A GEOPEDOLOGICAL APPROACH TO SOIL CLASSIFICATION TO CHARACTERIZE SOILS OF UPPER KABETE CAMPUS FIELD, UNIVERSITY OF NAIROBI, KENYA†

[UN ENFOQUE GEOPEDOLÓGICO DE LA CLASIFICACIÓN DEL SUELO PARA CARACTERIZAR LOS SUELOS DEL CAMPO DEL CAMPUS KABETE SUPERIOR, UNIVERSIDAD DE NAIROBI, KENIA]

S.M. Mwendwa*, J.P. Mbuvi, G. Kironchi and C.K.K. Gachene

Department of Land Resource Management and Agricultural Technology, College of Agriculture and Veterinary Sciences, University of Nairobi. P. O. Box 29053-00625 Kangemi, Nairobi, Kenya. Email: samuelmwendwa2@gmail.com
**corresponding author*

SUMMARY

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. **Objective.** 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. The first entry represents the physiographic unit (Uplands, U), followed by physiographic position (lower middle uplands, m or uplands, undifferentiated levels, x), geology (I), color (r) and slope class respectively. 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 IBM SPSS 25th edition and MS Excel. **Results.** All the mapping units are well drained and deep to very deep (>80 cm). The color of the upper B horizon is predominantly dark reddish brown. The texture of top horizon is 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 is predominantly subangular blocky throughout the profiles with the top horizon of cultivated areas having predominantly granular structure. Saturated hydraulic conductivity (K_{sat}) generally decreases with increasing clay content down the profiles and the bulk density ranges from 0.9 to 1.2gcm^{-3}. Means of soil reaction of top horizons generally slightly decrease with decreasing gradient ($r = 0.231$) having lower values in cultivated areas. Percent organic carbon regularly decreases down the profiles with higher values in uncultivated, steeper areas ($r = 0.521$; $p \leq 0.05$). In the top horizon: Total nitrogen is predominantly medium across the study area ranging from 0.2 to 0.56% ($r = 0.185$) and follows the organic carbon trend; Available phosphorus is deficient (<20 ppm) in the study area. Bases are sufficiently to richly supplied while micronutrients are richly supplied. All soils are non-saline and non-sodic; the cation exchange capacity (CEC) soil is 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. **Conclusion.** Soil characterization, land evaluation and precise input application are encouraged.
Keywords: First class catena; Soil Mapping Units; Stratified Random Sampling; Soil classification.

RESUMEN

Antecedentes. El área de estudio exhibe una catena de primera clase que tiene material parental homogéneo y forma un continuo espacial. Los suelos funcional y taxonómicamente distintos resultan de las diferencias en el drenaje y el movimiento lateral de los materiales en el suelo. **Objetivo.** Clasificar los suelos utilizando un enfoque geopedológico que implica una fuerte relación entre pedología y geomorfología. **Metodología.** El área se delineó en Unidades de

† *Submitted February 13, 2019 – Accepted March 20, 2020.*
ISSN: 1870-0462.

Mapeo de Suelos (SMU) a través de la perforación en suelos definidos por diferentes macro-relieves. Las unidades de mapeo se demarcaron de acuerdo con las categorías de pendientes, a saber, del 0 al 5%, del 5 al 8%, del 8 al 16%, del 16 al 30% y> 30% connotadas como planas a onduladas suaves (AB), onduladas (C), onduladas (D), moderadamente empinada (E) y empinada (F) respectivamente. Se cavaron pozos de perfil en las cinco unidades de mapeo identificadas utilizando la técnica de muestreo aleatorio estratificado. Las SMU identificadas incluyen UmIr / F, UmIr / E, UxIr / D, UxIr / C y UxIr / AB en el orden de gradiente de pendiente decreciente. La primera entrada representa la unidad fisiográfica (Uplands, U), seguida de la posición fisiográfica (tierras altas medias bajas, m o tierras altas, niveles indiferenciados, x), geología (I), color (r) y clase de pendiente respectivamente. Se produjo un mapa de suelo con una leyenda que describe las unidades de mapeo utilizando una escala de 1: 10000. La influencia topográfica en las propiedades del suelo fue presentada por el coeficiente de correlación de Pearson (r) con el valor p incluido donde la influencia fue significativa. El análisis estadístico se realizó utilizando SPSS 25th edition y MS Excel. **Resultados**. Todas las unidades de mapeo están bien drenadas y de profundas a muy profundas (> 80 cm). El color del horizonte B superior es predominantemente marrón rojizo oscuro. La textura del horizonte superior es arcilla en UmIr / F y UmIr / E y es franco arcilloso a arcilloso, franco arcilloso arenoso a arcilloso y franco arcilloso a franco arcilloso en UxIr / D, UxIr / C y UxIr / AB respectivamente, exponiendo lúcidamente la influencia de topografía sobre la profundidad de la iluviación de arcilla (arcilla: $r = 0.724$; $p \leq 0.01$). La estructura es predominantemente en bloques subangulares en todos los perfiles con el horizonte superior de las áreas cultivadas que tienen una estructura predominantemente granular. La conductividad hidráulica saturada (Ksat) generalmente disminuye al aumentar el contenido de arcilla en los perfiles y la densidad aparente oscila entre 0.9 y 1.2 gcm^{-3}. Los medios de reacción del suelo de los horizontes superiores generalmente disminuyen ligeramente con el gradiente decreciente ($r = 0.231$) que tiene valores más bajos en las áreas cultivadas. El porcentaje de carbono orgánico disminuye regularmente en los perfiles con valores más altos en áreas no cultivadas y más empinadas ($r = 0.521$; $p \leq 0.05$). En el horizonte superior: el nitrógeno total es predominantemente medio en el área de estudio que varía de 0.2 a 0.56% ($r = 0.185$) y sigue la tendencia del carbono orgánico; El fósforo disponible es deficiente (<20 ppm) en el área de estudio. Las bases se suministran de forma suficiente a abundante, mientras que los micronutrientes se suministran de forma abundante. Todos los suelos son no salinos y no sódicos; El suelo con capacidad de intercambio catiónico (CEC) es predominantemente medio en los perfiles que van desde 15 a 27.6 cmol (+) / kg con valores que aumentan ligeramente con el aumento de la pendiente ($r = 0,320$). Con base en los datos recopilados de la descripción de los perfiles y los datos fisicoquímicos de los suelos y de acuerdo con la leyenda de clasificación de suelos del Grupo de Trabajo IUSS WRB (2014), los suelos se clasificaron como Nitoles Mollic. **Implicaciones.** Los suelos son generalmente fértiles para la producción de cultivos, pero se recomienda el abono orgánico para amortiguar la reacción ácida del suelo, mejorar las fuentes de nitrógeno y fósforo. **Conclusión.** Se recomienda la caracterización del suelo, la evaluación de la tierra y la aplicación precisa de insumos.

Palabras clave: catena de primera clase; Unidades de mapeo de suelos; Muestreo aleatorio estratificado; Clasificación de suelos.

INTRODUCTION

Soil characterization helps to predict the behavior of different soils and present the results in a common language understandable by scientists worldwide (Brevik et al., 2016; Hartemink, 2015). This 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 practice Precision Agriculture (PA).

To establish the effect of relief on soil properties, this survey followed Dokuchaev's hypothesis 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 when any of these factors change, the soil changes. This concept was echoed by Hartemink and Bockheim (2013). 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 the incontrovertible concept of geological sorting along a toposequence. Therefore, 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; Vandenbygaart, 2001). 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 favor 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). 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 (Warrick and Nielson, 1980; 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 (Liu et al., 2015; Behera et al., 2016). 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 (Moosavi and Sepaskhah, 2012; Emadi et al., 2016; Shahabi et al., 2016, Moradi 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.

MATERIALS AND METHODS

Description of the study site

This research was done in Upper Kabete Campus field, University of Nairobi (Figure 1) covering an area of 168.63 ha. The site lies between longitude 247653, latitude 9861440 and 1876 altitude measured in Universal Transverse Mercator (UTM). The site is part of the Loresho Ridge which is an upland characterized by slopes ranging from 0 to 32% (Mwendwa et al., 2019); (Figure 1 and 2). It is categorized under Agro Climatic Zone III (Sombroek et al., 1982, Gachene, 1989). Rainfall is bimodal in distribution; 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 (Jiitzold and Kutsch, 1982). The geology comprises the Kabete grey-green porphyritic trachyte of middle division of Tertiary age (Mathu and Mwea, 2014; Saggerson, 1991) overlying the Nairobi trachyte and Kirichwa valley tuffs.

Soil survey procedure

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) observations (auger holes) were made to a depth of 100 cm or upon hitting a rock across the study area 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, color, 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 1). These delineations were the strata within which sampling points (profiles) were opened, described and sampled for chemical and physical analysis. The following map (Figure 1) was produced using detailed interpolation procedures in Arcview GIS 3.3 software.

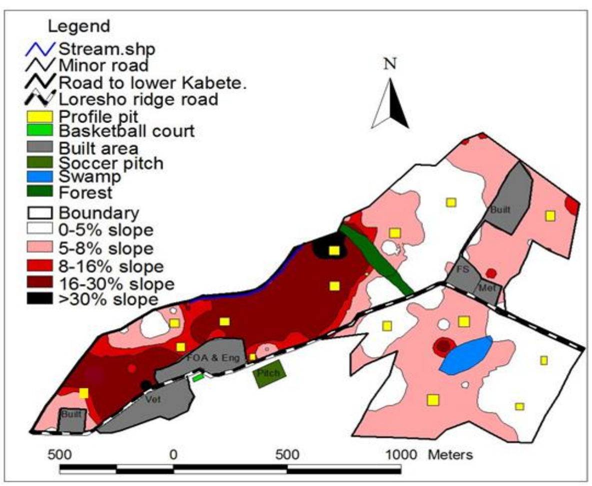

Figure 1. Study area map showing slope categories and location of profiles.

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. Profile pits were opened across the SMUs (strata) where soil samples for laboratory analysis and soil classification were collected. Location of the profiles was based on Stratified Random Sampling scheme. The slope classes were the strata and 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 so as 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. Information on geology was based on secondary data. Profile pits measured 2 meters in length, 1.5 meters in depth and 1 meter in width, with stairs opposite to the side of profile description where core ring samples for saturated hydraulic conductivity and bulk density were taken. 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 color charts, geological hammer and knife. Profile description included: Horizon designation, depth and boundary, color, structure, cutans, pores, texture and stoniness, consistence and concretions. For chemical analysis, 1 kilogram of disturbed sample was collected from each identified horizon. Core samples were collected for physical analysis (K_{sat} and bulk density) using 100 cm^3 rings in triplicate per horizon.

Soil analysis

Soil reaction was measured with a glass electrode pH meter (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, 1965) respectively. Base saturation and CEC were determined according to Bremner (1996) which involves leaching with 1N NH_4OAC and 1N KCl solution then analyzing the leachates. Exchangeable potassium (K) and exchangeable sodium (Na) were measured using a flame photometer while exchangeable calcium (Ca) and exchangeable magnesium (Mg) were analyzed 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 analyzed 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 (K_{sat}) was determined according to Reynolds and Elrick (2002) and the same sample used for determining bulk density (Grossman and Reinsch, 2002).

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 especially for the slope percentages. 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 vectorized and classified to obtain polygons then given a name and color. The mapping units map was further digitized and a legend was generated.

Soils

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 mapping units 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 WRB is the system used in Kenya by the Kenya Soil Survey (KSS) for soil classification. Van de Weg and Mbuvi (1975) used the FAO-UNESCO classification 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. 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. A nitic B horizon was found in all the profiles as characterized by moderately to strongly developed nutty structure with many shinny ped faces. Distinguishing properties included the clay distribution, CEC, base saturation, presence of cutans and organic carbon distribution. If the percent 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 colors was also indicative of horizon transition.

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), color (r) and slope class respectively (Table 1). All the mapping units were uplands in different physiographic levels. Geology was uniform in the study area as intermediate igneous rocks (I). Slope codes included AB, C, D, E and F (Figure 2). The soils were deep to very deep (>80 cm) and red in color represented by ‘r’. 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 (1987). The soil color was described using the Munsell soil color charts (Munsell, 1975). The moist color of the upper B horizon is given in the legend and color of the whole B is given in the report. The B horizon was described to a depth of 100 cm. Table 1 presents the soil mapping units and slope categories.

Table 1. Soil mapping units and slope categories.

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

Differentiating criteria for soil properties

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

Statistical analysis

IMB SPSS (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp) software was used to generate the Pearson's correlation coefficient (r). Variables including clay content, soil reaction, percent Organic Carbon, total Nitrogen, Phosphorus, Calcium, Magnesium, Potassium, Cation Exchange Capacity, Iron, Copper, Manganese, Zinc and bulk density were all correlated with slope. Summary statistics was generated in MS Excel.

RESULTS AND DISCUSSION

Diagnostic horizons and properties

A nitic B horizon, mollic A horizon and a percent base saturation (BS%) >50% by NH_4OAC were identified through observation and laboratory analysis across all SMUs.

Soil classification and correlation

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 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 is a thick, dark colored surface horizon caused by the accumulation of organic matter, having base saturation by 1M NH_4OAC, pH 7 of $\geq 50\%$ on a weighted average throughout the entire thickness of the horizon, having a soil structure that is not both massive and hard or very hard when dry and a moist color value of ≤ 3 and chroma of ≤ 3 (IUSS Working Group WRB, 2014). It has 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) colors when moist.

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; very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy. Weathering in Nitisols is moderate to high but the soils are highly productive under good management IUSS Working Group WRB, 2014. Many Nitisols correlate with: Nitossolos (Brazil); kandic Great Groups of Alfisols and Ultisols; and different Great Groups of Inceptisols and Oxisols (United States of America); Sols Fersialitiques or Ferrisols (France) and Ferrosols (Australia) (IUSS Working Group WRB, 2014).

Mapping units

All the identified mapping units were physiographically uplands. 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).

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 color 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) soil 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 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 which has one profile is presented in table 3.

The reddish color can be attributed to presence of iron compounds at various states of oxidation, an observation consistent with findings of Foth (2003) who attributed reddish color 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 Lelago and Buraka (2019) and Dengiz et al. (2013) 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 has the thinnest top horizon attributable to soil truncation by runoff along its steep topography. Former erosional processes may have continued for longer period on steep than on gentle slopes, delaying re-establishment of floral species therefore resulting to thinner solum depth. 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 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 this pedon which lies on the steepest slope category and has been mapped separately.

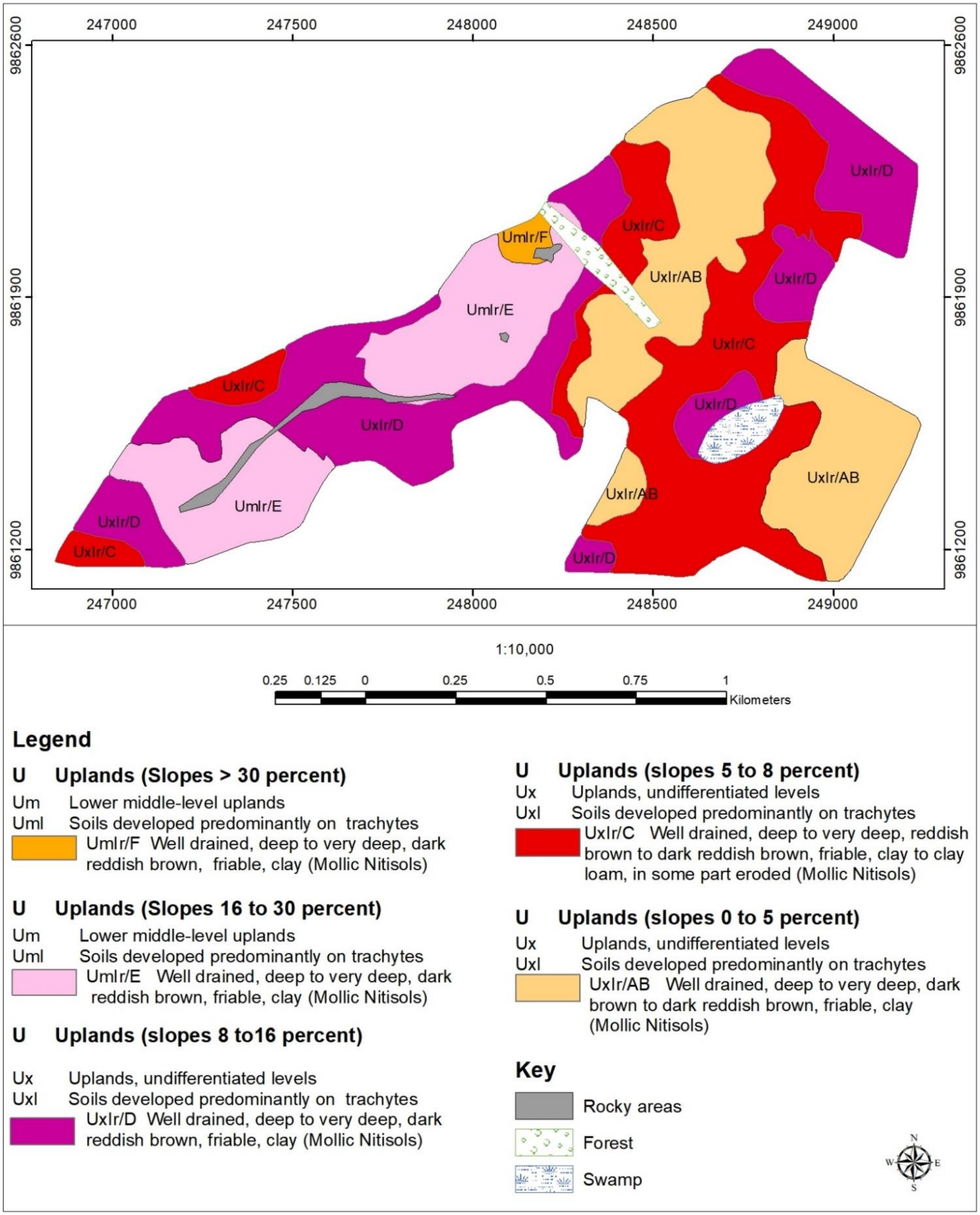

Figure 2. Soil Map of Upper Kabete Campus Area. Source: Author.

Table 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

Soil classification: IUSS Working Group WRB (2014): Mollic Nitisols. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

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. Thick vegetation just above the pit coupled with erosion control measures could have slowed down runoff resulting to considerable leaching of bases despite the steep topography. This finding is consistent with observations of Vasquez-Mendez et al. (2010) and Wei et al. (2014) who found that shrubs are very 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 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, decreasing faunal activities with depth 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 decreases regularly down the profile in the same trend of percent carbon indicating the role of C in binding N in soils ($r = 0.9868$). 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 favorable 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. 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 ($r = -0.293$).

U Uplands

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

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 color 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 in 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 in cmol(+)/kg is predominantly medium throughout the profiles. Base saturation is high in all the samples. The soils classify as Mollic Nitisols (Table 4 and 5). 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 which has 2 profiles is presented in table 6.

Table 3. Summary statistics for selected soil properties.

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

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

Table 4. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 5. 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

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
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 eluviation-illuviation process. 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 Lelago and Buraka (2019) and Dengiz et al. (2013) 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 Sekhar et al. (2014) and Lelago and Buraka (2019) 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. 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. 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 and decreasing faunal activities with depth. It could also be due to root systems in the rhizosphere or addition of aboveground biomass to the soil surface. Lelago and Buraka (2019), Browaldh (1995), Pillon (2000) and Burle et al. (2005) 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.

Table 6. Summary statistics for selected soil properties.

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

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

U Uplands

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

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 color 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 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 7 to 10). 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 profiles is presented in table 11.

Table 7. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 8. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 9. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 10. 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	0.1	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

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy.
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, decreasing faunal activities with depth and addition of aboveground biomass to the soil surface. Similar results were observed by Browaldh (1995) and Burle et al. (2005) who attributed the observation to decreasing organic matter with depth. 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 cations against leaching. The high base saturation reflects dominance of non-acid cations 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).

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 color 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 12 to 16). The summary statistics for profiles of this mapping unit is presented in table 17.

Table 11. Summary statistics for selected soil properties.

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

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

Table 12. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 13. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 14. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
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. This process was also suggested by Glassman et al. (1980). The variation in the type of structure 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.

Table 15. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 16. 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

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

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 organic matter observed in the top horizons can be attributed to organic inputs and decreasing faunal activities with depth. 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 (40.1ha).

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 color 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 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 (Table 18 to 21). The summary statistics for profiles of this mapping unit is presented in table 22.

Table 17. Summary statistics for selected soil properties.

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

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

Table 18. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
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 redistribution, and coagulating agents including oxides of iron. 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 is 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.

Table 19. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 20. 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. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Table 21. 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

Soil classification; IUSS Working Group WRB (2014): Mollic Nitisols. Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy
Where: TC=Textural Class

Physical properties

Saturated hydraulic conductivity (k_{sat}), bulk density and porosity

The K_{sat} 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 23). This observation is consistent with findings of Chakraborty et al. (2010) who attributed decreasing K_{sat} to decreasing organic matter and increasing clay. Compaction of the soil could have reduced macro to intermediate pores and with micro pores remaining constant, the k_{sat} decreased with depth. This finding has been observed in the same area and elsewhere (Karuku et al., 2012; Libohova et al., 2018).

Table 22. Summary statistics for selected soil properties.

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

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

Under ideal circumstances, high k_{sat} 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 k_{sat} 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) who found bulk densities of a profile ranging from 1 to 1.1 Mgm^{-3} and the k_{sat} ($cmhr^{-1}$) 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. (2015a). Results of this study show that argillans have the greatest influence on k_{sat} across all slope categories. Cutans on walls of voids and surface of peds could have resulted to prevention of the bulk of the soil material from allowing free water movement therefore low k_{sat}.

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 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 k_{sat} to just moderately rapid due to reduction of large pores to intermediate pores therefore reducing water percolation. This observation is consistent with findings of Karuku et al. (2012) who attributed low k_{sat} 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, 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 k_{sat} values which is 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.

CONCLUSION

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 crop 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 k_{sat} 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. This observation is consistent with findings of Porder and Ramachandran (2013) who found that parent materials have a great influence on the P status of the resulting soil. There is therefore need for phosphorus replenishment. Soil characterization should be used to understand the soil properties and their potential in different parts of the field. More training on areas of land evaluation (Mwendwa et al., 2019) and precision agriculture and their application in farm practises would be paramount.

Table 23: Physical properties.

Prof	Map unit	Depth	Sand	Silt	Clay	SCR	TC	K_{sat}	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

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.

Acknowledgement
The main author greatly acknowledges Prof. J.P Mbuvi for his generous financial support that made this work possible.

Funding. The authors have not received any funding or grant.

Conflict of interest. The authors declare that they have no competing interests.

Compliance with ethical standards. This research work meets all the ethical guidelines, adhering to the legal requirements of Kenya.

Data availability. Data are available with Samuel Mwendwa, (samuelmwendwa2@gmail.com) upon reasonable request.

REFERENCES

Amalu, U.C. 1997. Properties and relationship among fertility indices of some coastal plain soil under rubber trees. Global Journal of Pure and Applied Sciences, 4(4): 12-71.

Bailey, S., Brousseau, P., McGuire, K., Bullen, T. 2014. Influence of landscape position and transient water table on soil development and carbon distribution in a steep, headwater catchment. Geoderma, 226-227,279–289. https://doi.org/10.1016/j.geoderma.2014.02.017.

Batchelor, B., Whigham, K., De Witt, J., Hiett, T., Eastman, K.R. 1997. Introduction to precision agriculture. Lowa State University. University Extension, Ames, Iowa. http://www.extension.iastate.edu/publications/pm1703.pdf.

Behera, S.K., Suresh, K., Rao, B.N., Mathur, R.K., Shukla, A.K., Manorama, K., Ramachandrudu, K., Harinarayana, P., Prakash, C. 2016. Spatial variability of some soil properties varies in oil palm (Elaeis guineensis Jacq.) plantations of west coastal area of India. Solid Earth. 7:979-993.

Black, C.A. 1965. Methods of soil analysis. Part I and II. Amer. Soc. Agron. Madison, Wisconsin.

Bolan, N.S., Hedley, M.J. 2003. Role of carbon, nitrogen and sulfur cycles in soil acidification. In: Handbook of soil acidity (ed. Z. Rengel), pp. 29-52. Marcel Dekker, New York. Google Scholar.

Bosch, D.D., Hubbard, R.K., West, L.T., Lawrence, R.R. 1994. Subsurface flow patterns in a rapriaus buffer system. Trans-ASAE. St. Joseph, Mich: Am. Soc. Agric. Eng., 1958-37: 1783-1790.

Bourgault, R., Ross, D., Bailey, S. 2015a. Chemical and morphological distinctions between vertical and lateral podzolization at Hubbard Brook. Soil Sci. Soc. Am. J. 79, 428-439.

Bouma, J., Verhagen, J., Brouwer, J., Powell, J.M. 1996. Using systems approaches for targeting site-specific management on field level. Press, 1996:25-36. In: Kropff M.J. ed. Applications of systems approaches at the field level. Dordrecht, the Netherlands: Kluwer Academic.

Bremner, J.M. 1996. Total nitrogen. In Methods of Soil Analysis: Chemical Methods. Part 3. D.L. Sparks, editor. Soil Science Society of America. Madison WI.C.

Brevik, E.C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, J.N., Six, J., Van Oost, K. 2015. The interdisciplinary nature of soil. Soil. 1:117-129.

Brevik, Eric, C., Costanza Calzolari., Bradley A. Miller., Paulo Pereira., Cezary Kabala., Andreas Baumgarten and Antonio Jordán. 2016. “Soil Mapping, Classification, and Pedologic Modeling: History and Future Directions”. Geoderma 264: 256-274.

Brewer, R. 1960. Cutans: Their definition, recognition, and interpretation. Eur. J. Soil Sci. 11:280-292. doi:10.1111/j.1365-2389.1960.tb01085.x.

Browaldh, M. 1995. The influence of trees on nitrogen dynamics in an agrisilvicultural system
in Sweden. Agroforestry System, 30(3): 301-313.

Buol S.W., Southard, R.J., Graham, R.C. and McDaniel, P.A. Soil genesis and classification. John Wiley and Sons, Lowa state, US, 2011.

Burle, M.L, Mielniczuk, J., Focchi, S. 2005. Effect of cropping systems on soil chemical characteristics, with emphasis on soil acidification. Plant Soil, 190 (2005), pp. 309-316. Google Scholar.

Cadish, G., Oliveira, O.C., Cantarutti, R.B., Carvalho, E., Urquiaga, S. The role of legume quality in soil carbon dynamics in savannah ecosystems. In: Bergström, L.; Kirchmann, H. Carbon and nutrient dynamics in natural and agricultural ecosystems. Oxon: CAB International, 1998. p.47-70.

Chakraborty, D., Garg, R.N., Tomar, R.K., Dwivedi, B.S., Aggarwal, P., Singh, R., Behera, U.K., Thangasamy, A.,

Chalise, D., Kumar, L., Shriwastav, C.P., and Lamichhane, S. 2018. Spatial assessment of soil erosion in a moderately steep watershed of Western Nepal. Environ Earth Sci, 77, 685. doi:10.1007/s12665-018-7842-3.

Clemens, G., Fiedler, S., Dinh, N., Dung, N. Van, Schuler, U., and Stahr, K. 2010. Catena Soil fertility affected by land use history , relief position , and parent material under a tropical climate in NW-Vietnam. Catena, 81(2), 87-96. https://doi.org/10.1016/j.catena.2010.01.006.

Dengiz, O., Kızılkaya, R., Erkoçak, A., Durmuş, M. 2013. Variables of microbial response in natural soil aggregates for soil characterization in different fluvial land shapes. Geomicrobiology Journal 30(2); 100-107.

Emadi, M., Shahriari A.R., Sadegh-Zadeh, F., She-Bardan, B.J., Dindarlou, A. 2016. Geostatistics-based spatial distribution of soil moisture and temperature regime classes in Mazadaran province, Northern Iran. Arch Agron Soil Sci. 62:502-522.

Esu, E., Akpan-Idiok A.U. and Eyong M.O. 2008. Characterization and classification of soils along a typical Hillslope in Afikpo Area of Ebonyi State, Nigeria. Nigerian Journal of Soil and Environment, 8: 1-6.

Foth, H.D. 2003. Fundamentals of Soil Science, John Willey Sons. New York. USA. 360p.

Franzluebbers, A.J., and Hons, F.M. 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage, Soil Till Res 39: 229-239.

Gachene, C.K.K. 1989. Soils of the erosion research farm, Kabete Campus. Department of

Agricultural Engineering, University of Nairobi.

Gannon, J.P., Bailey, S.W., McGuire, K.J. 2014. Organizing groundwater regimes and response thresholds by soils: a framework for understanding runoff generation in a headwater catchment. Water Resour. Res. 50, 8403-8419. http://dx.doi.org/10.1002/2014WR015498.

García-Díaz, A., Bienes, R., Sastre, B., Novara, A., Gristina, L., Cerdà, A. 2017. Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain. Agric. Ecosyst. Environ. 236, 256-267.

Gaze, S.R., Simmonds, L.P., Brouwer, J. and Bouma, J. 1997. Measurement of surface redistribution of rainfall and modeling its effect on water balance calculations for a millet field on sandy soil in Niger. J. Hydrol. 188-189: 267-284.

Gillin, C.P., Bailey, S.W., McGuire, K.J., Gannon, J.P. 2015. Mapping of hydropedologic spatial patterns in a steep headwater catchment. Soil Sci. Soc. Am. J. 79, 440-453. http://dx.doi.org/10.2136/sssaj2014.05.0189.

Glasmann, J.R., Brown, R.B., and Kling, G.F. 1980. Division S-5 -Soil Genesis, Morphology, Soil-Geomorphic Relationships in the Western Margin of the Willamette Valley , Oregon 1, 1045-1052.

Glendon, W.G. and Doni, O.R. 2002. In J.H. Dane and G.C. Topp. Methods of Soil Analysis Part 4:2644-289. No.5 In Soil Science Society of America Book Series. SSSA, Inc. Madison, Winconsin, USA.

Grossman, R.B. and Reinsch, T.G. 2002. Bulk density and Linear Extensibility. In. J.H. Dane and G.Clarke Topp. Methods of Soil Analysis, part 4: 201-228. USDA-NRCS, National Soil Survey Center, Lincoln, Nebraska.

Hartemink, A.E. 2015. The Use of Soil Classification in Journal Papers between 1975 and 2014. Geoderma Regional 5: 127-139.

Hartemink, A.E., and Bockheim, J.G. 2013. Catena Soil genesis and classification. Catena, 104(January 2018), 251–256. https://doi.org/10.1016/j.catena.2012.12.001.

IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.

Ingram JSI. Tropical soil biology and fertility : A handbook of methods. Soil Sci. 1994;157 (4):265.

IUSS Working Group WRB. 2006. World Reference Base for Soil Resources 2006. World Soil Resources Report No. 103, FAO, Rome.

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

Jankowski, M. 2013. The evidence of lateral podzolization in sandy soils of northern Poland. Catena. https://doi.org/10.1016/j.catena.2013.03.013.

Jenny, H. 1941. Factors of soil formation: A system of quantitative pedology. MC Graw- Hill, New York, 281 pp.

Jiitzold, R., Kutsch, H. 1982. Agro-ecological zones of the tropics, with a sample from Kenya. J Agric Trop Subtrop. 1982;83:15-34.

Jury, W.A., Sposito, G. and White, R.E. 1986. A transfer function model of solute transport through soil, l, Fundamental concepts, Water Resources, 22: 243-247.

Karuku, G.N., Gachene, C.K.K., Karanja, N., Cornelis, W., Verplancke, H., and Kironchi, G. 2012. Soil Hydraulic Properties of a Nitosol in Kabete, Kenya. Tropical and sub-tropical agro-systems, 15 (2012): 595-609.

Kenya Soil Survey Staff, 1987. Manual for soil survey and land evaluation. Vol. 1, soil survey. Miscellaneus soil paper No. M24. Republic of Kenya.Ministy of Agriculture, National Agricultural Laboratories- https://library.wur.nl/isric/fulltext/isricu_i00011434_002.04.pdf

Laamrani, A., Valeria, O., Bergeron, Y., Fenton, N., Zhen, L., and Anyomi, K. 2014. Forest Ecology and Management Effects of topography and thickness of organic layer on productivity of black spruce boreal forests of the Canadian Clay Belt region. Forest ecology and management, 330, 144-157. https://doi.org/10.1016/j.foreco.2014.07.013.

Landon, J.R. 2014. Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. In: 2000 Symposium: Sugarcane: Research towards Efficient and Sustainable Production, Routledge, London, 237-240.

Lawal, B.A., Ojanuga, A.G., Tsado, P.A., and

Mohammed, A. 2013. Characterization, Classification and Agricultural Potentials of Soils on a Toposequence in Southern Guinea Savanna of Nigeria. World Academy of Science, Engineering and Technology International Journal of Biological, Veterinary. Agricult Food Eng 2013; 7(5): 330-5. [5]

Lelago, A., and Buraka, T. 2019. Determination of physico-chemical properties and agricultural potentials of soils in Tembaro District , KembataTembaro Zone , 8(2), 118-130. https://doi.org/10.18393/ejss.533454.

Li, Z., Nie, X., Chang, X., Liu, L., Sun, L. 2016. Characteristics of soil and organic carbon loss induced by water erosion on the loess plateau in China. PLoS One 11 (4), e0154591.

Libohova, Z., Schoeneberger, P., Bowling, L.C., Owens, P.R., Wysocki, D., Wills, S., Seybold, C. 2018. Soil Systems for Upscaling Saturated Hydraulic Conductivity for Hydrological Modeling in the Critical Zone. https://doi.org/10.2136/vzj2017.03.0051.

Liu, C.L., Wu, Y.Z., Lui, Q.J. 2015. Effects of land use on spatial patterns of soil properties in a rocky mountain area of Northern China. Arab J Geosci. 8:1181-1194.

Liu, Q.J., An, J., Wang, L.Z., Wu, Y.Z., and Zhang, H.Y. 2015. Soil and Tillage Research Influence of ridge height , row grade , and field slope on soil erosion in contour ridging systems under seepage conditions, 147, 50–59. https://doi.org/10.1016/j.still.2014.11.008.

Mathu, E., and Mwea, S.K. 2014. A study on the engineering behaviour of Nairobi subsoil. ARPN J Eng Appl Sci 2014; 6:7.

Mehlich, A.A., Pinkerton, Robertson, W., Kempton, R. 1962. Mass analysis methods for soil fertility evaluation. Internal publication, Ministry of Agriculture, Nairobi.

Metson, A.J. 1961. Methods of soil analysis for soil survey samples. New Zealand Dept Sci Ind Res Soil Bur Bull 12. Govt printer, Wellington, New Zealand.

Miller, B.A., and Schaetzl, R.J. 2015. Digital Classification of Hillslope Position. https://doi.org/10.2136/sssaj2014.07.0287.

Moore, I.D., Gessler, P.E., Nielsen, G.A., and Peterson, G.A. 1991. Soil Attribute Prediction Using Terrain Analysis, 443-453.

Moosavi, A.A. and Sepaskhah, A.R. 2012. Spatial variability of physic-chemical properties characteristics of a gravelly calcareous soil. Arch Agron Soil Sci. 58:631-656.

Moradi. F., Moosavi. A.A., Khalili Moghaddam, B. 2016. Spatial variability of water retention parameters and saturated hydraulic conductivity in a calcareous Inceptisols (Khuzestan province of Iran) under sugarcane cropping. Archives of Agronomy and Soil Science, 62:1686-1699. DOI: 10.1080/03650340.2016.1164308.

Munsell Colour Company. 1975. Munsell soil colour charts, Munsell colour company Inc. Baltimore 18, Maryland, USA.

Mwendwa, S.M., Mbuvi, J.P., and Kironchi, G. 2019. Land evaluation for crop production in Upper Kabete Campus field, University of Nairobi, Kenya. Chemical and Biological Technologies in Agriculture, 6(1). https://doi.org/10.1186/s40538-019-0156-1.

Nelson, E.W., and Sommers, L.E. 1996. Total Carbon, Organic Carbon, and Organic Matter. In Methods of Soil Analysis: Chemical Methods. Part 3. D.L. Sparks, editor. Soil Science Society of America. Madison WI.

Pabst, H., Kühnel, A., and Kuzyakov, Y. 2013. Effect of land-use and elevation on microbial biomass and water extractable carbon in soils of Mt. Kilimanjaro ecosystems. Applied Soil Ecology, 67, 10-19. https://doi.org/10.1016/j.apsoil.2013.02.006.

Park, S.J., Mcsweeney, K., and Lowery, B. 2001. Identification of the spatial distribution of soils using a process-based terrain characterization, 249-272.

Paz-Ferreiro, J., Fu, S. 2016. Biological indices for soil quality evaluation: perspectives and limitations. L. Degrad. Dev. 27, 14-25.

Pillon, C.N. 2000. Stocks and Quality of soil Organic Matter as Affected by No-Till Cropping System, Doctorate Thesis**.** Federal University of Rio Grande do Sul, Porto Alegre (2000)pp. 248. Google Scholar.

Porder, S. and Ramachandran, S. 2013. The phosphorus concentration of common rocks–a potential driver of ecosystem P status. Plant Soil 367, 41-55.

Reynolds, W.D., Elrick, D.E., and Youngs, E.G. 2002. Rings or Cylinder Infiltrometers (Vadose Zone). In J.H. Dane and G.C. Topp. Methods of Soil Analysis Part 4. Physical

Methods: 818-843. No.5 In Soil Science Society of America Book Series. SSSA, Inc.Madison, Wisconsin, USA.

Saggerson, E.P. 1991. Geology of the Nairobi Area. Mines and Geological Department Report 78. Nairobi Mines and Geological Department.

Schaetzl, R.J. 2013. Catenas and Soils. In: Shroder, J.F. (Ed.). Treatise on Geomorphology vol. 4. Academic Press, San Diego, California, pp. 145-158.

Schwanghart, W., and Jarmer, T. 2011. Geomorphology Linking spatial patterns of soil organic carbon to topography -A case study from. Geomorphology, 126(1-2), 252–263. https://doi.org/10.1016/j.geomorph.2010.11.008.

Sekhar, C.C., Balaguravaiah, D., Naidu, M.V.S. 2014. Studies on genesis, characterization and classification of soils in central and Eastern parts of Prakasam district in Andhra Pradesh. Agropedology 24: 125-137.

Shahabi, M., Jafarzadeh A.A., Neyshabouri, M.R., Ghorbani, M.A., Kamran, K.V. 2016. Spatial modeling of soil salinity using multiple linear regression, ordinary kriging and artificial neural network methods. Arch Agron Soil Sci. doi:10.1080/03650340.2016.1193162.

Shukla A.K., Behera S.K., Lenka N.K., Tiwari P.K., Malik, R.S, Sinha N.K, Singh, V.K., Patra, A.K., Chaudhary, S.K. 2016. Spatial variability of soil micronutrients in the intensively cultivated Trans-Gangetic Plains of India. Soil Till Res. 163:282-289.

Sombroek, W.G., Braun, H.M., and Van der Pouw. 1982. Exploratory Soil Survey. Report No. El. Ministry of Agriculture, Nairobi, Kenya.

Vandenbygaart, A.J. 2001. Erosion and deposition history derived by depth-stratigraphy of 137 Cs and soil organic carbon. Soil Till Res: 61, 187-192.

Van de Weg, R.F. and Mbuvi, J.P (eds.). 1975. Soils of the Kindaruma area. Report No. R1, Kenya Soil Survey/Government Printer, Nairobi.

Vasquez-Mendez, R., Ventura-Ramos, E., Oleschko, K. 2010. Soil erosion and runoff in different vegetation patches from semiarid Central Mexico. Catena, 80(3): 162–169.

Wanjogu, S.N and Mbuvi J.P. 1993. The Influence of Parent Materials on some Characteristics of the Soils of a Semi-Arid Catchment E. Afr. Agric. For. J. Vol. 58, No. 4. pp. 331-337. In: Asian Journal of Agriculture and Rural Development. Asian Economic and Social Society; 1993.

Warrick, A.W., Nielsen D.R. 1980. Spatial variability of soil physical properties in the field. In: Hillel, D. (Ed.) Applications of soil physics. New York: Academic Press, 1980. p.319-344.

Wei, W., Jia, F., Yang, L. 2014. Effects of surficial condition and rainfall intensity on runoff in a loess moderately steep area, China. Journal of Hydrology, 513: 115-126.

Wezel, A., Steinmüller, N., and Friederichsen, J.R. 2002. Slope position effects on soil fertility and crop productivity and implications for soil conservation in upland northwest Vietnam. Agriculture, ecosystems and environment: 91, 113-126.

Willy, D.K., Muyanga, M., Mbuvi, J.P., and Jayne, T.S. 2019. Geoderma. The effect of land use change on soil fertility parameters in densely populated areas of Kenya. Geoderma, 343(January), 254-262. https://doi.org/10.1016/j.geoderma.2019.02.033.

Zinck, J. A., Metternicht, G., Valle, H.F. Del, and Bocco, G. 2016. Synthesis and Conclusions (Geopedology: An Integration of Geomorphology and Pedology for Soil and Landscape Studies), (February). https://doi.org/10.1007/978-3-319-19159-1.