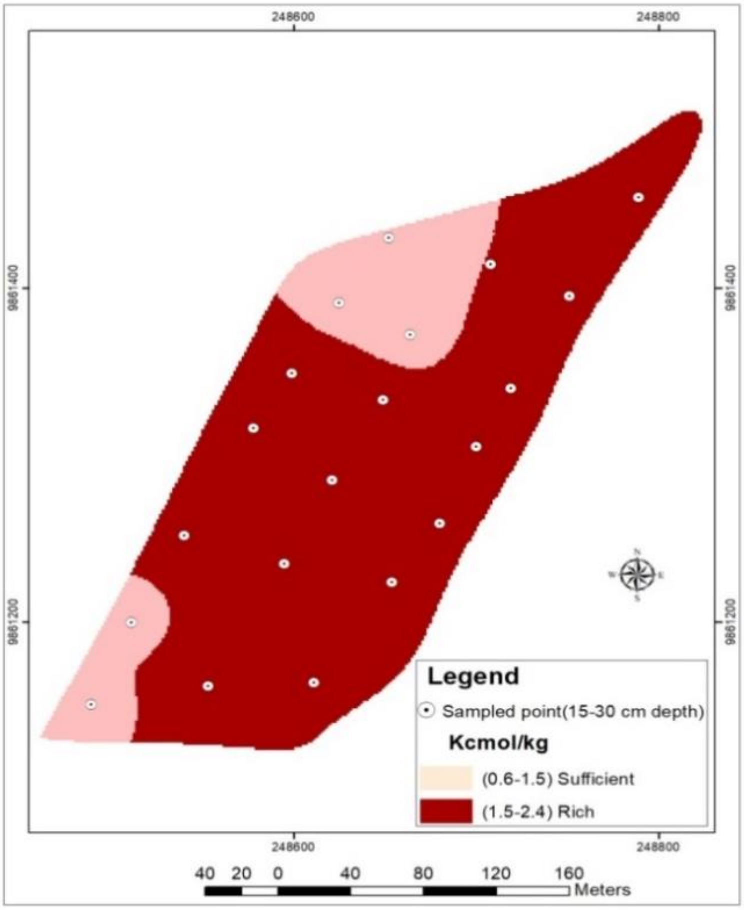

Figure 4. 4: Spatial distribution of K in 15 to 30cm depth

4.4.9 Exchangeable Calcium (Ca)

Calcium regulates how plants respond to endogenous stimuli and signals of stress (Lecourieux et al., 2006). It ranges from 4.5 to 14.5 cmol(+)kg^{-1} with a mean of 9.79 cmol(+)kg^{-1} and 3.8 to 14.2 cmol(+)kg^{-1} with a mean of 10.54 cmol(+)kg^{-1} indicating sufficient to rich supply (Figure 4.5) in both depths. It shows moderate variability of 26.3% in both depths. In 0 to 15 cm, sufficient covers an area of 3.17 ha while rich covers an area of 2.70 ha; In 15 to 30 cm depth, sufficient covers an area of 0.17 while rich 5.70 ha. Observed values are sufficient for optimum production of coffee given the critical values (1.6 to 10 cmol(+)kg^{-1}) as per Coffee Research Foundation. Deficiency of phosphorus could have compromised the uptake of Ca therefore its remedial fertilization is encouraged to boost Ca uptake. Slightly higher Ca content in the 15 to 30cm depth could be a result of leaching in the humid environment (Figure 4.5).

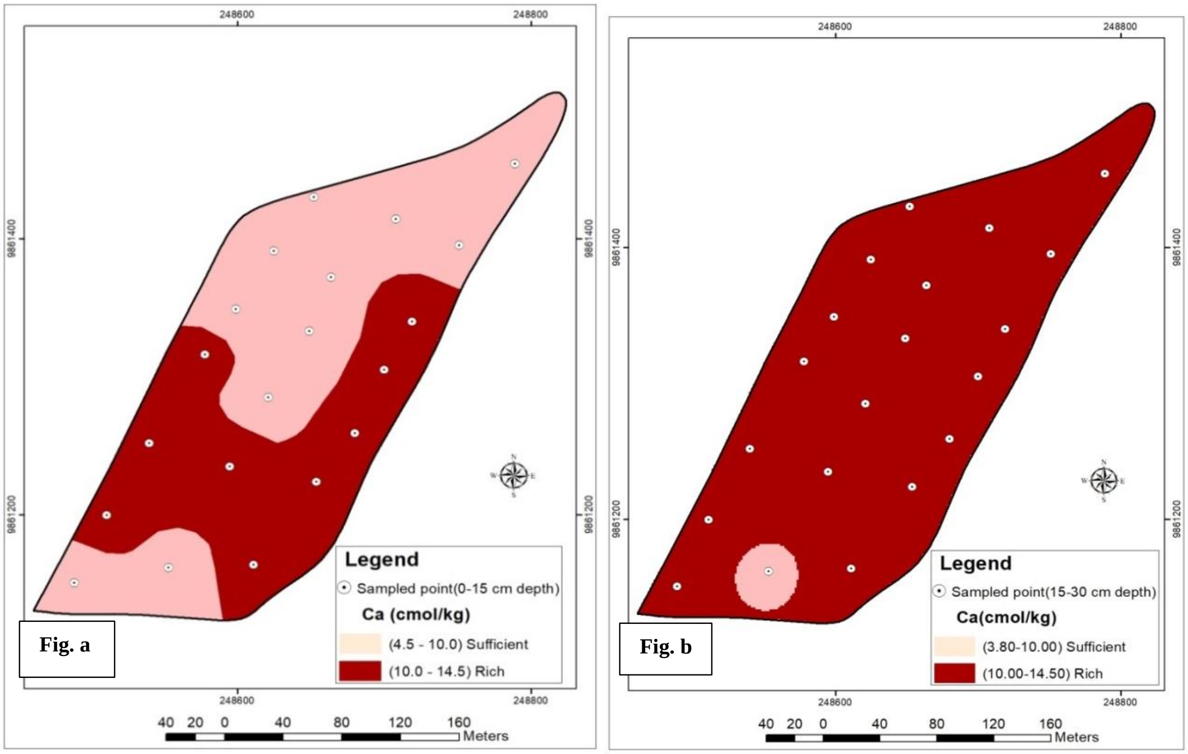

Figure 4. 5: Spatial distribution of Ca: a) 0 to 15 cm); b) 15 to 30 cm

4.4.10 Exchangeable Magnesium (Mg)

Magnesium plays an array of vital roles in plants including enzyme catalysis, photosynthesis and synthesis of the genetic material (Tanoi and Kobayashi, 2015). In 0 to 15 cm depth, magnesium varies from 1.50 to 4.21 cmol(+)kg^{-1} with a mean of 2.92 indicating sufficient status and showing low variability (22.1%). In 15 to 30 cm depth, Mg ranges from 1.68 to 3.32 cmol(+)kg^{-1} with a mean of 2.54 indicating sufficient supply (Figure 4.6) and showing low variability (19.2%). In 0 to 15 cm, sufficient covers an area of 2.05 ha while rich 3.82 ha; In 15 to 30 cm depth, sufficient covers an area of 0.11 while rich 5.76 ha. These values are within the critical values (0.8 to 4.0 cmol(+)kg^{-1}) for optimum production of coffee as adopted at CRF. Higher Mg content in the lower depth can be attributed to leaching in the humid environment.

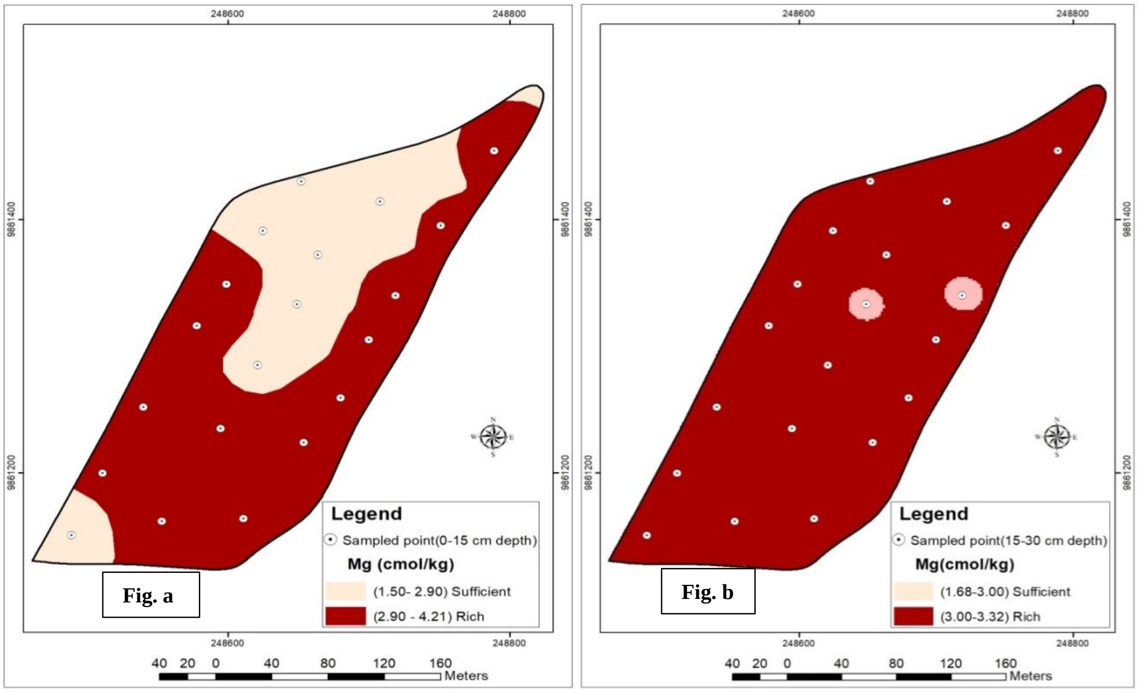

Figure 4. 6: Spatial distribution of Mg: a) 0 to 15 cm b) 15 to 30 cm

4.4.11 Exchangeable sodium

It is a monovalent so it can be a substitute for K in plant nutrition but its excess could be detrimental to the soil structure due to sodicity. All samples from both depths have sodium values ranging from 0.1 to 0.2 cmol(+)kg^{-1} with a mean of 0.2 cmol(+)kg^{-1} indicating non-sodicity. It shows moderate variability (45.3 and 33.6%) in 0 to 15 and 15 to 30 cm depth, respectively. These values are rated as adequate (Bould, 1974) therefore sodium is not a limitation to coffee production.

4.4.12 Available Iron (Fe)

Iron is the most essential micronutrient for its role in chlorophyll synthesis and electron transport. It impacts nitrification, respiration and synthesis of genetic materials (By and Kimata, n.d.). Iron varies from 19 to 68 ppm with a mean of 44.15 ppm and 28 to 82 ppm with a mean of 48.65 ppm in 0 to 15 and 15 to 30 cm indicating sufficient status and showing moderate variability (32.8 and 36.1%), respectively. The rich iron status across all samples can be attributed to good drainage and Fe availability in the exchange complex after leaching of bases. It can be concluded that the soils of Kabete are rich in iron but the status is not toxic to coffee production. This rich status of iron suggests high probability of iron rich minerals including hematite, goethite, olivine, magnetite and siderite being available. It may also be a function of Fe complexes with phosphate substances in the soil hence have limited chance for leaching losses. Nutrients including P, K, Mn and Zn should be well managed as their availability is inhibited by high iron availability (Fageria et al., 2008).

4.4.13 Available Zinc (Zn)

Zinc plays a key function in gene replication and a vital role in plant metabolism by influencing hydrogenase and carbonic anhydrase activity, cytochrome synthesis and stabilizing ribosomal fractions (By and Kimata, n.d.). It ranges from 17 to 44 ppm having a mean of 30.23 ppm and 9 to 43 ppm with a mean of 23.76 ppm in 0 to 15 and 15 to 30 cm, respectively. Both depths are sufficient in Zn and show moderate variability (26.5 and 38.8%), respectively. High zinc status in the soil can be attributed to the igneous parent material which is usually rich in Zn.

4.4.14 Available Copper (Cu)

Copper facilitates mitochondrial respiration, hormone signalling, photosynthetic electron transport and enzyme activation in plants (By and Kimata, n.d.; Adhikari et al., 2016). It ranges from 13 to 23 ppm with a mean of 18.76 ppm and 12 to 21 ppm having a mean of 15.41 ppm in 0 to 15 and 15 to 30 cm, respectively. All samples are sufficient in Cu and show low variability (13.3 and 17.3%) in 0 to 15 and 15 to 30 cm depth, respectively. The sufficient status of copper and higher concentration in the top horizon can be attributed to clay mineral and organic matter, respectively. This is because copper exists in soil mainly as a divalent Cu^{2+} ion adsorbed by clay minerals or associated with organic matter. It can also be attributed to low soil Phosphorus which is known to be a contradictory factor to copper availability.

4.4.15 Available Manganese (Mn)

Manganese originates primarily from decomposition of ferromagnesian rocks. It is important in photosynthesis, nitrogen assimilation, root pathogen resistance and enzyme activation. In 0 to 15 cm, it ranges from 17 to 86 ppm with a mean of 71.33 ppm and shows moderate variability (32%). In 15 to 30 cm, Mn varies from 63 to 82 ppm having a mean of 74.19 ppm and shows low variability (7.1%). These values indicate sufficient supply of Mn in the soil and is not rated as excessive (275ppm).

4.5 Conclusions and recommendations

This study concentrated on assessment of top soil parameters as most coffee feeder roots are found near the surface. Based on the findings, farm decisions should be based on the soil management zones to ensure precise input application. Phosphorus was the most deficient nutrient which can be attributed to soil genesis from a P-deficient parent material. It could also be due to the predominantly acidic soil reaction that could have resulted to fixing of P sources. There is need to apply manure to the soils due to its vital role in maintaining high organic matter and indirectly maintaining nitrogen and phosphorus sources. Micronutrients sufficiency in the studied farm can be attributed to the predominantly acidic soil reaction as micronutrient availability increases with increasing soil acidity. There is need to prevent soil erosion in the farm so as to maintain high soil and water quality. NPK fertilizer preferably 40:30:40 is recommended to be applied in three splits.

Input management based on spatial variability of soil properties is highly recommended so as to get maximum output using optimum inputs. Training on spatial variability and precision agriculture is highly recommended so that it can be included in extension services to farmers. Envisaging high value crops where they best fit is also recommended.

CHAPTER FIVE: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion

Soils of the study area were classified as Mollic Nitisols as identified having a nitic B horizon having nitic properties and a mollic A horizon. The soils have good drainage and are deep to very deep (>80 cm). This indicates that drainage and depth are not limitations to crop production. Of the major elements, phosphorus is the most deficient which can be attributed to soil genesis from a P-deficient parent material and also the predominantly acidic soil reaction that could have resulted to fixing of P sources, making it unavailable for plant uptake. This is in addition to P losses through crop harvest. Results show that the study area can be delineated into different mapping units based on slope that may have the same soil classification but requiring variable soil management practises. Saturated hydraulic conductivity decreased with depth in all profiles due to increasing clay and decreasing soil porosity. Aspects like physical barriers for example buildings and rocks slowing the velocity of water movement, resulting to clay translocation in upslope convex positions were observed in this study.

5.2 Conclusions

Results indicated that spatial variability occurred within the selected farm. The soils have good physical and hydrologic properties for crop production but use of heavy machinery on wet conditions should be avoided to prevent soil compaction. The decreasing saturated hydraulic conductivity with depth is attributable to increasing clay as shown by increasing cutanic surfaces. The rapid ksat values in steeper slopes reflects better drainage than in gentle slopes meaning that if this study is to be replicated elsewhere, crops that thrive in soils that are not well drained including arrow roots and sugarcane should not be planted on steep slopes. Physical barriers slowing water velocity shows the importance of water conservation methods including terraces and ridges. The effect of clay cutans on leaching and probable lateral flow lines is also accentuated as shown by more acidic soil reaction in lower horizon of some profiles. The impact of erosion on soil quality is lucidly exposed by the low fertility parameters in profile 148/4-11 therefore there is need to control erosion in soils so as to maintain high soil and water quality. This is because erosion carries away the fertile top layer of the soil and some ends up in rivers and other water sources polluting it.

5.3 Recommendations

Spatial variability within fields should be utilized in farm management to maintain soil fertility. There is need to apply manure to the soils as it plays a vital role in buffering the soil reaction, maintaining high organic matter, stabilizing the CEC and indirectly maintaining nitrogen and phosphorus sources in the soil. Application of phosphate fertilizer, preferably slow-release rock phosphate alongside smaller applications of super phosphate for short term response by the crops is recommended. Continuous cultivation without adequate replenishment of soil nutrients should be avoided. Erosion control measures are highly encouraged in sloping areas to prevent runoff. It would be paramount for agricultural colleges to consider inclusion of spatial variability concepts in the training curriculum so that that students are equipped with this useful skill. There is need for the government to fund these training exercises for the benefit of the nation and the environment. Precise farm input application can act as a panacea to food insecurity in different parts of the world.

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7.0 APPENDICES

Appendix 1: Soil morphological and physical data of the study area

Horizon design.	Depth (cm)	Colour Moist	Descr	Structure	Consistence			Texture								
					Dry	Mo	Wet	Sa	Cl	Si	SCR	TC	Ksat	Ksat class	BD	Por
Prof. 1																
A	0-16	2.5 YR3/2	dr	2,2,g	h	l	s,p	40	52	8	0.2	C	11.1	R	1.0	64
AB	16-35	2.5 YR3/3	drb	2,2,sbk	h	fr	s,p	32	54	14	0.3	C	10.0	R	1.0	61
Bt1	35-64	2.5 YR3/4	drb	2,3,sbk	h	fr	s,p	30	56	12	0.2	C	8.0	R	1.1	60
Bt2	64-91	2.5 YR4/4	rb	1,2-3,sbk	h	fr	s,sp	28	56	16	0.3	C	2.8	M	1.1	60
Bt3	91-140+	2.5 YR3/6	dar	1,3,sbk	h	fr	s,sp	28	60	12	0.2	C	2.0	M	1.1	59
Prof. 2																
A	0-23	2.5 YR2/3	drb	2,2,sbk	sh	fr	s,sp	31	39	30	0.8	CL	6.1	MR	1.2	53
Bt1	23-50	2.5 YR3/4	drb	2,3,sbk	h	fr	s,p	32	42	26	0.6	C	5.0	M	1.1	58
Bt2	50-73	2.5 YR3/4	drb	2,2,sbk	h	fr	s,p	36	46	18	0.4	C	5.0	M	1.1	59
Bt3	73-105	2.5 YR4/4	rb	2,2,sbk	h	fr	s,p	41	49	10	0.2	C	3.0	M	1.0	62
Bt4	105-152+	10R3/4	dr	2,2,sbk	sh-h	fr	s,sp	43	49	8	0.2	C	1.4	S	1.1	60
Prof. 3																
A	0-21	7.5 YR3/2	dab	2,2,sbk	h	fr	vs,p	32	46	22	0.5	C	7.9	MR	1.1	59
AB	21-45	2.5 YR3/3	drb	2,2,sbk	h	fr	vs,vp	30	50	20	0.4	C	6.0	MR	1.0	61
Bt1	45-70	2.5 YR3/3	drb	2,2-3,sbk	h	fr	vs,vp	34	54	12	0.2	C	3.3	M	1.2	55
Bt2	70-95	2.5 YR3/3	drb	1,3,sbk	h-vh	fr	vs,vp	32	54	14	0.3	C	3.0	M	1.1	59
Bt3	95-133+	2.5YR4/4	rb	1,3,sbk	h-vh	fr	vs,vp	38	46	16	0.3	C	2.0	M	1.1	59
Prof. 4																
A	0-27	2.5 YR3/2	dr	2,2,g	h	fr	s,p	32	46	22	0.5	C	6.1	MR	1.1	60
AB	27-38	2.5 YR3/4	drb	2,2,sbk	h	fr	s,p	30	50	20	0.4	C	5.0	M	1.0	63
Bt1	38-62	2.5 YR3/4	drb	2,2,sbk	vh	fr	s,p	28	50	22	0.4	C	5.0	M	1.1	59
Bt2	62-92	5 YR3/4	drb	1,3,sbk	sh	fr	s,p	28	52	20	0.4	C	4.0	M	1.1	58
Bt3	92-110+	2.5YR4/4	rb	1,3,sbk	h	fr	s,p	26	54	20	0.4	C	2.0	M	1.1	58
Prof. 5																
A	0-16	2.5 YR3/3	drb	2,2,sbk	sh	l	s,p	26	66	8	0.1	C	8.7	R	1.1	58
Bt1	16-38	2.5 YR3/4	drb	2,2-3,sbk	sh	fr	s,sp	24	68	8	0.1	C	6.3	MR	1.0	61
Bt2	38-66	2.5 YR3/4	drb	1,3,sbk	sh-h	fr	s,sp	22	68	10	0.1	C	5.0	M	0.9	64
Bt3	66-89	7.5 YR3/4	db	1,3,sbk	h	fr	s,sp	22	70	8	0.1	C	5.1	M	0.8	68
Bt4	89-140+	2.5YR4/4	rb	1,3,sbk	sh	fr	s,sp	18	72	10	0.1	C	3.0	M	1.0	62
Prof. 6																
A	0-33	2.5 YR3/2	dr	2,2,sbk	h	fr	s,p	30	48	22	0.5	C	8.5	R	1.1	58
AB	33-53	2.5 YR3/3	drb	2,2,sbk	sh	fr	s,p	24	52	24	0.5	C	8.0	R	1.0	61
Bt1	53-84	2.5 YR3/4	drb	2,2,sbk	sh-h	fr	s,p	24	54	22	0.4	C	5.0	M	1.0	62
Bt2	84-111	2.5 YR 4/4	rb	2,2,sbk	sh-h	fr	vs,vp	22	54	24	0.4	C	3.5	M	1.1	60
Bt3	111-140+	10R3/4	dr	2,2,sbk	sh	fr	vs,vp	18	64	18	0.3	C	1.3	S	1.1	60

Continued…..

Horizon design.	Depth (cm)	Colour Moist	Descr	Structure	Consistence			Texture						Ksat class		
					Dry	Mo	Wet									
Prof. 7								Sa	Cl	Si	SCR	TC	Ksat		BD	Por
Ap	0-14	2.5 YR3/3	drb	2,3,g	sh	fr	s,p	22	64	14	0.2	C	9.0	R	1.1	58
Bt1	14-39	2.5 YR3/3	drb	2,3,sbk	h	fr	s,p	24	66	10	0.2	C	8.0	R	1.0	62
Bt2	39-63	2.5 YR3/4	drb	2,3,sbk	sh	fr	vs,p	22	68	10	0.1	C	5.6	MR	1.1	58
Bt3	63-97	2.5 YR4/4	rb	2,3,sbk	h	fr	s,p	20	70	10	0.1	C	4.0	M	1.0	61
Bt4	97-163+	10R 4/4	wr	1,2,sbk	sh	fr	ss,sp	18	74	8	0.1	C	2.9	M	1.1	59
Prof. 8																
Ap	0-17	2.5 YR3/2	dr	2,2,g	sh	fr	s,sp	47	30	23	0.8	SCL	5.2	M	0.9	66
Bt1	17-38	2.5 YR3/3	drb	2,2,sbk	sh	fr	s,sp	39	42	19	0.5	C	3.4	M	1.0	61
Bt2	38-63	2.5 YR3/4	drb	2,2,sbk	sh	fr	s,sp	35	54	11	0.2	C	1.6	M	1.0	61
Bt3	63-100	2.5 YR4/4	rb	1,2,sbk	sh	fr	s,sp	33	60	7	0.1	C	1.1	S	1.1	59
Bt4	100-141+	10R 3/4	dr	1,2,sbk	sh-h	fr	s,sp	25	62	13	0.2	C	0.6	S	1.2	55
Prof. 9																
Ap	0-21	2.5 YR3/2	dr	2,3,g	sh	fr	s,sp	51	24	27	1.1	SCL	5.8	MR	1.1	60
Bt1	21-50	2.5 YR3/3	drb	1,3,sbk	sh	fr	s,sp	41	34	25	0.7	CL	5.0	M	1.1	60
Bt2	50-70	2.5 YR3/4	drb	1,3,sbk	sh	fr	s,sp	37	52	11	0.2	C	3.0	M	1.1	59
Bt3	70-92	2.5 YR4/4	rb	1,3,sbk	sh	fr	s,sp	39	50	11	0.2	C	3.0	M	1.0	61
Bt4	92-120+	2.5YR4/4	dr	1,3,sbk	sh	fr	s,sp	39	54	7	0.1	C	1.0	S	1.1	58
Prof. 10																
Ap	0-16	2.5 YR3/3	drb	2,2,sbk	s	l	vs,p	36	32	32	1.0	CL	3.6	M	1.2	53
AB	16-38	2.5 YR3/2	dr	2,3,sbk	sh-h	fr	vs,vp	36	38	26	0.7	CL	4.0	M	1.0	61
Bt1	38-72	2.5 YR3/3	drb	2,3,sbk	h-vh	fr	vs,vp	42	40	18	0.5	C	3.0	M	1.2	54
Bt2	72-93	2.5 YR3/4	drb	2,2,sbk	h-vh	fr	vs,vp	38	48	14	0.3	C	1.0	S	1.1	58
Btc	93-123+	2.5YR4/4	rb	2,3,sbk	h	fr	vs,vp	46	40	14	0.4	SC	1.0	S	1.3	52
Prof. 11																
A	0-25	2.5 YR3/2	dr	2,2,g	sh	fr	s,sp	30	40	30	0.8	CL	8.2	R	1.1	60
Bt1	25-50	2.5 YR3/3	drb	2,3,sbk	sh-h	fr	s,sp	28	48	24	0.5	C	6.2	MR	1.0	61
Bt2	50-74	2.5 YR3/4	drb	2,3,sbk	sh	fr	vs,sp	24	54	22	0.4	C	5.0	M	1.1	59
Bt3	74-103	2.5 YR4/4	rb	1,3,g	sh	fr	vs,sp	24	68	8	0.1	C	3.8	M	1.0	62
Bt4	103-115+	10R3/4	dr	2,2,g	sh-h	fr	vs,sp	22	69	9	0.1	C	2.0	M	1.1	58
Prof. 12																
Ap	0-18	2.5 YR3/2	dr	1,2,g	sh	l	s,p	35	25	40	1.6	L	3.6	M	1.1	58
AB	18-32	2.5 YR3/3	drb	1,3,g	sh-h	fr	s,p	41	27	32	1.2	L	3.7	M	1.1	60
Bt1	32-56	2.5 YR3/4	drb	2,3,sbk	sh	fr	vs,p	33	47	20	0.4	C	1.2	S	1.1	57
Bt2	56-82	2.5 YR4/4	rb	2,3,sbk	sh	fr	vs,vp	35	49	16	0.3	C	TR	VS	1.1	59
Bt3	82-136+	10R3/4	dr	2,2,sbk	sh-h	fr	s,sp	24	58	18	0.3	C	TR	VS	1.2	55

Continued…..

Horizon	Depth				Consistence			Texture						Ksat		
design.	(cm)	Colour Moist	Descr	Structure	Dry	Mo	Wet							class		
Prof. 13								Sa	Cl	Si	SCR	TC	Ksat		BD	Por
Ap	0-15	2.5 YR 3/3	drb	3,2-3,g	sh	fr	vs,vp	30	54	16	0.3	C	16.5	VR	1.0	64
AB	15-38	2.5 YR3/4	drb	2,2-3,sbk	sh-h	fr	s,p	26	56	18	0.3	C	14.7	VR	1.0	60
Bt1	38-61	2.5 YR4/4	rb	2,2-3,sbk	sh-h	fr	s,sp	24	58	18	0.3	C	7.9	R	1.0	62
Bt2	61-80	2.5 YR4/4	rb	1,2,sbk	sh	fr	s,sp	24	60	16	0.3	C	2.9	M	1.0	63
Bt3	80-134+	2.5YR4/6	r	1,2,sbk	sh	fr	s,sp	22	62	16	0.3	C	0.5	S	1.1	59
Prof. 14																
Ap	0-15	2.5 YR3/3	drb	2,3,sbk	l	fr	vs,p	45	28	27	1.0	CL	8.0	R	1.0	62
Bt1	15-40	2.5 YR3/4	drb	2,3,sbk	sh	fr	vs,p	39	46	15	0.3	C	6.5	MR	1.0	63
Bt2	40-60	2.5 YR3/4	drb	2,3,sbk	sh	fr	vs,vp	35	52	13	0.3	C	2.3	M	1.1	60
Bt3	60-100	2.5 YR3/4	drb	2,3,sbk	s-sh	fr	vs,sp	37	54	9	0.2	C	1.6	M	1.0	61
Bt4	100-125+	2.5 YR4/4	rb	2,3,sbk	h	fr	s,p	39	54	7	0.1	C	TR	VS	1.1	60
Prof. 15																
Ap	0-18	2.5 YR3/3	drb	1,3,g	s	l	s,sp	28	38	34	0.9	L	16.5	VR	0.9	66
AB	18-45	7.5 YR2.5/3	vdab	2,3,sbk	h	fr	vs,p	28	42	30	0.7	C	11.3	R	1.0	61
Bt1	45-79	7.5 YR3/3	db	2,3,sbk	h	fr	vs,p	30	48	22	0.5	C	10.0	R	1.1	60
Bt2	79-114	2.5 YR3/4	drb	1,3,sbk	sh	fr	vs,vp	32	52	16	0.3	C	7.0	MR	1.1	59
Bt3	114-138+	10R3/4	dr	1,3,sbk	sh	fr	vs,vp	28	52	20	0.4	C	4.0	M	1.1	57
Prof. 16																
Ap	0-25	2.5 YR3/2	dr	2,2,g	s	l	s,sp	44	32	24	0.8	CL	10.9	R	0.9	66
AB	25-51	2.5 YR3/2	dr	2,2,sbk	sh	fr	s,p	46	42	12	0.3	C	11.3	R	1.1	60
Bt1	51-74	2.5 YR3/4	drb	2,3,sbk	sh	fr	vs,p	38	52	10	0.2	C	9.8	R	1.1	60
Bt2	74-97	2.5 YR4/4	rb	2,3,sbk	sh	fr	s,p	38	52	10	0.2	C	5.7	MR	1.1	59
Bt3	97-123+	10R3/4	dr	2,3,sbk	sh	fr	s,sp	38	60	2	0.0	C	1.1	S	1.1	59

Where: Prof. = profile, Descr = descriptive, Mo = moist, Sa = sand, Cl = clay, Si = silt, SCR = Silt Clay Ratio, TC = texture class, BD = bulk density, Por = porosity, drb = dark reddish brown, rb = reddish brown, dr = dusky red, dab = dark brown, vdab = very dark brown, r = red, 1 = weak, 2 = fine/thin, 2 = moderate, 3 = strong, g = granular, sbk = subangular blocky structure, sh = slightly hard, h = hard, vh = very hard, s = soft, fr = friable, l = loose, s = sticky, ss = slightly sticky, vs = very sticky, p = plastic, sp = slightly plastic, vp = very plastic.

NB: Plant roots decreased with depth in all profiles.

Appendix 2: Soil fertility data for the mapping units

Mapping unit	**UmIr/F**	**UmIr/E**		**UxIr/D**				**UxIr/C**					**UxIr/AB**			
Profile 148/4-	**7**	**5**	**6**	**1**	**2**	**4**	**14**	**3**	**8**	**9**	**11**	**13**	**10**	**12**	**15**	**16**
Designation	Ap	A	A	A	A	A	Ap	A	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap
Depth(cm)	0-14	0-16	0-33	0-16	0-23	0-27	0-15	0-21	0-17	0-21	0-25	0-15	0-16	0-18	0-18	0-25
pH	6.0	5.6	6.2	5.7	6.2	6.4	5.7	5.9	5.9	5.4	5.7	6.2	6.3	5.8	5.6	5.5
%OC	2.95	3.18	4.03	3.68	3.45	3.80	2.55	3.95	3.14	3.30	2.51	1.99	2.13	1.66	2.73	2.40
% N	0.39	0.35	0.49	0.36	0.39	0.42	0.20	0.56	0.34	0.32	0.56	0.25	0.27	0.22	0.31	0.24
P(ppm)	8	7	6	6	2	12	13	6	17	5	11	8	11	20	15	11
K(cmol(+)/kg	1.75	0.75	2.15	1.8	1.8	2	1.75	1.4	3	2.7	1.3	1.7	3.05	1.4	2.5	1.5
Na(cmol(+)/kg	0.1	0.3	0.2	0.2	0.2	0.1	0.2	tr	0.2	0.2	0.2	0.3	0.2	0.2	0.2	tr
Mg(cmol(+)/kg	4.7	3.6	5.1	4.0	4.6	4.3	2.6	1.7	4.4	3.2	2.9	3.7	3.3	1.7	1.8	2.5
Ca(cmol(+)/kg	13.9	9.3	18.5	10.9	14.6	18.6	9.5	9.4	12.0	6.5	17.2	12.0	7.0	10.7	9.5	14.9
CEC(cmol(+)/kg	22.2	15.6	27.6	23	23.2	27	20	25.8	21.2	24.4	23	19.2	15	18	20.2	20.4
BS%	92	90	94	73	91	93	70	48	92	52	94	92	91	78	70	93
Fe(ppm)	62.1	53.7	36.0	57.5	46.4	67.3	57.9	92.8	59.9	45.4	40.5	78.3	81.1	45.5	57.8	57.7
Cu(ppm)	6.9	7.7	7.7	7.6	2.3	8.9	25.6	2.5	8.6	7.5	6.9	12.4	8.8	7.3	9.4	8.9
Mn(ppm)	75.0	48.8	79.8	79.9	77.7	77.1	81.6	79.2	81.5	76.5	66.8	82.4	76.8	75.9	83.4	82.6
Zn(ppm)	29.6	34	34.6	38.5	28.1	39.4	29.5	42.7	29.5	20.7	21.0	28.2	33.4	21.3	53.6	52.9

Legend: Mapping units= Slope categories, 148/4=Quarter degree sheet of Kabete area, Designation= top horizons based on profile descriptions.

Appendix 3 (a) Spatial variability data for Field 3 (0 to 15 cm depth)

Code	X	y	z	pH1	pH2	EC	%OC	%N	P	K	Na	Mg	Ca	CEC	%BS	Fe	Cu	Mn	Zn
PA1	248751	9861395	1840	5.7	5.4	0.1	3.11	0.34	14	3.0	0.1	3.09	8.1	19	77	28	19	86	44
PA2	248708	9861414	1837	5.2	4.4	TR	2.51	0.36	7	1.5	0.2	2.15	8.4	16	73	40	16	74	17
PA3	248652	9861430	1834	5.1	4.3	0.1	2.92	0.35	15	1.7	0.2	1.69	8.7	20	61	24	23	76	30
PA4	248625	9861391	1838	5.6	4.8	0.1	2.85	0.34	8	2.0	0.2	2.56	9.2	19	73	64	17	17	21
PA5	248664	9861372	1838	5.6	4.7	0.1	2.92	0.28	12	1.6	0.1	2.61	8.9	18	74	38	21	20	24
PA6	248719	9861340	1841	5.2	5.4	TR	3.03	0.38	8	2.7	0.2	3.46	14.5	24	87	37	19	85	39
PA7	248700	9861305	1842	5.9	5.3	0.1	2.62	0.34	12	2.6	0.2	3.23	12.5	20	90	26	18	82	25
PA8	248649	9861333	1843	5.4	4.5	TR	2.40	0.34	11	2.1	0.2	1.50	4.5	15	56	58	23	79	25
PA9	248599	9861349	1842	5.3	4.8	0.1	2.85	0.35	8	1.5	0.1	4.21	6.5	18	67	60	18	75	18
PA10	248578	9861316	1840	6.0	5.3	TR	3.18	0.32	13	2.5	0.1	3.12	12.3	24	76	44	19	76	36
PA11	248621	9861285	1837	5.7	4.9	0.1	2.32	0.31	10	2.1	0.2	2.56	7.3	16	76	26	21	75	22
PA12	248680	9861259	1834	5.9	5.2	0.1	2.41	0.34	12	2.4	0.2	3.04	12.0	20	91	45	16	84	33
PA13	248654	9861224	1833	5.9	5.2	0.1	2.86	0.38	8	2.3	0.2	3.56	10.4	18	93	68	13	85	34
PA14	248595	9861235	1837	6.0	5.2	0.1	2.75	0.30	6	2.5	0.2	3.39	12.7	20	94	51	20	82	39
PA15	248540	9861252	1842	5.8	5.0	0.1	3.04	0.23	10	2.2	0.1	2.99	11.6	20	84	55	18	82	42
PA16	248511	9861200	1843	5.5	5.0	0.1	2.12	0.25	8	2.4	0.2	2.97	12.9	21	86	57	21	84	37
PA17	248489	9861151	1845	5.2	4.6	0.1	2.71	0.32	7	1.5	0.1	2.46	6.7	16	67	57	18	21	35
PA18	248553	9861162	1834	5.6	5.1	0.1	2.89	0.36	16	2.6	0.2	3.36	8.5	18	80	47	19	83	32
PA19	248611	9861164	1828	5.7	5.0	0.1	2.89	0.30	10	2.0	0.1	3.42	10.6	19	86	41	20	79	28
PA20	248789	9861454	1841	5.5	4.8	0.1	2.60	0.28	18	2.5	0.2	3.04	9.9	19	84	19	17	84	25

Legend: PA=top horizon, PB= bottom horizon, x=longitude, y= latitude, z= elevation, pH1= soil reaction with water, pH2= soil reaction with calcium chloride, EC units in dS/m, P is in ppm, K, Na, Mg, Ca and CEC are in cmolkg^{-1}, Fe, Cu, Mn and Zn are in ppm, TR= trace.

Appendix 3(b): Spatial variability data for Field 3 (15 to 30 cm depth)

Code	X	y	z	pH1	pH2	EC	%OC	%N	P	K	Na	Mg	Ca	CEC	%BS	Fe	Cu	Mn	Zn
PB1	248751	9861395	1840	6.1	5.3	0.1	2.44	0.25	14	1.90	0.2	3.06	12.6	21	83	60	15	79	32
PB2	248708	9861414	1837	5.3	4.5	TR	2.29	0.29	7	1.50	0.1	2.19	8.0	18	65	55	18	65	11
PB3	248652	9861430	1834	5.1	4.3	TR	2.66	0.34	17	0.60	0.2	2.34	8.3	20	57	89	21	75	25
PB4	248625	9861391	1838	5.8	5.1	0.1	2.25	0.35	10	1.30	0.1	2.70	8.7	17	75	29	14	63	9
PB5	248664	9861372	1838	5.6	4.8	TR	2.32	0.32	8	0.90	0.1	2.81	9.8	16	86	62	14	70	10
PB6	248719	9861340	1841	6.2	5.4	0.1	2.85	0.28	14	2.40	0.2	1.71	14.0	22	84	82	14	82	30
PB7	248700	9861305	1842	6.1	5.3	0.1	2.44	0.32	17	2.30	0.2	3.17	11.5	21	82	62	16	80	27
PB8	248649	9861333	1843	5.3	4.5	TR	2.25	0.23	9	2.00	0.2	1.68	8.1	14	86	62	19	72	16
PB9	248599	9861349	1842	5.5	4.7	TR	2.47	0.25	11	1.85	0.2	2.11	11.0	17	91	50	18	67	20
PB10	248578	9861316	1840	6.3	5.3	0.1	3.07	0.31	8	2.20	0.1	2.88	13.4	20	93	57	17	77	37
PB11	248621	9861285	1837	5.7	4.9	TR	1.95	0.22	9	1.80	0.2	3.32	8.3	30	45	46	19	72	43
PB12	248680	9861259	1834	6.1	5.3	0.1	2.41	0.32	13	1.95	0.2	2.88	14.2	22	89	35	17	81	32
PB13	248654	9861224	1833	6.0	5.4	0.1	2.60	0.30	6	2.20	0.2	2.06	8.1	14	90	33	14	78	28
PB14	248595	9861235	1837	6.0	5.2	0.1	2.45	0.34	5	2.20	0.1	3.25	13.0	20	93	53	15	79	30
PB15	248540	9861252	1842	5.8	5.3	0.1	2.00	0.23	19	1.50	0.1	3.03	12.8	19	90	33	12	74	24
PB16	248511	9861200	1843	5.6	5.2	0.1	2.63	0.21	2	1.20	0.2	2.92	12.1	18	92	37	16	77	26
PB17	248489	9861151	1845	5.7	4.6	TR	1.82	0.25	11	1.15	0.2	2.47	8.2	14	84	34	12	69	12
PB18	248553	9861162	1834	5.7	5.0	0.1	2.12	0.31	6	2.30	0.2	3.13	3.8	16	58	28	13	77	20
PB19	248611	9861164	1828	5.8	5.1	0.1	2.67	0.31	9	1.85	0.2	3.24	12.5	19	93	36	12	75	21
PB20	248789	9861454	1841	5.4	4.7	TR	2.26	0.34	12	1.70	0.1	3.09	12.6	20	87	30	12	73	23

Legend: PA=top horizon, PB= bottom horizon, x=longitude, y= latitude, z= elevation, pH1= soil reaction with water, pH2= soil reaction with calcium chloride, EC units in dS/m, P is in ppm, K, Na, Mg, Ca and CEC are in cmolkg^{-1}, Fe, Cu, Mn and Zn are in ppm, TR= trace.

Appendix 4 (a): Summary statistics for selected parameters in UmIr/F

UmIr/F Topsoil								
Parameter	**Sand (%)**	**Silt (%)**	**Clay (%)**	**pH**	**%OC**	**% N**	**CEC**	**BS%**
Mean	23	12	65	6.25	2.385	0.29	19.5	86.5
SE	1	2	1	0.15	0.565	0.1	2.5	5.5
SD	1.414	2.828	1.414	0.212	0.799	0.141	3.536	7.778
SV	2	8	2	0.045	0.63845	0.02	12.5	60.5
Min	22	10	64	6.1	1.82	0.19	17	81
Max	24	14	66	6.4	2.95	0.39	22	92
Sum	46	24	130	12.5	4.77	0.58	39	173
Count	2	2	2	2	2	2	2	2

UmIr/F Subsoil								
Parameter	**Sand (%)**	**Silt (%)**	**Clay (%)**	**pH**	**%OC**	**% N**	**CEC**	**BS%**
Mean	20	9.333333	70.66667	6.2	0.746667	0.076667	16.33333	80
SE	1.154701	0.666667	1.763834	0.550757	0.2818	0.026034	1.20185	9.539392
SD	2	1.154701	3.05505	0.953939	0.488092	0.045092	2.081666	16.52271
SV	4	1.333333	9.333333	0.91	0.238233	0.002033	4.333333	273
Min	18	8	68	5.1	0.23	0.03	14	61
Max	22	10	74	6.8	1.2	0.12	18	91
Sum	60	28	212	18.6	2.24	0.23	49	240
Count	3	3	3	3	3	3	3	3

Legend: SE = Standard Error, SD = Standard Deviation, SV = Sample Variance, Min = Minimum, Max = Maximum; CEC in cmol(+)/kg

Appendix 4 (b): Summary statistics for selected parameters in UmIr/E

UmIr/E Topsoil

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	%OC	% N	CEC	BS%
Mean	26.66667	18	55.33333	6	3.18	0.373333	22.66667	92.33333
SE	1.763834	5.033223	5.456902	0.2	0.490748	0.061734	3.527668	1.20185
SD	3.05505	8.717798	9.451631	0.34641	0.85	0.106927	6.110101	2.081666
SV	9.333333	76	89.33333	0.12	0.7225	0.011433	37.33333	4.333333
Min	24	8	48	5.6	2.33	0.28	16	90
Max	30	24	66	6.2	4.03	0.49	28	94
Sum	80	54	166	18	9.54	1.12	68	277
Count	3	3	3	3	3	3	3	3

UmIr/E Subsoil

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	%OC	% N	CEC	BS%
Mean	21.42857	14.28571	64.28571	6.214286	1.108571	0.121429	16.42857	87.57143
SE	0.947607	2.597749	2.80912	0.246334	0.095878	0.014214	1.172241	1.950057
SD	2.507133	6.872998	7.432234	0.651738	0.253668	0.037607	3.101459	5.159365
SV	6.285714	47.2381	55.2381	0.424762	0.064348	0.001414	9.619048	26.61905
Min	18	8	54	5.3	0.7	0.07	13	80
Max	24	24	72	7.1	1.4	0.18	22	93
Sum	150	100	450	43.5	7.76	0.85	115	613
Count	7	7	7	7	7	7	7	7

Legend: SE = Standard Error, SD = Standard Deviation, SV = Sample Variance, Min = Minimum, Max = Maximum; CEC in cmol(+)/kg

Appendix 4 (c): Summary statistics for selected parameters in UxIr/C

UxIr/C Topsoil

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	%OC	% N	CEC	BS%
Mean	35.14286	22.28571	42.85714	5.942857	2.551429	0.35	22	81.71429
SE	3.667285	1.860802	4.595176	0.142857	0.344089	0.057776	0.9759	6.018678
SD	9.702724	4.92322	12.15769	0.377964	0.910374	0.152862	2.581989	15.92393
SV	94.14286	24.2381	147.8095	0.142857	0.828781	0.023367	6.666667	253.5714
Min	26	16	24	5.4	1.51	0.18	19	52
Max	51	30	56	6.6	3.95	0.56	26	94
Sum	246	156	300	41.6	17.86	2.45	154	572
Count	7	7	7	7	7	7	7	7

UxIr/C Subsoil

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	%OC	% N	CEC	BS%
Mean	31.11111	14.38889	54.5	5.961111	0.712778	0.079444	15.22222	89.55556
SE	1.626755	1.311435	2.05838	0.146001	0.086091	0.010145	0.659548	0.389589
SD	6.901738	5.563948	8.732967	0.619429	0.365253	0.043042	2.798225	1.652884
SV	47.63399	30.95752	76.26471	0.383693	0.133409	0.001853	7.830065	2.732026
Min	22	7	34	5	0.26	0.03	11	87
Max	41	25	69	6.8	1.63	0.17	21	93
Sum	560	259	981	107.3	12.83	1.43	274	1612
Count	18	18	18	18	18	18	18	18

Legend: SE = Standard Error, SD = Standard Deviation, SV = Sample Variance, Min = Minimum, Max = Maximum; CEC in cmol(+)/kg

Appendix 4 (d): Summary statistics for selected parameters in UxIr/D

UxIr/D Topsoil

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	%OC	% N	CEC	BS%
Mean	35	20.16667	44.83333	5.966667	3.183333	0.338333	22.83333	79
SE	2.476557	3.330832	4.003471	0.114504	0.25853	0.032085	0.945751	5.422177
SD	6.0663	8.15884	9.80646	0.280476	0.633267	0.078592	2.316607	13.28157
SV	36.8	66.56667	96.16667	0.078667	0.401027	0.006177	5.366667	176.4
Min	30	8	28	5.7	2.25	0.2	20	60
Max	45	30	54	6.4	3.8	0.42	27	93
Sum	210	121	269	35.8	19.1	2.03	137	474
Count	6	6	6	6	6	6	6	6

UxIr/D Subsoil

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	%OC	% N	CEC	BS%
Mean	33.57143	14.85714	51.42857	6.071429	1.176429	0.127143	16.31429	79.21429
SE	1.518075	1.529408	1.278367	0.14617	0.17776	0.019624	1.350574	3.565985
SD	5.680118	5.722522	4.783212	0.546919	0.665115	0.073425	5.053385	13.34269
SV	32.26374	32.74725	22.87912	0.299121	0.442379	0.005391	25.5367	178.0275
Min	26	7	42	4.9	0.41	0.04	5.4	51
Max	43	26	60	6.7	2.75	0.31	26	92
Sum	470	208	720	85	16.47	1.78	228.4	1109
Count	14	14	14	14	14	14	14	14

Legend: SE = Standard Error, SD = Standard Deviation, SV = Sample Variance, Min = Minimum, Max = Maximum; CEC in cmol(+)/kg

Appendix 4 (e): Summary statistics for selected parameters in UxIr/AB

UxIr/AB Topsoil								
Parameter	**Sand (%)**	**Silt (%)**	**Clay (%)**	**pH**	**%OC**	**% N**	**CEC**	**BS%**
Mean	36.75	28.75	34.5	5.9625	2.1025	0.2475	20.25	85.625
SE	2.366055	2.950484	2.299068	0.147524	0.168584	0.01333	1.114034	3.707798
SD	6.692213	8.34523	6.502747	0.417261	0.476827	0.037702	3.150964	10.48724
SV	44.78571	69.64286	42.28571	0.174107	0.227364	0.001421	9.928571	109.9821
Min	28	12	25	5.5	1.24	0.21	16	70
Max	46	40	42	6.6	2.73	0.31	26	95
Sum	294	230	276	47.7	16.82	1.98	162	685
Count	8	8	8	8	8	8	8	8

UxIr/AB Subsoil								
Parameter	**Sand (%)**	**Silt (%)**	**Clay (%)**	**pH**	**%OC**	**% N**	**CEC**	**BS%**
Mean	35.16667	14.5	50.33333	6.133333	0.755	0.083333	17.08333	85.58333
SE	1.770265	1.539874	1.859999	0.231704	0.14316	0.016712	0.782946	3.447569
SD	6.132378	5.33428	6.443225	0.802647	0.49592	0.057892	2.712206	11.94273
SV	37.60606	28.45455	41.51515	0.644242	0.245936	0.003352	7.356061	142.6288
Min	24	2	40	4.4	0.08	0.01	14	53
Max	46	22	60	6.9	1.76	0.2	22	93
Sum	422	174	604	73.6	9.06	1	205	1027
Count	12	12	12	12	12	12	12	12

Legend: SE = Standard Error, SD = Standard Deviation, SV = Sample Variance, Min = Minimum, Max = Maximum; CEC in cmol(+)/kg

Appendix 4 (f): Summary statistics for 0-15 cm depth

Soil property	Mean	SE	Median	SD	SV	Kurtosis	Skewness	Range	Min	Max
pH (H2O)	5.59	0.064	5.6	0.285	0.081	-1.090	-0.223	0.9	5.1	6
%OC	2.749	0.063	2.85	0.283	0.080	-0.283	-0.606	1.06	2.12	3.18
%N	0.32	0.01	0.34	0.04	0.001	0.211	-0.788	0.15	0.23	0.38
P (ppm)	10.65	0.741	10	3.313	10.976	-0.342	0.641	12	6	18
K(cmol(+)/kg)	2.185	0.099	2.25	0.444	0.197	-0.862	-0.238	1.5	1.5	3
Na(cmol(+)/kg)	0.165	0.011	0.2	0.049	0.002	-1.719	-0.681	0.1	0.1	0.2
Mg(cmol(+)/kg)	2.9205	0.144	3.04	0.646	0.417	0.611	-0.540	2.71	1.5	4.21
Ca(cmol(+)/kg)	9.81	0.577	9.55	2.580	6.658	-0.548	-0.121	10	4.5	14.5
Fe (ppm)	44.25	3.238	44.5	14.480	209.671	-1.063	-0.159	49	19	68
Cu (ppm)	18.8	0.541	19	2.419	5.853	0.624	-0.285	10	13	23
Mn (ppm)	71.45	5.095	80.5	22.784	519.103	2.499	-2.007	69	17	86
Zn (ppm)	30.3	1.786	31	7.987	63.800	-1.062	-0.016	27	17	44

Legend: SE = Standard Error; SD = Standard Deviation, Min = Minimum; Max = Maximum

Appendix 4 (g): Summary statistics for 15-30 cm depth

Soil property	Mean	SE	Median	SD	SV	Kurtosis	Skewness	Range	Min	Max
pH (H2O)	5.755	0.074	5.75	0.330	0.109	-0.688	-0.221	1.2	5.1	6.3
%OC	2.3975	0.068	2.425	0.304	0.092	0.226	0.166	1.25	1.82	3.07
%N	0.29	0.01	0.305	0.045	0.002	-1.26	-0.39	0.14	0.21	0.35
P (ppm)	10.35	0.979	9.5	4.380	19.187	-0.298	0.268	17	2	19
K(cmol(+)/kg)	1.74	0.113	1.85	0.504	0.254	-0.208	-0.726	1.8	0.6	2.4
Na(cmol(+)/kg)	0.165	0.011	0.2	0.049	0.002	-1.719	-0.681	0.1	0.1	0.2
Mg(cmol(+)/kg)	2.702	0.116	2.88	0.519	0.270	-0.658	-0.757	1.64	1.68	3.32
Ca(cmol(+)/kg)	10.55	0.615	11.25	2.751	7.570	-0.026	-0.640	10.4	3.8	14.2
Fe (ppm)	48.65	3.937	48	17.605	309.924	-0.002	0.777	61	28	89
Cu (ppm)	15.4	0.600	15	2.683	7.200	-0.742	0.395	9	12	21
Mn (ppm)	74.25	1.196	75	5.350	28.618	-0.416	-0.592	19	63	82
Zn (ppm)	23.8	2.051	24.5	9.174	84.168	-0.344	0.065	34	9	43

Legend: SE = Standard Error; SD = Standard Deviation, Min = Minimum; Max = Maximum

Appendix 5: Pictorial

Testing soil plasticity (Figure a) and identification of profile horizons (Figure b).

Soil description via augering (Figure a), profile description and sampling (Figure b).

Appendix 6: Selected profile description for profile 148/4-2

Profile description No. 2

General site information
Mapping unit : UxIr/D
Soil Classification : Mollic Nitisols
Agro Climatic Zone : III
Observation No./ date : 148/4-02; 19/07/2018
Location : Upper Kabete Campus
Coordinates (UTM) : 247507, 9861545, 1851
Parent material : Intermediate Igneous Intrusive
Physiography : Upland; upper level
Relief- Macro : Rolling, approx. 250m slope, convex
-Meso/Micro : Termite mounds, slight surface irregularities due to grazing
Slope at site : 15%, upslope
Vegetation : Open bushland
Land use : Grazing, natural
Ground water level : Always very deep
Drainage class : Well drained

Profile description

A	0-23 cm:	dark reddish brown (2.5 YR2/3 moist); clay loam; moderate, thin, subangular blocky structure; slightly hard when dry, friable when moist, sticky and slightly plastic when wet; few, fine pores; few, fine, live roots; few, fine, spherical and irregular Iron and Manganese concretions; gradual and smooth transition to:
Bt1	23-50 cm:	dark reddish brown (2.5 YR3/3 moist); clay loam; moderate, medium, subangular blocky structure; hard when dry, friable when moist, sticky and plastic when wet; few, patchy argillans; common, fine pores; few, fine, live roots; few, medium, irregular Iron and Manganese concretions; a piece of angular igneous rock seen; diffuse and smooth transition to:
Bt2	50-73 cm:	dark reddish brown (2.5 YR3/4 moist); clay loam; moderate, fine, subangular blocky structure; hard when dry, friable when moist, sticky and plastic when wet; few, patchy clay cutans; few, fine pores; few, fine, live roots; very few, fine, spherical and irregular Iron and Manganese concretions; diffuse and smooth transition to:
Bt3	73-105 cm:	reddish brown (2.5 YR4/4 moist); clay; moderate, fine, subangular blocky structure breaking in to nut shaped elements with shiny ped surfaces; slightly hard when dry, friable when moist, sticky and plastic when wet; common, broken argillans; few, very fine and fine pores; krotovina (10 cm diameter) few, fine, live roots; few, fine, spherical and irregular Iron and Manganese concretions; diffuse and smooth transition to:
Bt4	105-152 cm+:	dusky red (10R3/4moist); clay; moderate, thin, subangular blocky structure; slightly hard to hard when dry, friable when moist, sticky and slightly plastic when wet; few, patchy clay cutans; few, very fine and fine pores; few, fine, spherical and irregular Iron and Manganese concretions.

Appendix 7: Pearson's correlation

Pearson correlations

								cmol(+)/kg						**Micronutrients (ppm)**				**Texture (%)**						
	Slope cat.	pH (H2O)	pH (CaCl2)	EC mS/cm	%OC	% N	P	K	Na	Mg	Ca	CEC	BS(%)	Fe	Cu	Mn	Zn	Sand	Clay	Silt	Silt: Clay	Ksat(cm/hr)	Bulk density	Por. (%)
slope cat	-																							
pH (H2O)	0.231	-																						
pH (CaCl2)	0.277	.936**	-																					
EC mS/cm	0.136	-0.194	-0.005	-																				
%OC	.521*	0.187	0.347	.532*	-																			
% N	0.185	0.151	0.164	0.176	0.317	-																		
P	-0.195	-0.452	-0.473	0.473	0.044	-0.152	-																	
K(cmol/kg)	-0.293	0.247	0.134	0.302	0.116	-0.207	0.383	-																
Na(cmol/kg)	0.067	0.106	-0.015	-0.035	-0.360	-0.112	0.063	0.067	-															
Mg(cmol/kg)	.695**	.560*	.564*	0.065	0.451	0.024	-0.137	0.217	0.265	-														
Ca(cmol/kg)	0.344	0.428	0.361	-.514*	0.151	0.401	-0.428	-0.245	-0.081	0.477	-													
CEC(cmol/kg)	0.320	0.206	0.238	0.131	.653**	.588*	0.142	0.054	-0.416	0.312	.563*	-												
BS(%)	0.233	0.488	0.389	-.546*	-0.258	-0.116	-.533*	-0.067	0.370	.574*	.631**	-0.201	-											
Fe (ppm)	-0.210	0.310	0.406	0.094	0.060	-0.097	-0.244	0.106	-0.383	-0.227	-0.351	-0.169	-0.225	-										
Cu(ppm)	0.007	-0.160	-0.262	-0.249	-0.288	-.608*	-0.006	0.061	0.157	-0.141	-0.170	-0.271	-0.019	0.014	-									
Mn(ppm)	-0.367	0.201	0.110	-0.273	0.062	-0.181	0.037	.537*	-0.398	-0.076	0.054	0.327	-0.197	0.223	0.203	-								
Zn(ppm)	-0.367	0.089	0.029	-0.305	0.184	0.042	-0.189	0.319	-.663**	-0.216	0.172	0.320	-0.140	0.327	-0.001	.770**	-							
Sand(%)	-0.451	-.557*	-.577*	0.184	-0.322	-0.246	.572*	0.277	-0.163	-0.392	-0.286	-0.046	-0.323	-0.013	0.310	0.156	0.050	-						
Clay(%)	.724**	0.216	0.342	-0.003	0.352	0.167	-0.429	-0.402	0.175	.597*	0.253	0.049	0.352	-0.067	-0.208	-0.394	-0.284	-.698**	-					
Silt(%)	-0.478	0.282	0.208	-0.032	-0.063	-0.196	0.156	0.311	-0.146	-0.336	-0.163	-0.022	-0.220	0.174	0.020	0.393	0.224	0.009	-.664**	-				
Silt: Clay	-.621*	-0.033	-0.138	0.002	-0.227	-0.231	0.337	0.322	-0.092	-.533*	-0.274	-0.103	-0.331	0.055	0.140	0.342	0.200	0.318	-.861**	.916**	-			
Ksat(cm/hr)	-0.052	-0.351	-0.403	-0.362	-0.143	-0.040	-0.142	-0.176	0.056	-0.173	-0.111	-0.157	-0.070	0.075	0.159	0.176	0.280	-0.068	0.284	-.511*	-0.436	-		
Bulk density	0.303	0.476	.505*	0.180	0.070	0.177	-0.076	-0.136	0.133	0.264	0.024	-0.028	0.139	-0.034	-0.360	-0.401	-0.477	-0.457	0.235	0.233	-0.016	-.564*	-	
Porosity(%)	-0.302	-0.488	-.510*	-0.183	-0.062	-0.149	0.059	0.100	-0.131	-0.274	-0.020	0.030	-0.143	0.034	0.328	0.381	0.470	0.439	-0.215	-0.250	-0.004	.593*	-.998**	-

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

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