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For the degree of Master of Science

Is approved by the final examining committee:

Darrell G. Schulze
Chair

Stephen C. Weller

Gary Burniske

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Head of the Departmental Graduate Program Date

ASSESSING THE SPATIAL VARIABILITY OF SOILS IN UGANDA

A Thesis

Submitted to the Faculty

of

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by

Joshua O. Minai

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of

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ABSTRACT

Minai, Joshua O. M.S., Purdue University, May, 2015. Assessing the Spatial Variability of Soils in Uganda. Major Professor: Darrell G. Schulze.

Uganda's soils were once considered the most fertile in Africa, but soil erosion and soil nutrient mining have led to soil degradation and declining agricultural productivity. Lack of environmental awareness among farmers, traditional agricultural practices, minimal inorganic fertilizer use, and little to no use of improved crop varieties all contribute to continued soil degradation. The objectives of this study were: (1) to characterize the spatial distribution of selected physical and chemical soil properties in Uganda on a national scale utilizing the data collected by Nkonya et al. (2008), and (2) to identify the major factors and processes that are dominant in explaining the spatial variability of these physical and chemical soil properties in Uganda on a national scale.

This study used a 2003 Uganda National Household Survey dataset that included analyses of 2,185 soil samples that covered western, southwestern and northwestern Uganda, representing ~50% of the country. Variables included pH, organic matter, total N, available K, total K, total P, and soil texture (Nkonya et al., 2008, IFPRI Research Report 159). Ordinary kriging was used for spatial analysis, while a generalized linear model was used

to identify the most dominant factors influencing soil variability. ANOVA results found significant variation among soil properties means, as one would expect. Strong spatial correlation (< 25% nugget to sill ratio) was observed in available K, pH, sand, total N, and silt, while moderate spatial correlation (25% to 75% nugget to sill ratio) was observed for total K, clay, total P, and organic matter. Distances where spatial correlation occurred ranged between 69 and 230 km. Interpolated soil quality maps identified the Mt. Elgon and the southwestern highlands regions as having soils above the critical soil chemical and physical thresholds, indicating that these are the most favorable agricultural areas in the country. The remaining areas of the country had numerous constraints such as acidity, very sandy soils, low N and/or low organic matter, making these areas less optimal for agricultural production.

There was no dominant factor that solely explained the variability of all the soil properties. However, climate had the strongest effect on the variability of total N, with higher soil N found in the cooler, higher elevations of Mt. Elgon and the southwestern highlands. This study showed that geostatistical approaches can be used to evaluate spatial diversity of natural resources at larger scales. Policy makers can use this information to implement region-specific soil management approaches to address soil quality degradation. For example, programs to increase the soil pH of acid soils should be focused on the southwestern region where soils are generally more acid than other parts of the country.

LIST OF ACRONYMS

AEZ	Agroecological Zone
ANOVA	Analysis of Variance
Ca	Calcium
CEC	Cation Exchange Capacity
CL	Climate
CV	Coefficient of Variation
DEM	Digital Elevation Model
DGSM	Department of Geography Survey and Mines
FAO	Food and Agriculture Organization of the United Nations
GEGE	Geology and Geomorphology
GIS	Geographic Information System
GLM	Hierarchical Generalized Linear Model
GoU	Government of Uganda
GPS	Global Positioning System
IFPRI	International Food Policy Research Institute

ITCZ	Intertropical Convergence Zone
K	Potassium
LULUM	Land Use and Land Use Management
MFPED	Ministry of Finance, Planning and Economic Development
Mg	Magnesium
msl	Meters above sea level
mya	Million years ago
N	Nitrogen
Na	Sodium
NARL	National Agricultural Research Laboratories
NEMA	National Environment Management Authority
NM	Northern Moist Farmlands
P	Phosphorus
SOECO	Socioeconomic
SOM	Soil Organic Matter
SW	Southwestern
SWC	Soil and Water Conservation

SWH	Southwestern Highlands
TFL	Tobler's First Law of Geography
TRMM	Tropical Rainfall Monitoring Mission
UBoS	Uganda Bureau of Statistics
UMD	Uganda Metrological Department
UNDP	United Nations Development Program
UNESCO	United Nations Education, Scientific and Cultural Organization
UNHS	Uganda National Household Survey
WNW	West Nile and Northwestern

1.0 INTRODUCTION

Seventy percent of the population of Africa depends directly on agriculture as a source of livelihood (Africa Progress Panel, 2014). As Africa's population continues to grow, available arable land is decreasing in quality because farmers are intensifying land use for production using poor agricultural practices. Poor inherent soil quality (Greenland and Nabhan, 2001; Koning and Smaling, 2005) and other biophysical constraints limit agricultural productivity in most parts of Africa (FAO, 1995; Drechsel et al., 2001; Stocking, 2003; Voortman et al., 2003; Ehui and Pender, 2005). These concerns have motivated ongoing efforts to map both static soil qualities (Sanchez et al., 2009) and large-scale land degradation (Bai et al., 2008).

In the East African Highlands, which includes all of Uganda, soil degradation in the form of soil erosion and soil nutrient mining has become a leading cause of declining agricultural productivity, which has increased poverty and food insecurity among Uganda's rural smallholder farmers (Nkonya et al., 2005a, b; Pender et al., 2004). Uganda currently has some of the most severe forms of soil nutrient depletion in Africa (Stoorvogel and Smaling, 1990; Wortmann and Kaizzi, 1998). These areas are usually characterized by high populations (Ehui and Pender, 2005) living on very old, highly weathered soils (Voortman et al., 2003; Henao and Banaante, 2006).

Efforts to stop the continuing degradation of soil quality in Uganda frequently fail to acknowledge that farmers live in ecologically diverse environments and often lack the knowledge to address soil degradation problems within their farms (Rücker, 2005). Farmers often implement soil and water conservation (SWC) measures without taking into consideration the spatial variation in their soils and the site-specific solutions that might be appropriate for different areas of a field. Information for addressing the challenges of soil degradation has mostly been based on results from small experimental plots extrapolated to vast areas of arable lands (Sserunkuuma et al., 2001), an approach that does not take into account regional soil differences (Magunda and Tenywa, 1999).

Understanding the heterogeneity of Uganda's soil resources at the national scale is one of the first steps towards making region-specific decisions on fertilizer applications (Wei et al., 2009), soil and crop management practices, irrigation scheduling (Bruland et al., 2006), effective design of experimental sampling (Oliver and Webster, 1991), and also accurate estimates of nutrient budgets and cycling rates (Fraterrigo et al., 2005; Stutter et al., 2009). Current information on the spatial variability of soils in Uganda is limited (Rücker, 2005).

The only available large-scale maps of natural resources in Uganda include a status of natural resources map at a scale of 1:1,000,000 produced by Yost and Eswaran (1990), and an agro-ecological zone map on a 5 × 5 km grid produced by Wortmann and Eledu (1999). Neither map provides information on the heterogeneity of soil properties. Natural resources such as vegetation and water may influence the potential of soil resources through the interaction of different hydrologic and pedologic processes. Socioeconomic factors, such

as the distribution of markets impact the ability farmers to acquire inputs such as fertilizer for improving soil resources. Population density may also influence soil quality through the intensity of cultivation within a region (Rücker, 2005). For instance, in regions with high population densities, farmers have little land acreage to practice fallowing and are thus forced to practice continuous cultivation. With no nutrient replenishment, the quality of soil is expected to decline since soil nutrients are increasingly being depleted.

Understanding the spatial distribution of soils over large areas and the socioeconomic factors that could impact soil quality at larger scales is key to sustainable integrated natural resource management strategies for areas such as an entire country (Carter, 1997; Wood et al., 1999). Such an understanding can assist in the prioritization of agronomic investment and offer rational, integrated natural resource management strategies for regional, national, and/or local scales (Vlek, 1990; Kaizzi, 2002). To help address these issues, this study utilized a unique dataset collected during a baseline study conducted by Nkonya et al. (2008) that directly measured soil properties for 850 households representing 122 rural communities across Uganda.

1.1 Hypothesis

Geology is the most dominant factor influencing soil variability over larger scales. Classical geology concepts have been used to explain the differences observed in soils (Ruhe, 1956; Ovalles and Collins, 1986). For instance, soils that have weathered for long periods of time tend to have a different chemical and physical composition compared to those that are younger geologically (Elliot and Gregory, 1895; NEMA, 2010). Although the variation in soil is a result of systematic changes as a function of soil forming factors

(Wilding and Drees, 1983), or a result of stochastic changes such as soil management practices and/or socioeconomic factors (Beckett and Webster, 1971), we hypothesize that geology will be the most dominant factor over large areas.

1.2 Objective

Investigate the country level spatial variability of soils in Uganda to provide information to develop improved land management strategies and to promote effective and sustainable agricultural development. The specific objectives are:

1) To characterize the spatial distribution of selected physical and chemical soil properties in Uganda on a national scale utilizing the data collected by Nkonya et al. (2008).
2) To identify the major factors and processes that are dominant in explaining the spatial variability of these physical and chemical soil properties in Uganda on a national scale.

1.3 Thesis Outline

This thesis is structured into five chapters. Chapter 1 introduces the problem of soil quality degradation in Uganda and describes the necessity of research on spatial variability of soils. Chapter 2 gives the theoretical framework on soil variability and outlines factors that influence soil variation. Chapter 3 discusses the setting of this study, describing the distribution of the various environmental factors and outlines proposed criteria for assessing the spatial variation of soil at a larger scale. Chapter 4 describes the methods of data collection. Chapter 5 summarizes the findings, the challenges faced while conducting this study, draws conclusions, and gives recommendations.

2.0 SPATIAL VARIABILITY OF SOILS IN UGANDA

This chapter, reviews literature on the statistical theory of spatial variability in soils and how to model soil variability statistically. An in-depth overview of the factors influencing soil spatial variability at the national scale by outlining both the environmental and socioeconomic categories is also discussed.

2.1 Theory of Spatial Dependence

Spatial heterogeneity has been mainly viewed as consisting of two main variance components: systematic and stochastic variability (Burrough, 1993; Wilding 1994; McBratney et al., 2000). Wilding and Drees (1983) consider *systematic variability* as those changes in soils explained by soil forming factors at a given scale of observation whose sources have been viewed to originate from differences in topography, lithology, climate, biological activity and soil age, the five soil forming factors of Jenny (1941). The variability in soils that cannot be related to any known cause is considered to be the *stochastic variability* (Trangmar et al., 1985). Wilding and Drees (1983) termed this unexplained heterogeneity as ‘random’ or ‘chance’ variation. Webster and Cuanalo (1975) and Burrough (1983) termed it ‘noise’.

2.1.1 Nested Effects

Soil heterogeneity is the result of soil forming factors operating and interacting with each other over time and space (Trangmar et al., 1985). Processes that operate over large scales (for instance climate) or longer time periods (soil weathering) will tend to be modified by

other processes that act locally (erosion, deposition of parent materials, or frequently weather). This nested nature of variability in soil implies that the kind and sources of heterogeneity identified in soil will tend to depend on the scale or frequency of observation. Changes in soil spatial variability with increasing scale will depend on the soil property in question and the soil factors determining the spatial change (Wilding and Drees, 1983). Some soil properties will vary greatly over short distances (McIntyre, 1967; Protz et al., 1968; Beckett and Webster, 1971) (Fig. 1.1), while the opposite is true for other soil properties (Webster and Butler, 1976). The change may be linear, curvilinear (upward or downward), or irregular where different soil forming processes exert dominating effects at different spatial scales (Webster and Butler, 1976; Nortcliff, 1978; Burrough, 1983).

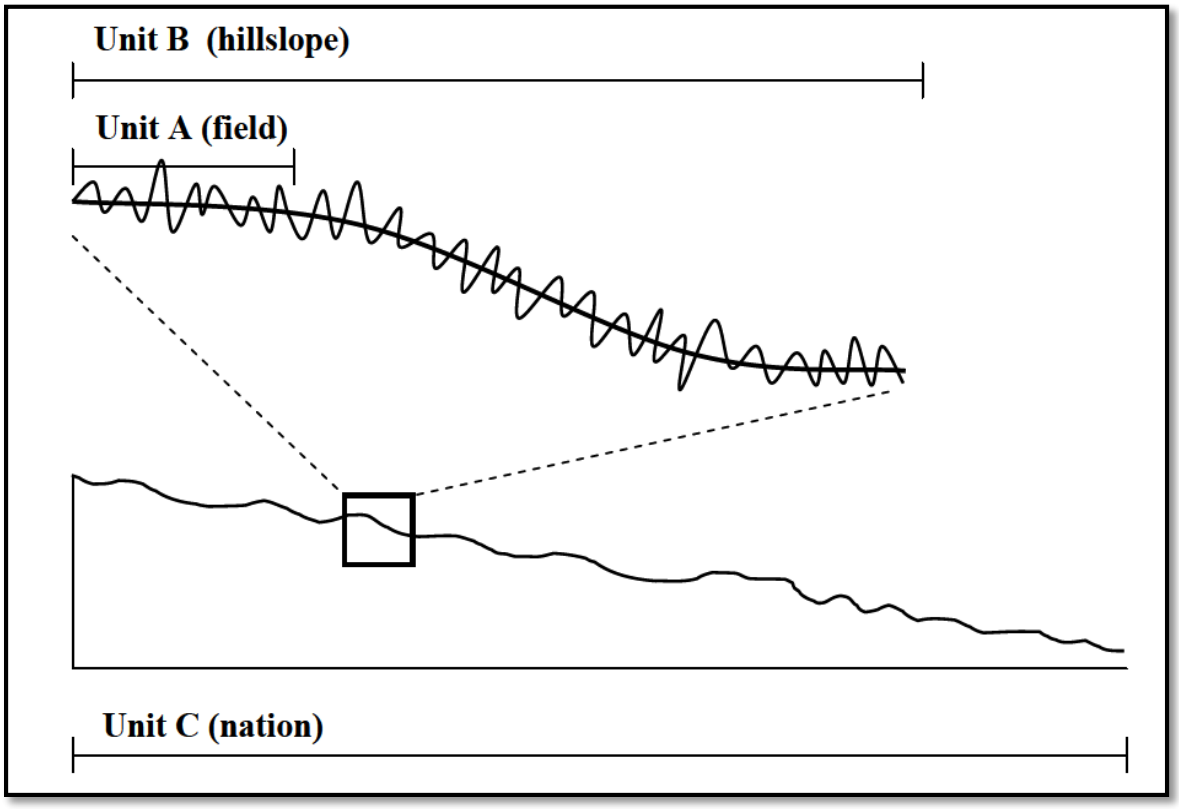

Figure 2.1: Scheme of spatial variability of soil on different geographical scales (from Park and Vlek, (2002 used with permission).

Along Unit C in Fig. 2.1, geology has been considered to be the most dominant factor determining the variability of soil (Ruhe, 1956; Ovalles and Collins, 1986). Topography is generally the most dominant factor influencing soil heterogeneity along a hillslope (Unit B in Fig. 2.1). Within Unit A, several factors may determine the seemingly random heterogeneity in soils (Trangmar et al., 1985).

In the past, spatial variability in soils was mainly captured and displayed by the use of maps that had discrete polygons representing boundaries between map units, suggesting homogeneity within map units (Burrough, 1986; Gessler, 1990). Since the boundaries are depicted as narrow lines across which soil properties change abruptly, discrete polygons do not capture the gradual variability across soil boundaries.

2.1.2 Scale Dependency

Soil properties vary from the nanometer scale to hundreds of kilometers. Feng et al. (2008) found that heterogeneity of soil properties in the loess hills of Northern Shaanxi, China occur both at larger and smaller amounts, within 40 by 40m sample grids, even within the same type of soil or in the same community. The heterogeneity within the same soil type makes it very complex for farmers, who often assume that soils are homogenous and continue making irrational choices when it comes to SWC strategies (Ayoubi, 2009). Fig. 2.2 illustrates that considerable soil variability can occur within a single field.

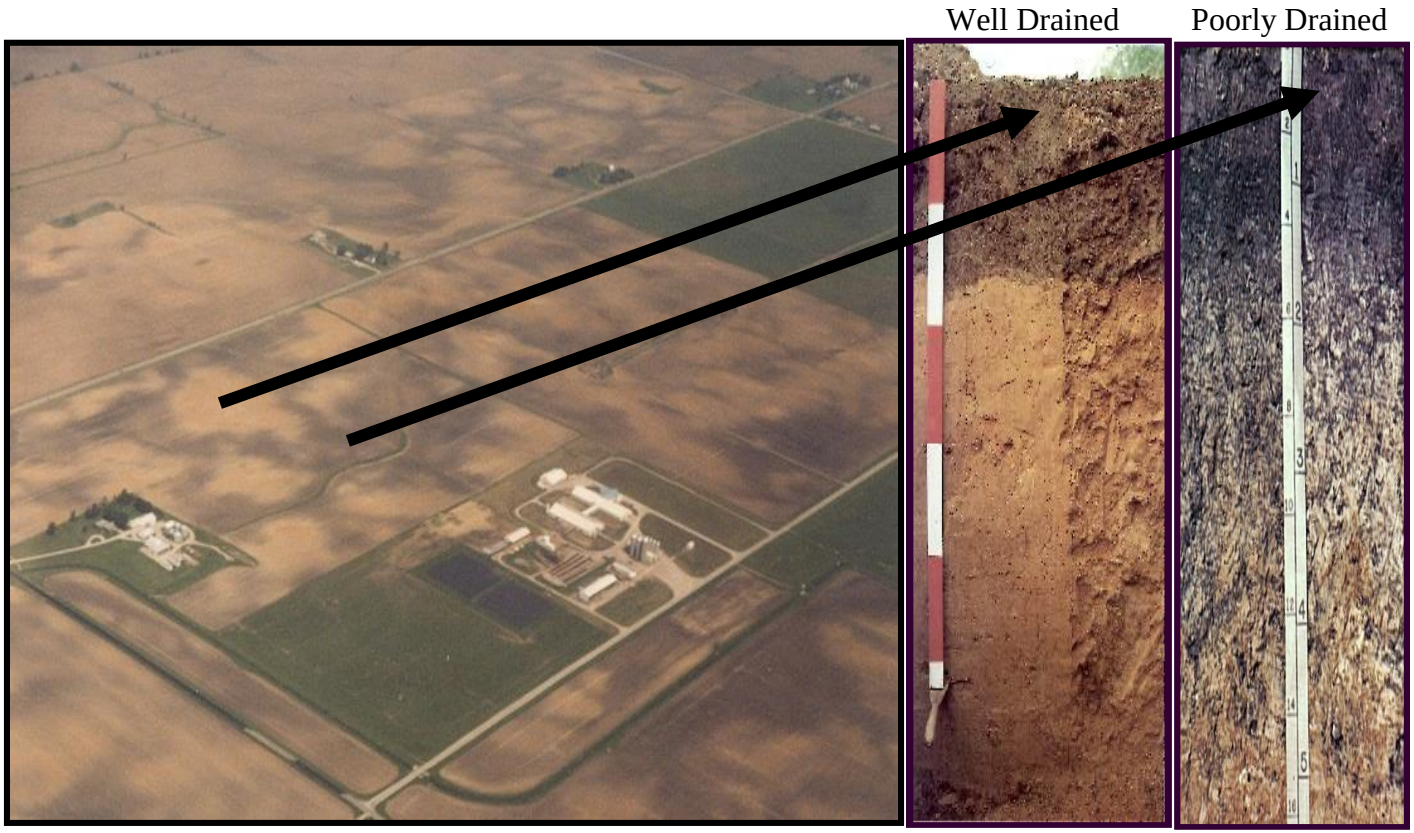

Figure 2.2: Spatial variability across a field as indicated by differences in soil color. This example is an aerial view of an agricultural field in the glaciated region of central Indiana, USA. On the left is an aerial view of an agricultural field, and the right are two soil profiles from the different areas in the field indicated by the arrows. Note: Soil color gives an indication of the various processes occurring in the soil. For instance, the dark color of soils is generally due to the accumulation of humified organic matter. The darker colored soils generally have more organic matter than the lighter colored soils and this can be mainly attributed to slope, resulting in different natural soil drainage classes. Heterogeneity in soil is a complex phenomenon and can occur even within the same soil type. Photos by Dr. John Graveel showing glaciated agricultural fields in Lake County, Indiana in 2002, used with permission.

2.2 Spatial Variability Studies in Uganda

Only one study that of Rücker (2005), has been conducted to investigate the spatial variability of soils in Uganda at a national scale. Rücker (2005) applied both non-geostatistical (inverse distance weighting) and geostatistical methods to investigate the spatial variability of soils in Uganda at both the national and hillslope level. In his study, the variability of soil properties was focused in the southern half of Uganda, where he studied 107 communities and 8 soil properties.

2.3 Modelling Soil Spatial Variability

Most studies view geostatistics as the most confident method for analyzing and predicting the spatial structure of soil variables (Cambardella et al., 1994; Saldana et al., 1998; Cambardella and Karlen, 1999). Such an approach leads to more accurate estimation with fewer errors (Sauer et al., 2006) compared to non-geostatistical methods such as inverse distance weighting (Rücker, 2005). Kresic (2006) acknowledged the use of geostatistics in interpolation and in the determination of spatial variability since this approach takes into consideration spatial variance, location and distribution of samples.

The geostatistical approach predicts unsampled locations based on the autocorrelation and the spatial structure of individual soil properties (Oliver and Webster, 1991). Soil property maps have been found to exemplify spatial dependency (Kavianpoor et al, 2012). Studies have shown that such observed variations can be caused by randomly occurring events such as changes in parent material, position in the landscape, soil forming factors and also distance. The guiding principle in the use of geostatistics in interpolation is Tobler's First Law of geography (TFL) which states, 'everything is related to everything else, but near

things are more related than distant things' (Tobler, 1970). The main limitation with such an approach is that accurate interpretations of the stochastic components of model input parameters over space require a large number of samples to identify the spatial dependency (Burrough, 1993; McBratney et al., 2000). In addition, soil is multivariate and it is therefore very difficult to apply interpolation methods to model its variation on the whole (McBratney and Odeh 1997).

2.4 Factors Influencing Soil Spatial Variability at Different Scales in Uganda

Topography is usually the dominant factor contributing to soil heterogeneity along hillslopes, (Unit B in Fig. 2.1). Rücker, (2005) reached the same conclusion for Uganda, but acknowledged that at larger scales, along Unit C (Fig. 2.1), other factors, such as geomorphology, and climatic factors, may have a stronger influence. Conversely, socio-economic factors such as population density, infrastructure, poverty density, and market access affecting natural resource management may have a large influence on soil spatial heterogeneity, and can thus be important drivers on regional scales (Dumanski and Craswell, 1996). Many factors have been identified as contributing to the spatial distribution of soils in Uganda (Davies, 1952; Harrop, 1970; Foster, 1976; Yost and Eswaran, 1990; Ssali, 2003; Bashaasha, 2001). These factors can be broadly grouped into two categories (1) the environmental category and (2) the socioeconomic category.

2.4.1 Environmental Category

Three subcategories, Geology/Geology, Climate, and Land Use / Land management, were identified as potential environmental category factors and discussed in detail below on how they influence soil variability.

2.4.1.1 Geology/ Geomorphology

The geology of Uganda is characterized by rocks from the pre-Cambrian, Paleogene and Neogene periods (see Appendix A) (Harrop, 1970). These rocks are exposed on geologic surfaces of different ages formed by tectonic uplift in the Paleogene and Neogene periods. Most soils were formed from weathered pre-Cambrian parent rocks, younger volcanic ashfalls, and materials that have been reworked by processes of erosion and deposition (Davies, 1952; Harrop, 1970; Ssali, 2003; Rücker, 2005). Given the fact that the parent material is not uniform in distribution, Uganda, soils are expected to vary considerably in inherent fertility after subsequent parent material weathering (Ssali et al., 1986).

Elevation dictates the rate of weathering of the parent material and the decomposition of organic matter, which also contributes to the spatial variability of corresponding soil parameters. It has a major influence on climate and soil and crop management, particularly in mountainous regions, and also affects rainfall distribution, soil erosion processes, and the growing cycles of crops, which in turn influences the soil resources by the combined interactions of hydrological, pedological, and agronomic processes (Wortmann and Eledu, 1999; Rücker, 2005). Slope is also important since it determines the probability of soil erosion, which is a strong indicator of soil nutrient loss (Wortmann and Kaizzi, 1998). Areas with steep slopes are expected to have higher rates of erosion compared to those of more gentle slopes (Wortmann and Kaizzi, 1998; Henao and Baanante; 1999).

In order to assess the effect of geology on the variability of soils in Uganda, geologic age, geotectonic land surface type, parent material, elevation and slope were selected as possible geology variables.

2.4.1.2 Climate

Climate is the "average state of the atmosphere at a given point on the earth's surface" (Beckinsale, 1965). It consists of the average physical elements including precipitation, temperature, wind speed and direction, atmospheric pressure, humidity, cloud cover and sunshine duration. Different climatic factors may influnce the variability of soil properties. For instance, precipitation influences many soil processes including weathering, leaching, erosion, and acidification (Jameson and McCallum, 1970; Ssali, 2003). Areas receiving high amounts of rainfall experience increased leaching of soluble nutrients, especially nitrates, comapred to those receiving low rainfall.

Temperature can be used for the explanation of soil organic matter dynamics. Higher temperatures increase the rate of microbial decomposition of organic matter (Ssali, 2003; Ruecker et al., 2003). The length of growing period is a justified climatic variable as it reflects on the number of days in a year that are suitable for crop growth. Areas with longer growing periods will experience more intense agricultural production than areas with shorter growing periods (FAO, 1996). The length of growing period is defined as "the period of the year when the prevailing temperatures are conducive to crop growth (mean temperature 5°C) and precipitation and soil moisture exceeds half the potential evapotranspiration" (FAO, 1996). The average annual precipitation, the length of growing period, and average annual temperature were used as possible climatic variables to assess the effect of climate on the variability of soils in Uganda.

2.4.1.3 Land Use / Land management

Land use and land use management practices may, to some extent, influence soil variability (Sserunkuuma et al., 2001; Ruecker et al., 2003). Different crops have different management practices, with commercial crops receiving intense agronomic management and conservation practices, while subsistence crops usually receive very little attention (Parsons, 1970; Bashaasha, 2001). In addition, different crops have different soil nutrient requirements. A study by Bekunda (1999) and Turner et al. (1989) found that areas under banana cultivation have very low soil potassium levels since potassium is a very critical nutrient for banana growth and is taken up in large quantities. Coupled with a lack of fertilizer application, areas under intense banana cultivation are expected to have low extractable potassium levels. In order to investigate the effect of land use on soil variability, the Uganda farming system classification (NEMA, 1998) was used as a potential land use/ land management variable.

2.4.2 Socio-economic Category

Even though variability is inherent in nature due to variations in soil parent material and microclimate (Zhao et al., 2009), much of the variability exemplified in soils may also be strongly influenced by highly diverse socio-economic conditions (Rücker, 2005). Some socio-economic factors like distribution of markets or market access may have some influence on the variation in soil quality. This study identified market access, poverty, population and infrastructure were identified as potential socioeconomic category factors that might influence soil heterogeneity and discussed in detail below.

2.4.2.1 Market Access

The ease of access to markets may be important because it impacts the ability of farmers to access farm inputs that can be used to improve their soil resources. Communities that cannot easily access a market have been found to have a weak comparative advantage relative to those communities that can access a market, preventing communities with poor market access from adopting diverse livelihood strategies that might stir agricultural growth. For instance the production of highly perishable goods such as dairy or horticultural crops are more likely to be greatest where there is high market access (Pender et al., 2001). Areas with higher market access are therefore expected to have better soil quality compared to areas with lower market access because their motivation to invest in land is higher.

2.4.2.2 Population

Population may exert pressure on the available land resources resulting in the degradation of soil quality if the carrying capacity is exceeded (Nkonya et al., 2008). For instance, when population increases, the average land area per household decreases, forcing households to expand into fragile lands and also to reduce their frequency of fallowing in order to feed the rising population. Fallowing is an important management strategy for rural smallholders in Uganda because by practicing fallowing, soil physical properties are improved and leached nutrients are replenished (Ruecker et al., 2003). The effect of population on soil quality is mixed. One view holds that as population increases, the increased scarcity of quality soil may force farmers to further deplete soil resources because farmers are in dire need of increasing their agricultural production to meet their household needs. This is the *neo-Malthusian theorem* (Malthus, 1959; Pender and Scherr, 1999;

Otsuka and Place, 2001; Gebremedhin et al., 2003, 2004). The second view holds that population increase may increase the scarcity of quality natural resources, herein soil, forcing farmers to resort to agricultural intensification while implementing soil and water conservation measures in order to protect the quality of their soil or other natural resources. This is the *neo-Boserupian theorem* (Boserup, 1965; Tiffen et al., 1994; Lindblade et al., 1996; Carswell, 2002).

2.4.2.3 Poverty

Poverty takes different forms, and differs among the poor, depending on their livelihoods and access to different forms of capital (Nkonya et al., 2008). The Uganda Participatory Poverty Assessment Process (UPPAP) defines poverty as 'the lack of basic needs and services (including food, clothing and shelter), basic healthcare, education, and productive assets' (MFPED, 2003). The impact of poverty on natural resources is mixed. Two major effects of poverty on soil quality can be argued to be: (1) that poverty may result in the degradation of natural resources since poor people have limited capital to purchase farm inputs that can be used to improve soil quality (Nkonya et al., 2008), and (2) that poverty may result in the conservation of natural resources since poor people are more highly dependent on natural resources, more than the well-off, and would therefore be highly motivated to conserve natural resources.

2.4.2.4 Infrastructure

Infrastructure is widely recognized as a catalyst for agricultural growth (FAO, 1996; Antle, 1984; Binswanger et al., 1993; Fan et al., 2004). Infrastructure determines how easily a farmer within a community can access a market to either buy farm inputs (fertilizers, pesticides) and or sell his or her farm produce. Infrastructure in the form of roads eases

access to and from rural areas and may motivate rural farmers to improve their soil quality. When farmers are in a position to easily access farm inputs such as fertilizers and also sell their agricultural produce they are motivated to increase their agricultural production by investing in their farm plots to improve their livelihood. In this study, a community's road density[1] was used as an indicator for infrastructure.

To identify the effect of socioeconomic factors on Uganda's soil variability, four variables, population density, poverty density, market access, and infrastructure were used as socioeconomic factor variables. Data for these variables was available for the year that the soil samples used in this study were collected (UBoS, 2002).

[1] A road density is the ratio of the length of the country's total road network to the country's land area. The road network includes all roads in the country: motorways, highways, main or national roads, secondary or regional roads, and other urban and rural roads (Ranganathan and Foster 2012; World Bank, 2014).

3.0 SETTING

This chapter provides an in depth overview of the study area and a discussion of the geographical and biophysical characteristics of Uganda, the geomorphology of the country, and an in-depth geological overview of Uganda, while highlighting the importance of using such criteria for assessing the spatial distribution of natural resources. Finally, the distribution and the chemical characteristics of the major soil types is discussed.

3.1 Background of Uganda

Uganda is located in East Africa and lies astride the equator, about 800 kilometers inland from the Indian Ocean (Fig. 3.1) between 1° 29’ south and 4° 12’ north latitude, and 29° 34’ east and 35° 0’ east longitude (Langlands, 1971, 1976). The country has a 765 km border with the Democratic Republic of Congo to the west, a 933 km border with Kenya to the east, a 169 km border with Rwanda to the south west, a 435 km border with South Sudan to the north and a 396 km border with Tanzania to the south, making it a landlocked country. Uganda has an area of 241,550 km^2 (93,263 mi^2), of which 41,743 km^2 (15%) is open water and swamps, while 199,807 km^2 is land (Drichi, 2003). The country had a total population of 34.1 million in 2011, with a life expectancy of about 54 years and an adult literacy rate of 71%, (UNDP 2011; UBoS, 2013). The terrain is mainly a plateau with a rim of high mountains with altitudes ranging between 900 and 1,500m above sea level (Avitabile et al., 2012).

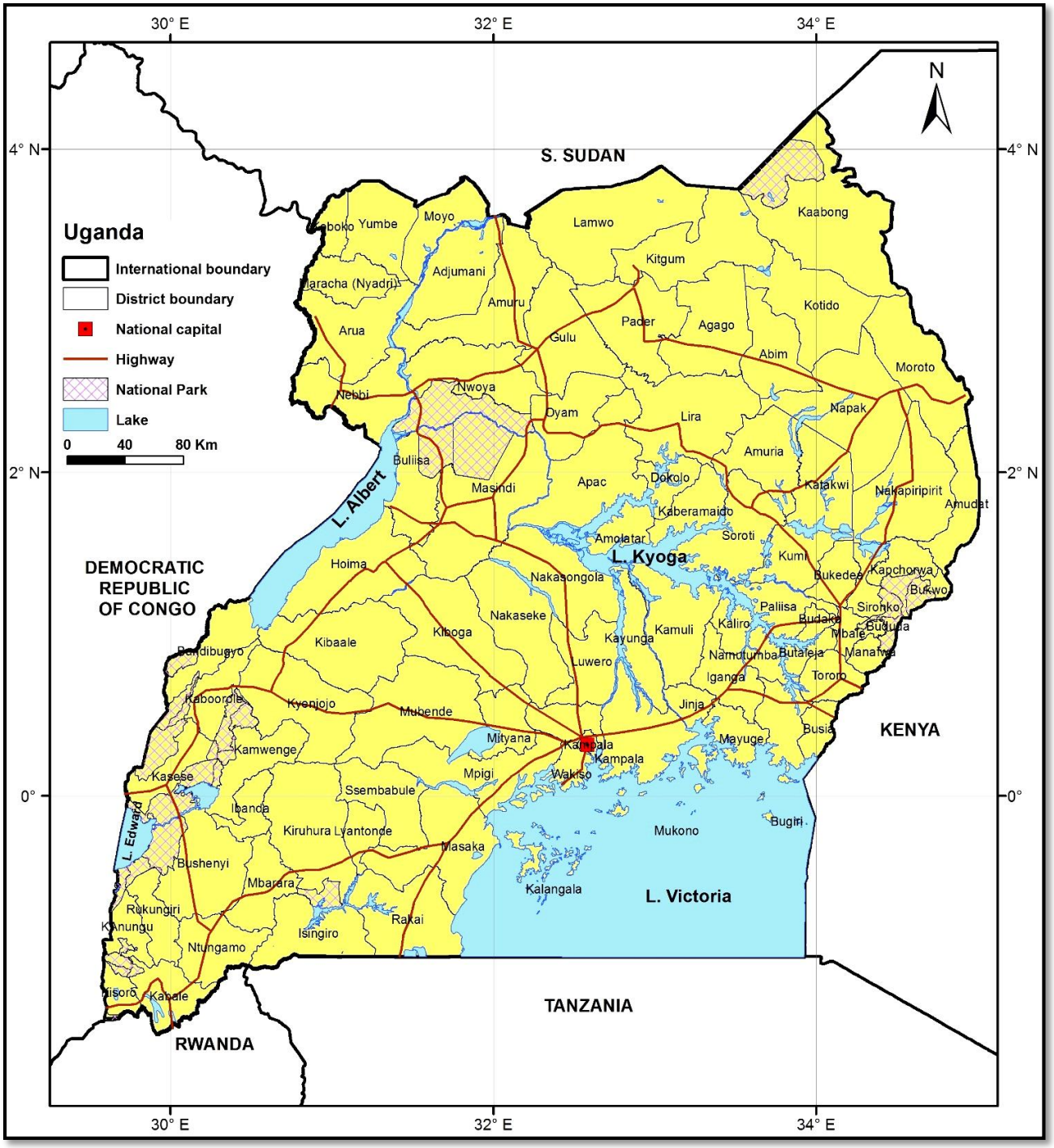

Figure 3.1: Map shows district boundaries, major roads and national parks of Uganda (UBoS, 2002, 2003a, b).

3.2 Climate

Uganda's climate is bimodal with two rainy seasons: March to June, and October/November to December/January. The climate is shaped by the Inter-Tropical Convergence Zone (ITCZ) and air currents such as the southeast and northeast monsoons (NEMA, 2010). Uganda has 5 climatic zones based on total rainfall as the dependent variable (Kakumirizi, 1989; NEMA, 2010). The average annual rainfall declines from 2160 mm in the south near Lake Victoria, to 510 mm in the northeast. Bimodal rainfall distribution occurs in the southern and central parts of the country, whereas a uni-modal rainfall distribution is dominant in northern Uganda and the drier parts of southwestern Uganda, including the highlands (Bagoora, 1988; Rücker, 2005). Average annual temperature shows little spatial variation in the lowlands, ranging from 30 to 32° C in central Uganda. The average annual temperature decreases distinctly in the highlands ranging from 25 to 4° C (Jameson and McCallum, 1970; Rücker, 2005).

3.3 Geographic and Biophysical Characteristics of Uganda

An Agroecological Zone (AEZ) is defined as 'a land resource mapping unit, defined in terms of climate, landform and soils, and or land cover, and having a specific range of potentials and constraints for land use' (FAO, 1996). Agroecological Zones are largely determined by the amount of rainfall, which captures variability in altitude, soil productivity, crop productivity, crop systems, livestock systems and land use intensity, the major factors which drive the agricultural potential and farming systems within each zone (FAO, 1976, 1984 and 2007; Fischer et al., 2012; Wasige, 2009). Several systems have been used to classify Uganda's agro-ecological zones. The Ministry of Natural Resources (1994) divided Uganda into 11 AEZs and 20 ecological zones. Ecological zones are "areas

where physical factors such as climate, soils, landforms and rocks interact to form an original environment in which a mix of plant life grows and provides a habitat for animal life" (Schultz, 2005). Earlier, Semana and Adipala (1993) described only 4 AEZs. Later, Wortmann and Eledu (1999) proposed more detailed criteria that divided Uganda into 33 different AEZs. This study uses the aggregated AEZs of Wortmann and Eledu (1999) that broadly divides Uganda into 14 broader categories (Fig. 3.2) since this gives a detailed representation of the country's natural resource distribution sufficient for this study. Ruecker et al. (2003) described these zones as 'homogenous' spatial domains within which natural resources and socioeconomic factors are fairly similar but differ from one domain to the other.

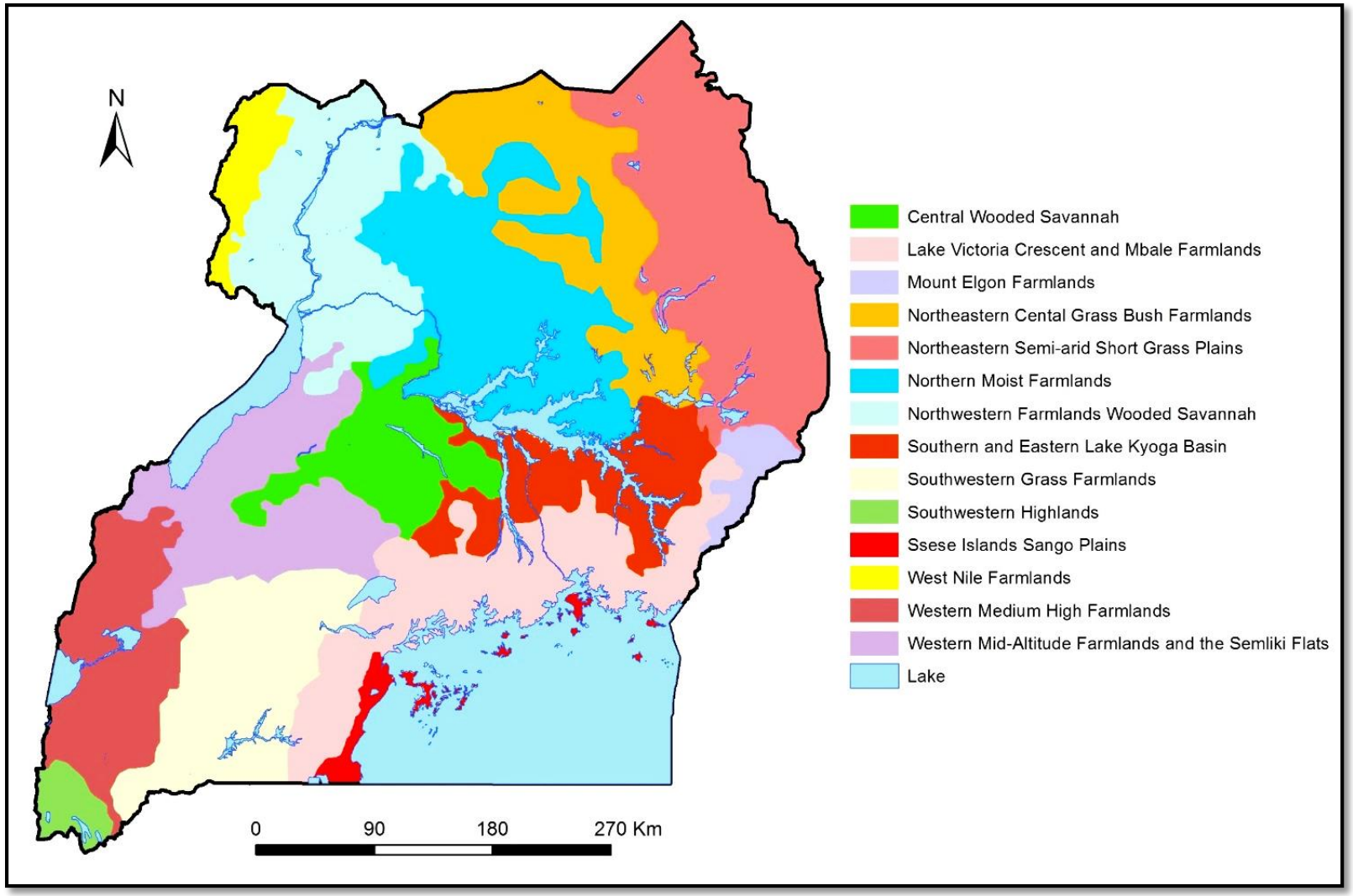

Figure 3.2: Agroecological zones of Uganda (Wortmann and Eledu, 1999).

3.4 Geomorphology of Uganda

Uganda lies within the African plate, which is a portion of continental crust that contains Archaean cratons that date to at least 2,700 million years ago (mya) (Macdonald, 1966). The oldest geological formations consist of rocks that formed between 3,000 and 6,000 mya during the pre-Cambrian era (NEMA, 2010). Younger rocks are either sediments or of volcanic origin, and are no older than about 66 mya (Cretacous Period). The country's geology has a wide variety of rock types grouped into eight geological litho-stratigraphic domains (Fig. 3.3).

Geology is important because it influences both the physical and chemical properties of soils. Acidic parent material like the Karagwe-Ankolean System (Fig. 3.3) (Elliot and Gregory, 1895) will usually weather to an acidic soil. Granitic parent material from the basement complex (Fig. 3.3) will result in soils of relatively high sand contents after weathering. The fairly young geologic material of the Mesozoic to Tertiary volcanics (Fig. 3.3) will often weather to fertile Andisols that are richer in nutrients as compared to soils from old, highly weathered rocks of the basement complex.

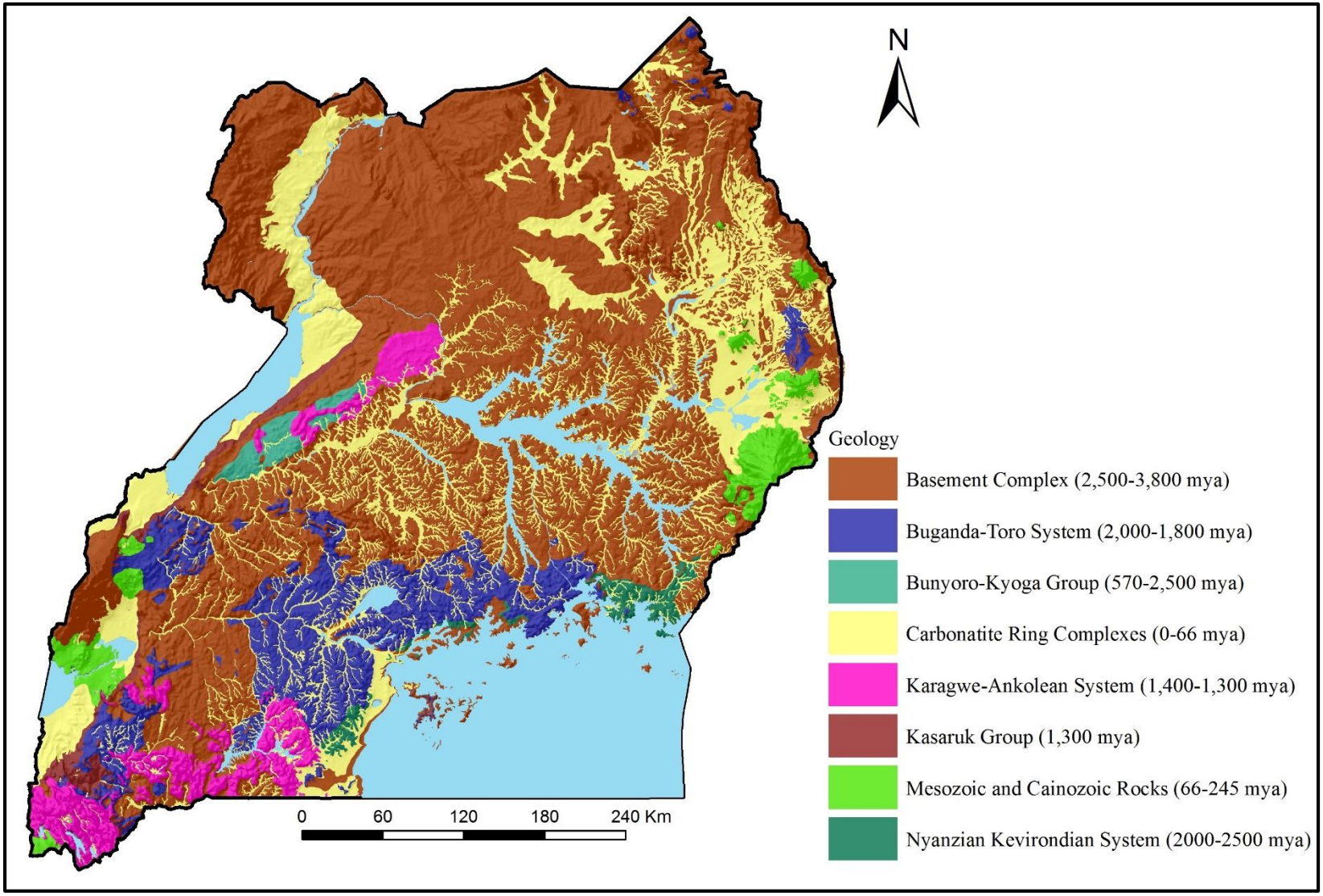

Figure 3.3: Geological overview of Uganda (DGSM, 2008).

3.5 Relief and Physiographic Regions of Uganda

Most of Uganda lies between 900 – 1500 msl (Bamutaze, 2010). The lowest point, Lake Albert drops to about 620 msl while the highest point, Magherita Peak on Mt. Rwenzori, is 5,029 msl (Fig. 3.4). Uganda's physiographic regions are divided into four regions; lowlands, plateaus, highlands, and mountains. Climate in the tropics is highly influenced by elevation. Temperature drops by approximately 6°C for every 1000 meters increase in altitude. Higher altitudes are cooler than low-lying areas. Uganda has steep climatic gradients between the cooler highlands and the warmer lowlands (NEMA, 2010).

Climate influences soil nutrient dynamics. For example, nitrogen in the soil is intricately linked with climate through the nitrogen cycle. Different forms of nitrogen such as nitrates, NO^-_3, are heavily affected by precipitation. The leaching of mineralized nitrates is high in areas that receive high amounts of precipitation (Pleysier and Juo, 1981; Giller et al., 1997). Mineralization and nitrification of nitrogen slows down with increasing altitude due to slower microbial activity at cooler temperatures in high altitude areas (Robinson, 1957). Mountainous regions like Mt. Elgon and the Southwestern Highlands (Fig. 3.4) are expected to have higher amounts soil nitrogen than the lowlands. Relief also influences the probability of erosion with bare soil on steep slopes are more vulnerable to erosion than on gentle slopes. Uganda's elevation was derived from Uganda's 90 m digital elevation model.

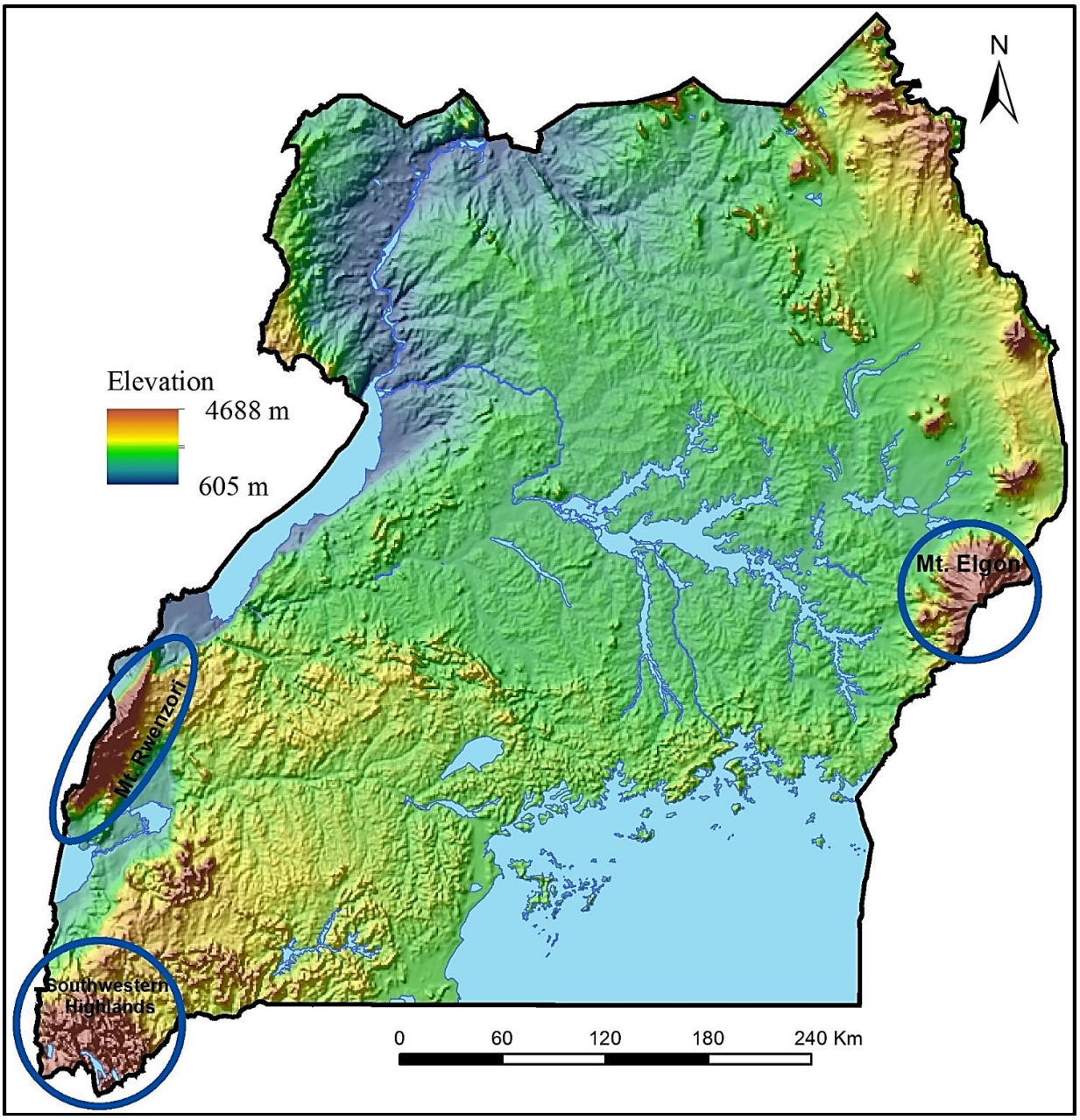

Figure 3.4: Uganda elevation. Uganda's elevation was derived from a 90 m digital elevation model, set to a transparency of 15% and then overlaid on the Uganda hillshade that was derived from the 90 m DEM, to give it a 3 dimensional effect. SRTM downloaded from DIVA-GIS on 6/4/2014.Retrieved from http://www.diva-gis.org/gdata.

3.6 Distribution and Chemical Characteristics of Major Soil Types of Uganda

Most of the agricultural soils in Uganda consist of Oxisols and Ultisols (Fig. 3.5) that are in their final stages of weathering and as a result have very low nutrient reserves (Eswaran et al., 1997; Henao and Banaante, 1999; Stocking, 2003; NEMA, 2009). The predominant minerals in these soils are quartz, which has no cation exchange capacity (CEC), and kaolinite, which has a very low CEC. Oxisols and Ultisols tend to be acidic, with low fertility and CEC. Nutrients such as phosphorus, which occur predominately in inorganic forms, are not readily available to crops because they are tightly bound to the surfaces of iron oxide minerals and gibbsite, and to the edges of aluminosilicates such as kaolinite (Buresh et al., 1997; Smeck, 1985, Palm et al., 2007).

Phosphorus is fixed by iron oxides and aluminum hydroxides and is a key limiting nutrient in Uganda (Mokwunye et al., 1986). Potassium, another major plant-essential element, is also limiting in these soils because there are few primary minerals that can supply it. Due to the low CEC, inorganic nutrient cations are easily leached out of the root-zone of most crops (NEMA, 2009). Nevertheless, there are some Andisols (volcanic soils) in eastern and southwestern Uganda that are young and fertile with considerable amounts of soil nutrients (Ssali, 2003; Palm et al., 2007).

Fig. 3.5 below shows the distributions of the different types of soils in Uganda under the FAO-UNSECO system where Ferrasols correspond to Oxisols, Nitisols correspond to Ultisols while the Andosols correspond to the Andisols (see appendix B).

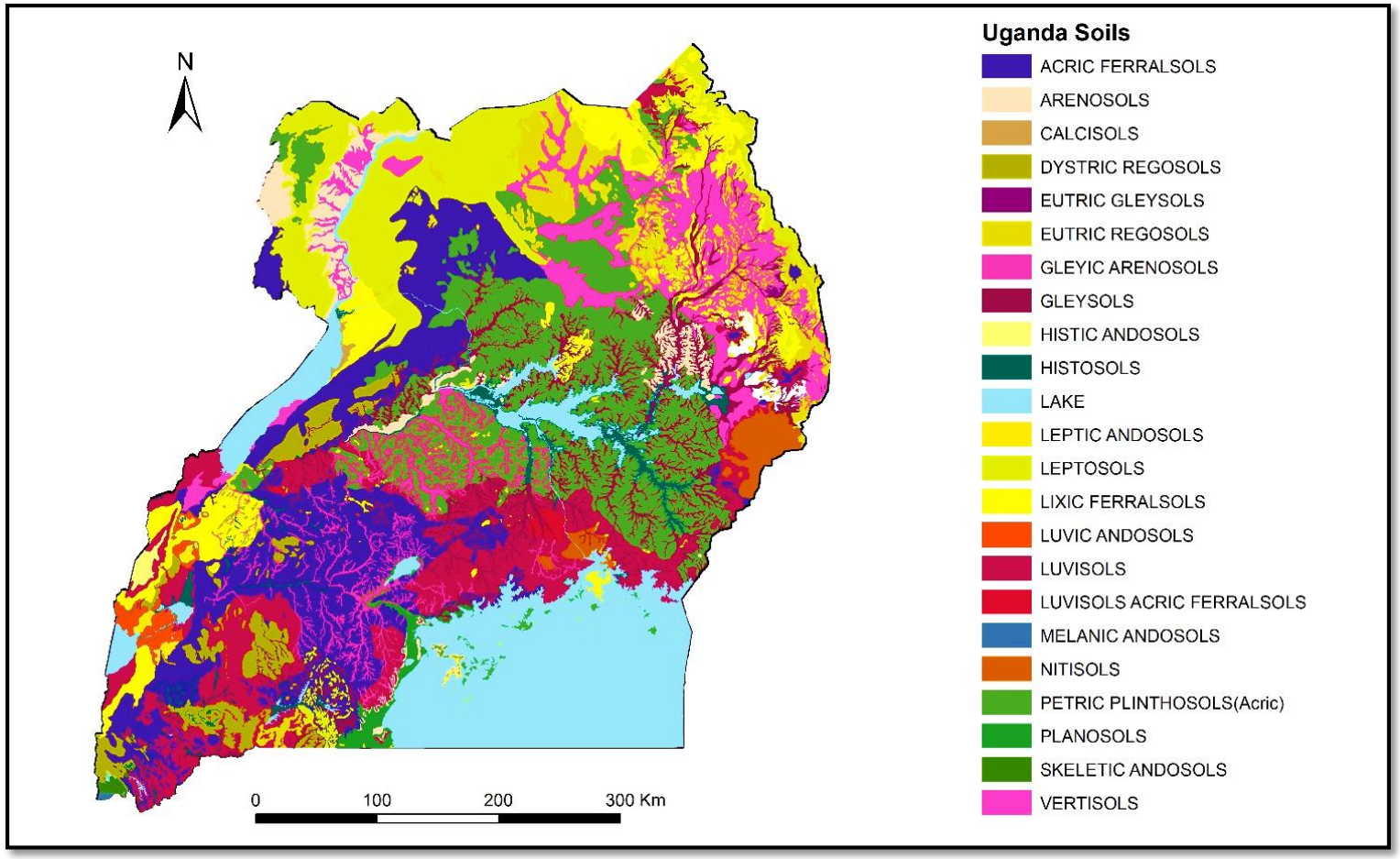

Figure 3.5: Major soil types of Uganda (NEMA, 2010, http://maps.nemaug.org/maps/ downloaded on 5/23/2014). Each soil type has its own chemical properties suitable for different purposes. For instance, Ferrasols are highly weathered soils with low supply of nutrients, characterized by low pH and low available phosphorus. Calcisols on the other hand are soils characterized with high accumulation of $CaCO_3$ and have serious problems with trace elements deficiencies for elements such as Zn, Cu, Fe and Mn (see Appendix B).

4.0 METHOD OF DATA COLLECTION AND ANALYSIS

The data used in this study was from the 2002-2003 International Food Policy Research Institute, Uganda Bureau of Statistics survey (IFPRI-UBoS) described by (Nkonya et al., 2008). The main objective of the IFPRI-UBoS survey was to investigate and understand the linkages between land degradation, land management, and poverty in order to assist in the design of policies that could reduce poverty and enhance the adoption of sustainable land management practices in Uganda. Here, I represent an in-depth overview on the methods of data collection used in the IFPRI-UBoS survey and the procedures used to collect and analyze primary data at the community, household and plot levels as used by Nkonya et al., (2008).

4.1 Data Collection

Data used in this study were collected using four different approaches (Nkonya et al., 2008). First, *community level* data were collected through group interviews conducted at the community level. Secondly, *household level* data were gathered to capture information such as endowments of different forms of capital and other household variables. Thirdly, *plot-level* data were collected from plots cultivated by each of the households sampled. Data collected included soil samples that were analyzed for physical and chemical properties. Fourthly, *information was also derived from the Uganda Bureau of Statistics (UBoS),* which assisted in computing some selected socioeconomic variables at the community level including population density, market access, infrastructure, and poverty.

4.1.1 Household and Plot Level Data Collection

Households surveyed were randomly sampled from communities selected for the IFPRI-UBoS survey (Table 4.1). Household level data were collected through household interviews by the enumerators. Plot-level data were collected only from those plots owned and/or operated by the household heads sampled in the 2002-2003 Uganda National Household Survey (UNHS) (Nkonya et al., 2008). Soil samples were then collected from each agricultural plot managed by the study households either independently by the enumerator if no household head was around or together with the household head. A total of 2,185 agricultural plots were visited. Soil samples were collected from the plow layer, 0-20 cm depth, from multiple sites distributed across each plot with a standard soil sampling tool and combined into a single aggregate sample. Corner locations of each plot and each study household were collected using a global positioning system (GPS) receiver.

4.1.2 Community Level Data Collection

A two stage sampling approach was used to select specific communities from the whole data set used in the Uganda Bureau of Statistics survey (UBoS, 2003a). Using the total number of districts in Uganda as the sampling frame, 972 enumeration areas (565 rural and 407 urban) were selected for first stage sampling, out of which 9,711 households were then randomly selected for second stage sampling. An enumeration area consisted of the smallest unit areas that were used for the census purpose and covered one or more communities (Nkonya et al., 2008). Out of the 9,711 households covered by the UBoS survey (UBoS, 2003a), only 851 households were successfully sampled for this study. The 851 households covered 123 communities which consisted of households that were drawn from the 565 rural enumeration areas covered by the UNHS. Data from only 55 out of 56

districts were used because insecurity in the Pader district during the time of the study prevented data from being collected (Nkonya et al., 2008; Rücker, 2005). Some areas in Gulu and Kitgum districts were not collected for similar reasons. Thus, northeastern Uganda was not covered by the study.

This resulted in a sample set that included eight (8) districts as the sampling frame including Arua, Inganga, Kabale, Kapchorwa, Lira, Masaka, Mbarara and Soroti (Table 4.1). The poverty status of selected districts were determined by their respective poverty indices, which measures the share of people living in households with real consumption per adult equivalent that falls below the poverty line for the region in which they live (Nkonya et al., 2008).

Handheld global position systems (GPS) receivers were used to obtain the latitude and longitude of the community center point and/or points of important infrastructure within the community, household, and point locations. The GPS locations were used to extract additional measures including: (1) elevation, slope and aspect from a digital elevation model (DEM), (2) geological parent material from an existing map (DGSM, 2008), (3) historical climate from WorldClim (Hijmans et al., 2005 and (4) socioeconomic factors including population density, poverty density, market access and infrastructure (Harvest Choice, 2014 a, b, c, d) as explained in section 4.2.

Table 4.1: Districts selected for the IFPRI-UBoS study along with selected data for each district.

District	Number of Communities Selected	Number of households selected	Poverty Incidence[a] (%)	Poverty Status[b]	Natural resource endowment (agricultural potential)[c]	Mean altitude (masl)	Mean annual rainfall (mm)
Arua	16	112	65	High	Low potential (WNW farmlands)	891	>1,200
Iganga	16	112	43	Medium	High potential (LVCM farmlands)	1103	>1,200
Kabale	16	112	34	Low	High potential (SWH)	1990	>1,200
Kapchorwa	8	55	48	Medium	High potential (Mt. Elgon farmlands)	1,200-1,466	>1,200
Lira	17	112	65	High	Low potential (NM farmlands)	1074	>1,200
Masaka	20	139	28	Low	High potential (LVCM farmlands)	1202	>1,200
Mbarara	20	139	34	Low	Medium potential (SW grass-farmlands)	1483	<1,000
Soroti	10	70	65	High	Low potential (NM farmlands)	1061	1,000-1,200

Source: Data from UBoS (2003a, b; Nkonya et al., (2008).

[a]Poverty incidence measures the percentage of people living in households with real consumption per adult equivalent below the poverty line of the region. It however does not measure how far below the poverty line the poor are, the depth of poverty (UBOS 2003a, b).

[b]Based on the 2002/03 Uganda National Household Survey (UNHS) data, the rural poverty status of a district was ranked as follows: <40=low; 40-50=medium; <50=high.

[c]Agricultural potential is an abstract compilation of many factors including rainfall level and distribution, altitude, soil type and depth, topography, presence of pest and diseases, and presence of irrigation that influence the absolute (as opposed to comparative) advantage of producing agricultural commodities in a particular place (Wortmann and Eledu, 1999; Nkonya et al. 2008).

LVCM-Lake Victoria crescent and Mbale; masl-meters above sea level; NM-northern moist; SW-southwestern. SWH-southwestern highlands; WNW- west Nile and northwestern.

Out of the 2,185 soil samples, only 80% had reliable GPS points. This was because in some cases, up to two or three soil samples from the same household shared the same GPS point. Therefore, in order to capture 100 % of the dataset, the total sample population was averaged by communities. In this way, all the soils sampled, including those that had no GPS point, could effectively be grouped into their respective communities. This resulted in data for a total of 122 rural communities (Fig. 4.1). The logic behind averaging the soil samples by community was also supported by the fact that households sampled were clustered around a community. This is a major challenge for effective spatial analysis since spatial statistics requires a high sampling density that is evenly distributed throughout the sampled area, in this case the entire country of Uganda.

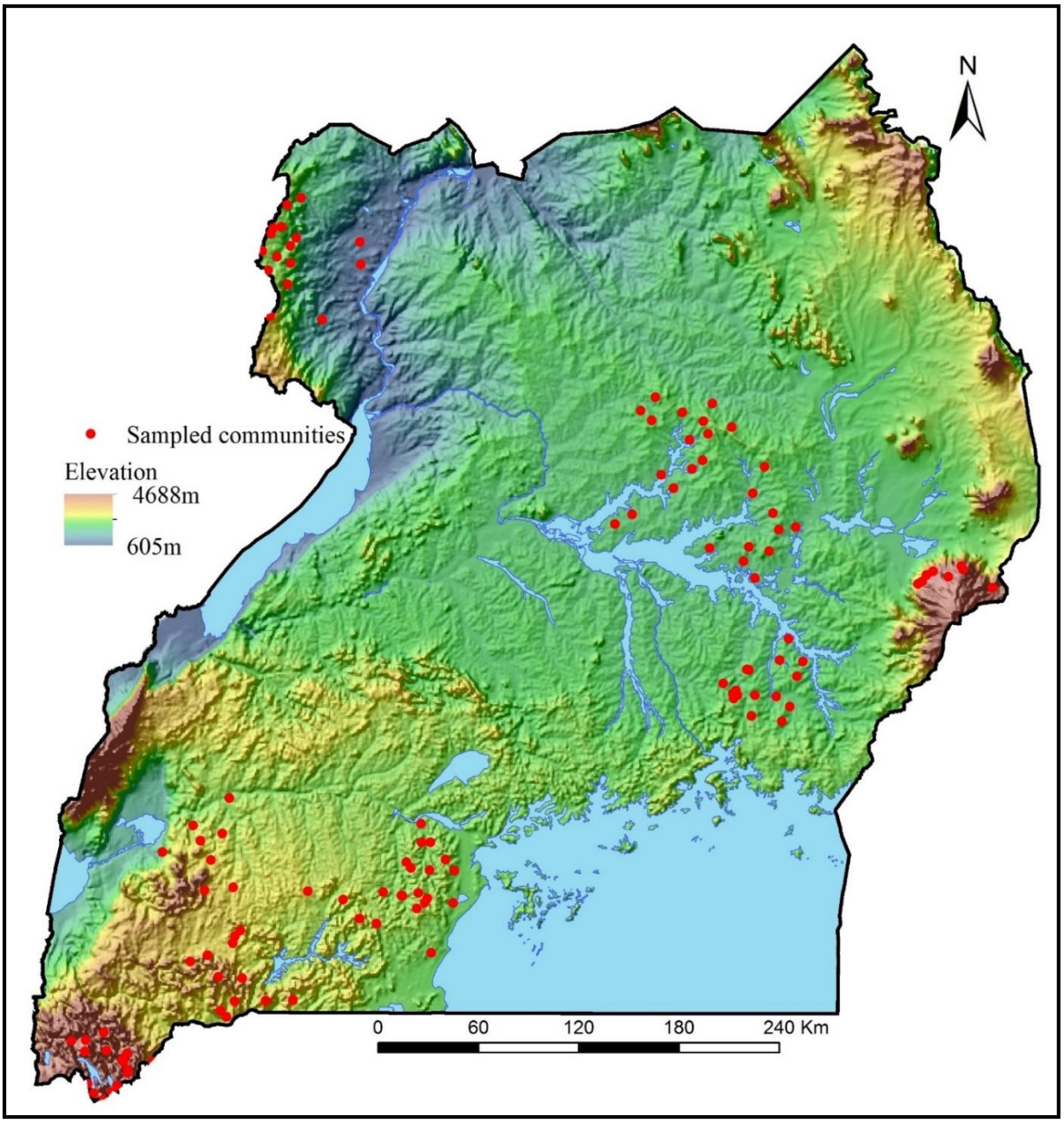

Figure 4.1: Spatial distribution of the sampled communities within Uganda. Sampled communities were not evenly distributed throughout the country. The lack of sampled communities in the Western and Northeastern Uganda was due to financial constraints and insecurity at the time of sampling (Nkonya et al., 2008).

4.2 Choice and Correlation of Environmental and Socioeconomic Data

Factors that may influence the spatial variability of soils were identified as discussed in section 2.4. These factors were identified based on their probability of influencing soil heterogeneity on a national scale. A review of the literature was used to identify the major environmental and socioeconomic factors and their respective variables determining national-scale spatial soil heterogeneity. These environmental variables (see Appendix C) and socioeconomic variables (see Appendix D) were then regressed with various soil properties using the General Linear Model (GLM) to identify the most dominant factor contributing to soil variability on a national scale. Table 4.2 provides a summary of the variables. The environmental and socioeconomic variables for each community were extracted by overlying the selected 122 rural communities on the large-scale environmental and socioeconomic maps. Thereafter, the 'Extract Multi Values to Points' tool in ArcGIS 10.2 toolbox was used to extract the variables for each community.

Table 4.2: Selected environmental and socioeconomic categories and variables determining spatial soil variability on a national scale in Uganda

Environmental/ Socio-economic Category	Variable	Spatial scale	Type	Definition of measurement	Influence on soil variability	Source
Geology/ Geomorphology* (GEGE)	Geologic age	National scale	Nominal	Geological era: Precambrian, Tertiary, Cenozoic, Mesozoic, Quaternary [0,1]	Parent material weathering	GoU (1962): Geology of Uganda, simplified by Harrop (1970).
	Geotectonic land surface type		Nominal	Erosion surfaces: Buganda, Tanganyika, Ankole, Volcanics [0,1]	Soil erosion	GoU (1962): Geomorphology of Uganda
	Parent material		Nominal	Parent rock types [0,1]	Soil nutrients and texture composition	Chenery (1960): Soil map of Uganda
	Elevation	90m raster	Interval	Elevation above sea level [m]	Parent material weathering	Hutchinson et al. (1995)
	Slope		Interval	Slope [%]	Water and soil redistribution	
Climate/ Drought proneness* (CL)	Annual precipitation	5 x 5 km raster 1: 50,000	Interval	Mean annual precipitation [mm/year]	Soil weathering and acidity	Corbett and O'Brien (1997); Corbett and Kruska (1994); Hijmans et al., (2005) Average data from long term monthly mean climatic records; algorithms for variables as cited in Ruecker et al., (2003)

	Length of growing period		Interval	Period with mean monthly rainfall exceeding half mean potential ET [month]	Soil weathering, Acidity, Nutrient cycling,	Harvest Choice (2014a)
	Annual temperature		Interval	Mean annual temperature [^{0}C]	Soil organic matter dynamics	Hijmans et al., (2005)
Land use/ Land* management (LULUM)	Farming system	National scale	Nominal	Major farming system [0,1]	Soil organic matter and nutrient dynamics	National Environmental Management Authority (1998): Stratification of Uganda into nine farming systems
Socio-economic Factors (SOECO)**	Population	5 x 5 raster 1: 50,000	Interval	Population densities; persons per square kilometer [km^2]	May either result in the depletion or conservation of natural resources	CIESIN, (2004); Harvest Choice (2014b)
	Market Access		Interval	Travel time (hours) to market centers of populations that were greater than 50,000.	Lack of access of farm inputs and or ability to sell of farm produce	Harvest Choice, (2014c)
	Infrastructure		Interval	Road density; number of roads per 100 km^2.		Ranganathan and Foster 2012; World Bank, 2014)
	Poverty		Interval	Poverty density; the number of people living below $1.25 per day per square kilometer.	May either result to the degradation and or conservation of natural resources	Harvest Choice (2014d)

Note:*= Environmental factors, **= Socioeconomic factors, [0, 1] = numerical values assigned to nominal variables. Modified from Rücker, (2005).

4.3 Sample and Data Processing

4.3.1 Soil Sample Analysis

Soil samples were analyzed at the Uganda National Agricultural Research Laboratories (NARL). Soil samples were first air dried, ground, and then passed through a 2 mm sieve. Soil texture was analyzed using the hydrometer method (Hartge and Horn, 1989). Soil organic matter content was measured by a modified Walkley and Black method (Nelson and Sommers, 1975) and pH was determined in a 1:2.5 H_2O solution using a pH meter (Dewis and Freitas, 1970). Total nitrogen, total phosphorus and total potassium were determined using Kjeldahl digestion with selenium powder and concentrated sulfuric acid, followed by heating on a hot plate at high temperature until the mixture was clear (Anderson and Ingram, 1994). Phosphorus was determined colorimetrically, and potassium was determined by flame photometry. Exchangeable potassium was measured in a single Mehlich-3 extract buffered at pH 2.5 (Mehlich, 1984).

4.3.2 Statistical Analyses

Several statistical and spatial analyses were performed to assess the different criteria that characterize the spatial variability of Ugandan soils on a national scale. The applied analyses included descriptive statistics, correlation analysis, ANOVA, semi-variance analysis, variogram analysis, spatial interpolation, and generalized linear modeling. All statistical analyses were performed in R software version 3.0.2, (R Core Team, 2013). Spatial analyses and visualization were performed using ArcGIS 10.2.

4.3.3 Variable Transformation and Descriptive Statistics

To aid in the analysis of the variations within the total sample population, the descriptive statistics included the mean, minimum, maximum, standard deviation and coefficient of variation (CV) of the whole dataset. The CV was used because it is considered the most discriminating factor used in the description of variability where different parameters are studied (Zhang et al., 2007). Soil properties have been observed to have skewed distributions and thus require transformations to the normal distribution prior to statistical analysis (Cassel and Bauer, 1975; Wagenet and Jurinak, 1978). Skewness and kurtosis were used to check for normality. Soil properties that had a skew > ±0.5 and or kurtosis > ±1 were transformed to a normal distribution. In most studies, nonnormal data distributions are transformed to nearly normal distributions by using either natural logarithm or square root methods (Hamilton, 1990; Cambardella et al., 1994; Iqbal et al., 2005), whereas they are not transformed in others (Özgöz, 2009). Excessive transformation was avoided to reduce interpretation difficulties. The best function to reduce skewness was used once a variable failed to test for normality.

4.3.4 Correlation Analysis

Pearson's product moment correlation coefficient was used to identify spatial correlation among soil samples. In order to determine which of the environmental and socioeconomic factors was most dominant in contributing to the spatial variability of the soils, a generalized linear model (GLM) was used. The GLM is described in detail below. Table 4.3 outlines the rules used for interpreting the correlation coefficient and the coefficient of determination.

Table 4.3: Interpretation of the coefficient of variation and the coefficient of determination (after Hamilton, 1990).

Correlation coefficient (r)	Coefficient of determination (R^2)	Interpretation
1.00 (-1.00)	1.00	Perfect positive (negative) correlation
(-) 1.00 > r > (-) 0.8	$1.00 > R^2 > 0.64$	Strong positive (negative) correlation
(-) 0.8 > r > (-) 0.5	$0.64 > R^2 > 0.25$	Moderate positive (negative) correlation
(-) 0.5 > r (-) 0.2	$0.25 > R^2 > 0.04$	Weak positive (negative) correlation
(-) 0.2 > r > 0	$0.04 > R^2 > 0.00$	No correlation

4.4 Semi-variance Analysis

The spatial dependency of soil properties over the national-scale study sites was modeled by the geostatistical technique of semi-variogram analysis. A semi-variogram is "a graph that shows how semi-variance changes as the distance between observations changes" (Karl and Maurer, 2010). It measures the spatial dependence between two observations as a function of the distance between them (Fig. 4.2). Semi-variograms are characterized by: (1) the *nugge*t which is the "variability at distances smaller than the shortest distance between sampled points, including the measurement error", (2) the *sill*, which is the "total observed variation of the variable" and (3) the *range* parameter, which is "the distance at which two observations could be considered independent" (Karl and Maurer, 2010). Constructed empirical semi-variograms for each soil property were then fitted using different variogram models, such as exponential, Gaussian, spherical, and linear, and the one that gave the least mean square error was used in each case. The semi-variogram is described by the equation:

$$\gamma(h) = \frac{1}{2N\,(h)} + \sum_{n=1}^{N\,(h)} (Z\,(x_i) - Z\,(x_i + h)^2),$$

where γ is the semi-variance for interval class h, N(h) is the number of sample pairs that are located in the sampled area separated by the lag distance h from each other, Z (xi), and Z (xi +h) are the values of the regionalized variable at location xi and xi + h respectively (Karl and Maurer, 2010). A semi-variogram model consists of three basic parameters that describe the spatial structure: C_0 represents the nugget effect, C_s is the structure component, $C_0 + C_s$ is the sill, and the distance at which the sill is reached is the range. The value of the proportion of the spatial structure $C_s/(C_0+C_s)$ is a measure of the proportion of sample variance (C_0+C_s) that is explained by the spatially structured variance (C_s).

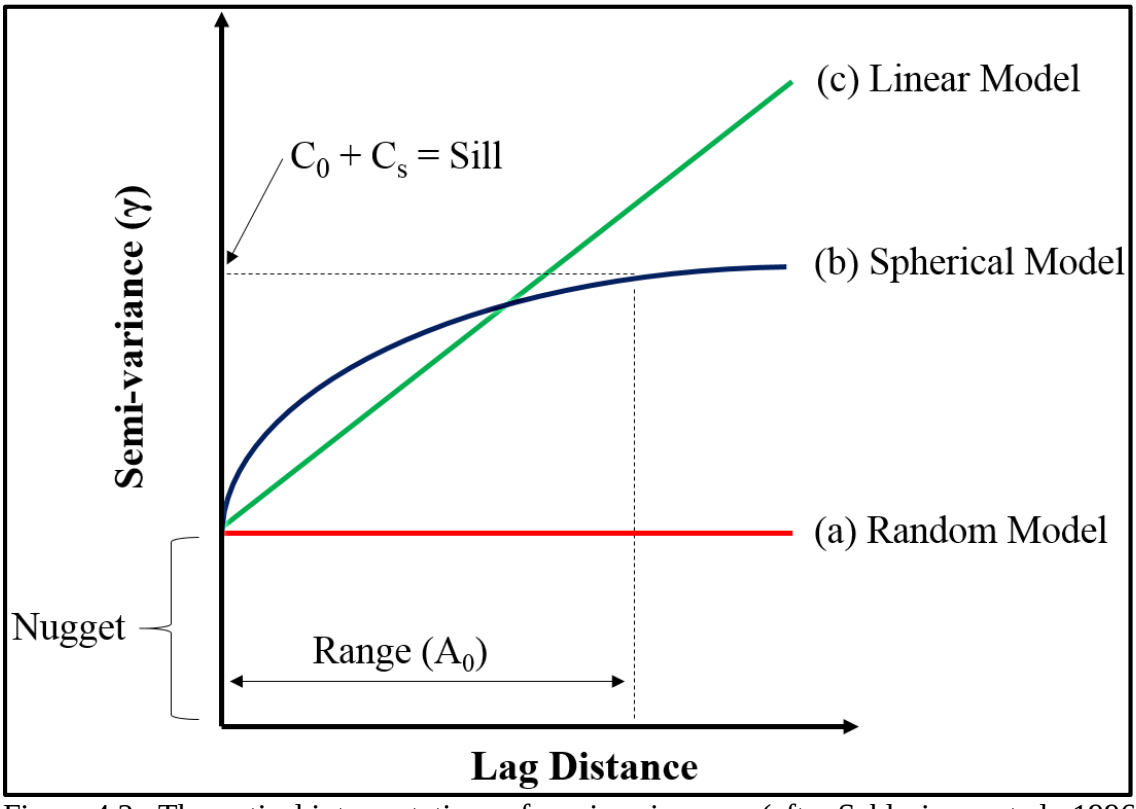

Figure 4.2: Theoretical interpretations of semi-variograms (after Schlesinger et al., 1996).

Fig. 4.2 shows the proportions of variance (semi-variance, γ) found at increasing lag distances of paired soil samples. Curve a (red line) is observed when soil properties are randomly distributed and there is no spatial variability in the soil properties, a pure nugget effect, (Cambardella and Karlen, 1999). Curve b (blue line) is observed when soil properties show spatial autocorrelation over a range (A_0) and independence beyond that distance. The variation that is found at a scale finer than the field sampling is the nugget variance (C_0). Curve c (green line) is observed when there is a largescale trend in the distribution of soil properties, but no local pattern within the scale of sampling (Schlesinger et al., 1996).

4.5 Spatial Interpolation

After each soil property was fitted, as described above, interpolation over the whole national-scale sampling frame was conducted to visualize and identify the spatial extent and spatial patterns of each of the soil properties examined. Fitted semi-variogram models of each soil parameter were used for kriging. For this study, ordinary kriging was used because the mean of the sampled population was unknown. The 122 communities sampled are a better representation of Uganda's national soil spatial pattern relative to the 107 communities as used by Rücker (2005). This is because Rücker's study sampled communities only from the southern half of Uganda. However, the IFPRI-UBoS study not only covered the southern half of Uganda but also included the northeastern Uganda (Fig. 4.1). In addition the data used in this study includes Northwestern Uganda, which was not part of Rücker's (2005) study due to insecurity in the area at the time he conducted his field work.

4.6 Generalized Linear Model (GLM)

The correlation of soil parameters against both environmental and socioeconomic variables was performed using the generalized linear model (GLM) within R software (R Core Team, 2013). The GLM was used for two purposes: 1) to explain the spatial variability of soil parameters and, 2) to identify the most dominant factor(s) that determine the spatial variability of soil parameters.

The GLM was adopted as the correlation technique for explaining the spatial variability of soils because it has a number of advantages compared to multiple regressions (McCullagh and Nelder 1989). The advantages of GLM over multiple regressions are as follows. (1) The dependent and response variable do not have to be continuous, but can be categorical or of nominal scale[2]. This is used in this study since soil data is continuous, while geological age and land use are nominal scale variables (Table 4.2). (2) Linear combinations among dependent variables are allowed in the GLM. These advantages makes it easy to model the interactions of independent variable categories, such as geology/geomorphology and land use/land management in terms of their relationship with the soil parameter predictors (Rücker, 2005).

[2] Nominal data is a situation in which the observations can be assigned a code in the form of a number where the numbers assigned are simply labels. The numbers can only be counted to get their frequency, but not put in a certain order or measured.

The other reason for using the GLM was to identify which of environmental and socioeconomic factors is more dominant in explaining soil spatial variability on a national scale. Variables in each factor were successfully entered into the GLM either individually or in combination with other factors and regressed against each soil parameter. The combination of the four different environmental and socioeconomic factors (GEGE, CL, LULUM, and SOECO) in the GLM (Table 4.2) resulted in thirteen different combinations of regression analyses being performed on each of the nine (9) soil parameters. The comparative assessment of changes in the coefficients of determination (adjusted R^2) revealed the performance of both the environmental and socioeconomic factors that explain the variability of the soil parameter under consideration. This allowed identification of the single most dominant factor and the combination of two or more predictor factors for the estimation of soil spatial parameter variability. The generalized linear model was determined by:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \ldots \beta_p X_{ip} + €_i$$

Where for *n* observations of *p* independent variables, Y_i is the community's i^{th} observation of the response variable (soil property), β_1 is the estimate of the specific variable, and X_{ij} is the community's (i^{th}) observation of the j_{th} independent variable contributing to either the environmental or socioeconomic factor, j = 1, 2, ..., *p* and $€_i$ is the ith independent identically distributed normal error.

5.0 RESULTS AND DISCUSSIONS

5.1 Spatial Distribution of Soils on a National Scale

Soil variability of selected physical and chemical parameters on the national-scale for Uganda was investigated by first assessing the variability of the selected soil properties over the total sample population. The AEZ criteria was then used to assess the variation of soil properties across the whole of Uganda. Thereafter, an analysis of variance (ANOVA) was also used to investigate the significance of the variance of the soil properties across all communities sampled. Lastly, spatial statistics was applied to the spatially characterize and interpolate soil quality maps of selected soil properties.

5.1.1 Total Variability of Soils across the Entire Sample Population

The total variability on the national-scale was analyzed by descriptive statistics based on the entire dataset of 2,185 samples. The results of these statistics were compared with the critical threshold values of Foster (1971) (Table 5.1).

Table 5.1: Descriptive statistics and critical threshold values of top soil samples on the national scale in Uganda (*n = 2,185*).

Soil Parameter	Mean	Minimum	Maximum	Critical Value[1]	STD[2]	CV (%)[3]	Skew	Kurtosis
pH (water 1:2.5)	6.10	4.0	7.8	5.2	0.6	10	-0.9	1.1
SOM (%)	3.48	0.1	33.7	3.0	2.1	60	2.9	23.1
Total N (%)	0.21	0.02	2.7	0.2	0.2	100	3.8	32.3
Available K (mg/kg)	299.2	60.0	2720.0	-	29.6	10	2.8	10.4
Total P (%)	0.10	0.00	1.6	-	0.1	100	7.8	100.9
Total K (%)	0.44	0.00	5.1	-	0.5	113	2.4	7.46
Sand, 0-20 cm (%)	61.9	13.3	93.1	-	14.9	24	-0.5	-0.2
Clay, 0-20 cm (%)	25.1	2.9	60.9	-	10.0	40	0.4	-0.1
Silt, 0-20 cm (%)	13.0	0.6	53.1	-	8.5	65	1.5	2.3

[1] = Below this value, the soil parameter level is deficient (Foster, 1971); [2] = Standard deviation; [3] = Coefficient of variation.

Based on this national scale analysis (Table 5.1), the average soil textural class in Uganda is sandy clay loam, which is consistent with Rücker (2005). Sandy clay loam soil, in general, provides both good water infiltration and water retention, and is suitable for a majority of crops grown in Uganda (Rücker, 2005). The higher mean values for pH (6.10), SOM (3.48 %) and total N (0.21%), relative to the critical thresholds provided by Foster (1971), indicate that in general Uganda's soil is well suited for crop growth. This finding is consistent with the nationwide study conducted by Chenery (1960) where he compared African soils and concluded that "compared to other places in the tropics, the soils of Uganda are, on the whole, very fertile".

However, such general findings mask possible degraded soil conditions in a specific household or relatively higher values in one area versus another (Rücker, 2005). This argument is supported by the fact that minimum values for pH, soil organic matter, and total N, (Table 5.1) are far below their critical thresholds. Suggesting that soils in some

farm plots are decidedly less fertile than the average. The range between the minimum and maximum values varied greatly depending on the soil property (Table 5.1). Small ranges were observed in total P (1.6 %), total N (2.7 %), pH (3.8) and total K (5.1 %). On the other hand, large ranges were observed in soil organic matter (33.6 %), silt (53 %), clay (58 %), sand (80 %) and available K (2660 mg/kg). Similarly, wide ranges were observed by Kaizzi (2002) and Rücker (2005). These wide ranges in soil properties is what is expected in any population of soils over a relatively large sampled area

5.1.2 Variability of Selected Physical and Chemical Properties by AEZs

To obtain a better understanding of the spatial variability of Uganda soils, the total sample population was assessed using the AEZs of Uganda as defined by Wortmann and Eledu (1999) (Fig. 3.2, Fig. 5.1). AEZs are considered as homogenous spatial domains where the 'spatial distribution of natural resources are relatively similar within but different between each spatial domain' (Ruecker et al., 2003). Nkonya et al. (2008) used a similar approach to identify the variation of soil nutrient balances in Uganda. Earlier, Wortmann and Eledu (1999) devised these broader categories to enhance the management of natural resources in Uganda due to the similar agricultural potential portrayed within each zone.

Table 5.2: Mean of selected physical and chemical soil characteristics by AEZs *(n = 2,185)*.

	pH	OM (%)	Tot. N (%)	Avai. K (mg/kg)	Tot. P (%)	Tot. K (%)	Sand (%)	Silt (%)	Clay (%)
West Nile & Northwestern	6.1	2.3	0.10	189.0	0.06	0.21	76	16	8
Northern Moist	6.3	2.3	0.14	214.9	0.07	0.16	70	20	10
Mt. Elgon farmlands	6.3	4.6	0.30	830.0	0.15	0.63	43	40	17
Southwest grass-farmlands	6.3	3.8	0.19	452.1	0.08	0.54	59	26	15
Lake Victoria Crescent & Mbale	6.4	3.2	0.20	253.7	0.90	0.33	62	29	10
Southwestern highlands	5.3	5.5	0.37	315.2	0.18	0.95	49	30	21

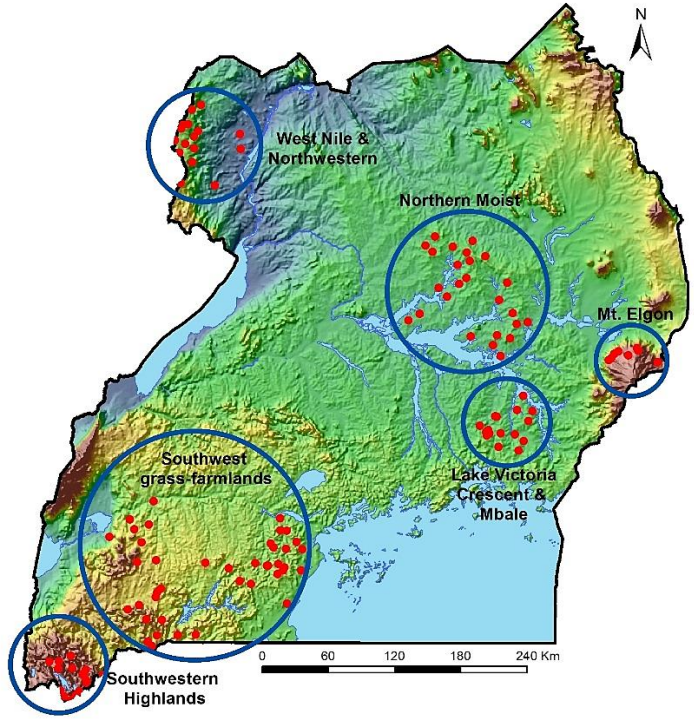

Figure 5.1: Distribution of the sampled communities by AEZs.

The means of the soil properties vary between the different AEZs (Table 5.2). The Southwestern Highlands have a much lower average soil pH (5.3) than the other AEZs. This may be due to the acidic parent rocks found in this region, the Karagwe-Ankelean System (Fig.3.3) (Elliot and Gregory, 1895), which weather to acid soils.

High levels of organic matter were observed in the Southwestern highlands (5.5 %), Mt. Elgon farmlands (4.6%) and the Southwest grass-farmlands (3.8%). The soils in these AEZs are mainly Andisols (Fig. 3.5) formed from volcanic materials that are pedologically young (NEMA, 2010) and rich in soil nutrients (Nkonya et al., 2008). Soils found in the Northern Moist and West Nile and Northwestern AEZs are Ferrasols (Fig. 3.5). Ferrasols are highly weathered soils with low nutrient capacities (NEMA, 2001) and this explains the low levels of organic matter in these zones. Foster, (1978; 1980 a, b) found that pH and organic matter are important soil properties that determine inherent soil quality of Uganda soils and influence crop yields. The low pH (5.3) of the soils in the Southwestern Highlands affects root growth and the availability of plant nutrients and, if severe, may also lead to problems of aluminum toxicity (Kochian et al., 2004).

High total N, 0.37% was observed in the Southwestern Highlands, followed by the Mt. Elgon farmlands, 0.3 %. The high levels of total N observed in these zones are due to the fact that soils in these regions are young and relatively fertile Andisols (Bagoora, 1988) and have high stock of soil nutrients (Appendix B). Given that the soils in these regions have high organic matter contents, soil nitrogen would be expected to be high.

High levels of available K were observed around Mt. Elgon, 830 mg/kg, followed by Southwest grass-farmlands with 452 mg/kg. Although soils found in both the Mt. Elgon and the Southwestern Highlands AEZs are young and fairly fertile Andisols (Fig. 3.5), the high levels of available K in the Mt. Elgon AEZ might have been contributed by tephras that are higher in potassium than those from the Muhavura volcanoes found in the Southwestern Highlands AEZ. K mobility is often related to soil texture, with K leaching being greatest in soils with higher sand content (Werle et al., 2008; Rosolem et al., 2010). All the AEZs with low levels of exchangeable K have soils with high sand contents. These AEZs include the West Nile and Northwestern (76 % sand), Northern Moist (70 % sand) and Lake Victoria Crescent and Mbale (62 % sand).

High phosphorus levels of up to 0.9 % were observed in the Lake Victoria Crescent and Mbale which is much higher in than the other AEZs. The high total phosphorus in the soils of this zone is probably related to the Busumbu and Sukulu phosphate deposits in this area (McClellan and Notholt, 1986; Van Kauwenbergh, 1991; Jackson et al., 2005).

Total potassium levels were high in the Southwestern Highlands (0.95 %), followed by the Mt. Elgon (0.63 %) farmlands, and then by the Southwest grass-farmlands (0.54 %). Soils in these regions are young and fertile Andisols rich in soil nutrients (Bagoora, 1988), in contrast to the highly weathered Ferrasols found in the Northern Moist and the West Nile and Northwestern farmlands AEZs (Appendix B).

Soil texture varied across the AEZs, with sandier soils observed in the West Nile and Northwestern farmlands (76% sand) and the Northern Moist farmlands (70% sand) AEZs. The high sand contents in these two AEZs is inherited from the highly weathered granitic rocks of the basement complex (Fig. 3.3). Assessing Uganda soil properties by AEZs clearly shows the importance of geology in explaining the spatial variability of soil properties at the country scale. Young fertile Andisols (Fig. 3.5) found in the Mt. Elgon farmlands and Southwestern highlands AEZs have high levels of soil nutrients while the highly weathered Ferrasols (Fig. 3.5) found in the Northern Moist and West Nile and Northwestern AEZs have low soil nutrients. In order to determine, statistically, the strength of variability of soil each property from the whole sample population, the coefficient of variation was used as described in section 5.2.

5.2 Soil Variability

All the soil properties were subjected to a natural log transformation to reduce the skewness except for sand, pH and clay, which showed a normal distribution without transformation. Standardized variability was compared using the variation coefficients (CV) of soil parameter values (Table 5.3).

Table 5.3: Ranked variations of the transformed coefficients.

Total variability	**Soil Parameter**	**CV (%)**	**Transformation**
Least (CV <15%)	pH	10	None
	Available K (mg/kg)	10	Logarithmic
Moderate (15% ≥ CV<35%)	Sand (%)	24	None
High (CV≥35%)	Clay (%)	40	None
	SOM (%)	60	Logarithmic
	Silt (%)	65	Logarithmic
	Total N (%)	100	Logarithmic
	Total P (%)	100	Logarithmic
	Total K (%)	113	Logarithmic

CV (%) = Coefficient of variation ((standard deviation/mean)*100).

The different CV ranks indicate that pH and available K had the least variability. Moderate variability was observed in sand content whereas high variability was observed in clay, SOM, silt, total N, total P, and total K. Such variability in soil properties may be due to the heterogeneity in the distribution of the factors that contribute to soil development at a larger scale (Rücker, 2005). Soil parameters are known to have different relationships. Correlation analysis was therefore conducted among the soil parameters and the results are shown in the following section.

5.2.1 Correlation Analysis Among Soil Parameters

Pearson's product moment correlation coefficient was used to analyze the relationships among the soil parameters of the total sample population to reveal any possible dependency on soil forming factors and or corresponding pedological processes (Table 5.4).

Table 5.4: Correlation matrix of selected soil parameters (*n =2,185*).

Soil Parameter	SOM (%)	pH	Tot. N (%)	Avail. K (mg/kg)	Tot. P (%)	Tot. K (%)	Sand (%)	Clay (%)	Silt (%)
SOM (%)	1.00								
pH	-0.24**	1.00							
Tot. N (%)	0.61**	-0.30**	1.00						
Avail. K mg/kg)	0.40**	0.26**	0.25**	1.00					
Tot. P	0.42**	-0.16**	0.34**	0.21**	1.00				
Tot. K	0.54**	-0.27**	0.47**	0.33**	0.26**	1.00			
Sand (%)	-0.57**	0.29 **	-0.44**	-0.26**	-0.32**	-0.51**	1.00		
Clay (%)	0.45**	-0.19**	0.32**	0.22**	0.24**	0.37**	-0.84**	1.00	
Silt (%)	0.49**	-0.24**	0.37**	0.22**	0.28**	0.45**	-0.75**	0.33**	1.00

** Significant at $P \leq 0.01$.

This matrix shows that the majority of the soil parameters are correlated. There is a positive correlation between soil organic matter and soil nutrients, clay, and silt. This relationship may be due to: (1) the general soil chemical properties like OM is negatively charged and therefore attracts positively charged soil nutrients such as K^+; and (2) environmental

processes such as soil erosion, fine earth material and OM from the topsoil is lost from intensively cultivated land that is often not covered by vegetation (Bamutaze, 2005; Mugabe, 2006; Majaliwa et al., 2012). Similar studies have observed the depletion of soil organic matter and other essential soil nutrients due to unsustainable agricultural land use systems being practiced around L. Victoria region (Tenywa and Majaliwa, 1998; Magunda et al., 1999).

pH had a either a weak positive correlation or a weak negative correlation with soil nutrients. Areas with higher acidity are often found on geologically old eroded surfaces of mainly granite, gneiss, amphibolites and quartzite rock types that have low amounts of soil nutrients (Rücker, 2005; NEMA, 2009). Due to the generally sandy clay loam texture of Uganda soils (Table 5.1), compounded by the high tropical rainfall (Rücker, 2005), most of soil nutrients are leached from the soil (Rosolem et al., 2010). The basement complex parent material (Figure 3.3), is highly weathered, and thus has few remaining weatherable materials and consequently pH is relatively low (Ssali, 2003). Sandy soils generally have low cation exchange capacity (CEC) because they are low in both clay minerals and organic matter Brady and Weil (2002). The negative correlation between sand content and soil nutrients is attributed to the low surface area of sand particles in comparison with organic matter and clay minerals (Brady and Weil, 2002).

5.3 Analysis of Variance (ANOVA)

Correlations and descriptive statistics of the total sample population cannot reveal the effect of soil processes causing soil variations on a larger scale. Therefore, to test whether there were significant differences between the soil property means, a one-way analysis of variance (ANOVA) was conducted. The p-value and the F value resulted from the ANOVA analysis was used to test whether soil properties in Uganda are homogenous. Since the aim of the ANOVA was only to determine if there were significant differences between the soil property means, a post hoc analysis was not conducted to identify which communities had significant differences (Table 5.5). In order to conduct a one-way ANOVA, the total sample population was further grouped into communities, which acted as groups. This resulted to 122 different rural communities.

Table 5.5: Variance of communities' soil parameters in Uganda (*n = 122*).

Soil parameter	**Descriptive statistics**		**F value**	**Pr(>F)**
	Mean	**Std.**		
Tot. N (%)	0.21	0.17	16.70	<2e-16 ***
Tot. K	0.45	0.49	22.63	<2e-16 ***
pH	6.09	0.60	12.84	<2e-16 ***
Tot. P (%)	0.13	1.43	7.75	<2e-16 ***
SOM (%)	3.50	2.14	19.70	<2e-16 ***
Avai. K (mg/kg)	300	29.4	10.67	<2e-16 ***
Silt (%)	13.05	8.52	13.81	<2e-16 ***
Clay (%)	25.17	10.07	15.03	<2e-16 ***
Sand (%)	61.80	14.96	20.44	<2e-16 ***

Significance level = *** less than 0.00; Degrees of freedom = 119;
Std = Standard deviation.

The high F-ratios for all the soil parameters indicate that there was significant variation of soil properties among the communities that geographically lie within and between selected AEZs (p-value < 2e-16).

5.4 Spatial Structure and Patterns of Soils on the National Scale

5.4.1 Spatial Structure of Soils

Semi-variogram analysis was used to analyze individual soil properties on a national scale. Each empirical semi-variogram was fitted and the nugget, sill, and range parameters were extracted for spatial structure analysis (Table 5.6). Graphs of fitted semi-variograms of each soil property are shown in Appendix E.

Table 5.6: Variogram model parameters of transformed soil parameters on the national scale in Uganda (*n = 122*).

Soil parameter	Model	Nugget	Sill	Nugget / Sill (%)	Range (Km)	Strength of spatial dependence
Avail. K (mg/kg)	Gaussian	0.07	1.00	7.00	70	Strong
pH	Gaussian	0.14	1.24	11.3	111	Strong
Sand (%)	Spherical	0.09	0.73	12.3	137	Strong
Tot. N (%)	Exponential	0.08	0.62	12.9	69	Strong
Silt (%)	Spherical	0.19	0.93	20.4	227	Strong
Tot. K (%)	Spherical	0.22	0.78	28.3	230	Moderate
Clay (%)	Spherical	0.18	0.62	29.3	144	Moderate
Tot. P	Gaussian	0.31	1.04	29.8	124	Moderate
SOM (%)	Spherical	0.20	0.49	40.8	116	Moderate

Note that the model, spherical, Gaussian, or exponential, that provided the best fit varied depending on the soil parameter (Table 5.6). Fitted variograms showed very low nugget effect ranging between 0.07 and 0.31, indicating that soil properties had spatial variability over small distances (Some'e et al., 2011).

The nugget effect is always expected to be zero (Tobler, 1970). However, silt, total K, clay, total P and SOM had large nugget effects. This is due to: (1) measurement error during soil analysis (Baalousha, 2010) or, (2) variability of the soil property at shorter distances than could be captured during sampling (Webster, 1985). Ranges greater than 100 km were observed in all the soil properties except for total N and available K, indicating that all the

soil parameters showed spatial dependence. Trangmar et al. (1987) found that soil properties that are sensitive to management practices, for instance nitrogen and potassium, usually have shorter geostatistical ranges. Isaaks and Srivastava (1989) and Goovaerts, (1997) found that large geostatistical ranges observed in soil properties can be attributed to other factors such as parent material and terrain, as well as random factors such as land use (application of fertilizers) and soil management practices.

The nugget to sill ratio is used to determine the strength of spatial dependence (Li and Reynolds, 1995). Cambardella et al. (1994) concluded that a variable has either a strong or moderate spatial dependence if its nugget variance is less than 25%, moderate spatial dependence if the nugget to sill ratio ranges between 25% and 75%, and weak if it is greater than 75%. Using a similar approach, strong spatial dependence was observed in available K, pH, sand, total N and silt content, while moderate spatial dependence was observed in total K, clay, total P and soil organic matter. These fitted variograms provide the nationwide spatial structure for each soil property. The nugget, sill, and range from the fitted semi variograms for each soil property can be used to create interpolated soil quality maps.

5.4.2 Spatial Interpolation and Analysis of Selected Soil Properties

5.4.2.1 pH

The kriging results indicate Ugandan soils are mildly acidic with pH ranging between 5.1 and 6.7 (Fig. 5.4). Aluminum toxicity is often a problem when soil pHs are <5.2. Aluminum toxicity is likely to be limiting for crop growth in parts of the southwestern highlands where soil pHs are <5.2 as indicated by the reddest colors in Fig. 5.4. Most plant nutrients are optimally available between pH 6.0 to 7.5 (Doran and Jones, 1996).

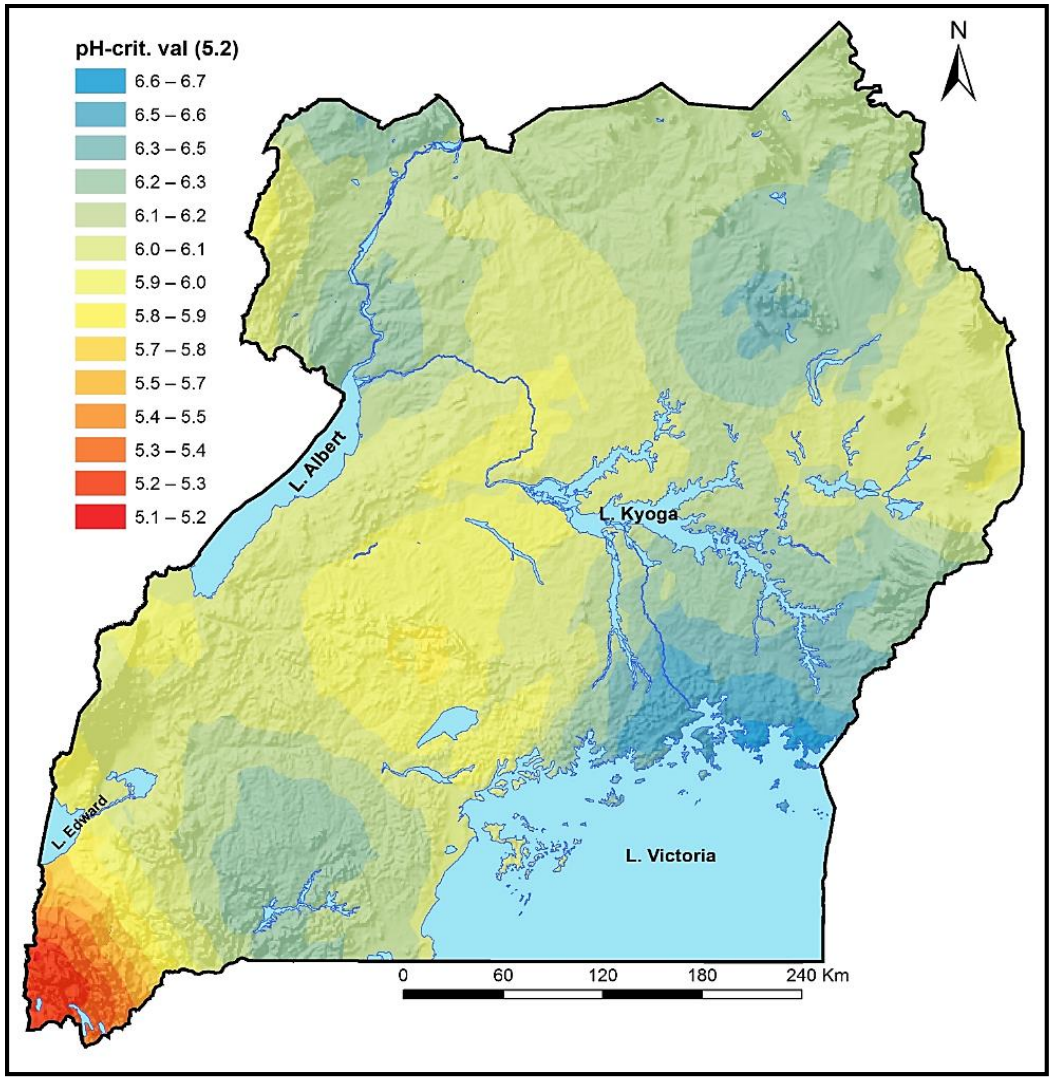

Figure 5.2: Interpolated pH map for Uganda.

The soils in the southwestern highland region have a lower pH than other soils in Uganda for the following possible reasons. (1) This region has an acidic parent material, the Karagwe-Ankolean system (Fig. 3.3) that resulted in the acidic nature of the soils after subsequent parent material weathering (Elliot and Gregory, 1895), and (2) the common farming practiced in this region, subsistence farming (Bekunda and Lorup, 1994; Miracle, 1966), must have further lowered the pH of the soils since farmers in this region do not add any agricultural inputs into the soils such as lime (Raussen et al., 2002; Okalebo et al., 2010). Therefore during growth, these crops absorb basic soil elements including calcium, magnesium, and potassium to satisfy their nutritional requirements. Unlike the southwestern highland region where the volcanic soils overlay an acidic parent material, soils in the Mt. Elgon region are formed entirely in young volcanic materials still rich in nutrients and highly basic (Bagoora, 1988). Most studies have also found that farmers in the Mt. Elgon region practice SWC approaches to prevent the loss of nutrients from the soil (Bekunda and Lorup, 1994; Sserunkuuma, 2001; Nkonya et al., 2008).

Soil pH is important in determining the microbial activity in soils. The process of microbial nitrification in soils is largely the result of aerobic bacteria that obtain energy from the oxidation of NH^{+}_{4} and NO^{-}_{2} to NO^{-}_{3} (Doran and Jones, 1996). The optimum pH for nitrification is between 6 and 8, above which NH^{+}_{4} is present in the soil and NH_3 gas can easily be lost. Below pH of 5.5 to 6, bacterial nitrification is greatly reduced. These pH levels (6.4 - 6.7), which are more favorable for crop cultivation, are found to be along the shores of L. Victoria, the northeastern parts of Uganda, some selected parts of northwestern parts of Uganda and also the southern parts of Uganda.

5.4.2.2 Soil Organic Matter

Soil organic matter is a key indicator of soil quality, with areas having high SOM considered areas with good soil quality (Ngugi et al., 1990; Palm et al., 2007; Bastida et al., 2008). The interpolated soil organic matter map shows that only two regions in Uganda have soil organic matter levels above the 3.0% organic matter critical threshold given by Foster (1971). These two regions are: (1) the Mt. Elgon area, and (2) the southwestern highlands region (Fig. 5.5).

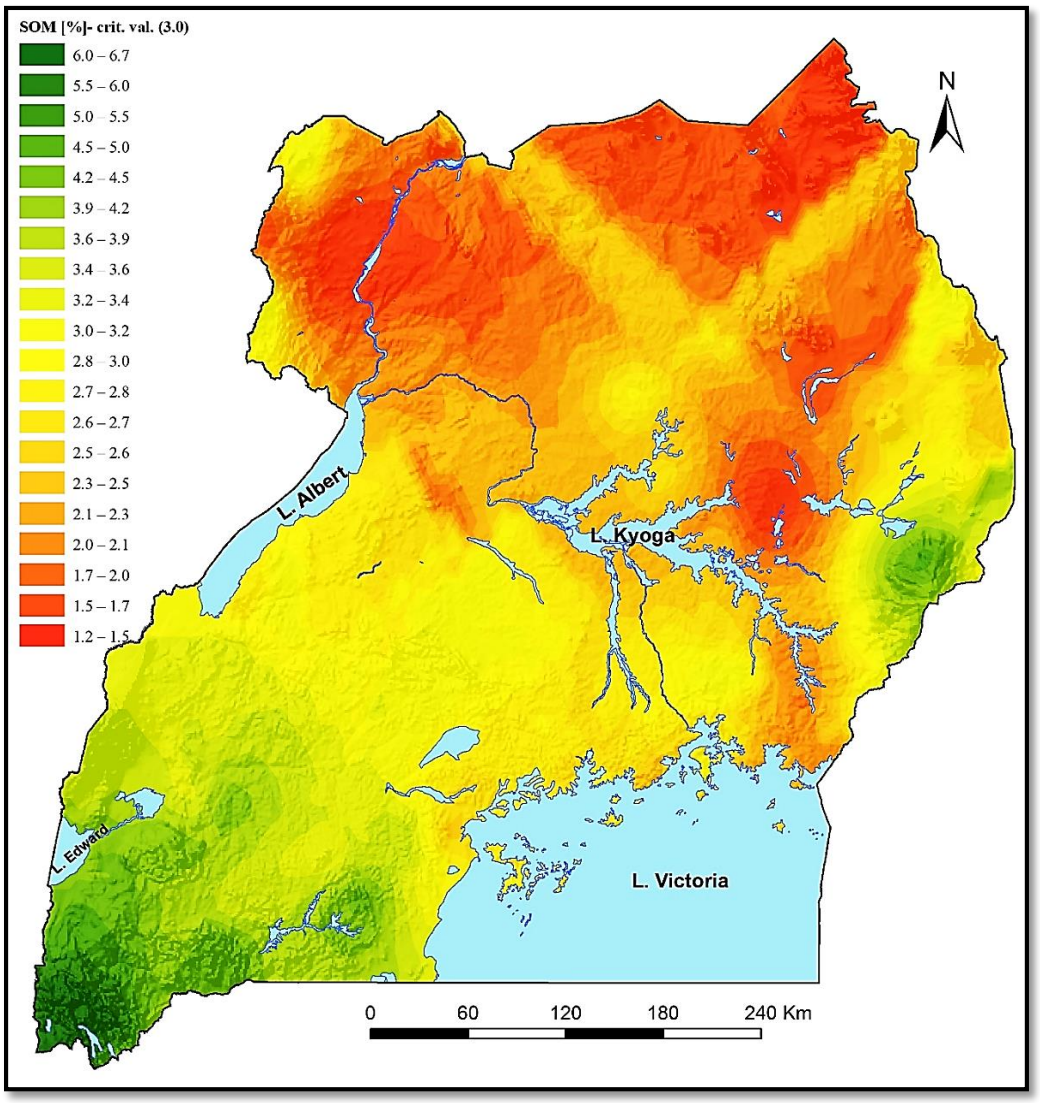

Figure 5.3: Interpolated soil organic matter map for Uganda.

The higher soil organic matter contents in the southwestern highlands of Uganda are likely due to the young volcanic soils formed in volcanic ash blown in from the Muhavura volcano, which lies on the border between Uganda and Rwanda (Bagoora, 1988). This thick layer of volcanic ash was blown over the southwestern region and explains the high organic matter in this region (Bagoora, 1988). Similarly, the soils in the Mt. Elgon region are Andisols that formed from the weathering of the volcanic material deposited by the volcanic eruption of Mt. Elgon during the Pleistocene epoch. These two regions have high SOM content because they have young and relatively fertile volcanic soils (Nkonya et al., 2008). On the other hand, the rest of the country has soils with SOM as low as 1.2 % (Fig. 5.3). These areas have very highly weathered Ferrasols and Nitisols (Oxisols and Ultisols in the USDA soil classification system) that are in their final stages of weathering and as a consequence have very low nutrient reserves (Eswaran et al., 1997; Ssali, 2003; Palm et al., 2007; NEMA, 2009).

5.4.2.3 Total Nitrogen

Nitrogen is an essential plant nutrient and is needed for crop growth in larger quantities than any other soil nutrient (Giller et al., 1997). The capacity of soils to supply N to plants in unfertilized agricultural systems is heavily linked to the amount and nature of soil organic matter. Ordinary kriging results showed high soil N levels in the Mt. Elgon and the southwestern highland regions. The rest of Uganda has soil N levels below the critical thresholds given by Foster (1971). The Mt. Elgon region and the southwestern highlands of Uganda have relatively young Andisols that are rich in soil organic matter compared to the rest of Uganda (Fig. 5.6).

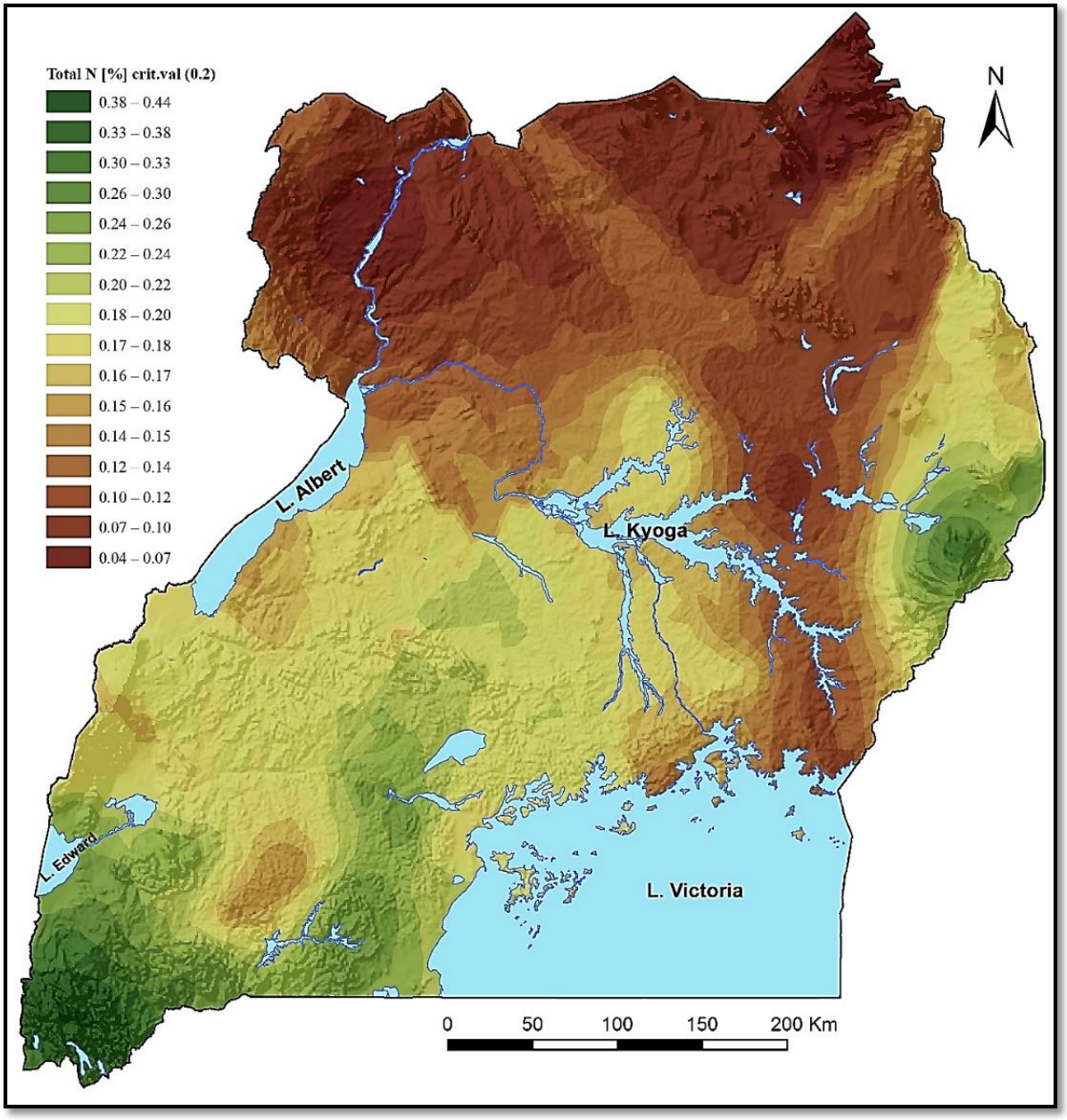

Figure 5.4: Interpolated total nitrogen map for Uganda.

Mineralization and nitrification is slower in cooler climates than in warmer climates (Giller et al., 1997). This can explain the high total N levels in the higher altitudes where the loss of N through nitrification is very low.

5.4.2.4 Available Potassium

High available K levels ranging between 883 and 1137 mg/kg occur in the Mt. Elgon region and some parts of the southwestern region (Fig. 5.7). These two regions have young and relatively fertile soils weathered from volcanic tephras, which probably were high in K-containing minerals.

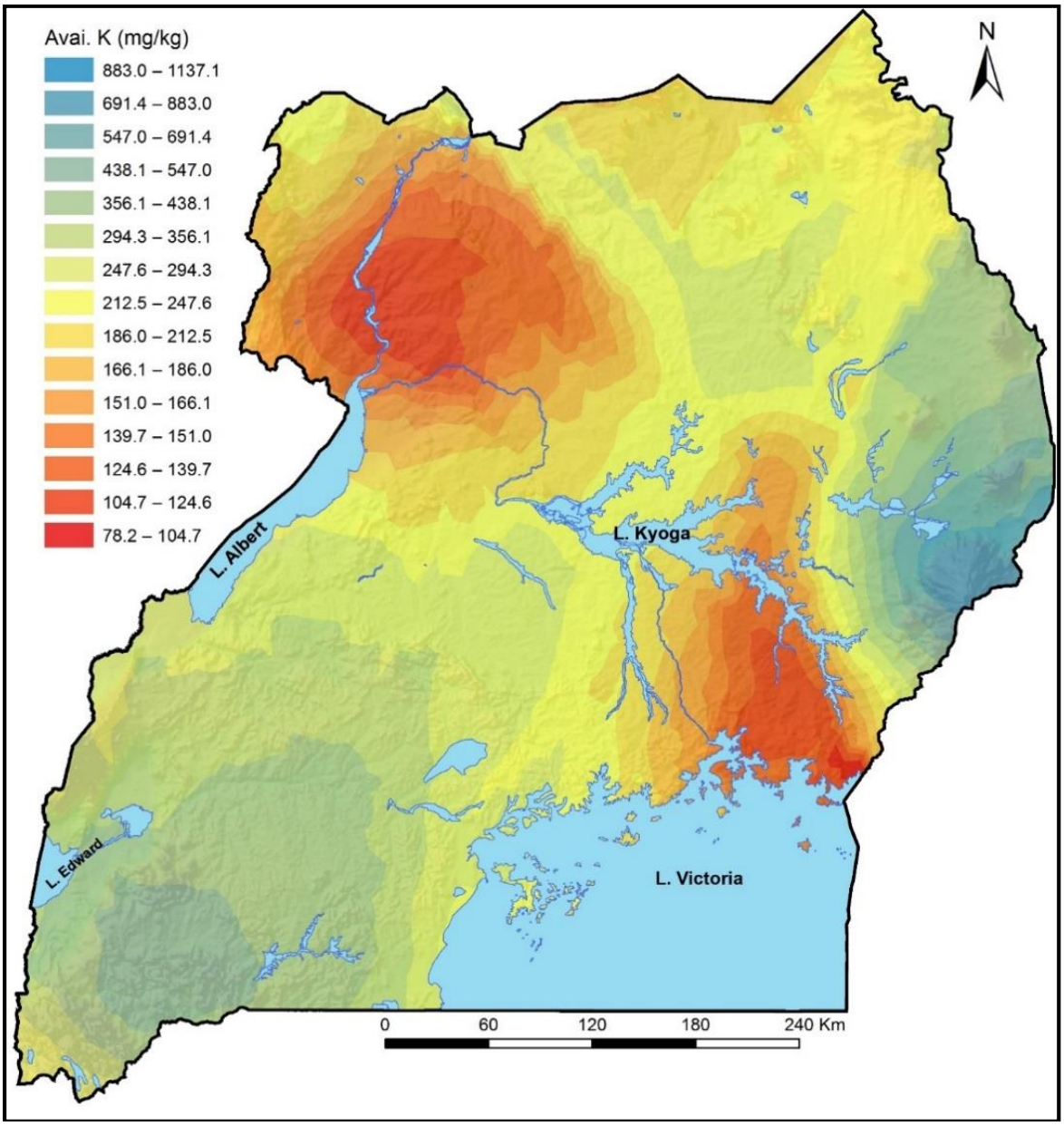

Figure 5.5: Interpolated available K map for Uganda.

Low available potassium was observed in northwestern Uganda and along the shores of L. Kyoga. Potassium mobility in the soil is often related to soil texture (Werle et al., 2008; Rosolem et al., 2010). All the soils with low exchangeable K are sandy, with sand contents of up to 82% (compare Fig. 5.10 and Fig. 5.11). High available K content has been observed to be greatest in clayey soils, followed by loam and coarse-textured sands. Clay and organic matter hold potassium ions (and other positively charged soil nutrients) preventing them from leaching easily from silty and clayey soils. Organic matter and clay hold most of the positively charged nutrients tightly, but the attraction between potassium ions and organic matter is relatively strong and may thus not be leached from soils with organic matter.

5.4.2.5 Total Potassium

High total potassium ranging between 1.33 % and 1.66 % was observed in the Mt. Elgon and the southwestern region (Fig. 5.7). Since the soils in these regions are relatively fertile Andisols (NEMA, 2001), they contain high amounts of soil nutrients as compared to the highly weathered Ferrasols and Nitisols soils found in the northern parts of Uganda.

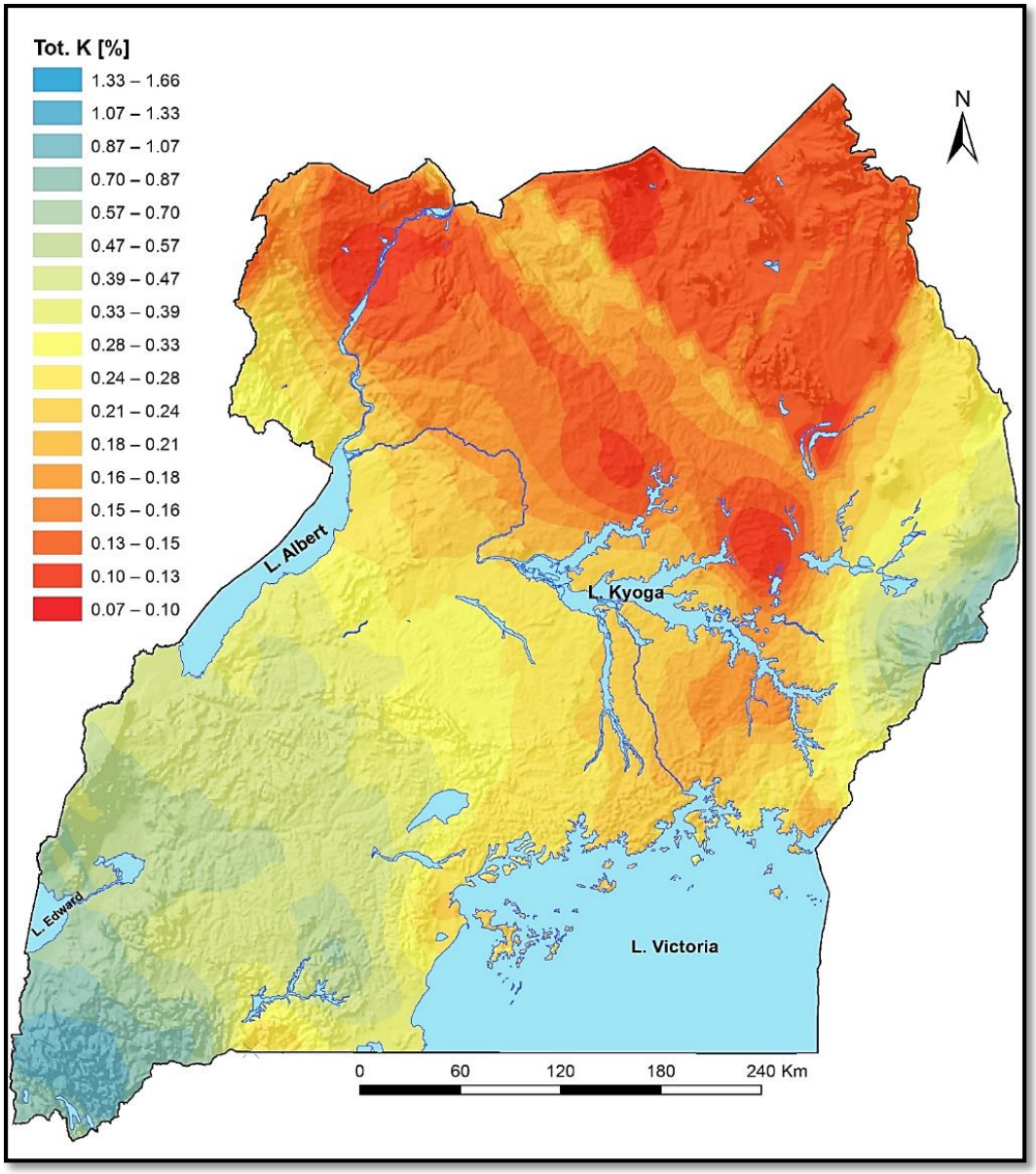

Figure 5.6: Interpolated total K map for Uganda.

5.4.2.6 Total Phosphorus

Areas with moderate phosphorus levels of up to 0.3 % were observed in the Mt. Elgon and southwestern highlands regions (Fig. 5.9). Similarly, these regions have young and relatively fertile soils rich in soil nutrients. Low levels of total phosphorus were observed in the northern half of Uganda.

Since two thirds of Uganda soils are highly weathered Ferrasols and Nitisols (Nakileza, 2010), nutrients such as phosphorus that occur in inorganic organic forms are not readily available to crops because phosphorus is held tightly by iron oxide surfaces and is a key limiting nutrient (Smeck, 1985; Mokwunye et al., 1986; Buresh et al., 1997). The opposite is true for the Mt. Elgon and southwestern regions where soils are young and fertile.

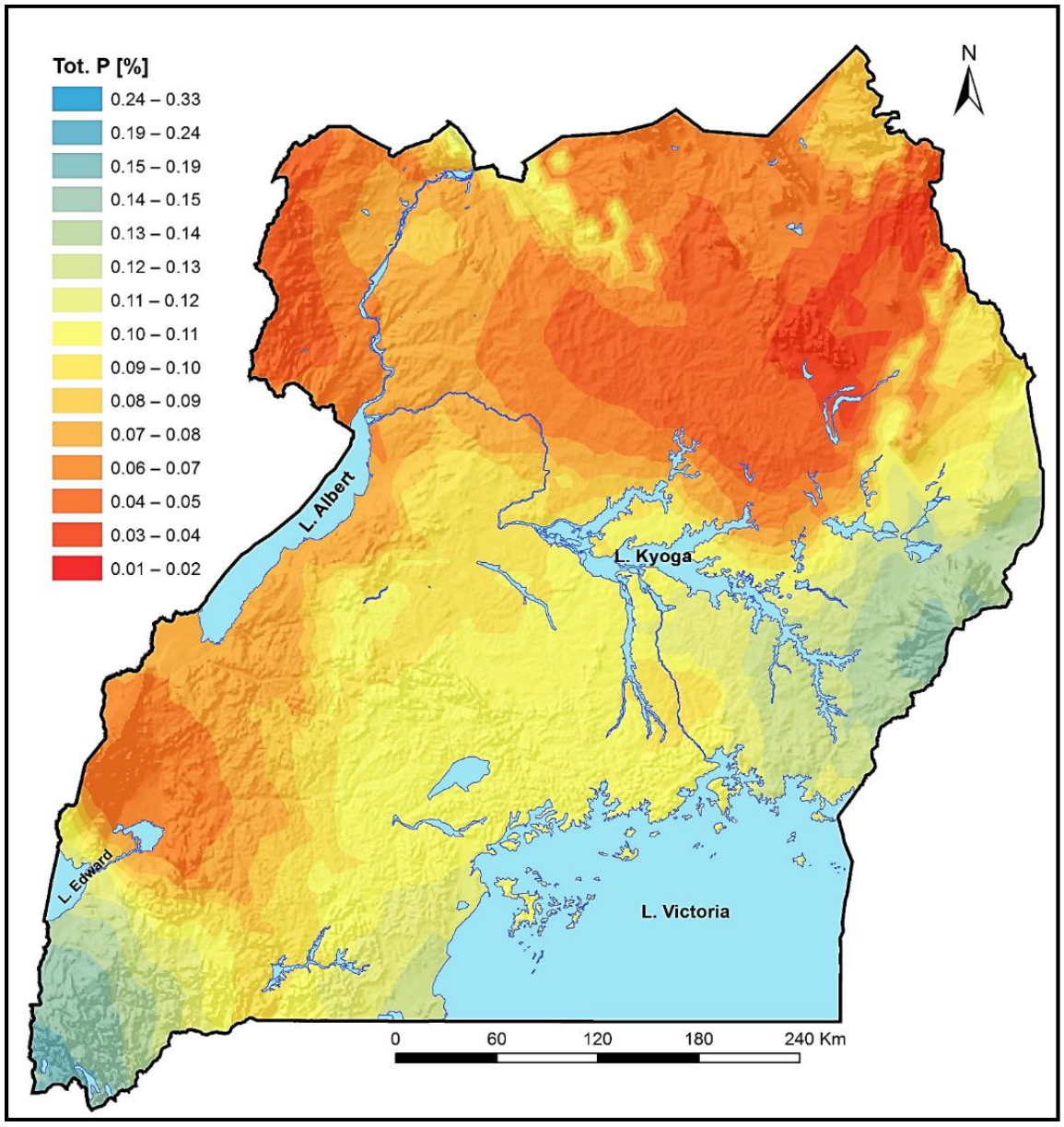

Figure 5.7: Interpolated total phosphorus for Uganda.

The regions with high total phosphorus highlighted above are areas where economic deposits of phosphate rocks occur. Most of the mining activity takes place in the Busumbu and Sukulu carbonatite deposits found in eastern Uganda next to Mt. Elgon (McClellan and Notholt, 1986, Van Kauwenbergh, 1991). These igneous phosphate rocks are rich in apetite and contain up to 30% rock phosphate (P_2O_5) for Busumbu and 12.5 % for Sukulu. Roche et al. (1980) recommended that in areas where phosphorus is highly deficient, especially in the northwestern part of Uganda, farmers should be encouraged to increase the application of P fertilizers in order to increase the availability of P in soils. However, areas that have very low pH levels are susceptible to aluminum toxicity and these areas should also receive $CaCO_3$ to reduce P-sorption (Buresh et al., 1997).

5.4.2.7 Sand

High sand contents (up to 82 %) are observed along the northern half of Uganda, excluding the Mt. Elgon region, and stretch narrowly towards L. Victoria (Fig. 5.10). These regions have soils formed in residuum from granitic rocks (Fig. 3.3) which leads to coarse textured soils.

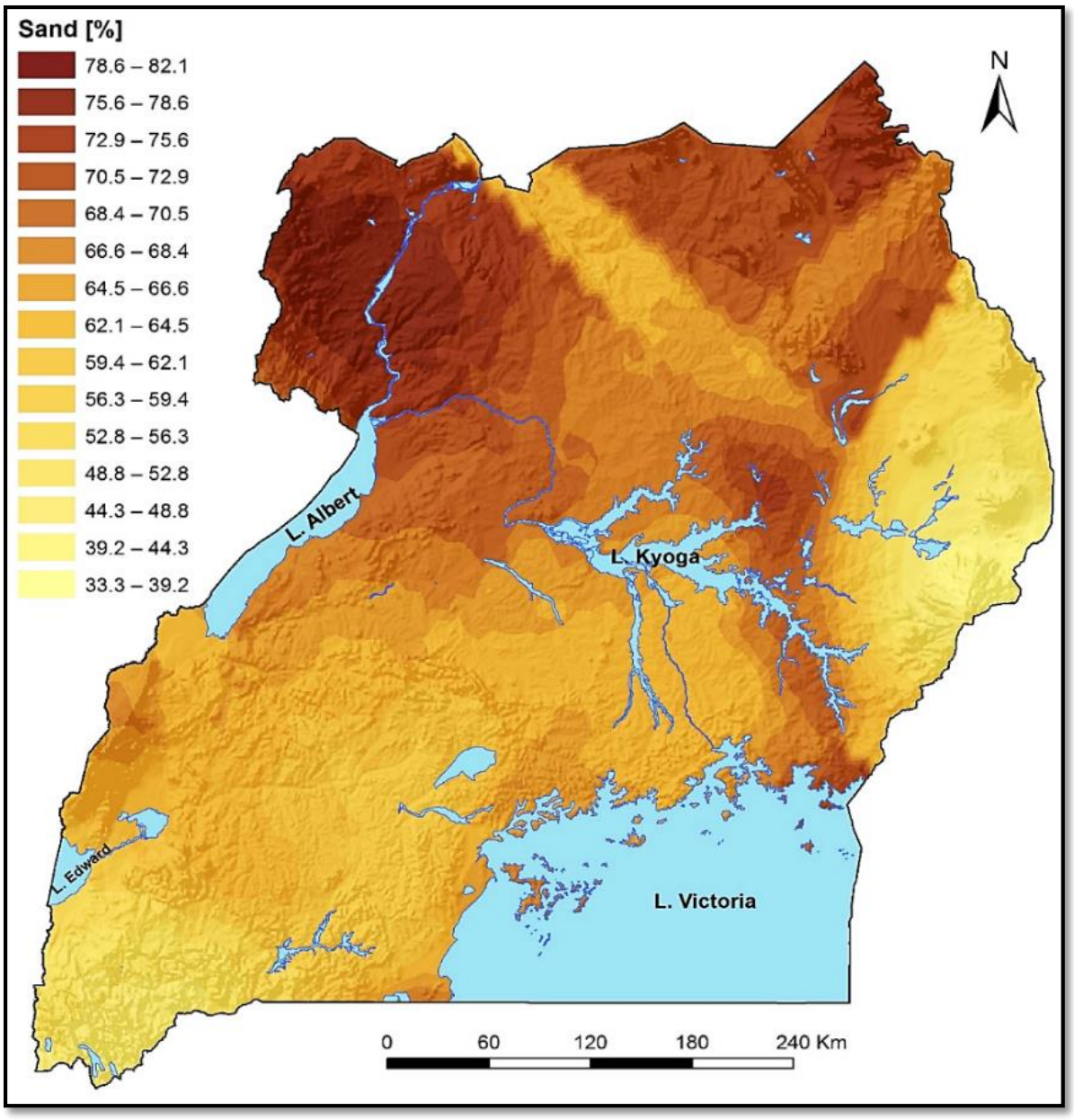

Figure 5.8: Interpolated sand map for Uganda.

5.4.2.8 Clay

High clay contents occur in the southwestern highlands and the Mt. Elgon highlands. Clay content is low in the highly weathered soils in the north but higher in the relatively young and fertile volcanic soils in Mt. Elgon region and the southwestern highlands (Fig.5.11).

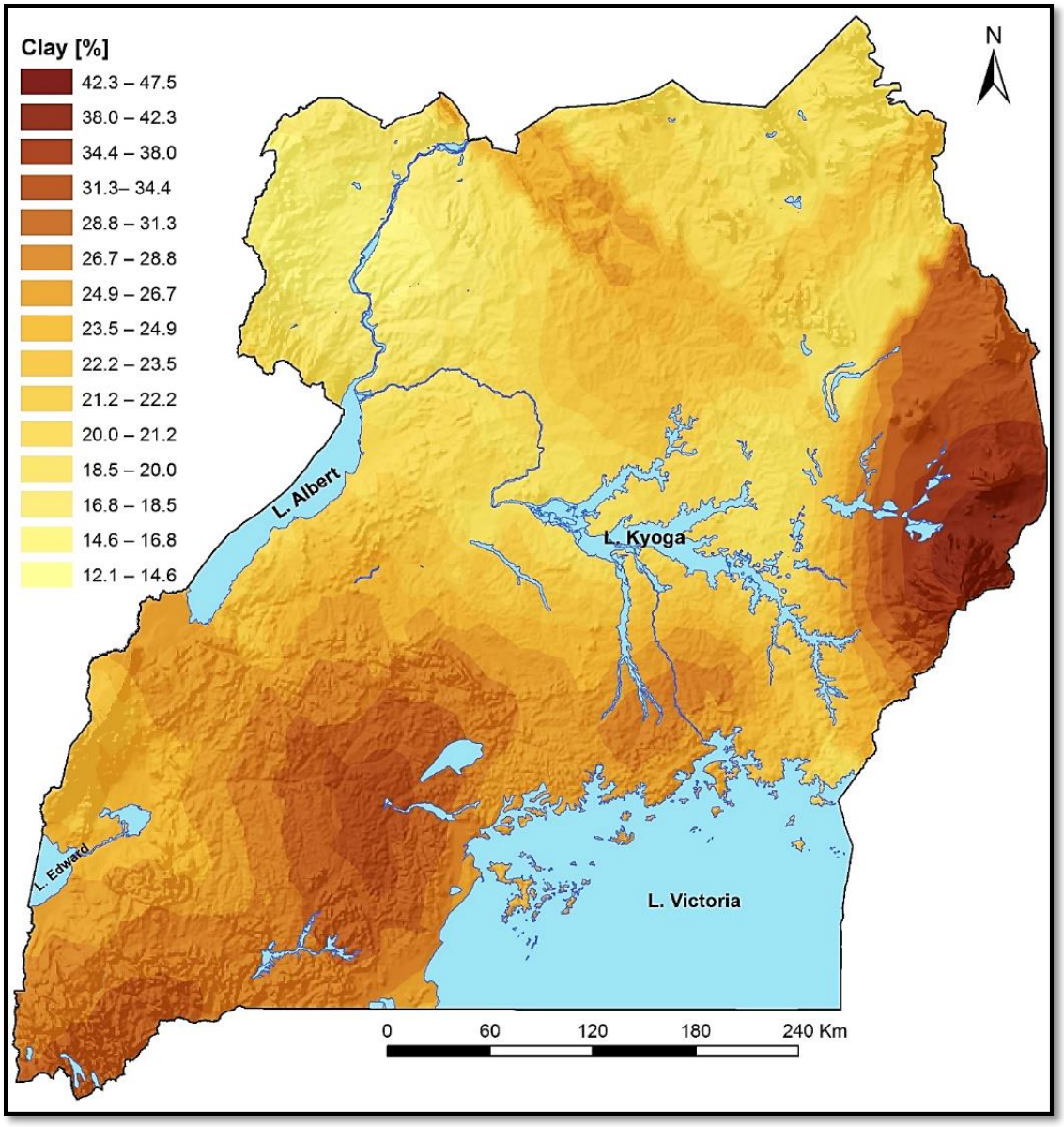

Figure 5.9: Interpolated clay map for Uganda.

5.4.2.9 Silt

Relatively high silt contents ranging between 25% and 30% occur in the southwestern highlands. Similarly, fairly high silt contents, ranging between 21.1% and 25% are also observed in the Mt. Elgon region. The rest of the soils in the other districts of Uganda have low silt content ranging from 5.2% to11.1% (Fig. 5.12).

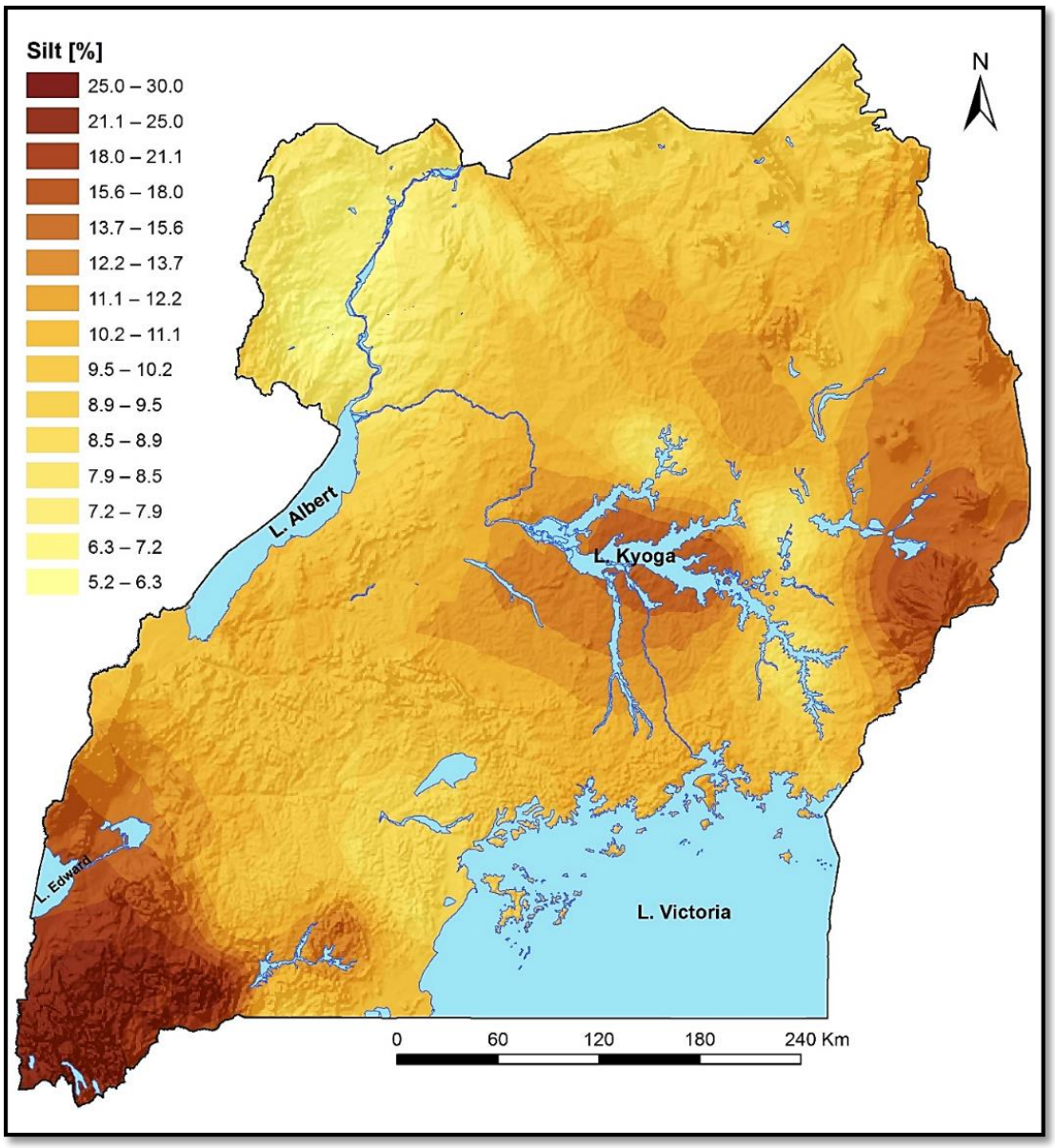

Figure 5.10: Interpolated silt map for Uganda.

5.5 Cross Validation

To determine the accuracy of the predicted soil quality maps, the predicted soil properties were compared to their observed values. The standard error of the estimate was used to determine the accuracy of prediction. The standard error of the estimate is defined by the equation:

$$\boldsymbol{\sigma_{est}} = \frac{\sum(\mathbf{Y}-\mathbf{Y'})^{\mathbf{2}}}{\mathbf{N}},$$

where $\boldsymbol{\sigma}$ is the standard error of the estimate, Y is the observed soil property, in this case for each community, Y' is the predicted soil property for that specific community, and N is the number of observations, namely the 122 rural communities. Table 5.7 shows the average standard errors for each prediction.

Table 5.7: Average standard error of the estimate

Soil Property	Average standard error of the estimate
Total N (%)	0.01
pH	0.14
Total K (%)	0.17
Total P (%)	0.29
SOM (%)	0.75
Available K (mg/ kg)	1.15
Silt (%)	2.52
Clay (%)	4.97
Sand (%)	7.36

The lower the standard error, the better the prediction. Only total N had a better prediction. The rest of the soil properties had higher average standard errors of the estimate indicating that the prediction was not as accurate. This was expected because only 122 points were used in this study. The 122 points were also not evenly distributed across the sampling region. To improve on the prediction and reduce the prediction error, a higher sampling density, more evenly distributed across all of Uganda is required (Burrough, 1993; McBratney et al., 2000). The uneven distribution of sampling points explains the 'V-shaped' structure observed in the northern part of Uganda extending narrowly towards L. Victoria.

5.6 Factors Influencing Spatial Variability on a National Scale

In order to identify the most dominant factor that influences soil variability, a generalized linear model (GLM) was used to regress a linear combination of the variables that contribute to a factor with the response variable, a given soil parameter. The adjusted R^2 was used to determine the variation in the response variable as a result of the linear combination of the variables that feed into the specific causal factor under consideration. The factor with the highest R^2 values (>70%) when regressed with all the soil parameters was regarded as the most dominant factor in explaining the variation of a soil parameter. The environmental and socioeconomic factors identified to correlate with nationwide soil variability in Uganda include geology and geomorphology (GEGE), climate (CL), land use and land management (LULUM), and socioeconomic factors (SOECO). Each factor was regressed alone and then as combinations of two or more in a generalized linear model (Table 5.8).

Table 5.8: Generalized linear model (GLM) of the environmental and socioeconomic factors that explain spatial variability of soil parameters on the national-scale in Uganda.

Soil Parameter	Environmental/ Socioeconomic factors	R^2	Adjusted R^2	Residual standard deviation	df
pH in water	GEGE, CL, LULM, SOECO	0.71	0.68	0.13	108
	CL, LULM, SOECO	0.68	0.66	0.14	113
	GEGE, CL, LULUM	0.65	0.62	0.16	112
	CL, LULM	0.59	0.58	0.19	117
	CL, SOECO	0.55	0.53	0.20	114
	GEGE, SOECO	0.53	0.49	0.21	112
	GEGE, CL	0.53	0.49	0.21	113
	GEGE, LULUM	0.49	0.46	0.23	115
	CL	0.42	0.40	0.26	118
	GEGE	0.40	0.38	0.27	116
	LULM, SOECO	0.39	0.36	0.28	116
	SOECO	0.33	0.31	0.30	117
	LULM	0.02	0.02	0.44	120
SOM (%)	GEGE, CL, LULM, SOECO	0.68	0.64	0.55	108
	GEGE, CL, LULUM	0.66	0.63	0.58	112

	CL, LULM	0.63	0.62	0.63	117
	GEGE, CL	0.65	0.62	0.60	113
	GEGE, LULUM	0.64	0.62	0.62	115
	CL, LULM, SOECO	0.64	0.61	0.61	113
	CL	0.60	0.59	0.68	118
	CL, SOECO	0.61	0.59	0.66	114
	GEGE	0.61	0.59	0.67	116
	GEGE, SOECO	0.62	0.59	0.64	112
	LULM, SOECO	0.48	0.45	0.89	116
	LULM	0.43	0.42	0.98	120
	SOECO	0.40	0.38	1.03	117
N (%)	GEGE, CL, LULUM	0.73	0.71	0.36	112
	GEGE, CL	0.72	0.70	0.36	113
	GEGE, CL, LULM, SOECO	0.73	0.70	0.35	108
	CL, LULM, SOECO	0.72	0.70	0.37	113
	CL	0.71	0.70	0.37	118
	CL, SOECO	0.72	0.70	0.37	114
	CL, LULM	0.71	0.70	0.38	117
	GEGE, SOECO	0.65	0.63	0.45	112
	GEGE	0.64	0.63	0.47	116
	GEGE, LULUM	0.64	0.62	0.47	115
	LULM, SOECO	0.40	0.38	0.78	116
	SOECO	0.39	0.37	0.80	117
	LULM	0.32	0.31	0.89	120
Avai. K (ppm)	GEGE, CL, LULM, SOECO	0.70	0.66	62.84	108
	GEGE, CL, LULUM	0.66	0.63	70.98	112
	CL, LULM, SOECO	0.64	0.62	73.53	113
	CL, LULM	0.62	0.61	78.30	117
	GEGE, LULUM	0.55	0.53	93.08	115
	LULM, SOECO	0.52	0.50	98.50	116
	LULM	0.40	0.40	123.07	120
	GEGE, CL	0.39	0.34	126.88	113
	CL, SOECO	0.36	0.32	133.28	114
	CL	0.30	0.28	145.29	118
	GEGE, SOECO	0.27	0.21	150.18	112
	SOECO	0.19	0.17	166.57	117
	GEGE	0.17	0.14	170.71	116
Tot. P (%)	GEGE, CL, LULM, SOECO	0.72	0.69	66.09	108
	LULM, SOECO	0.68	0.66	77.42	116
	CL, LULM, SOECO	0.68	0.65	77.31	113
	GEGE, CL, LULUM	0.66	0.64	80.74	112
	CL, LULM	0.63	0.62	87.64	117
	GEGE, LULUM	0.63	0.61	89.14	115
	LULM	0.62	0.61	91.45	120
	GEGE, CL	0.46	0.43	128.15	113
	CL, SOECO	0.43	0.40	135.78	114
	GEGE, SOECO	0.45	0.40	132.24	112
	CL	0.38	0.36	149.02	118
	GEGE	0.36	0.34	152.44	116

	SOECO	0.34	0.32	156.75	117
Tot. K (%)	GEGE, CL, LULM, SOECO	0.67	0.63	2.24	108
	GEGE, CL, LULUM	0.65	0.63	2.36	112
	GEGE, CL	0.65	0.63	2.36	113
	CL, LULM, SOECO	0.62	0.60	2.54	113
	CL, LULM	0.62	0.60	2.62	117
	GEGE, LULUM	0.62	0.60	2.59	115
	CL	0.60	0.60	2.69	118
	GEGE, SOECO	0.63	0.60	2.50	112
	CL, SOECO	0.62	0.59	2.60	114
	GEGE	0.60	0.59	2.71	116
	LULM, SOECO	0.51	0.49	3.37	116
	SOECO	0.46	0.44	3.71	117
	LULM	0.42	0.42	3.94	120
Sand (%)	GEGE, CL, LULM, SOECO	0.63	0.58	0.01	108
	GEGE, CL, LULUM	0.61	0.58	0.01	112
	GEGE, LULUM	0.60	0.58	0.01	115
	GEGE, CL	0.61	0.58	0.01	113
	GEGE, SOECO	0.61	0.58	0.01	112
	GEGE	0.60	0.58	0.01	116
	CL, LULM, SOECO	0.55	0.52	0.01	113
	CL, LULM	0.54	0.52	0.01	117
	CL, SOECO	0.55	0.52	0.01	114
	CL	0.53	0.52	0.01	118
	LULM	0.29	0.29	0.02	120
	LULM, SOECO	0.31	0.28	0.02	116
	SOECO	0.25	0.23	0.02	117
Silt (%)	GEGE, CL, LULM, SOECO	0.61	0.57	0.16	108
	GEGE, SOECO	0.59	0.56	0.18	112
	GEGE	0.55	0.54	0.19	116
	GEGE, CL, LULUM	0.56	0.53	0.19	112
	GEGE, LULUM	0.56	0.53	0.19	115
	GEGE, CL	0.56	0.53	0.19	113
	CL, LULM, SOECO	0.56	0.52	0.20	113
	CL, SOECO	0.53	0.51	0.20	114
	CL, LULM	0.49	0.48	0.22	118
	CL	0.49	0.48	0.21	118
	LULM, SOECO	0.28	0.25	0.30	116
	LULM	0.24	0.23	0.33	120
	SOECO	0.20	0.17	0.34	117
Clay (%)	GEGE, CL, LULM, SOECO	0.61	0.56	0.05	108
	GEGE, SOECO	0.57	0.53	0.05	112
	GEGE, CL, LULUM	0.55	0.51	0.06	112
	GEGE, CL	0.54	0.51	0.06	113
	CL, LULM, SOECO	0.52	0.49	0.06	113
	GEGE, LULUM	0.51	0.48	0.06	115

CL, SOECO	0.51	0.48	0.06	114
GEGE	0.47	0.45	0.07	116
CL, LULM	0.42	0.40	0.07	117
CL	0.41	0.39	0.07	118
LULM, SOECO	0.36	0.33	0.08	116
SOECO	0.31	0.29	0.09	117
LULM	0.29	0.28	0.09	120

Abbreviations: GEGE; Geology/Geomorphology, CL; Climate, LULM = Land use/ Land use management, SOECO; Socioeconomic

The adjusted R^2 values in Table 5.8 were used to rank the percentage of variation in the response variable (soil parameter) as a result of the linear combination of either one or more predictor variables (Mittlbock and Heinzl, 2004). In order to identify the most dominant predictor factors influencing spatial variability, the adjusted coefficients of determination were ranked by highest, moderate and least dominant explanatory power using the rules shown in Table 4.3 and displayed in Table 5.9. The higher the adjusted R^2 value for a given factor, the higher the probability of that factor influencing the variability of a specific soil property.

Table 5.9: Ranked adjusted R^2 as a result of the linear relationship with predictor variables from a single factor.

Soil Parameter	GEGE	CL	LULM	SOECO
pH	**	**	**	.
SOM (%)	**	**	**	**
Tot. N (%)	**	***	**	**
Avai. K (mg/kg)	*	**	**	*
Tot. P (%)	**	**	**	**
Tot. K (%)	**	**	**	**
Sand (%)	**	**	**	*
Clay (%)	**	**	**	**
Silt (%)	**	**	*	*

***= strongest, **=moderate, *=weak, . = no explanatory rank of a predictor based on adjusted R^2. Abbreviations: GEGE; Geology/ Geomorphology, CL; Climate, LULUM; Land use and land use management, SOECO; Socioeconomic.

There was no key dominant factor that could explain the spatial variability of all the soil properties. All the factors identified had either moderate to least explanatory powers.

Although GEGE is a key factor explaining the variability of soils (Franzmeier et al. 2004) (Section 5.1.2), GLM results showed that it was not the most dominant factor.

Of all the four factors, only CL was strongly correlated with total N, indicating that CL had a stronger power in explaining the variability of total N than the other three causal factors (adjusted R^2=70%). CL, which included the variables precipitation, temperature and length of growing period (Table 4.2), greatly influences soil N. Nitrogen in the soils is intricately linked with climate through the nitrogen cycle (Giller et al., 1997). Different forms of nitrogen such as nitrates (NO_3) are heavily leached from the soil in areas that receive high precipitation. Nitrification, a process by which NH_4^+ is converted to nitrites and nitrates, has been observed to be high in warmer climates (Giller et al., 1997). The resulting forms of soil nitrogen, nitrites and nitrates, are highly mobile in soils and are therefore easily lost by leaching (Pleysier and Juo, 1981). Areas that had higher amounts of soil N were the higher altitude areas (Fig.4.1) with cool climates where mineralization of organic matter is slow. High temperatures and precipitation also favor the rapid decomposition mineralization of soil N (Wild, 1972).

GLM results showed that LULUM was moderately correlated with the soil physical and chemical properties, indicating that at larger scales, Unit C (Fig. 2.1) land use/land use management does not have a strong influence on soil variability. However, at the field level, Unit A (Fig. 2.1), land use and land use management plays a key role in explaining soil nutrient dynamics. For instance, agricultural fields under commercial farming are expected to have high soil nutrients due to high agricultural inputs in form of fertilizers in

contrast to subsistence farming systems that use little or no fertilizer (NEMA, 2010). Different agricultural practices have different implications on soil nutrient dynamics. Parsons (1970) and Bashaasha (2001) observed low available potassium levels in areas under banana cultivation because potassium is taken up in greater quantities by banana than all other soil nutrients combined (Turner et al., 1989). Intensive, continuous farming of banana with little or no fertilizer inputs results in low to extremely low levels of extractable potassium in soil (Ssali, 2002).

The socioeconomic factor was the weakest of the four factors, having low to moderate correlation with selected soil properties. This shows that at larger scales, Unit C, (Fig. 2.1), socioeconomic factors do not play an influential role in explaining for the variability observed in soil properties. Even though most studies have found that socioeconomic factors have a large influence on the decision making processes with respect to soil conservation (Nkonya et al., 2008) and thus its variability, such studies have mainly been at household level or field level (Unit A in Fig. 2.1). For instance, studies conducted by Lindblade (1996) and Carswell (2002) were focused in the Kigezi district in the southwestern highlands to identify the effect of population on fallowing. Extrapolation of such findings to larger scales, Unit C (Fig. 2.1), can be erroneous (Scoones and Toulmin, 1998).

The weak correlation observed between the socioeconomic factor and soil properties might be explained by the scale at which this study is conducted. The nationwide sampling scheme (Unit C in Fig. 2.1), fails to capture the contribution of socioeconomic factors on

soil variability. In order to capture the effect of socioeconomic factors on the spatial variability of soil properties, several considerations need to be adhered to, including (1) a higher sampling density, (2) a smaller sampling region since socioeconomic factors are very complex and vary from one region to another (Reardon and Vosti, 1995), and (3) more socioeconomic information is need to be included such as land tenure, culture and gender dynamics (Pender et al., 2001), and education (Jollife, 1997), all of which might be more useful in explaining the variability of soils (Nkonya et al, 2008). The drawback with the socioeconomic factors used in this study is that key variables such as land tenure, gender and cultural dynamics were not included. These key socioeconomic factors are only available at the household level (Nkonya et al., 2008).

These results affirm that there is no dominant factor that can explain the variability of soils properties. A factor is considered to be dominant if it has strong correlation with all the soil properties after regression. These results are consistent with results by Wilding and Drees (1983) who found that soil heterogeneity is a result of soil forming factors compounded by other stochastic factors (Burrough, 1983) continuously interacting with each other over a time and space (Trangmar et al., 1985).

5.6.1 Effect of Multiple Factors on Soil Variability

In order to test if variation in soil is strongly influenced by a combination of both the environmental and socioeconomic factors interacting together, a linear combination of two or more factors were regressed against each soil property and the adjusted R^2 values were compared and ranked (Table 5.10).

Table 5.10: Ranked adjusted R^2 as a result of the linear relationship with predictor variables from two or more predictor factors.

	Two Factors						Three Factors		Four Factors
Soil Parameter	GEGE, CL	GEGE, LULUM	GEGE, SOECO	CL, LULUM	LULUM, SOECO	CL, SOECO	GEGE, CL, LULUM	CL, LULUM, SOECO	GEGE, CL, LULUM, SOECO
pH	**	**	**	**	**	**	**	***	***
SOM (%)	**	**	**	**	**	**	**	**	***
Tot. N (%)	***	**	**	***	***	***	***	***	***
Avai. K (mg/kg)	**	**	*	**	**	**	**	**	***
Tot. P (%)	**	**	**	**	***	**	***	***	***
Tot. K (%)	**	**	**	**	**	**	**	**	**
Sand (%)	**	**	**	**	**	**	**	**	**
Clay (%)	**	**	**	**	**	**	**	**	**
Silt (%)	**	**	**	**	**	**	**	**	**

***= strongest, **=moderate, *=least, · = no explanatory rank of a predictor based on adjusted R^2. Abbreviations: GEGE; Geology/ Geomorphology, CL; Climate, LULUM; Land use and land use management, SOECO; Socioeconomic.

As the number of factors increase from two to four, the correlation between the soil property and the causal factors increases. This was observed in pH, SOM, total N, available K, total N, available K, and total P, and is consistent with the findings of Burrough (1993), Wilding (1994) and McBratney et al. (2000) who concluded that the combination of both the systematic and stochastic factors continuously interact with each other resulting in the variations observed in soil.

Therefore, in order to identify the single most dominant factor explaining the variability of soils in Uganda, a smaller sampling region would be required that has uniform geology. This is because, at larger scales, Unit C in Fig. 2.1, geology is the most influential in explaining the variability observed soil variability (Section 5.1.2). Such a region would clearly show the effect of each factor on the variability of soil.

Even though geology is influential in explaining the variability of soils, GLM results found that there is no dominant factor that can solely explain the variability of soil properties at larger scales. This is probably due to the fact that soil heterogeneity is a complex phenomenon that is resulted from the interaction of a myriad of factors (Fig. 5.11) some of which have not been considered in this study. Figure 5.11 shows the variation of soil property as a result of a linear combination of two or more factors.

As show in Table 5.8 above, the highest correlation for the spatial variability of total nitrogen (71%) is obtained by the combined factors of GEGE, CL and LULUM. However, the lowest prediction was 2% in the case of the spatial variation of pH when explained by LULUM alone. The prediction of the best single, pair, three and four combinations of factors for explaining spatial variability of soil parameters in Uganda is displayed in Figure 5.11. See Appendix F for the ranked, from highest to lowest, adjusted R^2 values.

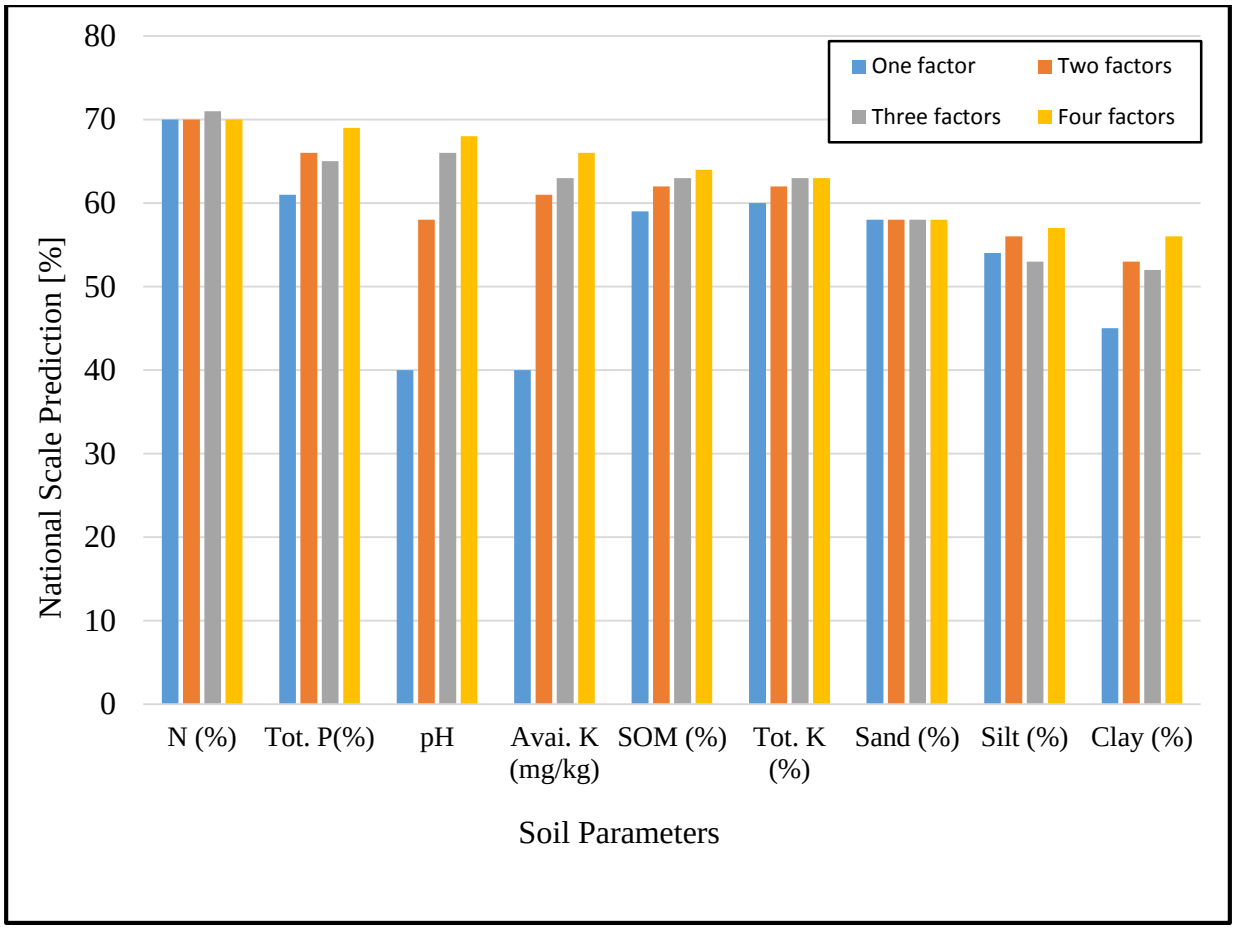

Figure 5.11: Prediction of spatial variability of soil parameters in Uganda by number of environmental and socioeconomic predictor factors. Soil properties are strongly influenced by the combination of both the environmental and socioeconomic factors as seen in total P, pH, available K, SOM, and texture.

5.7 Challenges Faced While Conducting the Study

This study illustrates the importance of geostatistics in showing the variation of soil properties at a national scale and goes a long way in providing important information that extension officers can use to improve efforts in addressing soil quality degradation in Uganda. Large scale studies, however, offers several challenges. The geostatistical approach used in this study only used 122 sampling points to interpolate the whole of Uganda, which was an improvement over Rücker's study. Geostatistics, however, requires

a high sampling density with points evenly distributed throughout the sampling frame. Larger scales offer a major challenge in identifying the single most dominant factor influencing soil variability, since geology will be most influential but not dominant as shown in Section 5.1.2. Future studies that aim at identifying the key factors that influence soil variability in Uganda should narrow down the scope of the study to a smaller region. For instance, narrowing the scope of the study to a district that has a homogenous geology would provide more information on factors that influence soil variability in a district. Narrowing the scope would also offer room for analysis of key socioeconomic variables that were not included in the GLM. Variables such as land tenure, education, capital, gender and culture dynamics are key in determining variability of the soil at the field level. Further studies need to delve deeper to try and identify which variable within a factor is more significant at influencing the variability of soil at a local scale. This would aid in designing effective SWC approaches. For instance, identifying which variable among the socioeconomic factors, population density, poverty density, market access, infrastructure, is most significant at influencing soil variability.

5.8 Summary and Conclusions

This study assessed the spatial variability of soils on a national-scale in Uganda. The assessment relied on an extensive survey conducted in 2003 when 2,185 topsoil samples were collected across 122 rural communities (Nkonya et al., 2008). The soil samples from these communities were analyzed for pH, SOM, total phosphorus, available and total potassium, total nitrogen, sand, silt and clay. At the same time, environmental and socioeconomic factors were collected as well in order to identify the most important factor(s) determining spatial variability.

The environmental and socioeconomic variables were grouped into four major factors: (1) Geology/Geomorphology (GEGE) with the variables geological age, geotectonic land surface type, parent material, elevation, and slope, (2) Climate (CL) with the variables annual precipitation, mean annual temperature, and the length of growing period, (3) Land Use/ Land Use Management (LULUM) with farming system as the main variable, and (4) Socioeconomic factors (SOECO) with the variables poverty density, population density, market access and infrastructure.

Descriptive statistics showed that the average soil texture in Uganda is sandy clay loam. The average soil pH (6.1), SOM (3.48 %) and total N (0.21 %) are higher than the critical soil fertility thresholds established by Foster (1971), reflecting overall favorable agricultural conditions. However, all soil parameters exhibit wide ranges, for instance pH ranges from 4 - 7.8, SOM from 0.1 - 33.7 %, total N from 0.02 - 2.72 %, available K from 60 – 2720 mg/kg, total K from 0 - 5.1 %, and total P from 0.0 - 1.6 % as one would expected for soil properties from a large sample population. In general, soils in Uganda are well suited for crop growth. However, the high average values may mask values that are often well below critical thresholds of Foster (1971). For instance 4.0 compared to 5.2 for pH, 0.1 % compared to 3 % for SOM and 0.02 % compared to 0.2 % for total N suggesting that in some farm plots, soil properties have more soil nutrients than others.

The coefficients of variation of the soil properties showed that, apart from pH and available K, all the other soil properties have moderate to strong variability, indicating that soil properties are not homogenous. ANOVA results showed that all the soil property means

were highly significant, affirming that Uganda soil properties are indeed heterogeneous as one would expect. Semi-variance analysis showed strong (≤ 25 %) spatial autocorrelation for silt, available K, pH, total N, and sand, and moderate (>75 %) spatial dependence for total P, clay, SOM, and total K. Strong spatial dependence may be due to intrinsic variations in soil characteristics such as texture and mineralogy (Carmbadella, et al., 1994), while moderate spatial correlation can be controlled by other factors such as fertilizer applications, land use and land use management practices (Rücker, 2005).

Three models described the spatial correlation of the selected soil properties in Uganda. The spherical model described silt, SOM, clay, and total K, a Gaussian model described total P and available K, and an exponential model described total N. Major and minor ranges of all the soil properties were > 220 km and 89 km. Spatial visualization of soil properties showed that the Mt. Elgon region and the southwestern highlands were the two regions found most suitable for plant growth. These areas have higher pH, SOM, total N, clay, silt, and less sand than other parts of the country. Most studies have found that these areas are heavily dominated by perennial crops that provide good soil cover throughout the year, and therefore these soils are likely to have high infiltration capacity and hence low erodibility potential (Sserenkuuma et al., 2001). In addition, most of the livestock are zero-grazed, implying less soil erosion due to animal traffic (Bekunda and Lorup, 1994). The central area of Uganda around Lake Kyoga region, the Lake Victoria region and northern Uganda had soil parameter levels that were markedly lower and often close to limit for good crop growth. In addition, these areas had higher sand and lower clay contents, with extremes being observed in the northern parts of Uganda.

Of all the environmental and socioeconomic factors, climate had the strongest power to explain the national-scale spatial variability of total N, and moderate power for all the soil parameters. Geology and land use and land use management were the second most dominant factors explaining the variability of soils in Uganda. Socioeconomic factors had either moderate to low power to predict soil properties. Land use and land management was a key factor that influenced the variability of soil parameters. For instance, the combination of geology and climate and geology and socioeconomic factors both had moderate strength powers in explaining for the variability of pH.

Combining all four factors, the explanatory powers ranked from highest to lowest prediction were: Nitrogen (71%) > Total P (69%) > pH (68%) > Available K (66%) > SOM (64%) > Total K (63%) > Sand (58%) > Silt (56%) > Clay (56%). Interpolated soil quality maps clearly revealed Uganda´s regional soil heterogeneity, highlighting the deficient, nearly deficient, and favorable soil quality areas. Agricultural planners and policymakers can use these maps to focus soil improvement programs on specific soil regions in Uganda.

The development of soil quality maps offers important first steps in the identification of regions that need SWC measures. For instance, the northern half of Uganda is most in need of SWC measures. These findings are important for informing agricultural policymakers in Uganda. For instance, poor soil quality in the northern parts of Uganda calls for activities that can improve the soil organic matter levels, which will enhance soil quality. There is also a need to educate farmers on better land use practices that will assist them in improving soil fertility when practicing SWC (Foster, 1978; Foster, 1980a, b). Given the fact that the

Mt. Elgon region and the southwestern highlands have fairly soil good conditions, SWC practices are needed in these areas to conserve these soil resources. Many studies have noted alarming levels of soil nutrient depletion in the highlands of Uganda, with negative nutrient balances being a norm in these areas (Wortmann and Kaizzi, 1998).

These results can also be used to provide information for region specific soil management to address where to implement effective SWC interventions and also where to integrate natural resource management. For instance, farmers should be encouraged to increase their application of NPK fertilizers in the northern half of Uganda, which has soils deficient in these nutrients. Other practices include promoting liming of soils by farmers who cultivate in the southwestern highlands of Uganda that have acidic soils (Pender et al., 2004).

This study also shows that Gaussian process regression, kriging, can be used to understand the spatial distribution of diverse natural resources even within spatial domains that are considered to have homogenous natural resources. However, the accuracy of such an approach can only be improved by the use of a higher sampling density (Some'e et al., 2011) and the use of better interpolation approaches such regression kriging. Since this study only used one hundred and twenty two sampling points, further studies should aim for a higher sampling density to effectively capture the heterogeneity of soil properties in Uganda.

Further research should involve trying to identify which variable within a causal factor is most significant in explaining the variability in observed soil properties. In order to identify

the single most dominant factor that causes soil variability, the scope of the study needs to be narrowed down to a smaller region like a single district. This is because large scale studies have numerous challenges, such as limiting the available socioeconomic factor information. For instance, key socioeconomic factors such as land tenure, gender, and culture dynamics that may play important roles in variability within individual fields are not available at large-scales.

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Appendix A: Geological Time Scale

EON	ERA	PERID		EPOCH	DATES (millions of years ago)	AGE OF	EVENTS
Phanerozoic	Cenozoic	Quaternary		Holocene	0-2	Mammals	Humans
				Pleistocene			
		Tertiary	Neogene	Pliocene	2-5		
				Miocene	5-24		
			Paleogene	Oligocene	24-37		
				Eocene	37-58		
				Paleocene	58-66		Extinction of dinosaurs
	Mesozoic	Cretaceous			66-144	Reptiles	Flowering plants
		Jurassic			144-208		1st birds/mammals
		Triassic			208-245		First Dinosaurs
	Paleozoic	Permian			245-286	Amphibians	End of trilobites
		Carboniferous	Pennsylvanian		286-320		First reptiles
			Mississippian		320-360		Large primitive trees
		Devonian			360-408	Fishes	First amphibians
		Silurian			408-438		First land plant fossils
		Ordovician			438-505	Invertebrates	First Fish
		Cambrian			505-570		1st shells, trilobites dominant
Proterozoic	Also known as Precambrian				570-2,500		1st Multicelled organisms
Archean					2,500-3,800		1st one-celled organisms
Hadean					3,800-4,600		Approximate age of oldest rocks 3,800

Thompson and Turk, (1993).

Appendix B: Uganda Soils and their Susceptibility to Land Degradation

This table highlights the soils according to the FAO classification (1974, soil Map of the World edition) that are widespread in Uganda.

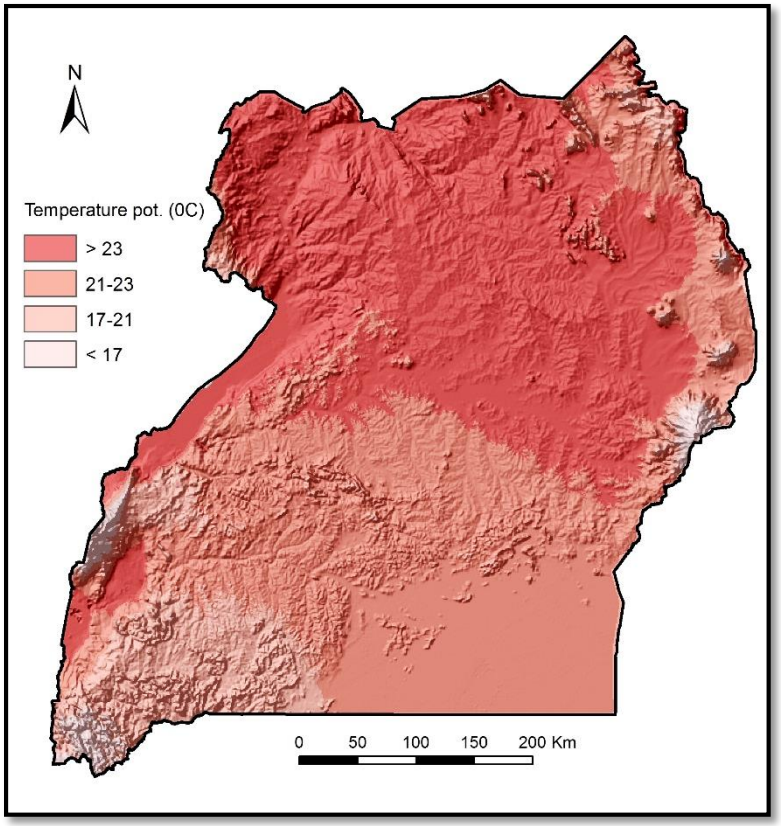
FAO-UNESCO Soil name: Soil Unit & Subunit	US Soil Taxonomic Name	Main Properties & Susceptibility to Land Degradation	Area covered (Km^2)	Districts/ Region
Andosols - Histic - Leptic - Luvic - Melanic - Skeletic	Andisols	From volcanic ash parent material; high in organic matter. Highly erodible, and limited in phosphorus. Chemical fertility is variable, depending on degree of weathering. Have low resilience, and variable sensitivity.	18,16.87	Mbale, Kisoro, Kasese, Manafwa, Sironko, Moyo
Arenosols - Gleyic	Entisols	Consists of unconsolidated wind-blown or water-deposited sands. One of the most inherently infertile soils of the tropics and subtropics with very low reserves of nutrients. Yet if chemical inputs provided, they yield well. Arenosols have moderate resilience and low sensitivity.	11,310.54	Arua
Calcisols	Aridisols	Soils with secondary accumulation of $CaCo_3$ of calcareous parent material. Such soils have serious problems with trace elements including Zn, Cu, Fe and Mn because inadequate concentrations of available forms of these elements can cause deficiencies in crops.	-	Bulisa
Ferralsols - Acric - Lixic	Oxisols	Ferralsols are the classic red soils of the tropics, because of high iron. Have low supply of plant nutrients and therefore not greatly impacted by erosion; they have strong acidity and low levels of available phosphorus. Have very few reserves of available minerals and easily lost topsoil organic matter. Are characterized by low resilience and moderate sensitivity.	38,067.01	Lira, Apac and widespread in the central and northern parts of Uganda

Gleysols - Eutric	Aquepts	Soils that are water saturated. Water logging is the main limitation of such soils. Are characterized by iron reduction	11,955.54	Rkai, Masaka, Mpigi
Histosols	Histosols	Organic or peat soils. When drained, highly prized for agriculture. Land degradation is often caused through shrinkage of the organic matter and subsidence.	37,04.34	Mbale, Sironko, Manawa, Kapchorwa, Bukwa, Kisoro
Leptosols	Lithosols	Are shallow in depth and with weak profile development. Erosion is their greatest threat. Excessive internal drainage and the shallowness of such soils can cause drought even in humid environments.	21,583.63	Moyo, Kitgum, Kotido and Moroto
Luvisols	Alfisols	The tropical soil most used by small farmers because of its ease of cultivation and no great impediments. Base saturation >50%. Greatly affected by water erosion and loss in fertility. Nutrients are concentrated in topsoil but have low levels of organic matter. Luvisols have moderate resilience to degradation and moderate to low sensitivity to yield decline.	21,277.87	Bugiri, Kaabong, Kapchorwa, Nakipiripirit, southern Uganda and along the shore of L. Victoria
Nitosols - Dystric - Eutric - Humic	Alfisols & Ultisols	One of the best and most fertile soils of tropics. They can suffer acidity and P-fixation, and when organic carbon decreases, they become very erodible. But erosion has only slight effect on crops. Nitosols have moderate resilience and moderate to low sensitivity.	3,053.96	Kapchorwa, Jinja and minute areas in Mukono
Planosols	Alfisols & Ultisols	Soils with a light colored layer over a soil layer that restricts water drainage and hence subjected to water saturation in wet periods. Have weak soil structure and are chemically degraded characterized by low pH and loss of clay. In addition ion exchange properties have degraded.	1,836.01	Masaka. Mpigi and Mabende
Plinthosols - Petric	Oxisols	New class of mottled, clayey soils that irreversibly harden after repeated drying. They are characterized	30,941.57	Gulu and Tororo

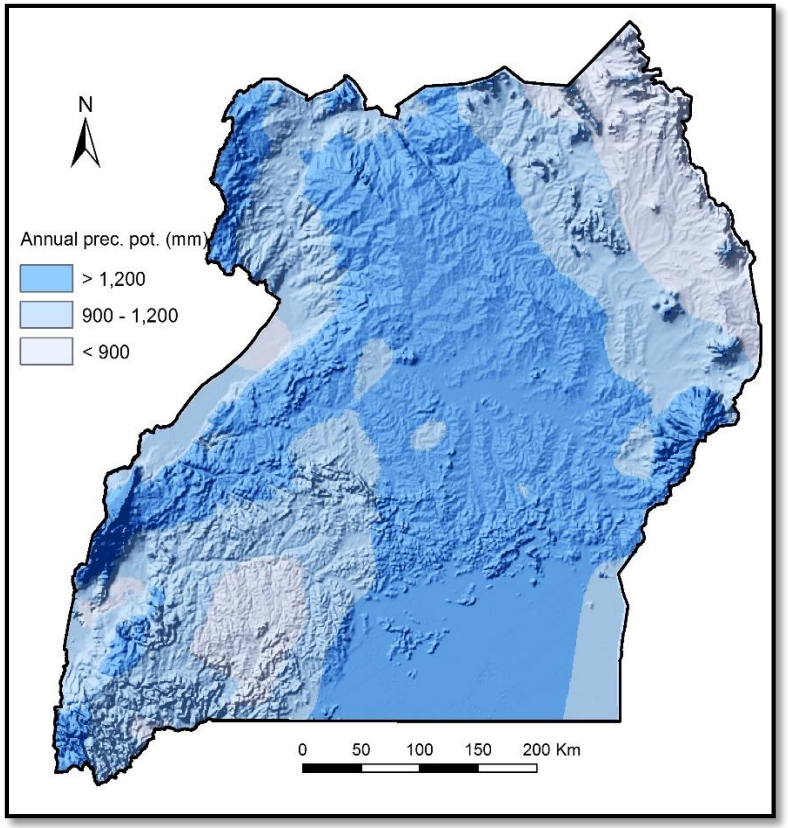
		by poor natural soil fertility, water logging in bottom lands and drought on shallow or skeletal plinthososls. Such soils occurring outside the wet climates have a shallow continuous petroplinthite which limits root penetration. Their stoniness also adds a complication of workability. Have high content of Al and or Fe and are also prone to waterlogging.		
Regosols - Dystric - Eutric	Entisols [Orthents & Psamments]	Surface layer of rocky material. Have low coherence within the soil matrix and this makes it prone to erosion in sloppy areas. Most of these soils have a low water holding capacity and their high permeability to water makes them very sensitive to drought. Regosols of colluvial material are prone to slaking. In addition, most of these soils form a hard surface crust early in the dry season hindering the emergence of seedlings, infiltration of rain and irrigation.	13,848.39	North eastern parts of Uganda and the southwest quarter of Uganda
Vertisols	Vertisols	Soils with 30% or more clay. Clays usually active, cracking when dry and swelling when wet. Extremely difficult to manage (hence easily degraded) but very high natural chemical fertility if physical problems overcome	14,561.23	Moroto, Kotido, Nkapiripirit, Arua, Nebbi, Kabalore, Kasese and Hoima

Modified from (FAO-UNESCO, 1974; Szott et al., 1991; Soil Survey Staff, 1998; Stocking and Murnaghan 2000; Nakileza, 2010; Selinus et al., 2013; Landon, 2014).

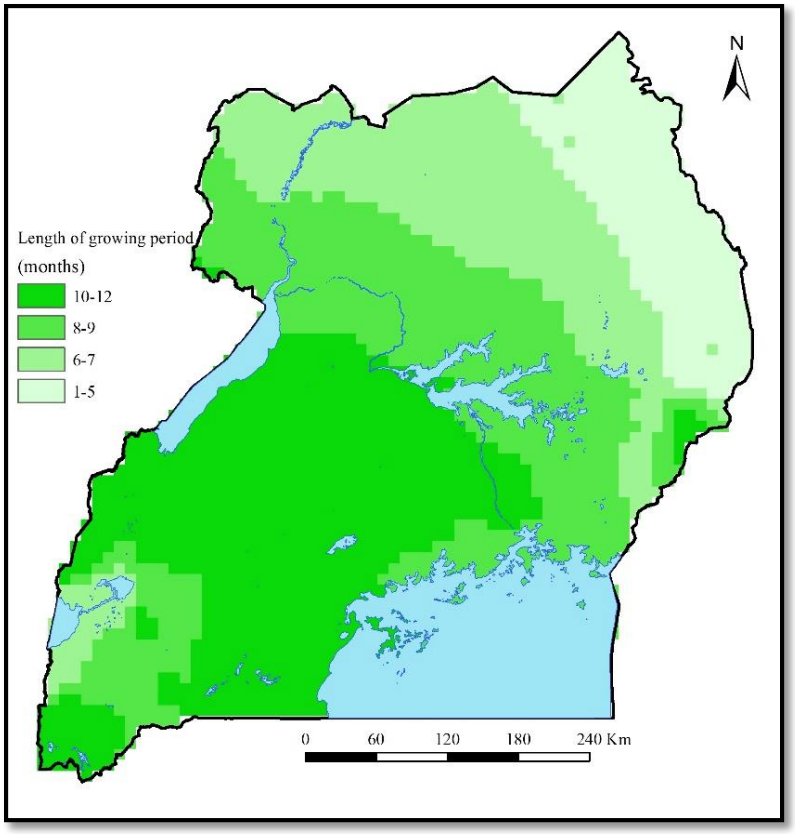
Appendix C: Spatial Distributions of selected environmental variables



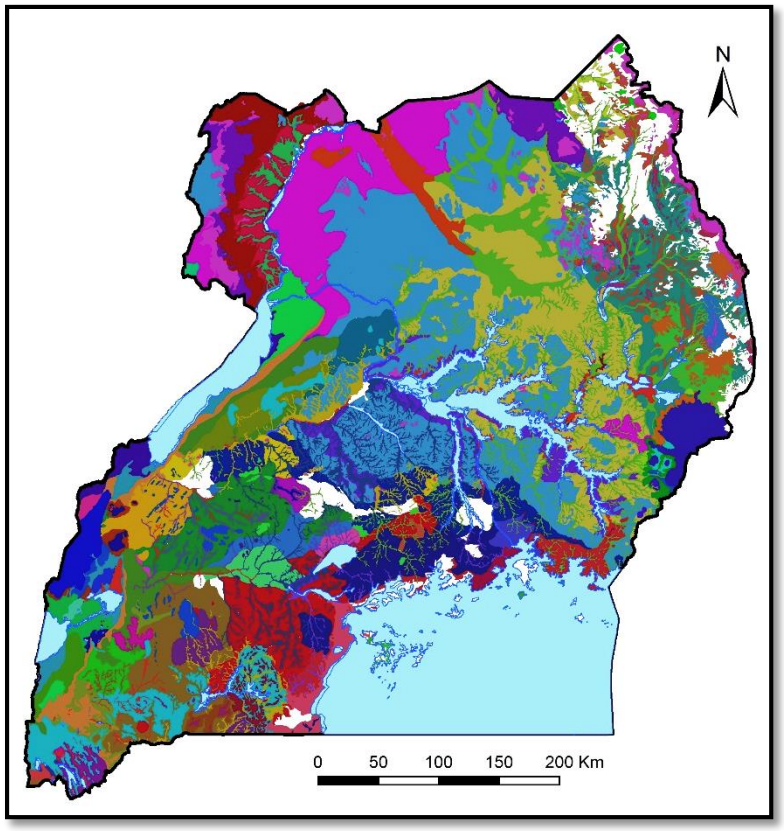
Temperature potential



Mean annual precipitation

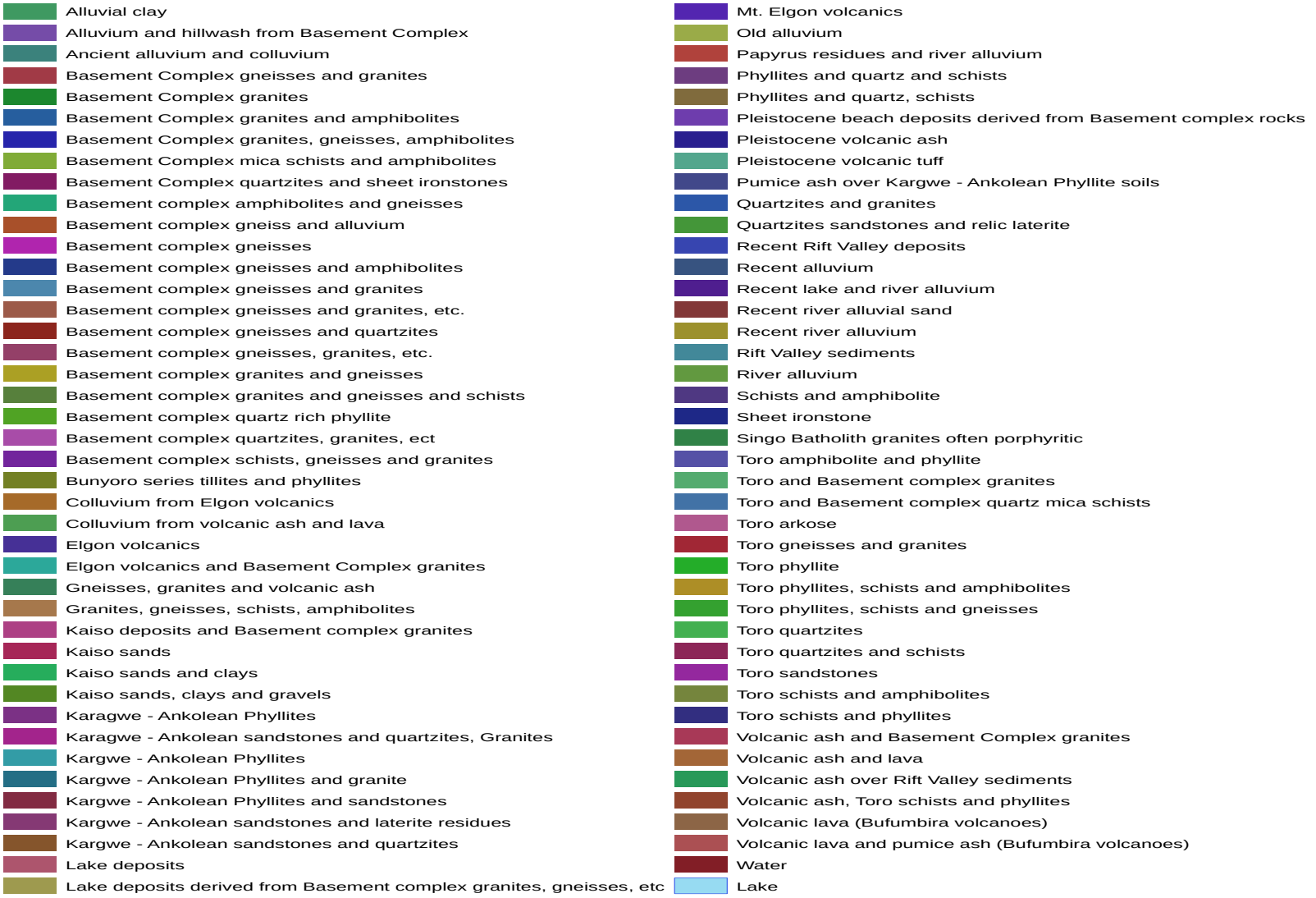


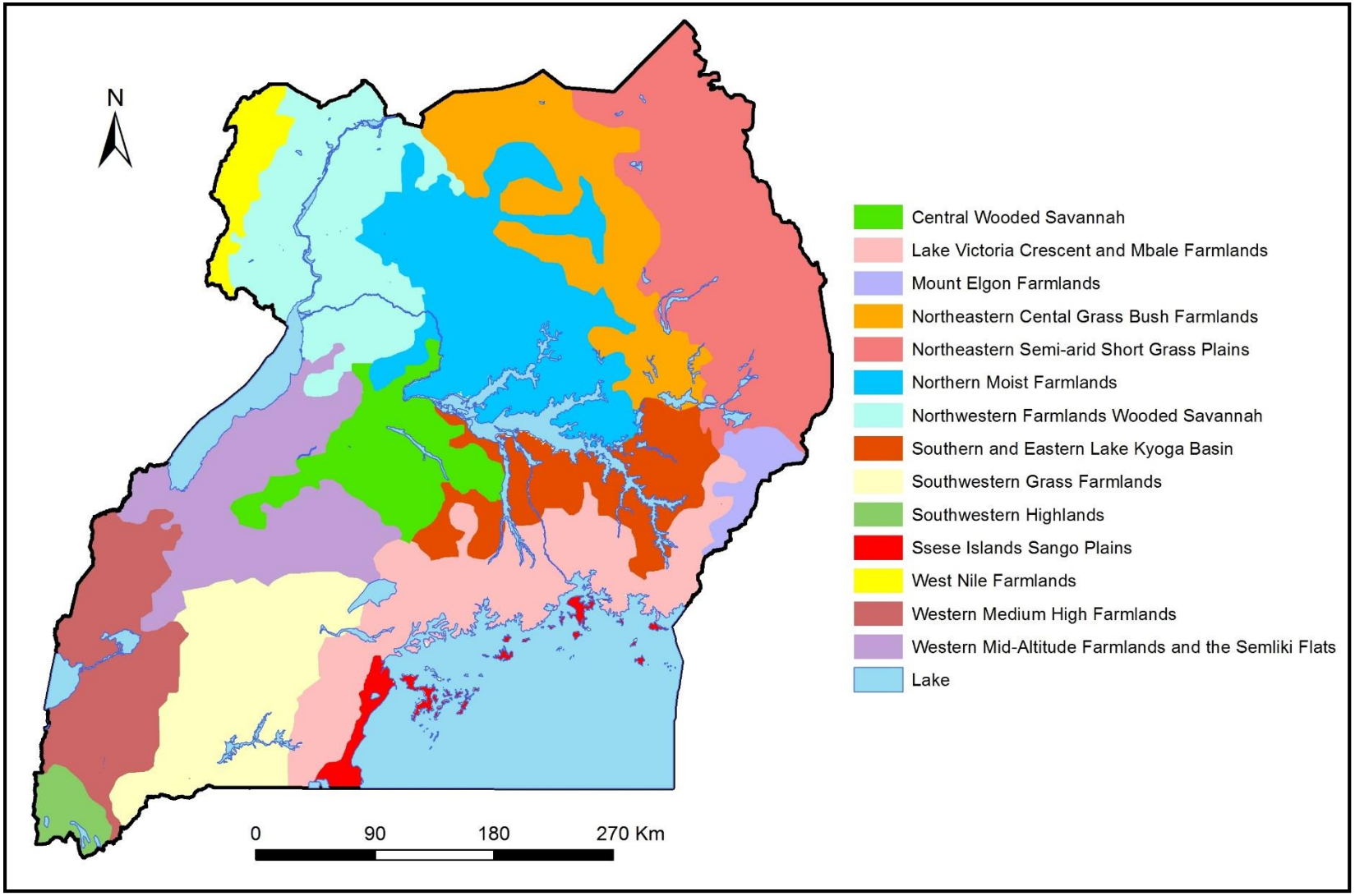
Length of growing period



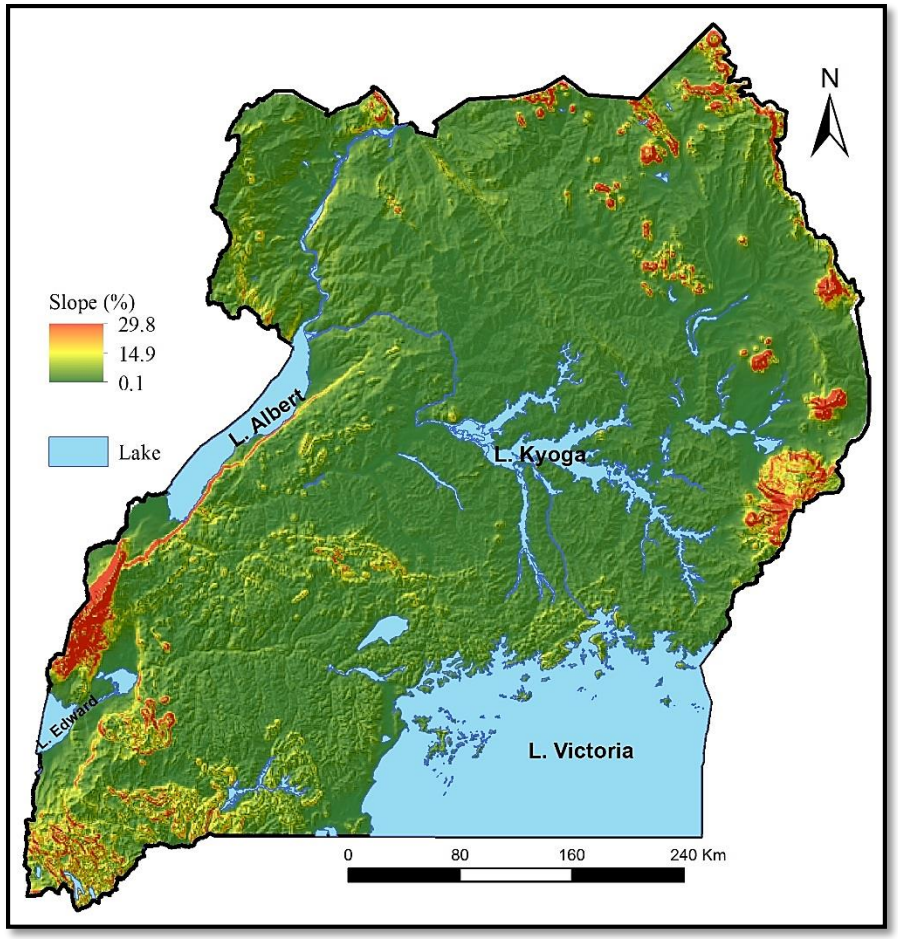
Parent material (key on next page)

Parent material key



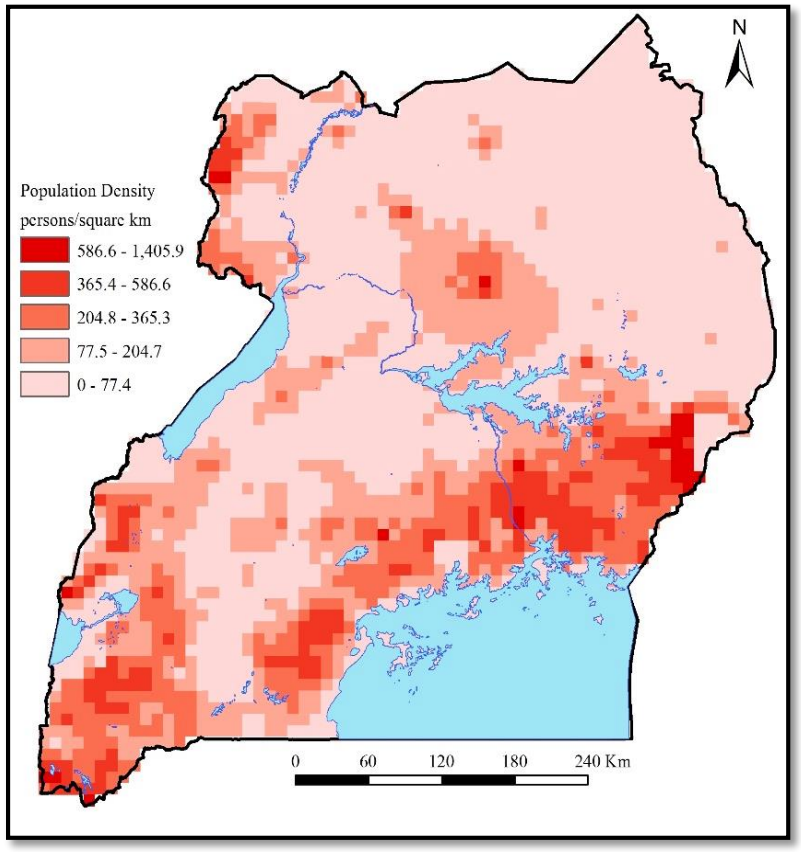


Uganda farming systems (Parsons, 1970; NEMA, 1998)

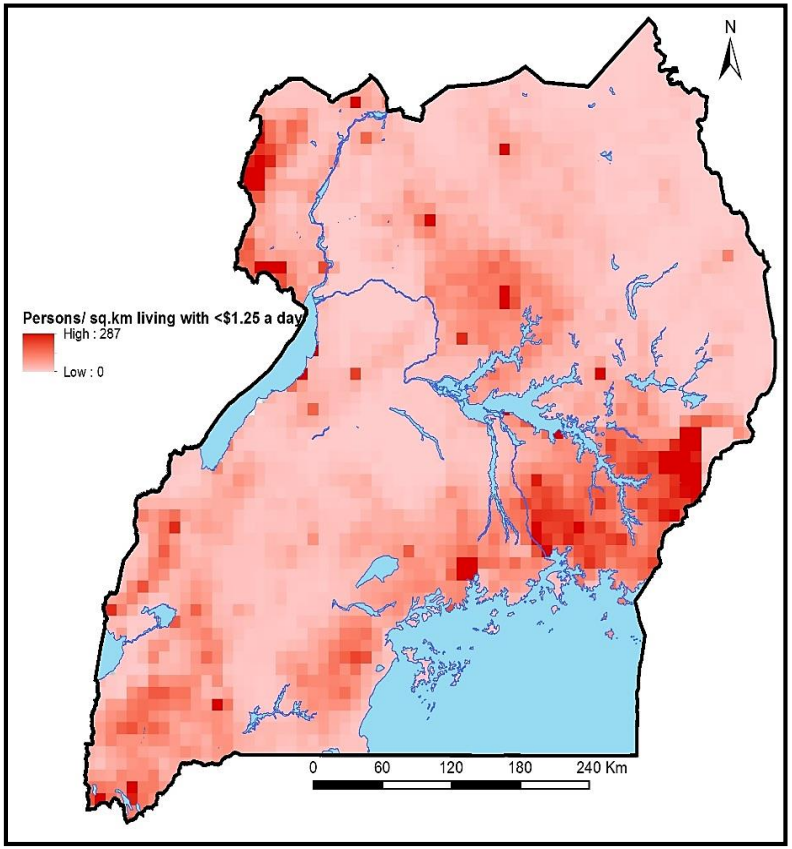


Uganda slope

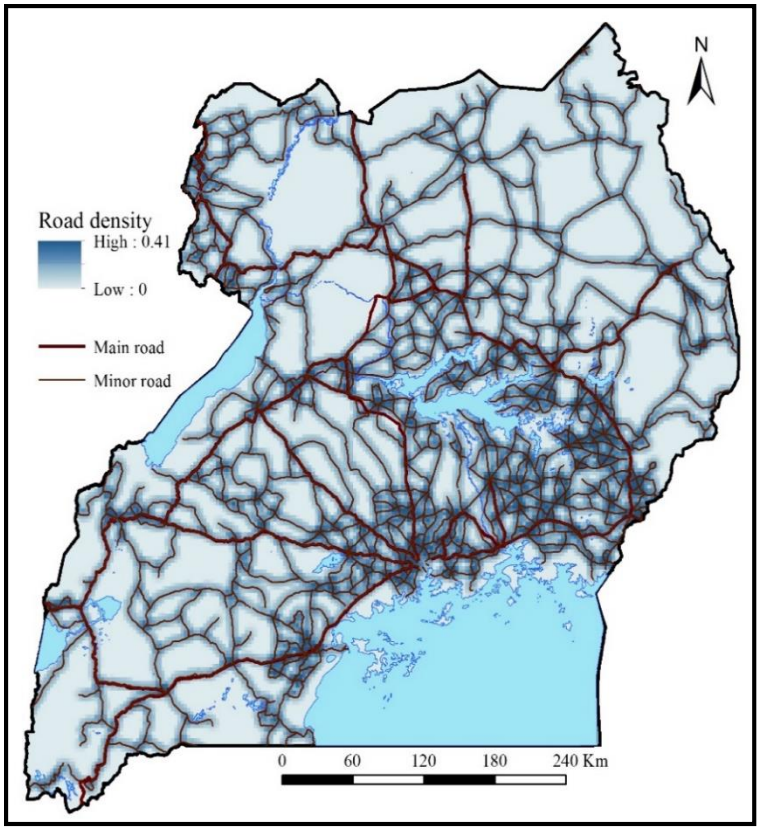
Appendix D: Spatial Distributions of selected socioeconomic variables



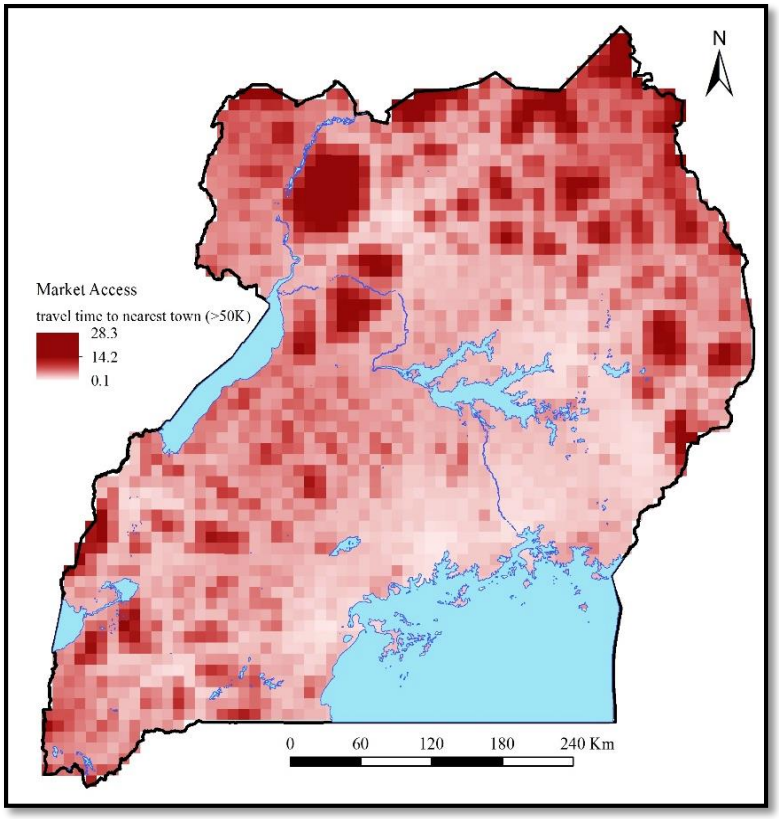
Uganda population density



Uganda poverty density

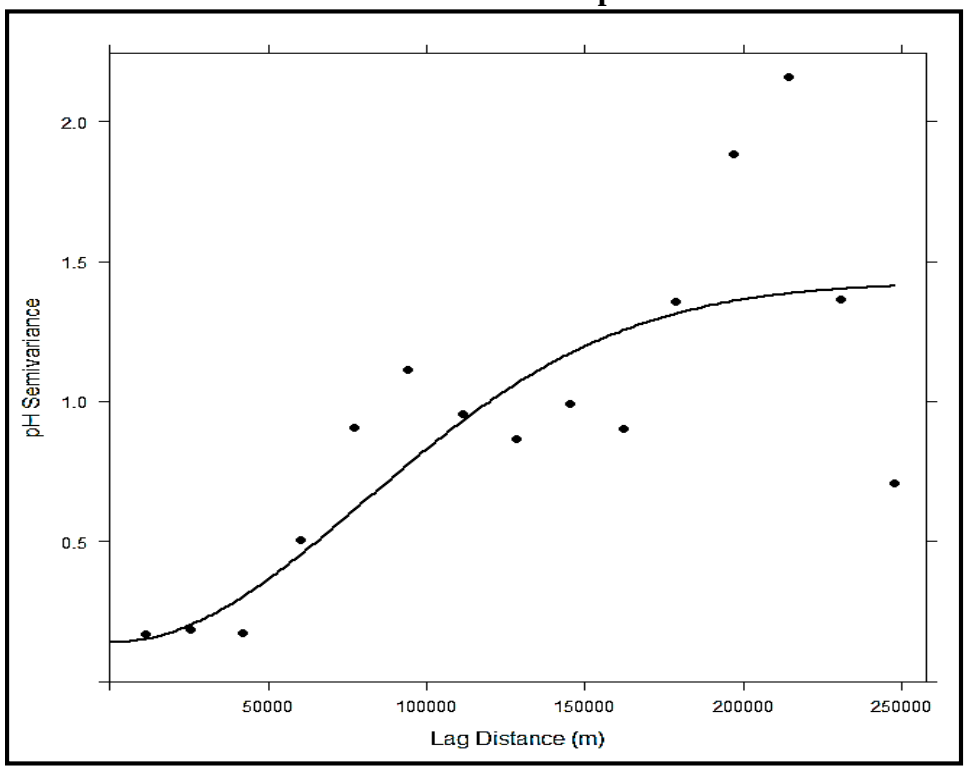


Uganda road density

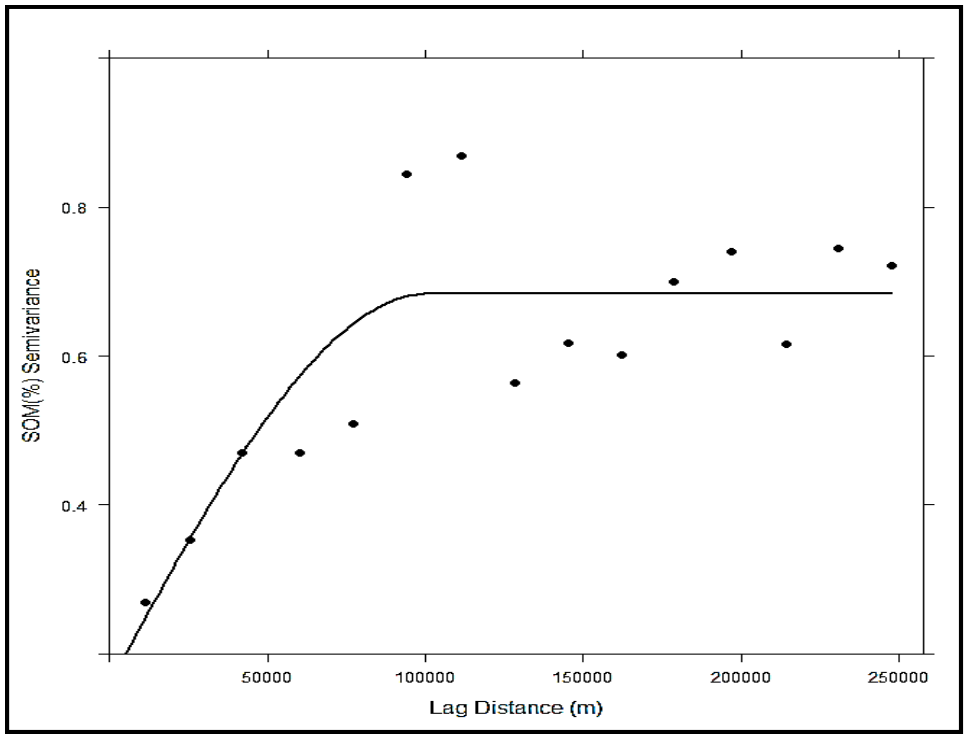


Uganda market access

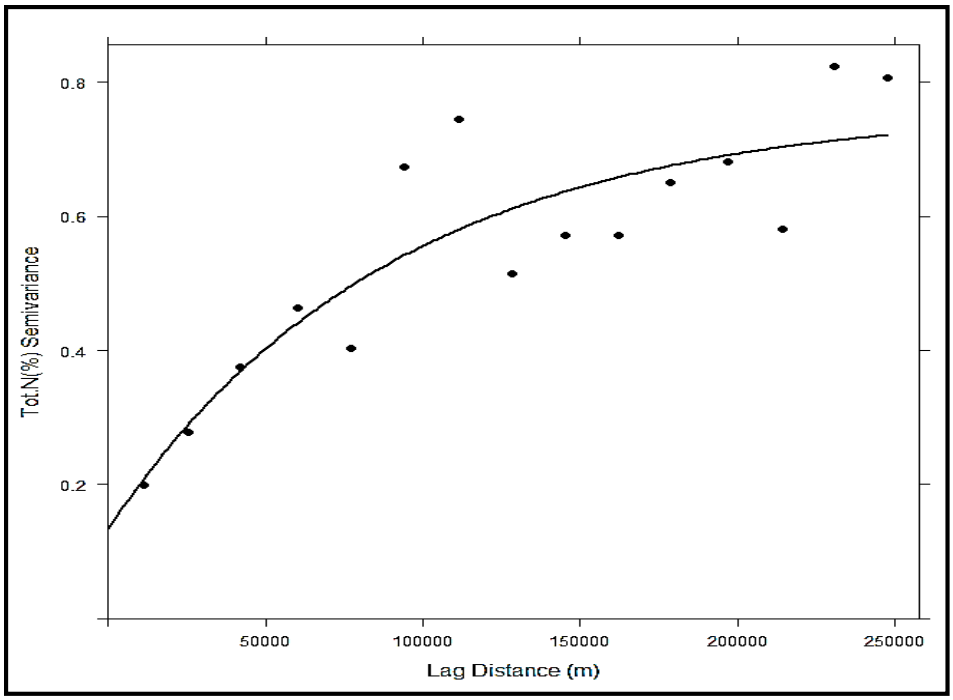
Appendix E: Fitted Semi-variograms of Selected Soil Chemical and Physical Properties



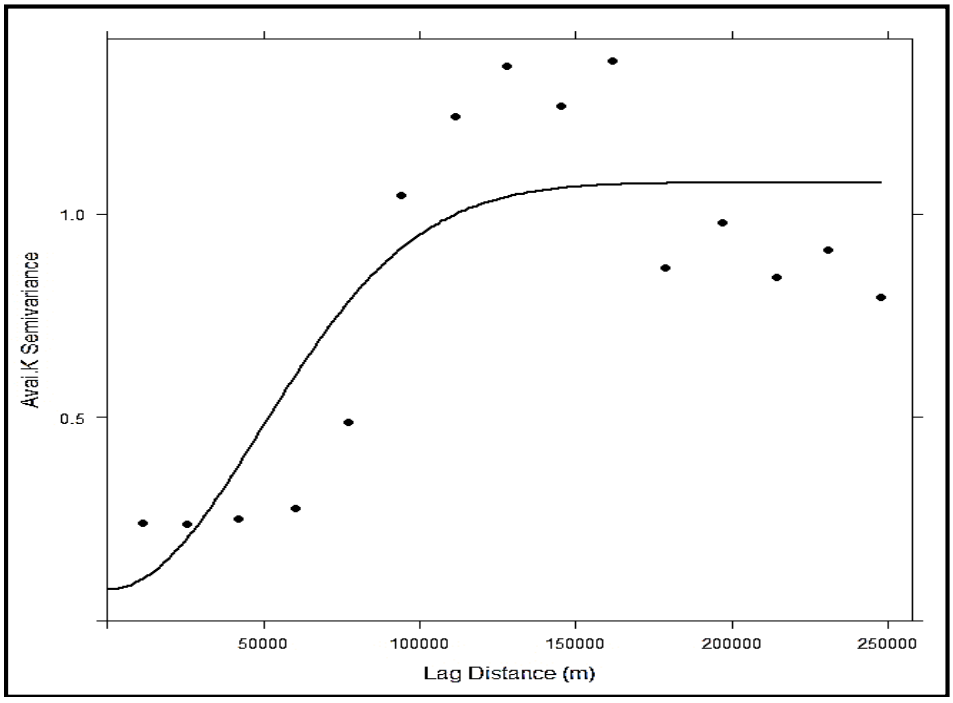
pH



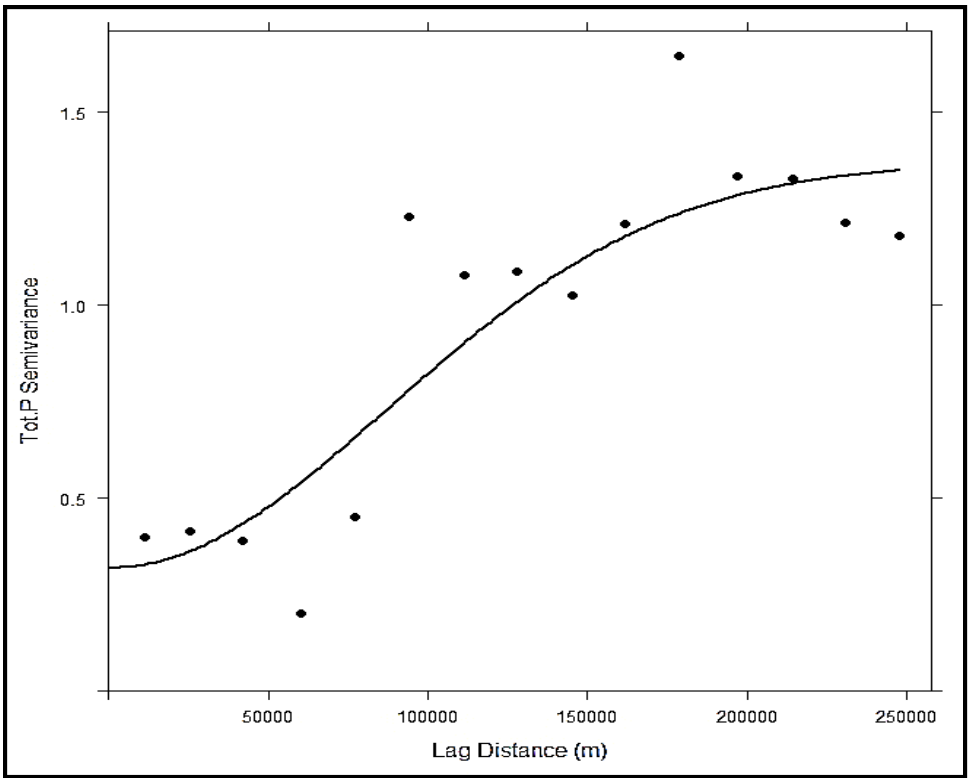
Soil organic matter



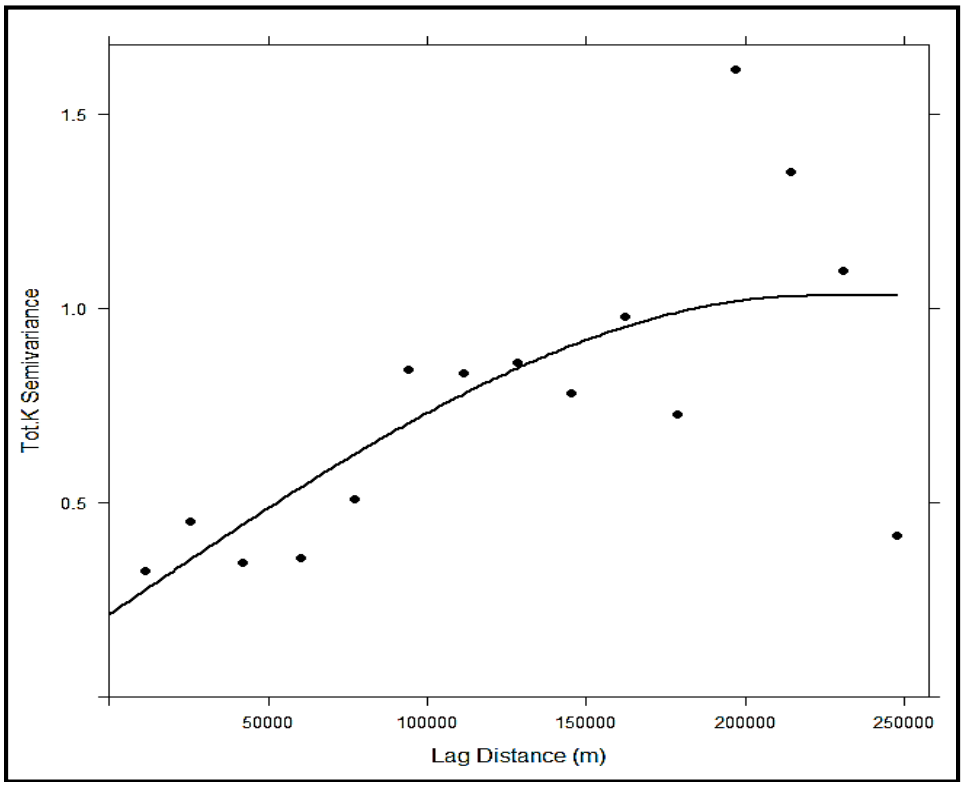
Total Nitrogen



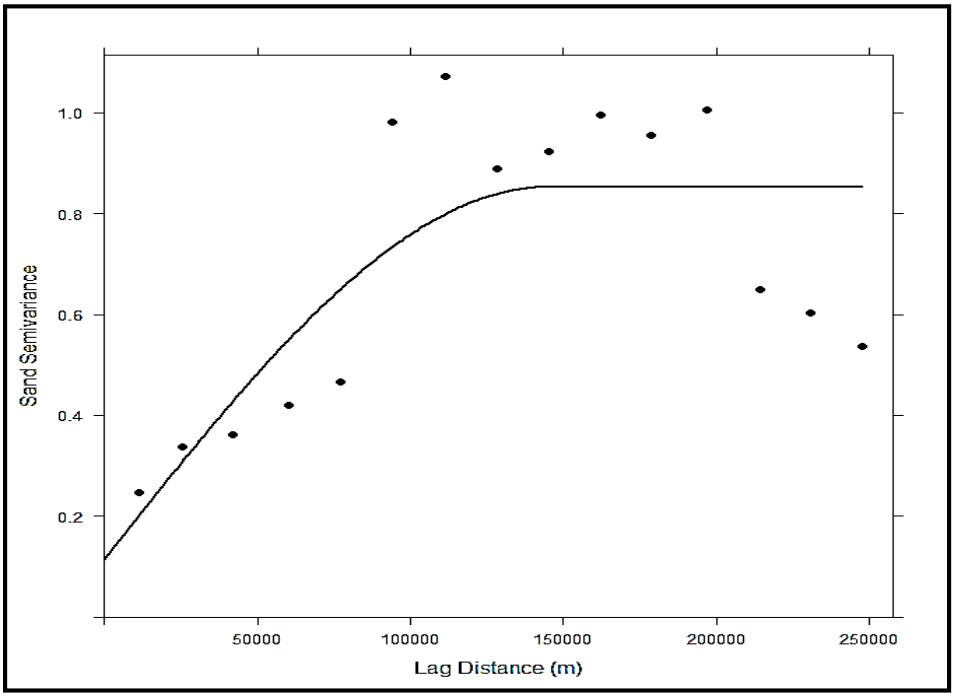
Available potassium



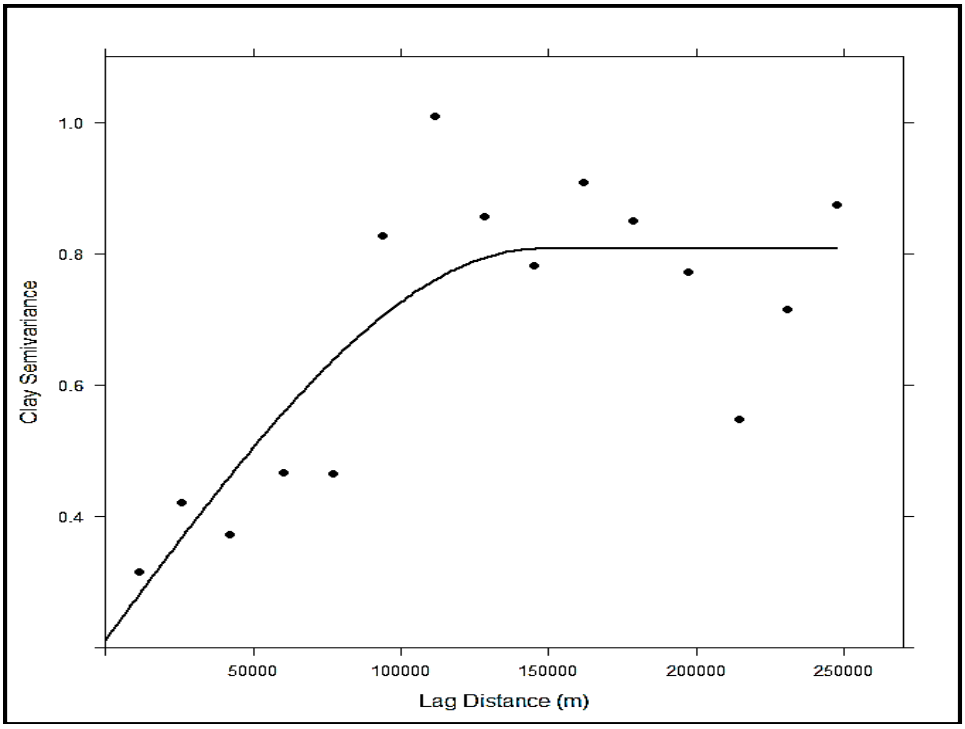
Total phosphorus



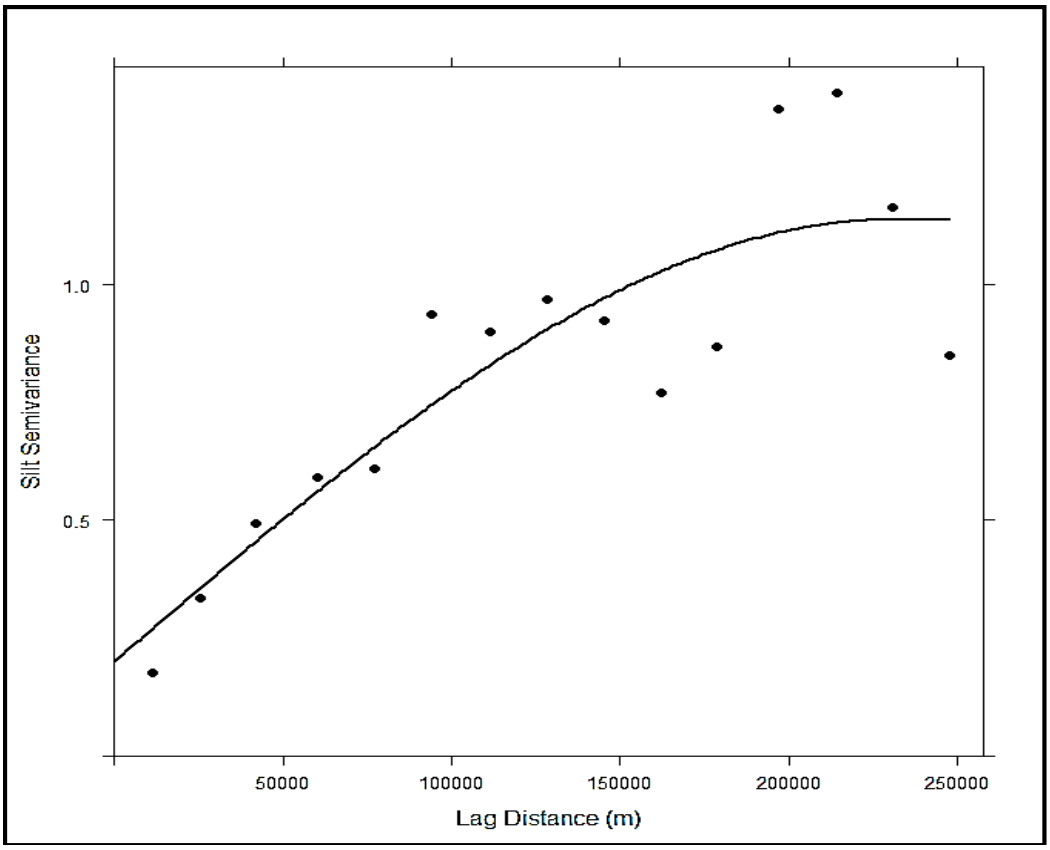
Total potassium


Sand Semivariance
1.0
0.8
0.6
0.4
0.2
50000
100000
150000
200000
250000
Lag Distance (m)

Sand


Clay Semivariance
1.0
0.8
0.6
0.4
50000
100000
150000
200000
250000
Lag Distance (m)

Clay


Silt Semivariance
1.0
0.5
50000
100000
150000
200000
250000
Lag Distance (m)

Silt

Appendix F: Chronologically ranked adjusted R^2 explaining for the variability of selected soil properties on a national scale.

Strength of Environmental/ Socioeconomic Correlation	Soil Parameter	Environmental/ Socioeconomic factors	Adjusted R^2
Strong (1.00 > adj. R^2 >= 0.64)	N (%)	GEGE, CL, LULUM	0.71
	N (%)	GEGE, CL	0.70
	N (%)	GEGE, CL, LULM, SOECO	0.70
	N (%)	CL, LULM, SOECO	0.70
	N (%)	CL	0.70
	N (%)	CL, SOECO	0.70
	N (%)	CL, LULM	0.70
	Tot. P (%)	GEGE, CL, LULM, SOECO	0.69
	pH in water	GEGE, CL, LULM, SOECO	0.68
	pH in water	CL, LULM, SOECO	0.66
	Avai. K (ppm)	GEGE, CL, LULM, SOECO	0.66
	Tot. P (%)	LULM, SOECO	0.66
	Tot. P (%)	CL, LULM, SOECO	0.65
	SOM (%)	GEGE, CL, LULM, SOECO	0.64
	Tot. P (%)	GEGE, CL, LULUM	0.64
Moderate (0.64 > R^2 > =0.25)	SOM (%)	GEGE, CL, LULUM	0.63
	N (%)	GEGE, SOECO	0.63
	N (%)	GEGE	0.63
	Avai. K (ppm)	GEGE, CL, LULUM	0.63
	(%)	GEGE, CL, LULM, SOECO	0.63
	Tot. K (%)	GEGE, CL, LULUM	0.63
	Tot. K (%)	GEGE, CL	0.63
	pH in water	GEGE, CL, LULUM	0.62
	SOM (%)	CL, LULM	0.62
	SOM (%)	GEGE, CL	0.62
	SOM (%)	GEGE, LULUM	0.62
	N (%)	GEGE, LULUM	0.62
	Avai. K (ppm)	CL, LULM, SOECO	0.62
	Tot. P (%)	CL, LULM	0.62
	SOM (%)	CL, LULM, SOECO	0.61
	Avai. K (ppm)	CL, LULM	0.61
	Tot. P (%)	GEGE, LULUM	0.61
	Tot. P (%)	LULM	0.61
	Tot. K (%)	CL, LULM, SOECO	0.60
	Tot. K (%)	CL, LULM	0.60
	Tot. K (%)	GEGE, LULUM	0.60
	Tot. K (%)	CL	0.60
	Tot. K (%)	GEGE, SOECO	0.60
	SOM (%)	CL	0.59

	SOM (%)	CL, SOECO	0.59
	SOM (%)	GEGE	0.59
	SOM (%)	GEGE, SOECO	0.59
	Tot. K (%)	CL, SOECO	0.59
	Tot. K (%)	GEGE	0.59
	pH in water	CL, LULM	0.58
	Sand (%)	GEGE, CL, LULM, SOECO	0.58
	Sand (%)	GEGE, CL, LULUM	0.58
	Sand (%)	GEGE, LULUM	0.58
	Sand (%)	GEGE, CL	0.58
	Sand (%)	GEGE, SOECO	0.58
	Sand (%)	GEGE	0.58
	Silt (%)	GEGE, CL, LULM, SOECO	0.57
	Silt (%)	GEGE, SOECO	0.56
Moderate (0.64 > R^2 > =0.25)	Clay (%)	GEGE, CL, LULM, SOECO	0.56
	Silt (%)	GEGE	0.54
	pH in water	CL, SOECO	0.53
	Avai. K (ppm)	GEGE, LULUM	0.53
	Silt (%)	GEGE, CL, LULUM	0.53
	Silt (%)	GEGE, LULUM	0.53
	Silt (%)	GEGE, CL	0.53
	Clay (%)	GEGE, SOECO	0.53
	Sand (%)	CL, LULM, SOECO	0.52
	Sand (%)	CL, LULM	0.52
	Sand (%)	CL, SOECO	0.52
	Sand (%)	CL	0.52
	Silt (%)	CL, LULM, SOECO	0.52
	Silt (%)	CL, SOECO	0.51
	Clay (%)	GEGE, CL, LULUM	0.51
	Clay (%)	GEGE, CL	0.51
	Avai. K (ppm)	LULM, SOECO	0.50
	pH in water	GEGE, SOECO	0.49
	pH in water	GEGE, CL	0.49
	Tot. K (%)	LULM, SOECO	0.49
	Clay (%)	CL, LULM, SOECO	0.49
	Silt (%)	CL, LULM	0.48
	Silt (%)	CL	0.48
	Clay (%)	GEGE, LULUM	0.48
	Clay (%)	CL, SOECO	0.48
	pH in water	GEGE, LULUM	0.46
	SOM (%)	LULM, SOECO	0.45
	Clay (%)	GEGE	0.45
	Tot. K (%)	SOECO	0.44
	Tot. P (%)	GEGE, CL	0.43
	SOM (%)	LULM	0.42

	Tot. K (%)	LULM	0.42
	pH in water	CL	0.40
	Avai. K (ppm)	LULM	0.40
	Tot. P (%)	CL, SOECO	0.40
	Tot. P (%)	GEGE, SOECO	0.40
	Clay (%)	CL, LULM	0.40
	Clay (%)	CL	0.39
	pH in water	GEGE	0.38
	SOM (%)	SOECO	0.38
	N (%)	LULM, SOECO	0.38
	N (%)	SOECO	0.37
	pH in water	LULM, SOECO	0.36
	Tot. P (%)	CL	0.36
	Avai. K (ppm)	GEGE, CL	0.34
	Tot. P (%)	GEGE	0.34
	Clay (%)	LULM, SOECO	0.33
	Avai. K (ppm)	CL, SOECO	0.32
	Tot. P (%)	SOECO	0.32
	pH in water	SOECO	0.31
	N (%)	LULM	0.31
	Sand (%)	LULM	0.29
	Clay (%)	SOECO	0.29
	Avai. K (ppm)	CL	0.28
	Sand (%)	LULM, SOECO	0.28
	Clay (%)	LULM	0.28
	Silt (%)	LULM, SOECO	0.25
	Sand (%)	SOECO	0.23
	Silt (%)	LULM	0.23
Weak ($0.25 > R^2 >= 0.04$)	Avai. K (ppm)	GEGE, SOECO	0.21
	Avai. K (ppm)	SOECO	0.17
	Silt (%)	SOECO	0.17
	Avai. K (ppm)	GEGE	0.14
No correlation ($0.04 > R^2 >= 0.00$)	pH in water	LULM	0.02

Ranking is based on adjusted R^2 in the order from the highest to the lowest value.
Note: Abbreviations: GEGE; Geology/Geomorphology, CL; Climate, LULUM; Land use/ Land use management, SOECO; Socioeconomic.