MORPHOLOGY, PHYSICO-CHEMICAL PROPERTIES AND CLASSIFICATION OF THE SOILS DEVELOPED ON VOLCANIC PARENT MATERIALS OF NORTHERN PROVINCE OF RWANDA

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE AND LAND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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ABSTRACT

A study was carried out on soils developed from volcanic parent materials of Northern Province of Rwanda to expose the current soil conditions, aiming largely on pedological characterization but to a certain extent on assessment of potentials and limitations of soils for production of major crops in the area. Three representative pedons namely KNG-P1, KNG-P2and GHNG-P1were identified and described. Sixteen soil samples were collected from different pedogenic horizons and analysed in the laboratory for physico-chemical properties. Pedons were classified using USDA Soil Taxonomy and FAO-WRB for Soil Resources. Results showed that soils were shallow to very deep and well drained. Topsoils were very dark coloured with colour values of ≤ 2 in all pedons. Texture was generally loamy with bulk densities of < 1.35 g/cm^3. Studied topsoils were medium acid (pH 5.57) to mildly alkaline (pH 7.41), with high to very high organic carbon ranging from 3.97 to 13.03%. pH_{NaF} was > 9.5 in Pedons KNG-P1 and KNG-P2, reflecting exchange complex dominated by amorphous materials and/or humus complexes. Pedons KNG-P1 and KNG-P2 met the "andic properties" requirement of phosphorus retention capacity≥ 85%. Melanic index values indicated that these two pedons were characterised more by fulvic than humic acids. Nutrient imbalance was observed in studied soils, implying suboptimal nutrient uptake and toxicity. Degree of weathering of studied soils was low as indicated by weathering indices. Pedons KNG-P1 and KNG-P2 were classified as Andisols/Andosols and GHNG-P1 as Mollisols/Phaeozems. Land units represented by Pedons KNG-P1 and KNG-P2 were rated as marginally suitable while land unit represented by Pedon GHNG-P1 was rated as moderately suitable for the major crops of the area. Application of P fertilizers coupled with efficient placement and soil conservation should be undertaken in the study area.

DECLARATION

I, Providence Uwitonze, do hereby declare to the Senate of Sokoine University of Agriculture, that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

…….. ……

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The above declaration is confirmed by;

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DEDICATION

I wish to dedicate this work to my late father, my belovedmother, brother and sisters, my niece and nephew,friends and relatives.

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LIST OF ABBREVIATIONSAND SYMBOLS

AEZ	Agro-ecological zone
AGRA	Alliance for Green Revolution in Africa
Al	Aluminium
AWC	Available Water Capacity
C/N	Carbon to Nitrogen ratio
Ca	Calcium
CEC	Cation Exchange Capacity
CEC_{clay}	Cation Exchange Capacity of clay
CEC_{soil}	Cation Exchange Capacity of soil
cm	centimetre
cmol(+)	centimole
Cu	Copper
e.g.	For example
EC	Electrical conductivity
et al.	and others
Eq.	Equation
FAO	Food and Agricultural Organization of the United Nations
Fe	Iron
g	gramme
GHNG-P1	Gahunga pedon 1
K	Potassium
kg	kilogramme
KNG-P1	Kinigi pedon 1
KNG-P2	Kinigi pedon 2

m	metre
ma.s.l.	meter above sea level
Mg	Magnesium
mm	millimetre
Mn	Manganese
Na	Sodium
^{o}C	degree Celsius
OC	Organic carbon
OM	Organic matter
P	Phosphorus
pH	Hydrogen ion concentration (soil reaction)
PRC	Phosphate Retention Capacity
Si	Silicon
SUA	Sokoine University of Agriculture
TEB	Total Exchangeable Bases
UNESCO	United Nations Education and Scientific Organization
USDA	United States (of America) Department of Agriculture
WRB	World Reference Base
Zn	Zinc

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information and Justification

Rwanda is a hilly, densely populated country that covers an area of 26 338 km^2. The average population density in 2012 was 415 people per km^2(National Institute of Statistics of Rwanda (NISR), Ministry of Finance and Economic Planning (MINECOFIN), 2012).Based on relief, elevation and climate, the country is divided into 3 agro-ecological zones (AEZs),also known as altitudinal zones namely, Highlands, Midlands and Lowlands (Van Wambeke, 1963; International Service for National Agriculture Research, 1982; Verdoodt and Van Ranst, 2003a).The Highlands, Midlands and Lowlands occupy 17, 32 and 38% of the territory, respectively (Verdoodt and Van Ranst, 2003a). The remaining 13% of the country is constituted by escarpments, marshes, islands and lakes (Verdoodt and Van Ranst, 2003a).

Rwandan soils are generated by physico-chemical weathering of basic schistose, quartzite, gneiss, granite and volcanic rocks that make up the superficial geology of the country. Soils derived from volcanic materials occupy 14% of the total area (Twagiramungu, 2006). Soils derived from recent volcanic materials are found at the piedmonts of volcanoes and soils derived from old volcanic materials are found in the plateau of Cyangugu in the Southwest part of the country (Twagiramungu, 2006). Due to the complexity of relief and parent materials, Rwanda's biophysical environment varies across very short distances (Birasa *et al.,* 1990; Steiner, 1998).

The first soil survey in Rwanda started in1955 at Rubona station and was undertaken by a team of the Institut National d'Études Agronomiques au Congo (INEAC). After

independence in 1962, INEAC activities were continued by the Institut des Sciences Agronomiques du Rwanda (ISAR) which was integrated in 2012 into the Rwanda Agriculture Board (RAB) (Rushemuka *et al*., 2014). By 1963, the major soil types of the country had been described (Van Wambeke, 1963). In the 1980s, almost all soil knowledge acquired by the INEAC-ISAR team was synthesized into a soil association map at a scale of 1:250 000 (Prioul and Sirven, 1981 cited byRushemuka *et al*., 2014).

Pedological surveys in Rwanda have indicated the presence of volcanic ash soils derived predominantly from basic ashes (Mizota and Chapelle, 1988).Soils formed from volcanic materials have many distinctive properties that are rarely found in soils derived from other parent materials (Wada, 1986). These soils typically form from weathering of loose volcanic ejecta (tephra) such as cinder, pumice, ash, tuff and other volcanic ejecta (Yatno and Zauyar, 2008) and they have high potentials for agricultural production. They are characterized by properties such as low bulk density, high water retention capacity, an exchange complex dominated by variable charge surfaces, and high anion retention capacity (Shoji *et al.,* 1993; Ugolini and Dahlgren, 2002; Msanya *et al*., 2007).These soils are veryimportant for human use and support high human population densities (Msanya *et al*., 2007; McDaniel *et al*., 2012) due to their high potential for agricultural production. However, some of them produce well below their potential capacity due to farmers' lack of understanding of the nature and properties and proper management of these soils (Verdoodt and Van Ranst, 2003a).

Soils developed on volcanic materials are generally classified as Andisols (Shoji *et al*., 1993), but not all volcanic soils are Andisols, depending on the extent of weathering and soil formation processes they can be classified into other orders (Shoji *et al*., 1993).Rwandan soils are naturally fragile. The hilly nature of the Rwandan topography is

one of the main factors of soil vulnerability (Twagiramungu, 2006). Indeed, in Rwanda, 50% of cultivated lands are on more than 18% slope, 20% have more than 40% of slope, while the remaining occur on surfaces with more than 60% slope (Roose *et al*., 1993). Soil erosion, pollution and sedimentation of water sources by cultivation of steep slopes without proper erosion control, soil nutrient depletion, and soil acidity associated with Al toxicities, are the main soil-related constraints to agricultural development in Rwanda (Mbonigaba and Culot, 2010).

The northwest region of Rwanda, which is a steeply sloping highland experiences abundant rainfall that usually causes erosion, flooding and landslides (Twagiramungu, 2006). Also soil erosion has been accelerated by deforestation attributed to high population density (Twagiramungu, 2006; Mbonigaba and Culot, 2010). The Government of Rwanda has implemented mechanical and biological methods to reduce soil erosion. According to Kabiligi (1985), erosion control has been formally practised in Rwanda since 1937 at Institut National d'Études Agronomiques au Congo(INEAC) research station, and was widened to the whole country in 1947 (Rushemuka *et al*., 2014). Many bench (radical) terraces were thus constructed. As a result, in many regions of the country, the landscape has changed remarkably (Rushemuka *et al*., 2014). Terracing reduces slope steepness and divides the slope into short gently sloping sections (Morgan, 2005), due to the cut and filling during its construction, B horizon is exposed to the surface (Bizoza and De Graff, 2012).Terracingtransforms the landscape into stepped agro-ecosystems(Rwanda Environment Management Authority,2009).

In addition to soil erosion, land degradation has been also accelerated by human activities through application of acidifying fertilizers, deforestation and pollution (Mbonigaba and Culot, 2010). Due to land scarcity farmers have converted pasture and woodland into

cropland (Verdoodt and Van Ranst, 2003a). As reported by Kiakojouri and Taghavi Gorgi (2014) and Mukhlis *et al*. (2014), land use conversion may cause important changes in physical and chemical properties of soils. Agricultural activities such astillage(mechanised or by hand), weeding, terracing, subsoiling, deep ploughing, manure, compost and fertiliser application, liming, draining and irrigation have been reported tochange the soil chemical, physical, or biological properties (Bridges and de Bakker, 1997). Shoji *et al*. (1993) found that farming changes chemical and biological properties of volcanic soils, such as decreasing organic carbon content, enrichment of phosphorus through fertilization and accumulation of heavy metals.

Soils are known to vary greatly across landscapes, and are influenced by topographical features, vegetation types, lithology, climate and land use; and these may influence spatial and temporal variations in soil physico-chemical properties (Msanya *et al.*, 2003).Due to the anthropogenic activities mentioned above, the over 30 year-old land resources surveys of the country (Van Wambeke, 1963) may no longer show the reality.Thus, pedological characterization is needed to produce database for land use planning. Therefore research on soil physical, chemical and morphological properties and the classification of soils developed on volcanic parent materials of Northern Province in Rwanda was deemed necessary to expose the current situation and provide opportunities for a more rational management of the land resources. Pedological characterisation provides information and knowledge on soil properties aimed at identifying potentials and limitations of the characterised soils, thereby helping to determine the correct type and amounts of fertilizer to be applied for optimum crop production and sustenance, and enabling the prediction of type of crop to grow.

1.2 Objectives

1.2.1 The overall objective

The overall objective of this study was to characterisesoils developed on volcanic parent materials of Northern Province of Rwandain order to generate the needed database for land use planning.

1.2.2 Specific objectives

The specific objectives were:

i. To identify and describe representative soils of the study area in terms of their morphological properties and ecological conditions.
ii. To determine the physical and chemical properties of the soils.
iii. To classify the soils using the 'United States Department of Agriculture (USDA) Soil Taxonomy' and the 'World Reference Base for Soil Resources' (WRB) classification systems.
iv. To appraise the potentials and limitations of the soils for some important crops grown in the area.

1.2.3 Research questions

i. What are the major morphological and ecological features and soil formation processes in the study areas?
ii. What are the chemical, physical and mineralogical characteristics of the dominant soils in the selected study areas?
iii. What are the soil types in the study areas as per FAO-WRB for Soil Resources and USDA Soil Taxonomy schemes of soil classification?
iv. What are the potentials and limitations of the soils for production of major crops in the study areas?

CHAPTER TWO

2.0LITERATURE REVIEW

2.1Weathering of Volcanic Materials

Weathering comprises all physical and chemical changes produced in rocks at or near the earth's surface by atmospheric agents (Brady and Weil, 2008).

2.1.1Physical weathering

This is the physical break down of rocks whereby their chemistry is not altered. Several forces are responsible for physical weathering, such as ice, heat and pressure differences, biological influence through prying or wedging effect of plant roots growing in rock fissure and through animal burrowing (Ellis and Mellor, 1995; Brady and Weil, 2008; Schaetzl and Thompson, 2015).

2.1.2Chemical weathering

Chemical weathering, also known as decomposition, involves the chemical and biochemical breakdown of rocks and minerals into different products and compounds. Common end products of chemical weathering are clays, soluble acid compound and various ionic species (Brady and Weil, 2008). The intensity of weathering is largely governed by climatic conditions that govern temperature and movement of water in the soil and rock, water quality and chemical and mineral composition of the rock themselves (Schaetzl and Thompson, 2015).The reactions involved are hydrolysis,oxido-reduction reaction,hydration, dissolution and carbonation (Eq. 1 - 3) (Brady and Weil, 2008). Volcanic materials are easily decomposed (Shoji *et al*., 1993;Legros, 2013). They abruptly yield large amounts of Si, Al, Fe, directly if they are glassy or after hydrolysis of minerals that they usually contain (Legros, 2013).

$CaFeSi_2O_6$ (augite) + $2H_2O \rightarrow Ca^{2+} + Fe^{2+} + SiO_2 + 4OH^-$ ..... (1)

$KAlSi_3O_8$ (microcline) + $2H_2O \rightarrow K^+ + Al^{3+} + SiO2 + 4OH^-$ ..... (2)

$2NaAlSi_3O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2Na^+$ ..... (3)

(Plagioclase) (Kaolinite) (Silica)

2.2Soil Formation

Soils are often defined as "dynamic natural bodies having properties derived from the combined effect of climate and biotic activities (organisms), as modified by topography, acting on parent materials over periods of time" (Brady and Weil, 2008). The parent material determines the starting mineral composition, topography determines the amount of water entering the profile and climate determines the temperature at which the reactions take place (Brady and Weil, 2008). Biota, particularly plants, determines the types and amounts of humus in the profile and finally time determines the period over which the sum of all the processes acts (Singer and Munns, 2002; Brady and Weil, 2008).

2.2.1 Formation of Andisols

2.2.1.1Climate

Formation of Andisols is strongly influenced by climatic factors (Shoji *et al*., 1993). Climate has many different components such as temperature, precipitation, evaporation, transpiration, evapotranspiration, humidity, duration, seasons etc. (Shoji *et al*., 1993).The climate influences the nature and intensity of the weathering that occurs over large geographic areas (Brady and Weil, 2008). The principal climatic variables influencing soil formation are effective precipitation and temperature, both of which affect the rates of chemical, physical, and biological processes (Brady and Weil, 2008). Temperature and precipitation have a controlling influence on the formation and properties of Andisols (Shoji *et al*., 1993). Andisols generally form rapidly in humid climates (Ugolini and

Dahlgren, 2002). The rate of chemical weathering in tephras increases remarkably with increasing temperature in Andisols in the udic moisture regime while a decrease in precipitation decreases soil moisture and leaching, hence decreasing the rate of chemical weathering in the soil (Shoji *et al*., 1993).

2.2.1.2 Topography

Topography is central to the catena concept for soil development (Hook and Burke, 2000), which is characterized by leaching and redistribution of elements and soil material along hill slopes (Hook and Burke, 2000; Brady and Weil, 2008). The direction of the slope influences the amount and intensity of solar radiation to which a location is exposed and subsequently the temperature regime, which affects soil biological and chemical processes as well as evaporation (Seibert *et al*.,2007). Soil forming processes are affected by the topography. However, the relationship of topography to tephra, deposition, erosion and redistribution of moisture are especially important factors affecting the genesis and properties of Andisols (Shoji *et al*., 1993).The differences in soil characteristics associated with landscape position are usually attributed to differences in the runoff, erosion and deposition processes which affect soil genesis (Dahlgren *et al.*, 1997; Dengiz, 2010).

2.2.1.3Parent material

Parent material is one of the five factors of soil development (Jenny, 1941). Soil starts out as parent material and gradually develops, as various pedogenic, geomorphic and biological processes act on initial parent materials changing them into soil that is unique to that location in time (Schaetzl and Thompson, 2015). Genesis of Andisols is strongly influenced by the properties of the parent material such as ash, tuff, pumice, cinders, lahars, and other volcanic ejecta (Yatno and Zauyah, 2008). Glass, the most abundant volcanic ejecta component is a metastable supercooled liquid which results from the

reduction in nucleation and crystallization rates due to rapid cooling of the magma ejecta. Volcanic glass shows the least resistance to chemical weathering among rock. Thus glass weathering primarily determines the genesis of volcanic ash soils (Shoji *et al*., 1993; Ugolini and Dahlgren, 2002; Arnald, 2015). Kirkman (1980) showed that weathering of andesitic and coloured glasses is very rapid compared to that of rhyolitic or non-coloured glass and that fine, soft, structure and extensive substitution of Al for Si in andesitic glass favour the rapid weathering.

The Andisols order is defined by characteristics inherited from weathering products of volcanic material not on assumed presence of volcanic ejecta. The distinctions of the parent materials may result in different characteristics of the soils. As a consequence, the productivity of the soils may also be different (Yatno and Zauyah, 2008). Most Andisols have formed in acidic volcanic deposits and because of that deposits contain Al and Si rich materials, they weather to form allophane and other short range minerals (Schaetzl and Thompson, 2015).

2.2.1.4Biological factors

Biological factors include plant, microorganisms and animal activity. Organic matter accumulation, biochemical weathering, profile mixing, nutrient cycling, and aggregate stability are all enhanced by activities of organisms in the soil. Vegetative cover reduces natural soil erosion rates, thereby slowing down the rate of mineral surface soil removal. Organic acids produced from certain types of plant leaf litter bring iron and aluminium into solution by complexation and accelerate the downward movement of these metals and their accumulation in the B horizon (Brady and Weil, 2008). Vegetation rapidly recovers on tephras deposits due to favourable physico-chemical properties for plant growth which in turn facilitate soil development by the rapid release of nutrient through weathering

(Shoji *et al*., 1993). Human beings alter volcanic soils in many ways and new soils are created when intensive farming is practiced (Shoji *et al*., 1993).

2.2.1.5Time

The time of soil formation starts when the new rock is exposed to the weathering environment (Brady and Weil, 2008). Time of tephra deposition is regarded as time zero of Andisols formation. Andisols show rapid change or development of horizon sequences with time. The rate of development in Andisols profiles is determined by various factors such as soil moisture and temperature, rock types, texture of tephras etc. It is greater in humid warm climates than in dry cooler climates and in mafic tephras compared to felsic tephras (Shoji *et al*., 1993). Volcanic soil occurring closer to the volcanoes often develop a multisequum as soil age increases since they are formed by intermittent tephra deposits (Shoji *et al*., 1993).

2.3Dominant Pedogenic Processes Leading to Formation of Volcanic Soils

The processes by which soil formation, or pedogenesis occurs, are known collectively as pedogenic processes, of which there are four main groups namely additions, transformations, transfers and losses (Ellis and Mellor, 1995; Sarkar and Haldar, 2014). Additions involve both organic and mineral materials added to soil, and can occur at surface or within the soil itself (Sarkar and Haldar, 2014). These materials are then transformed by the process of organic matter decomposition, mineral weathering and clay mineral formation (Sarkar and Haldar, 2014). Soil components can also undergo transfer from one part of the soil to another by a variety of processes which involve either transport in water or mechanical mixing. Some of the materials are lost from the soil via a number of processes, either as individual components or in combination with others (Ellis and Mellor, 1995). The pedogenic processes produce soil horizons combination giving rise to

different soil types (Sarkar and Haldar, 2014). Formation of non-crystalline materials and the accumulation organic matter are the most dominant pedogenic processes occurring in most soil formed in volcanic materials (Shoji *et al*., 1993).This combination of processes, occurring preferentially in soils formed in volcanic materials, is termed andosolization (Shoji *et al*., 1993; Ugolini and Dahlgren, 2002).

Formation of non-crystalline materials is directly related to the properties of volcanic materials as parent material. The small particle size, the glassy nature of the particle and the high porosity and permeability of volcanic materials enhance chemical weathering rates. Rapid weathering releases elements, such as Si, Al, and Fe faster than crystalline minerals can form, resulting in soil solutions becoming over saturated with respect to meta-stable, no crystalline materials such as allophane, imogolite, opaline silica and ferrihydrate (Shoji *et al*., 1993; Ugolini and Dahlgren, 2002; Arnald, 2015).

A second factor contributing to the relative absence of crystalline minerals in the clay size fraction is that volcanic ash parent materials typically contain few precursor minerals (e.g. chlorite, mica) that can weather directly to crystalline 2:1 and 1:1 layer silicates. This deficiency of layer silicate clays may further impede formation of crystalline clay minerals due to the lack of a template that can serve to catalyse precipitation of crystalline layer silicates from soil solution (Shoji *et al.*, 1993). The accumulation of organic matter is due to the protection of organic matter. Organic matter is protected against bio-degradation by Al toxicity to microorganisms, sorption of degradation enzymes and organic matter substrate, physical protection within abundant microaggregates, and or phosphorus deficiency of microorganisms caused by high P retention (Ugolini and Dahlgren, 2002). Organic matter stabilisation may occur through formation of Al humus complexes and

sorption to allophane, imogolite and ferrihydrite and/or burial of soil by intermittent addition of volcanic materials (Ugolini and Dahlgren, 2002).

Development of A horizons by andosolization is characterised by accumulation of organic matter, organic matter stabilization by active Al and Fe, carbonic acid weathering (allophanic) versus organic acid weathering (nonallophanic) and formation of laminar opaline silica (Shoji *et al*., 1993). Formation of B horizon proceeds primarily by carbonic acid weathering with no significant translocation of Al, Fe and dissolved organic carbon. Therefore, preferential formation of noncrystalline materials such as allophane, imogolite, laminar opaline silica, ferrihydrite and Al/Fe humus complex is characteristic feature of the process of andosolization (Shoji *et al*., 1993).

Such formation of noncrystalline materials is not specific to Andisols. It is also widely observed for tephra–derived Spodosols making it difficult to separate Andisols and tephra derived Spodosols according to solid phase chemical criteria (Shoji and Ito, 1990). However, the major difference between andosolization and podsolization occurring in tephras was successfully cleared out by soil solution studies of Ugolini *et al*. (1988) and Ugolini and Dahlgren (1991). Andosolization is characterised by accumulation of Fe, Al, and dissolved organic carbon in the A horizon with little subsequent leaching of these component to B horizon and that formation of B horizon is dominated by in situ weathering. On the other hand, podzolization is a process driven in the upper profile (O, E and Bhs) by organic acids originating in the canopy and humus layer (Shoji *et al*., 1993). These organic acids play significant roles such as lowering of pH, preventing dissociation of carbonic acid, formation of mobile complexes with Fe, Al and other metals and migration as soluble metal-humus complexes to the B horizon where they are arrested (Ugolini and Dahlgren, 1991).

2.4 Soil Development on Volcanic Materials

Climate, together with its influence on vegetation, and time of exposure to weathering are the primary factors regulating soil development pathways in volcanic materials (Shoji *et al*., 1993;Ugolini and Dahlgren, 2002). Generally, Andisols form rapidly in humid climates and alter to other soil orders as soil ages and the degree of weathering increases (Ugolini and Dahlgren, 2002). Andisols are the typical product of weathering in both temperate and tropical environments with sufficient moisture (Ugolini and Dahlgren, 2002). With increased weathering intensity, metastable noncrystalline materials are gradually transformed into more stable crystalline minerals. This leads to the formation of Inceptisols (Ugolini and Dahlgren, 2002). Transition of Andisols to Inceptsols proceeds with formation of 1:1 layer silicate or increased concentration of 2:1 layer silicate clays (Shoji *et al*., 1993; Ugolini and Dahlgren, 2002). Formation of these minerals can consume a significant amount of active Al, resulting in a decrease of acid oxalate extractable Al and P retention and increased bulk density (Shoji *et al*., 1993).

On stable landscapes in the perhumid tropics, volcanic soils may transform to Oxisols (Ugolini and Dahlgren, 2002, Van Ranst *et al*., 2002). Tephra derived Oxisols accumulate a large amount of non-crystalline materials but they tend to be dominated by low activity clays such as oxyhydroxides of Al or ferric ironOxisols (Ugolini and Dahlgren, 2002, Van Ranst *et al*., 2002). Soil development is stalled in the Entisols/Vitrands stage under dry climate conditions as weathering is limited by moisture (Shoji *et al*., 1993 and Ugolini and Dahlgren, 2002). Spodosols are often the dominant soil in cool to cold humid conditions that favour the coniferous vegetation and predominance of organic acid weathering regime (Ugolini and Dahlgren, 2002).

2.5Properties of Volcanic Soils

2.5.1Mineralogical properties

The major primary minerals in fresh tephras are volcanic glass, plagioclase, quartz, pyroxenes, biotite, and olivine and so on. Minor minerals like apatite and tourmaline are also present. Allophane, imogolite, opaline silica, halloysite, ferrihydrite and 2:1 minerals are the most secondary minerals that can be found in volcanic soils (Nanzyo, 2002). However, those minerals are not exclusive to Andosols as they are also commonly found in Podzols but to a lesser degree (Arnald, 2015).

According to Shoji *et al*. (1993) the mineralogical composition of the colloidal fraction of soils derived from volcanic materials varies widely depending firstly on chemical, mineralogical and physical properties of the parent material. These determine the rate of chemical weathering, the amount and the distribution of reactants for synthesis of secondary materials and the pH through its influence on the base status of the soil. Secondly, post depositional weathering environment which is determined by interaction between soil temperature, rainfall and leaching, drainage effects, organic matter accumulation, addition of overburden ash deposition and the pH of the weathering environment (Shoji *et al*., 1993). Lastly the stage of soil formation which relates to the length of time that weathering has proceeded in a given deposition. As weathering proceeds in a well-drained profile, the soil profile transform from a Si-rich to Si-depleted environment as weathering reactions consume the glassy components of the parent and Si is leached from the profile (Shoji *et al*., 1993).

Andisols are often divided into two groups based on their mineralogical composition. Allophanic Andisols, dominated by allophane and imogolite and nonallophanic Andisols dominated by Al humus complexes and 2:1 layer silicates (Ugolini and Dahlgren, 2002).

2.5.1.1Allophane

Allophane is a group of non-crystalline, hydrous Al silicate with a varying chemical composition. It has a very large specific surface area ranging from 500 to 1 100 m^2/g (Gustafsson *et al*., 1998, Nanzyo, 2002).

2.5.1.2Imogolite

Imogolite isa short range order clay mineral belonging to the aluminosilicates with the chemical formula $SiO_2.Al_2O_3.2H_2O$. The specific surface area of imogolite ranges from 900-1 100 m^2/g (Gustafsson *et al*., 1998; Nanzyo, 2002). Imogolite has high anion adsorption capacity but is less reactive with phosphate than allophane (Nanzyo, 2002). The high anion adsorption capacity is a consequence of the gibbsite groups of the outer sheet, which causes imogolite to behave much like gibbsite. As in the case of gibbsite extra hydrogen ions are easily incorporated into the hydroxyls at the surface. Because of this, the outer surface of imogolite, in its pure form, possesses a net positive charge below pH 10, which favours the adsorption of anions in the natural pH range (Gustaffon *et al*., 1998).

2.5.1.3 Opaline silica

Opaline silica, with thechemical formula of $SiO_2.nH_2O$, is commonly found in organic rich A horizons of young soils forming on volcanic ash. Formation of opaline silica is favoured by rapid weathering of glass rich parent material, a pronounced seasonal period of dessication or freezing to concentrate solutes, and low Al activities which prevent formation of alumina silicate materials (Shoji *et al*., 1993; Ugolini and Dahlgren, 2002). Opaline silica is most often associated with the presence of high concentrations of organic matter (A horizon in Andosols) or soluble organic acids (E horizons of Spodosols) (Ugolini and Dahlgren, 2002).

2.5.1.4Halloysite

Halloysite, the hydrated form of kaolinite, is a 1:1 aluminosilicate clay mineral with the empirical formula $Al_2Si_2O_5(OH)_4.2H_2O$. Halloysite is a common constituent in volcanic derived soils and occurs as the dominant clay mineral in many Si-rich environments (Parfitt and Wilson,1985).

2.5.1.5Ferrihydrite

Ferrihydriteisa short range order iron hydroxide with the chemical formula $5Fe_2O_3$**.** $9H_2O$. Ferrihydrite is typically found as dominant iron oxyhydroxide in Andisols. Because Fe has a greater stability in oxyhydroxides as compared to humus complexes, concentration of Fe- humus complexes are typically low (Ugolini and Dahlgren, 2002).

2.5.2Chemical properties

Volcanic soils are characterised by the accumulation of organic matter (Ugolini and Dahlgren, 2002). Noncrystalline materials and humus contribute to the chemical properties of soils. The short range minerals that imbue soils with andic soil properties are amphoteric (Nanzyo, 2002). They have high surface area and variable charges surfaces. The variable charges are negative and positive charges depending on soil pH and salt concentration in the equilibrating phase (Nanzyo, 2002).

The functional groups that contribute to variable negative charges are carboxyl groups of humus and silanol groups of allophane and imogolite. The amount of negative charges increases with an increase in salt concentration and pH value. Variable positive charges are due to the protonated hydroxyl groups bound to aluminium of allophane and imogolite and those bound to iron minerals. The amount of positive charge increases with an increase in salt concentration and decrease in pH (Nanzyo, 2002; Ugolini and Dahlgren,

2002). High surface area influences productivity through their positive role in retaining and supplying nutrient elements and retaining plant available water. Phosphorus is often the growth determining nutrient element for agricultural crops. This element is strongly sorbed by noncrystalline aluminium and iron materials (Yatno and Zauyah, 2008). Farming of these soils requires heavy application of phosphatic fertilizers and liming to obtain optimum crop yields. Andisols may exhibit substantial limitation including P fixation, low contents of exchangeable bases especially Potassium and other nutrient, and strong acidity and aluminium toxicity (Lowe and Palmer, 2005).

2.5.3 Physical properties

Andisols have low bulk density. The low bulk density is due to high porosity caused by well-developed aggregate structures made of noncrystalline minerals (Shoji *et al*.,1993). The low bulk density also is due to the accumulation of organic matter making highly porous aggregates. The macropores and micropores contribute to air permeability and retention of plant available water. High porosity contributes to quick gravitational drainage of water in the soils (Nanzyo, 2002). Low bulk density contributes to more favourable soil tilth leading to easy tillage, seedling emergence, and root development. Aggregates of the volcanic ash soils are highly stable, being cemented by noncrystalline materials and soil organic matter. Stable aggregate and high porosity of soils minimize water erosion. These properties significantly contribute to maintaining the high productivity of the volcanic ash soils (Yatno and Zauyah, 2008).Andisols do pose some engineering challenges. The low bulk densities result in low weight bearing capacity. Andisols also exhibit thixotropic and sensitivity properties that cause them to behave in a fluid like manner when loading pressures are applied (Arnalds, 2008).

2.6 Environmental Implications of Volcanic Soils

Volcanism is probably the most obvious mechanism of recycling large amounts of geological material and gases (e.g. CO_2, SO_2) on the planet earth. By providing a source of easily weatherable materials, this natural phenomenon represents an effective sink for carbon dioxide through carbonic acid weathering (Eq. 4) (Ugolini and Dahlgren, 2002).

$$CO_2+H_2O \rightarrow H^+ + HCO_3^- \quad (4)$$

Due to high surface area, and variable charges of volcanic soils minerals, these soils can often mitigate the adverse effect of anthropogenic pollution. Acidic deposition is effectively neutralized by rapid chemical weathering reaction, pH buffering by variable charge materials and sorption of SO_4^{2-}. High concentrations of soil organic matter have a high capacity to retain heavy metals, trace elements (cations and anions) and organic compounds of both natural and anthropogenic origins. These properties of volcanic soils attenuate many pollutants, hence preventing their transmission to surface and ground waters (Ugolini and Dahlgren, 2002).

2.7 Soil Survey in Rwanda

Soil survey is defined as systematic examination, description, classification and mapping of soils in an area (Brady and Weil, 2008). According to Soil Survey Division Staff (1993), soil survey describes the characteristics of the soils in a given area, classifies the soils according to a standard system of classification, plots the boundaries of the soils on a map, and makes predictions about the behaviour of soils. The different uses of the soils and how the response of management affects them are considered. The information collected in a soil survey helps in the development of land-use plans and evaluates and predicts the effects of land use on the environment.

In Rwanda, the first soil survey was undertaken by a team of the "Institut National d'Études Agronomiques au Congo" (INEAC), beginning in 1955 at Rubona Station. INEACwas replaced by the "Institut des Sciences Agronomiques du Rwanda" (ISAR) after independence in 1965, which was integrated in 2012 into the Rwanda Agriculture Board (RAB) (Rushemuka *etal*., 2014). By 1963, the major soil types of the country had been described (Van Wambeke, 1963). In the 1980s, almost all soil knowledge acquired by the INEAC-ISAR team was synthesized into a soil association map at a scale of 1:250000 (Prioul and Sirven, 1981, cited by Rushemuka *et al*., 2014). During the same period, Pietrowicz (1985) undertook a soil survey in the mandate area of the project "Projet Agro-Pastoral (PAP) Nyabisindu.During the period 1981-1990, the project "Carte Pédologique du Rwanda" (CPR) conducted a comprehensive soil survey of Rwanda. The CPR project produced a soil association and a medium scale (1:50000) soil map (43 sheets) under the "Soil Taxonomy" classification system (Birasa *et al*., 1990). During 1994 period much information has been lost and it hastaken eight years (1994-2002) to rebuild the database and then publish the digital version (Rushemuka *et al*., 2014). In 2002, the soil map was digitized and the associated database published (Verdoodt and Van Rant, 2003b).

2.8Classification of Soils Developed on Volcanic Parent Material

Soil classification is the systematic arrangement of soils into groups or categories on the basis of their characteristics. Soil classification system organises knowledge about sets of soil properties and concepts, and groups them into taxonomic classes (Msanya, 2003). Soil classification is important as it identifies, organizes and names soils in an orderly fashion and it stimulates the revelation and formulation of relationships within the soil population, it enables soil surveyors to maintain consistency in soil surveys from place to place and soil classification serves as a base for transfer and application of soil technology

(Beinroth, 1978). There are many soil classification systems in the world, most of which are national and others international in terms of their usage. There is no general agreement on the classification of tropical soils (Msanya, 2003). Soils developed on volcanic materials are generally classified as Andisols, but not all volcanic soils are Andisols, depending on the weathering and soil formation processes (Shoji *et al*., 1993). In 1990, Andisols were added to soil taxonomy as the 11th soil order (Soil Survey Staff, 2014). A very similar taxonomic grouping, Andosols is the one of 32 soil reference groups recognised in the World Reference Base for Soil Resources. Andisols are classified on the basis of selected chemical physical and mineralogical properties acquired through weathering and not on parent material (McDaniel e*t al.*, 2012). Andosols or Andisols are classified based on a measure of the colloidal constituents; Ammonium oxalate extractable Al and Fe (Al_{ox}+1/2Fe_{ox} >2%), low bulk density (<0.9 g/cm^3) and high phosphate retention (>85%) (Arnald, 2015).

2.9 Land Evaluation in Rwanda

Land evaluation is the process of estimating the potential of land for alternative kinds of use. These include productive uses, such as arable farming, livestock production and forestry, together with uses that provide services or other benefits, such as water catchment areas, recreation, tourism and wildlife conservation(FAO,1976).The main objective of land evaluation is to appraise the potential of land for alternative kinds of land use by a systematic comparison of the requirements of this land use with the resources offered by the land (Dent and Young, 1981).Land evaluation helps to evaluate the suitability of land for alternative uses based on biophysical, economic and social criteria (Hansen *et al*., 1998).Land suitability is the fitness of a given type of land for a defined use (FAO, 1976). In land suitability classification, the land is classified according to its suitability for the cultivation of a specific crop by comparingcrop-specific requirements

with actual or potential land characteristics(Verdoodt and Van Rant, 2003a).In 2003, a set of soil suitability maps of Rwanda for 10 subsistence crops (sorghum,maize, cassava, sweet potato, potato, bean, pea, groundnut, soybean and banana) and 2 cash crops (arabica coffee and tea) at scale of 1:250 000 was published (Verdoodt and Van Rant, 2003a).

2.10Land Use Requirement for the Selected Crops Grown in the Birunga AEZ

Land productivity depends on the chemical and physical properties that characterise the soil. These properties vary with the underlying parent material that weathers into mineral soil upon the impact of climatic elements such as temperature and rainfall (Verdoodt and Van Rant, 2003a).

2.10.1Maize

Maize (*Zea mays* L.) is grown under a wide range of ecological conditions. From a climatic point of view, maize is more sensitive to water shortage and low temperature. Maize grows in the temperature ranging from 14 to 40°C.The highest production, however, occurs between 18 and 32°C. It is a drought sensitive crop, which grows in the regions that have a total annual precipitation ranging from 500 to 5 000 mm (Sys *et al*., 1993). From an edaphic viewpoint, maize requires a higher chemical soil fertility level than commonbean (Verdoodt and Van Rant, 2003a). Maize requires well structured, well drained, well aerated permeable soils deep loam and silt loam soils with high organic matter content (Sys *et al*., 1993). It is fairly sensitive to salinity, since an ECe of 5 dS/cm results in a yield reduction of 10% (EUROCONSULT, 1989). The optimum soil pH range for maize growth is 5.5 to 7.0 but satisfactory yield can be obtained at pH ranging from 5.0 to 8 (Landon, 1991). Strongly acidic soils (pH <5.0) are unsuitable for maize production (Young, 1976) probably because of the high levels of exchangeable Al in acid

soils causing Al toxicity (Norman *et al*., 1984). At very low pH, soils are likely to be deficient in P due to tying up with the active Al component.

2.10.2Common bean

Common beans (*Phaseolus vulgaris L.*) prefer temperature ranging from 18 to 30 ^{o}C. The optimum temperature range is 15 -20 ^{o}C (Sys *et al*., 1993).Common beans grow successfully on a moderately wide range of soil textures ranging from light sands to heavy clays (Young, 1976; Norman *et al*., 1984;Landon, 1991). Bean is a drought sensitiveand prefersdeep soils, freely drained with optimum pH ranging from 6.0 to 7.0 (Landon, 1991,Sys *et al*., 1993). Beans also grow successfully on soils with good structure and highin nutrient content(Young, 1976; Landon, 1991).

2.10.3Potatoes

The potato(*Solanum tuberosum* L.) is a typical crop of high-altitude tropical regions and requires temperatures below 22 ^{o}C. Taking into consideration the diurnal variations, marginal conditions have been found at an altitude between 1 500 and 1 800 m.Higher temperatures at lower altitudes are unsuitable for the production of this crop (Verdoodt and Van Rant, 2003a).In tropical areas, potato should be grown where the climate is tempered by altitude (1 500 - 4 200 m) or at lower altitudes provided the crop is grown during the cool season (FAO, 2009).Optimum yields are obtained where mean daily temperatures are in the range of 18-20°C.Soil pH ranging from 4.5 to 6.0 is suitable for potatoes production (Landon, 1991). Loose, moist and well-drained slightly acid soil or volcanic upland soils are preferred (FAO, 2009).Naturally loose soils, andloamy and sandy loam soils that are rich inorganic matter with good drainage andaeration, are the most suitablefor potato production (FAO, 2009).

2.10.4Pyrethrum

Pyrethrum(*Chrysanthemum cinerariae-folium*)tolerates high temperatures but cannot withstand cold weather. If well distributed, an annual rainfall of 1000-1250 mm is optimal for pyrethrum production. The crop needs at least ten days of temperature below 15°C to trigger flowering. For this reason, normal harvests are extremely rare below 1800 m a.s.l. In fact only crops planted above 2000m altitude have yielded well. The content in pyrethrins is also higher at high altitude (Raemaekers, 2001).

Pyrethrum requires a light, permeable soil. Heavy soils do not suit it. In Africa, it is grown in soils of low pH (5.5-7.0), usually on volcanic soils (Raemaekers, 2001). Pyrethrum needs fertile soils with a good internal drainage and high content of organic matter. Pyrethrum cannot grow under water logging condition and therefore it is grown on beds in order to control drainage conditions. A minimum altitude of 2000m a.s.l. is needed for proper flowering, and a minimum annual rainfall of 1000mmis required with one or two months tostimulate the flower yield and so do alternating rain and sunshine (EUROCONSULT, 1989). Pyrethrum was introduced in Rwanda in 1931 where it was grown successfully in the highlands and it has remained important in the Northern part of Rwanda only(Raemaekers, 2001). Climatic conditions of Rwanda are ideal for growing pyrethrum, particularly in volcanic mountainous regions (1 500 - 3 000 m a.s.l.) where there is average rainfall, good drainage and high soil fertility (Rwanda Development Board,2010).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location of the study area

The study was carried out in the north-western part of Rwanda in Northern Province. Three sites were identified and studied.Two sites were located in Musanze District and one site was located in Burera District.The profile on Kinigi pedon one (KNG-P1) was excavated in Musanze district, Kinigi Sector, Nyabigoma Cell, Gahura Village;Kinigi Pedon two (KNG-P2) was excavated in Musanze District, Kinigi Sector, Kaguhu Cell, Kabeza Villageand Gahunga Pedon one (GHNG-P1) was excavated in Burera District, Gahunga Sector, Rwasa Cell, Kabindi Village and their detailed information is given in the Table1.Figure 1 presents a map of Rwanda showing location of the studied sites.

3.1.2 Physiography

Musanze District is situated in the north-western highlands of Rwanda and is the most mountainous part of Rwanda that contains the largest part of the Volcanoes National Park. Five of the eight volcanoes of the Virunga chain namely Karisimbi, Bisoke, Sabyinyo, Gahinga and Muhabura are within the district boundaries.Karisimbi is the highest point in Rwanda at 4 507m a.s.l. and is the sixth tallest peak in Africa.Musanze has a landscape divided in two main areas: the volcanic plains and the mountain range. The volcanic plain covers the central and north part of the district. Its average altitude is 1 860 ma.s.l. (Ministry of Disaster Management and Refugee Affairs, 2012; Musanze District, 2013).The mountain range is located in the South-East of the district, covering over a third of the total surface of the district. Its altitude ranges from 1 900 m to 2 000 m (MIDIMAR, 2012; Musanze District, 2013).

Table 1: Salient characteristics of studied sites in Northern Province of Rwanda

Pedons[1]	Village	District	Coordinates	AEZ[2]	Alt[3]	MAR[4]	Lithology/ parent materials	Landform	Land use	STR[5]	SMR[6]
KNG-P1	Gahura	Musanze	E 029° 31' 27.6" S 01° 26' 10.7"	B	2629	1400-1800	Cenozoic volcanic rocks of Birunga chain (undifferentiated). Relatively fresh and some partly weathered basaltic scoria appear to dominate	Mountain	Cultivation, Tourism, Forest	Mesic	Udic
KNG-P2	Kabeza	Musanze	E 029° 32' 21.2." S 01° 26' 13.1"	B	2471	1400-1800	As above	Hill	Cultivation (maize beans, potatoes, pyrethrum)	Mesic	Udic
GHNG-P1	Kabindi	Burera	E 029° 41' 12.5." S 01° 27' 00.9"	B	1936	1400	Cenozoic volcanic rocks of Birunga chain. There is a clear evidence of transported volcanic rocks mainly basaltic scoria derived from the nearby Mt. Muhabura transported by gravity and fluvial action. Parent material at the site may be considered as colluvio-alluvium derived mostly from volcanic rocks. The pedon has stratification typical of alluvial deposition	Colluvio-alluvial plain	Cultivation (Beans, sorghum, maize, banana)	Thermic	Udic

[1]**Soil Pedons: KNG-P1**; Kinigi pedon 1; **KNG-P2**: Kinigi pedon 2; **GHNG-P1:** Gahunga pedon 1

[2]**AEZ**: Agro ecological zone- **B**: Birunga = located in highland zone and groups the volcanic soils that descend from the limit of the Volcano National Park at an altitude of 2 500 - 1 900 m near Ruhengeri and even below 1 600 m near Gisenyi. Rainfall varies between 1 300 and 1 600 mm and the fertile soils create favourable conditions for agricultural production (Verdoodt and Van Ranst, 2003). The most crops grown are Irish potatoes, green peas, maize, bean, pyrethrum, wheat and sorghum.

[3]**Alt=** Altitude in m a.s.l [4]**MAR =** Mean Annual Rainfall in mm [5]**STR**= Soil Temperature Regime; [6]**SMR** = Soil Moisture Regime

Source: Theunissen *et al*. (1991)

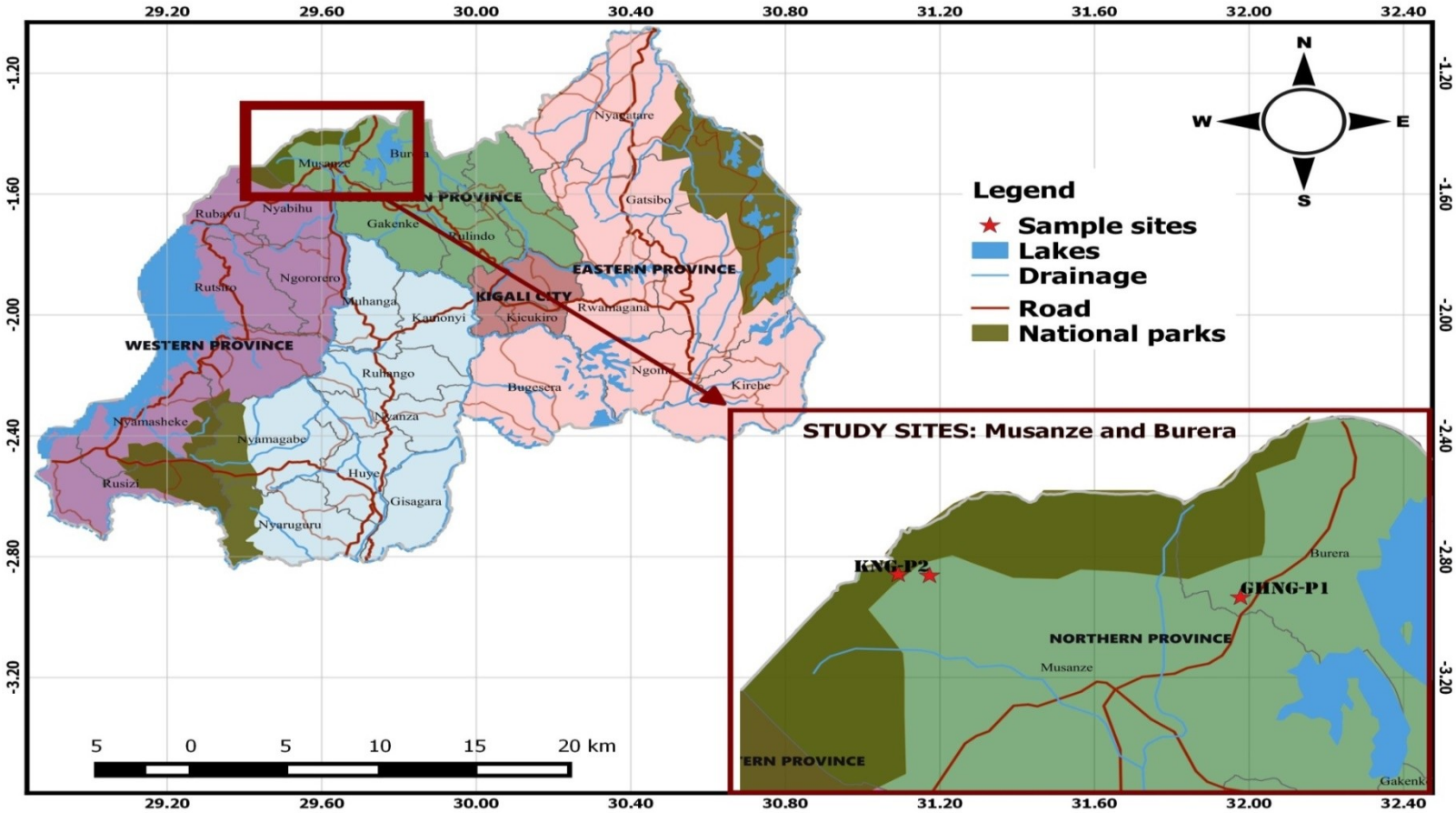

Figure 1: Pedological study sites in Northern Province of Rwanda.

The hydraulic network in the district is formed by temporary torrents and permanent rivers. Torrents surge during strong storms, and they are provoked by water coming downhill from the volcanoes, some 20 km away (Musanze District, 2013).

Burera District has average altitude of 2 100m. Its relief is characterized by steeply sloping hills connected either by valleys steep-sided or by flooded marshes. The most remarkable hills are: Bisaga (2 401m a.s.l.); Kabyaza (2 392m a.s.l.); Kabona (2 348m a.s.l.); Karurunga (2 305 m a.s.l.); Seta (2305m a.s.l.); Nyanamo (2 225m a.s.l.).The Burera district has an important hydrologic network formed by the Burera and the Ruhondo lakes (55 km^2 and 28 km^2, respectively), the Rugezi swamps (6 735 hectares), and the Urugezi, Cyeru, Kabaya and Kabwa rivers (MIDIMAR,2012; Burera District, 2013).

3.1.3 Climate

The climate of Musanze and Burera is humid with two dry seasons and two rainy seasons. In Musanze District rains are generally abundant, ranging from 1 400 mm to 1 800 mm annually with an average temperature of 20 ºC(Musanze District, 2013). In Burera District yearly rains reach 1 400 mm, the temperature ranges between 9^oC to 29^oC varying wth location and season (MIDIMAR, 2012; Burera District, 2013). The mean monthly rainfall and temperature are shown in Figure 2.

3.1.4. Agro Ecological Zone of the Studied Areas

Burera District is part of the Buberuka and the Laves (Birunga) highlands. Musanze is part of Birunga agro ecological zone.

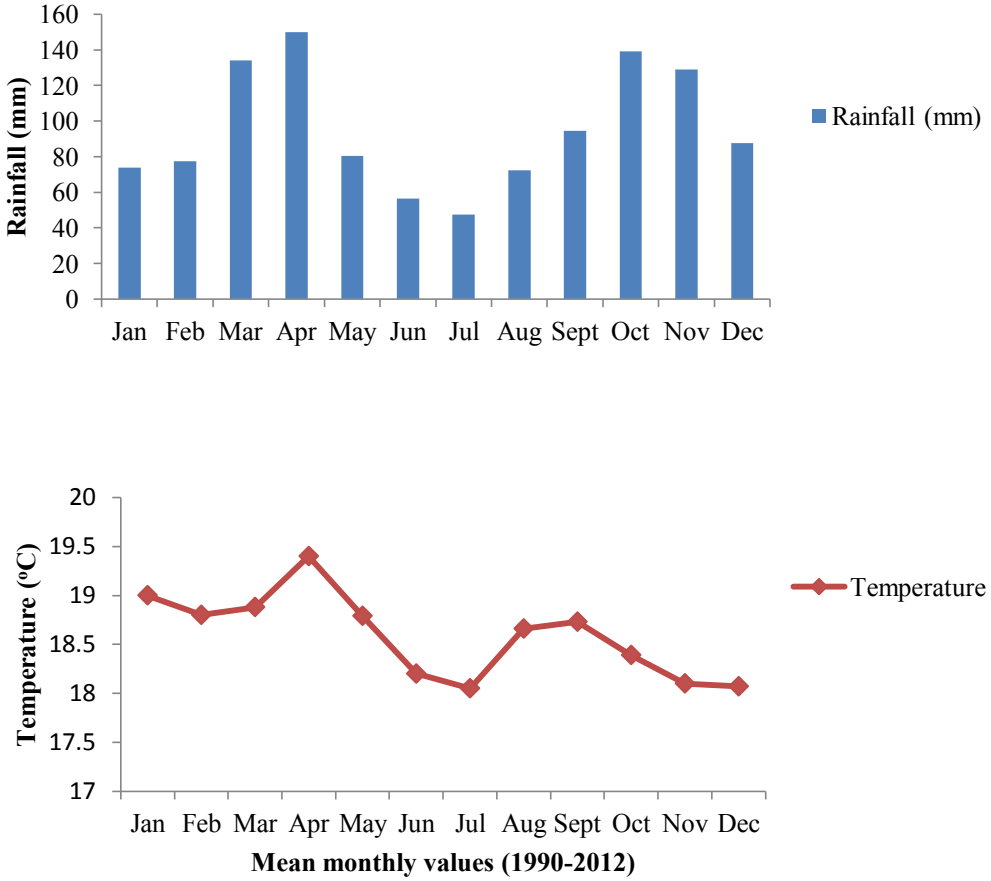

Figure 2: Mean monthly rainfall and temperature of the studied area of Northern Province of Rwanda

3.1.4.1 Birunga

The agricultural zone of the Birunga groups the volcanic soils that descend from the limit of theVolcano National Park at an altitude of 2 500 m to an altitude of 1 900 m near Ruhengeri and even below 1 600 m near Gisenyi.Regularly distributed rainfall, varying between 1 300 and 1 600 mm and fertile soils create favourable conditions for agricultural production (Verdoodt and Van Ranst, 2003a).

3.1.4.2 Buberuka Highlands

In the North of Rwanda, high altitude plateaus traversed by quartzitic chains that attain an altitude of 2300 m characterise the agricultural zone of the Buberuka Highlands. It is the

lower altitudinal limit that corresponds to 1900 m a.s.l. It receives total annualrains of about 1 200 mm with a dry season of 2 months. The soils of this region are generally fertile (Verdoodt and Van Ranst, 2003a).

3.1.5Geology and soils

The geology of the studied sites is largely composed of volcanic rock (Mizota and Chapelle, 1988; Burera District, 2013; Musanze District, 2013). The main soil types found in Musanze can be grouped into three categories: volcanic soils, lateritic and humus-bearing soils; and clayey soils(Musanze District, 2013).Burera soils are mostly formed by black schist and in some places are lateritic and in volcanic area the soils are volcanic (MIDIMAR, 2012; Burera District, 2013).

3.1.6 Vegetation and land use

Musanze District contains few indigenous trees and exotic types namely*Bambusa spp*, *Eucalyptus species*, *Grevillea spp*, *Ricinus communis*and*Perseaamericana.* Thenatural vegetation found in the area is *Hagenia abyssinica,Cynodon spp*, *Cyanotis barbata,Digitaria abyssinica, Dombeya goetzenii* K. Schum and *Setaria spp.*The dominant land uses in Musanze District aremainly cultivation(maize, beans, pyrethrum, potato, sorghum, wheat, coffee, green peas, fruits and vegetables),tourism and forest(Musanze District, 2013).

In Burera District the most exotic tree species is the eucalyptus. Other agro-foresting species present in the area are *Alnusspp* and *Grevillea spp*. Otherwise, crops cover most of the surface of the district. Main crops are beans, potatoes, maize, green peas, sorghum, wheat, bananas, vegetables and fruits. The commercial crops present are coffee, pyrethrum and tea, but their inception is on an early stage (MIDIMAR, 2012; Burera District, 2013).

Thenatural vegetation found in the area is*Vernonia amygdalina* Del*, Iboza riparia, Euphorbia tirucalli, Erythrina abyssinica,Ficus thonningii*and*Ricinus communis* L.

3.2 Pre-field Work Activities

Before the actual field work was conducted, review of previous studies and reports on soil survey done in Rwanda (Verdoodt and Van Ranst, 2003a, 2003b; Rushemuka *et al*., 2014), geological map at a scale of 1: 250 000 (Theunissen *et al.,* 1991, Verdoodt and Van Ranst, 2003b), districts reportsand map of Rwanda for navigation in study areas were consulted.

3.3 Field Work Activities

3.3.1 Reconnaissance survey

Reconnaissance field survey involving transects walks, auger observations, and descriptions were carried out to establish representative study sites on the basis of landform and other physiographic attributes. Data onland use/crops, landform,lithology (parent material) vegetation, elevation, slope gradient andsoil morphological characteristics were collected at each observation site. In each identified landform unit, soil observations were made to a maximum depth of 1.5 m or to a limiting layerto identify soil properties by augering along the transect. These data were filled in forms adopted from the FAO guidelines for soil description (FAO, 2006). The soil profile pits were studied, described and sampled according to FAO Guidelines for Soil Profile Description (FAO, 2006).Sample sites were located by international coordinates determined by using a Global Positioning System (Garmin Model etrex 20).Soil colour was determined by using Munsell Color Charts (Munsell Color Co, 1992).From the reconnaissance survey, sites that represent the major landforms and soils were selected along a transect from Musanze District to Burera District.

3.3.2 Soil profile excavation

Three profile pits, representing the dominant physiographic units and soil variability in the study area, were selected and fully geo-referenced. The selection was based on the information obtained from free reconnaissance survey. Soil profile pits were dug to a depth of 2 m or to a limiting layer. The selected units and their respective soil profiles (abbreviated in parentheses) are: Kinigi pedon one(KNG-P1),Kinigi pedon two (KNG-P2) in Musanze District and Gahunga pedon one (GHNG-P1) in Burera District. Soil pedons pits were studied and described according to FAO Guidelines for Soil Description (FAO, 2006).

3.3.3 Soil sampling

Because there were insufficient core samplers, in each profile pit, undisturbed (core) soil samples at depths of 0-5 cm, 45-50 cm and 95-100 cm were sampled while disturbed samples were taken from all the designated natural horizons for laboratory physical and chemical analysis. Sixteen soil samples representing the soil horizon of three pedons were collected and prepared for analysis

3.4 Post-field Work Activities

Laboratory analyses

Disturbed soil samples were air-dried and ground topass through a 2 mm sieve to obtain the fine soil fractions for determination of physical and chemical soil properties. Undisturbed core samples were oven dried at 105°C to constant weight. Undisturbed core samples were used for the determination of bulk density, porosity and moisture retention characteristics. Bulk density was determined by the core method (Blake and Hartge, 1986). Particle density of the soil was calculated by determining the mass of the solid particles and the volume they occupy. Mass of the solid particles was then obtained by

weighing the solid particles and likewise the volume was determined from the mass and density of water displaced by the sample (Blake and Hartge, 1986). Total soil porosity has been calculated by using particle density and the bulk density of a soil. Soil moisture retention characteristics were studied using sand kaolin box for low suction values and pressure apparatus for higher suction values (Klute, 1986; National Soil Service NSS, 1990). Particle size analysis was determined by the hydrometer method after removal of organic matter using H_2O_2 and dispersion with sodium hexametaphosphate 5% (Bouyoucos,1962; NSS, 1990). Textural classes were determined using the USDA textural class triangle (USDA, 1975). Penetrometer resistance was measured using Japanese push cone penetrometer model DIK-5551 (Daiki Rika Kogyo Co. Ltd., 2000).Penetration resistance R (kg/cm^2) was calculated as follows (Eq. 5):

$R= (100*x)/ [0.7952(40-x)^2]$ ……. (5)

Where x=mm penetrometer reading.

Soil pH was measured potentiometrically in water and 1 N KCl at a ratio of 1:2.5weights to volume basis (McLean, 1986; NSS,1990). Electrical conductivity (EC) was measured on a 1:2.5 soil: water suspension using electrical conductivity meter (Morberg, 2000).Sodium-fluoride pH was also determined potentiometrically at 1:50 weights to volume basis and pH measurements were taken after 2 minutes (Fieldes and Perrot, 1966;NSS, 1990). Organic carbon was determined by the Walkley and Black wet oxidation method (Nelson and Sommers, 1982) and Organic carbon was converted to organic matter by multiplying by a factor of 1.724 (Duursma and Dawson, 1981). Total N was determined using micro-Kjeldahl digestion- distillation method as described by Bremner (1996). Available phosphorus was extracted using dilute NH_4F-HCl as per Bray and Kurtz-1 method (Bray and Kurtz, 1945) and determined spectrophotometrically at 884 nm following colour developed by the Molybdenum blue method(Watanabe and Olsen,

1965) for low pH soil (pH<7) and Olsen method for higher pH soil (pH_{water}> 7) (Okalebo,2002).Melanic index (MI) (the ratio of humic and fulvic acids) was calculated according to the method of Honna *etal*. (1988) for the pedons which had andic properties.Cation exchange capacity of soil (CEC_{soil}) and exchangeable bases were determined by saturating soil with neutral 1 M NH_4OAc (ammonium acetate) and the adsorbed $NH4^+$were displaced using 1 M KCl and then determined by Kjeldahl distillation method forestimation of CEC of the soil (Chapman, 1965). The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were measured by atomic absorption spectrophotometer (AAS) (Thomas, 1982).The total exchangeable bases (TEB) were calculated arithmetically as a sum of the four exchangeable bases (Ca^{2+}, Mg^{2+}, $Na^+$and K^+) for agiven soil sample.

The micronutrients Fe, Mn, Zn and Cu were extracted using buffered 0.005M DTPA (Diethylene Triamine Pentaacetic Acid) (Lindsay and Norvell, 1978), and their concentrations determined by an Atomic Absorption Spectrophotometer (AAS) (UNICAM 919 model).Phosphate-retention capacity was determined according to the method of Blakemore *et al*. (1981). Total elemental composition of fine earth soil samples and rock samples was determined by X-Ray Fluorescence. Powdered samples were pressed into XRF sample cups and mounted with PANalytical B.V X-Ray film-polyesterpetp. Elemental oxides were measured using PANalytical, Minipal 4 Energy Dispersive X- Ray Fluorescence Spectrometer (ED-XRF) Model PW4030/45B.Chemical index of alteration (CIA) as an indicator of degree of weathering was calculated for selected horizons using the formula by Nesbitt and Young (1982) given as (Eq. 6):

$$CIA = \{Al_2O_3/ (Al_2O_3 + K_2O + Na_2O + CaO)\} * 100 \quad (6)$$

3.5 Classification of Soils

Using field and laboratory data, the soils were classified to family level of the USDA Soil Taxonomy (Soil Survey Staff, 2014) and to tier-2 of the FAO World Reference Base (IUSS Working Group WRB, 2015).

3.6 Data Analysis

Descriptive statistics were employed to assess soil parameters, Pearson's correlation matrix was used to assess correlations among soil parameters, and data integrity and graphs were constructed using MS-Excel software.

3.7 Determination of Potential and Limitations of Soils for the Production of Major Crops

Using field and laboratory data, rating of potential and limitations of soils was done using known guidelines (FAO, 1976; EUROCONSULT, 1989; Landon, 1991; Sys, 1993; Raemaekers, 2001). Rating involved matching the ecological crop requirements such as amount of rainfall in the growing season, temperature, physical condition, ground water, soil pH and natural fertility with what the land can offer in terms of its quality.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Soils

4.1.1 Soil morphology

Some key morphological characteristics of thestudied profiles are presented in Table 2. Pedon KNG-P1 was very deep,well drained with very friable to friable moist consistence and slightly sticky and slightly plastic wet consistence. This pedonwas very deep (>150 cm), with brownish to black colour (Plate 1). The texture was sandy loam inall horizons except CR which was loamy sand. The structure wasdominantly subangularblocky in the A and B horizons with minor components of crumbs;but structureless single grained in the CR horizon. Many rounded iron concretions/nodules were observed in this pedon. This is probably because the area is located at the lower quarter of the mountain and it is possible that there were occasions of waterlogging conditions in the past years. The horizon boundaries were diffuse to clear with wavy topography throughout.

Pedon KNG-P2 (Plate 2) was typically shallow soil (30 - 50 cm) resting directly on rock boulders with minor pockets of soil. It was well drained with very friable moist consistence, and non-sticky and non-plastic wet consistence. The structure ranged from weak fine and medium crumby to weakfine and medium subangular blocky.The colour ranged from brownish black to black.The horizon boundaries were diffuse to clear with smooth topography. The pedon was rocky throughout its depth withrocks right from the surface, increasing with depth. The texture was dominantly sandy loam in Ap1 and Ap2 horizons overlying loamy sandy inthe RA horizon.Both Pedons KNG-P1 and KNG-P2 had thixotropic properties typical of volcanic soils (FAO, 2006).

Table 2: Selected morphological characteristics of the studied soil pedons

Soil pedons[1]	Horizon symbols	Depth (cm)	Texture[2]	Moist colour[3]	Consistence[4]	Structure[5]	horizon boundary[6]
KNG-P1	Ap1	0-35/47	SL	b (10YR1.7/1)	vfr, sst & spl, th	mo, m, sbk / mo,f,cr	dw
	Ap2	35/47-87	SL	b (10YR1.7/1)	vfr, sst & spl, th	mo, m, sbk/ mo, f,cr	dw
	Ap3	87-136/140	SL	b (10YR1.7/1)	vfr, sst & spl, th	mo, m, sbk/mo, f, cr	cw
	Bw	136/140-166/210	SL	bb (10YR2/3)	fr, sst & spl	mo-s, f, m, c, a+sbk	cw
	CR	166/210-280+	LS	br (2.5YR2/4)	-	ssg	-
KNG-P2	Ap1	0-24	SL	b (10YR1.7/1)	vfr, nst & spl, th	w, f+m, cr	ds
	Ap2	24-40	SL	b (10YR1.7/1)	vfr, nst & spl, th	w, f+m, cr	cs
	RA	40-93	LS	bb (10YR2/2)	vfr, nst & spl, th	w, f+m, sbk	-
GHNG-P1	Ap	0-31/40	SCL	b (10YR/2/1)	fr, sst & pl	mo, m+c, sbk	cw
	Bw1	31/40-52/65	SCL	bb (10YR3/2)	fr, st & pl	mo, m+c, sbk	cw
	BC	52/65-71/73	gSL	dob (2.5Y3/3)	fr, sst & spl	mo, m+c, sbk	cw
	2Bw2	71/73-105/120	SCL	db (10YR3/3)	fr, st & pl	w, m+c, sbk	cw
	2CB	105/120-119/134	gSL	dob (2.5Y3/3)	fr, sst & spl	w, m+c, sbk	cw
	3Bw3	119/134-140/151	SCL	bb (10YR3/2)	fr, st & pl	mo, m+c, sbk	cw
	3C	140/151-160	S	bb (7.5YR2/2)	l, nst & npl	ssg	cw
	4Bw4	160-180+	SL	bb (10YR2/3)	fr, st &spl	mo, m+c, sbk	-

[1]**Soil pedons:**KNG-P1 = Kinigi pedon 1; KNG-P2 = Kinigi pedon 2; GHNG-P1 = Gahunga pedon 1
[2]**Texture: S =** sand **S**L=sandy loam, LS= loamy sandy, SCL= sandy clay loam, gSL= gravelly sandy loam, *= loose coarse fragments
[3]**Moist colour:** b= black; bb= brownish black; br=brown; dob= dark olive brown; db= dark brown
[4]**Consistence:**vfr = very friable; fr= friable, l= loose; nst= nonsticky; sst = slightly sticky; st = sticky; npl = nonplastic; spl = slightly plastic; pl = plastic; th = thixotropic
[5]**Structure:**

Grade: mo = moderate; mo-s=moderate to strong; w= weak
Size: m= medium; m+c= medium and coars; f+m= fine and medium; f= fine; m= medium; c= coarse
Form: sbk= subangular blocky; a+sbk= angular and subangular blocky; cr= crumby; ssg= structure less single grained

[6]**Horizon boundary:**dw= diffuse wavy, cw=clear wavy, ds= diffuse smooth, cs=clear smooth

Plate 1:Pedon KNG-P1

Plate 2:Pedon KNG-P2

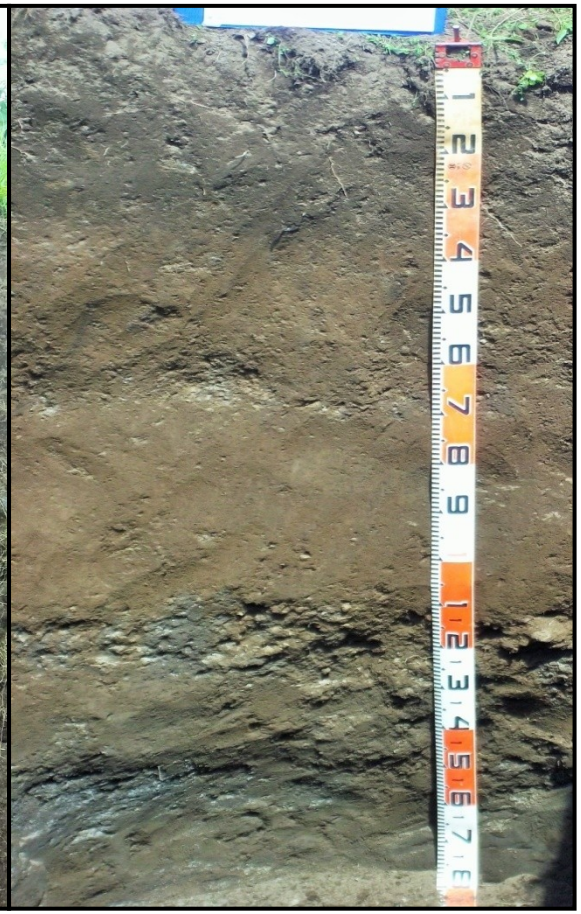

Plate 3: Pedon GHNG-P1

PedonGHNG-P1 was very deep (> 150 cm), well drained with loose to friable moist consistence; non-stickyand non-plastic to sticky and plastic when wet.A typical feature of this pedon is that it shows evidence of stratification and lithological discontinuity in a form of buried horizons such as 2Bw2, 2CB, 3Bw3, 3C, 4Bw4 (Plate 3). The buried horizons reflect different cyclic deposition of soil material detached by gravity from Muhabura Mountain or surrounding area and then transported later by water to the depositional site. The field texture was quite variable but dominantly sandy clay loam alternating with sandy loam and sand. The soil colours are also quite variable but with colour values and chromas of ≤ 3.0.The pedon is prone to seasonal flooding during the rainy season. This may limit the production of crops grown in the area. Therefore soil and water conservation measures should be undertaken in this area

4.1.2 Soil physical properties

Particle size distribution

Particle size distribution and textural classes of thestudied soils are presented in Table 3. The topsoils of Pedons KNG-P1 and KNG-P2 were sandy loam butsandy clay loam inPedon GHNG-P1.Pedon GHNG-P1 had variable textures with a pattern that reflects lithological discontinuity. Soil texture is the most permanent characteristic of soil which influences a number of other soil properties including structure, consistence,infiltration rate, workability,soil moisture availability, erodibility, root penetration and soil fertility (EUROCONSULT, 1989; Landon,1991; Msanya *et al*.,2003). This is because texture is a composite of the coarse fraction (sand) and the finer fractions (silt and clay) and an increase or decrease in one component imparts the opposite effect on the other and hence affects physico-chemical properties of the soils (Brady and Weil, 2008). Clay has been reported to interact with organic matter and increases water and nutrient holding capacity (Landon, 1991).

Table 3: Soil physical properties of studied pedons in the Northern Province of Rwanda

Profile No	Horizons	Depth Cm	Soil texture %clay	% silt	%sand	Textural Classes	Silt/clay Ratio	Bulk density g /cm^3	Particle density g/cm^3	Total Porosity	R kg/cm^2
KNG-P1	Ap1	0-35/47	14.0	23.2	62.8	SL	1.66	0.43	1.87	76.73	1.92
	Ap2	35/47-87	18.1	18.4	63.5	SL	1.02	0.41	2.00	79.44	2.94
	Ap3	87-136/140	18.4	18.6	63.0	SL	1.01	0.47	1.93	75.51	2.30
	Bw	136/140-166/210	15.4	9.2	75.4	SL	0.60	nd	nd	nd	3.49
	CR	166/210-280+	8.7	5.5	85.8	LS	0.63	nd	nd	nd	nd
KNG-P2	Ap1	0-24	16.5	21.3	62.2	SL	1.30	0.39	1.83	78.87	1.92
	Ap2	24-40	11.8	21.2	67.0	SL	1.80	nd	nd	nd	2.67
	RA	40-93	9.2	11.7	79.1	LS	1.27	0.39	1.91	79.38	2.13
GHNG-P1	Ap	0-31/40	31.6	19.3	49.1	SCL	0.61	0.94	2.54	63.10	3.58
	Bw1	31/40-52/65	22.7	23.5	53.8	SCL	1.04	1.06	2.58	59.03	5.84
	BC	52/65-71/73	18.7	11.5	69.8	gSL	0.61	nd	nd	nd	7.70
	2Bw2	71/73-105/120	24.7	25.5	49.8	SCL	1.03	1.34	2.62	48.92	5.28
	2CB	105/120-119/134	16.7	9.5	73.8	gSL	0.57	nd	nd	nd	8.77
	3Bw3	119/134-140/151	22.7	25.5	51.8	SCL	1.12	nd	nd	nd	3.49
	3C	140/151-160	6.7	3.5	89.8	S	0.52	nd	nd	nd	7.13
	4Bw4	160-180+	16.7	11.5	71.8	SL	0.69	nd	nd	nd	4.79

KNG-P1 = Kinigi pedon 1, KNG-P2 = Kinigi pedon 2, GHNG-P1 = Gahunga pedon 1, R = Penetration resistance, nd: not determined

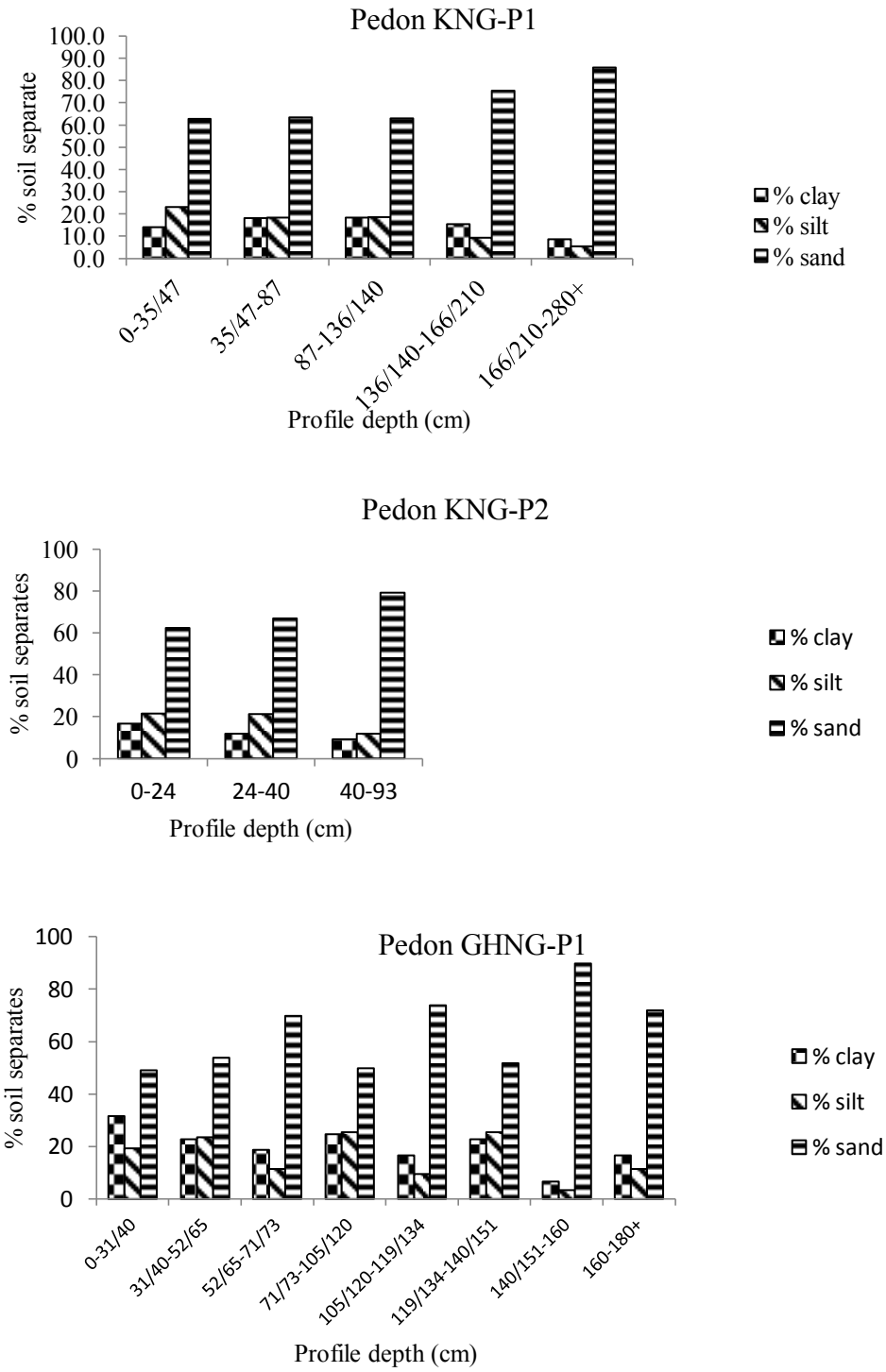

Figure 3: Particle size distribution against soil depth in studied pedons ofNorthern Province

Clay contents of the studied soils ranged from 8.7 to 18.4%, 9.2 to 16.5% and from 6.7 to 31.6% in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. The clay contents of

topsoils of the studied pedons ranged from14.0 to 31.6%, whereas they ranged from11.8 to 22.7% in the subsoils (Table 3 and Figure 3). The particle size distribution in the three pedons did not show any clear trend with depth. This may be due to the fact that soils have been formed in very unstable landscapes where trends/paths of pedogenesis are often being disturbed or altered.

Bulk density

The analytical results on bulk densityare given in table 3.The bulk density of the studied soils ranged from 0.41 to 0.47g/cm^3; 0.39 to 0.40g/cm^3 and from 0.94 to 1.34 g/cm^3 in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. Topsoil bulk densities of the studied soils ranged from 0.39 to 0.94 g/cm^3 while subsoils bulk densities ranged from 0.40 to 1.06 g/cm^{3}in all studied soil pedons. Pedons KNG-P1 and KNG-P2 had lower values of bulk density instudied topsoils and subsoils, valued 0.43 to 0.47 g/cm^3 and 0.39 to 0.4 g/cm^3, respectively compared to Pedon GHNG-P1.Low bulk density may be due to high amount of organic matter. Soils with high organic matter tend to have better aggregates and porous structures. The development of porous soil structure is the primary factor responsible for the low bulk density(Dalal and Mayer, 1986; Shoji *et al*., 1993; Nanzyo, 2002; Yatno and Zauyah, 2008; Brady and Weil, 2008).

The presence of allophane minerals in the volcanic ash may also contribute to low bulk density. Allophaneis one of the most important non-crystalline materials contributing to the low bulk density of volcanic soils through the development of porous soil structure (Shoji *etal*., 1993).Pedon GHNG-P1 showed higher bulk density values compared to other pedons and this may be due to low organic matter values. The bulk density values observed in the studied pedons particularly those of Pedons KNG-P1 and KNG-P2 are

typical volcanic ash soils which normally have ≤ 0.90 g/cm^3)(Soil Survey Staff, 2014; IUSS Working Group WRB, 2015).

Generally, bulk densities of the studied soils increase with soil depth. This increase may result from a lower content of organic matter, less aggregation, and compaction caused by the weight of the overlying layers. The bulk density values suggest that studied soils were not compact; therefore the movement of air between soil and atmosphere would be unhindered and plant roots can penetrate easily into soilsearching for water and plant nutrients (Shoji *et al.,* 1993; Msanya *et al.,* 2016). Low bulk density also contributes to more favourable soil tilth leading to easy tillage, seedling emergence and root development.

Particle density

The analytical results on particle densityare given in Table 3.Particle density (PD) of the studied soils ranged from 1.87 to 2.00g/cm^3,1.83 to 1.90g/cm^3 and from 2.54 to 2.62g/cm^3 inPedons KNG-P1, KNG-P2and GHNG-P1, respectively. Whereas the PD values in topsoils ranged from 1.83to 2.54 g/cm^3,those of thesubsoils ranged from 1.90 to 2.58g/cm^3.Generally, there was an increase in particle density with soil depth, except in Pedon KNG-P1.

According to Brady and Weil (2008), particle density depends on the chemical composition and the crystal structure of the mineral particles and is not related to particle size or to the arrangement of the particles. The particle density of mineral soils varies between narrow limits of 2.60 to 2.75g/cm^3. Some mineral topsoil high in organic matter (15 to 20%) may have particle densities as low as 2.4 g/cm^3(Brady and Weil, 2008). The low values of particle density in all horizons of pedons KNG-P1and KNG-P2 may be

attributed to higher content of organic matter in these pedons compared to Pedon GHNG-P1.The low values of particle density may also be due to low amount of micas, feldspar,quartz, and the colloidal silicate in these studied pedons.

Total soil porosity

Total soil porosity of the studied soils ranged from 75.51 to79.44%,78.87 to 79.00% and from 48.92 to 63.10% inPedons KNG-P1,KNG-P2, and GHNG-P1, respectively (Table 3). In the surface horizon,the total porosity ranged from 63.10 to 78.87% and from 48.92% to 79.00% in the subsoils (Table 3).Pedon GHNG-P1 showed a decrease in total porosity with soil depth, this being attributed to the decrease of organic matter. The total porosity of soils lies between 30 and 70% and may be used as a very general indicator of the degree of compaction in a soil (Landon, 1991). The highvalues of total porosity in some topsoil horizons may be attributed to relatively high soil organic matter content. Moreover, the lowtotal porosity in some subsoil horizons may be due tocompaction caused by the weight of the overlying layers.

Penetration resistance

Section 4.1.2 presents the penetration resistance of the three studied pedons. Soil resistance is commonly used as an indicator of soil strength. In agriculture, soil strength affects root growth, seedling emergence, aggregate stability, erodibility and erosion, compaction and compatibility(Lal and Shukla,2004). Penetration resistance ranged from 1.92 to 3.49kg/cm^2, 1.92 to 2.67 kg/cm^{2}and from 3.49 to 8.77kg/cm^{2}inPedons KNG-P1, KNG-P-2and GHNG-P1, respectively. The topsoils'penetration resistance ranged from 1.92 to 3.58kg/cm^2 while it ranged from 2.67 to 5.84 kg/cm^2 in subsoils. Soil resistanceincreases with increase in bulk density.Low penetration resistance in studied topsoilsmay be attributed to low bulk density. According to Ball and Sullivan(1982)

andCass(1999), the topsoils are loose and this facilitatesroot growth. The penetration resistance of the intermediate horizons of Pedon GHNG-P1 were medium; therefore the root growth of some cereal plants may be restricted.

Moisture retention characteristics

Figure 4 presents moisture characteristic curves of the studied pedons. Soilmoisture characteristic curves depend on soil particle size distribution and organic matter content (Lal and Shukla, 2004). The soil moisture of Pedons KNG-P1 and KNG-P2 indicates a high retention capacity with a gradual decrease as the suction potentialincreases. This may be attributed to the high organic matter observed in these pedons.Soil organic matter enhances soil water retention because of its hydrophilic nature and its positive influence on soil structure. Increasing SOM increases soil aggregate formation and aggregate stability, thereby increasing porosity in the range of pore sizes that retain plant available water and enhancing infiltration and water retention throughout the rooting zone (Lal and Shukla, 2004).

High water retention capacity in these soils may also be attributed to the presence of allophane and allophane like materials due to its fine particle size and hollow spherical structure (Shoji *et al*., 1993). Water retention capacity in Pedon GHNG-P1 was lower compared to other studied pedons. This may be attributed to low organic matter and loamy texture observed in the area. In loamy soils, the pores are relatively large thus likely to be emptied at low matric suctions leaving small amounts of water to be released at high suctions (Landon, 1991; Lal and Shukla, 2004; Brady and Weil, 2008).

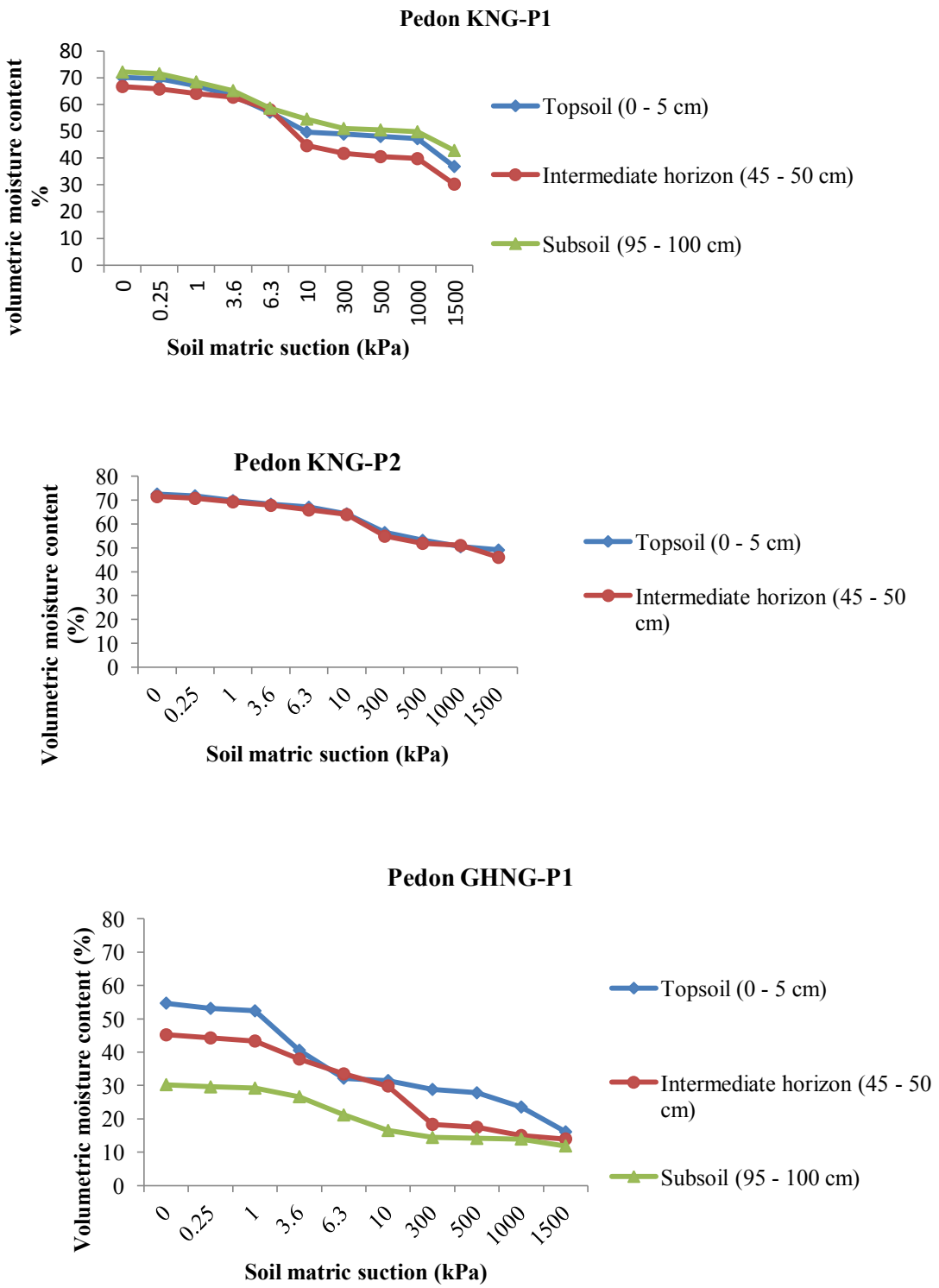

Figure 4:Moisture characteristic curves of studied pedonsin Northern Province of Rwanda

4.1.3 Soil chemical properties

Soil pH

Analytical results on soil pH are given in Table 4. Soil pH influences the supply and availability of essential plant nutrients as well as toxic elements (Brady and Weil, 2008). Soil pH ranged from 5.57 to 6.83, 5.78 to 5.98 and from 7.25 to 7.51 inPedons KNG-P1, KNG-P2 and GHNG-P1, respectively. Topsoils' pH ranged from 5.57 to 7.41 while the subsoils' pH ranged from 5.83 to 7.49.According to Landon (1991), these soils are rated to have medium to high pH values. Generally, soil pH increased slightly with soil depth except inPedon GHNG-P1 which did not show a clear trend of increasing or decreasing with soil depth.The higher values of pH were observed in Pedon GHNG-P1 compared to other studied pedons. The high soil pH values observed in Pedon GHNG-P1 may be attributed to the application of liming materials and/or continuous addition of less weathered material eroded from the surrounding area (Poudel and West, 1999). According to EUROCONSULT (1989), most plants thrive well in soils with pH values of 6 to 7.5. From this point of view, soil acidity was not a serious constraint for agricultural production in the studied areas. Soil pH_{KCl} values were lower than pH_{water} values in all studied pedons, indicating that the soils have net negative charge in the colloidal exchange complex (Bohn *et al.,* 1985).

Soil pH in NaF is a measure of surface OH^- ions released by exchange with F^- ions, although some OH^- ions may be reabsorbed and others neutralized by soil acidity (Gilkes and Hughes, 1994). Soil reaction (pH_{NaF}) values of the studied soils ranged from pH 11.04 to 11.69, 10.96 to 11.77 and from 9.08 to 10.03 in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. The pH_{NaF} ranged from 10.02 to 11.64 in the topsoils and from 10.3 to 11.65 in the subsoils, respectively.

Table 4: Selected soil chemical properties of pedons from selected areas in Northern Province of Rwanda

Profile No	Horizons	Depth (cm)	pH H_2O	pH KCl	pH NaF	EC dS/m	OC %	OM %	N %	C/N Ratio	Avail P mg P/kg	P ret %
KNG-P1	Ap1	0-35/47	5.57	4.47	11.64	0.13	11.67	20.12	1.13	10.33	6.39	99.25
	Ap2	35/47-87	5.90	4.54	11.65	0.08	10.04	17.31	1.03	9.75	6.70	98.00
	Ap3	87-136/140	6.02	4.73	11.42	0.10	11.13	19.19	1.11	10.03	4.08	98.00
	Bw	136/140-166/210	6.40	5.01	11.69	0.09	6.99	12.05	0.75	9.32	3.97	98.00
	CR	166/210-280+	6.83	5.20	11.04	0.08	0.53	0.91	0.06	8.83	3.28	99.58
KNG-P2	Ap1	0-24	5.78	4.31	10.96	0.20	13.03	22.46	1.62	8.04	4.39	96.58
	Ap2	24-40	5.83	4.47	11.48	0.13	12.54	21.62	1.45	8.65	4.28	98.75
	RA	40-93	5.98	4.56	11.77	0.08	9.64	16.62	0.89	10.83	3.49	99.42
GHNG-P1	Ap	0-31/40	7.41	5.96	10.02	0.19	3.97	6.84	0.36	11.03	65.14	39.25
	Bw1	31/40-52/65	7.49	5.85	10.03	0.11	1.89	3.26	0.22	8.59	55.28	49.00
	BC	52/65-71/73	7.40	5.82	9.73	0.06	0.69	1.19	0.09	7.67	12.53	35.50
	2Bw2	71/73-105/120	7.37	5.78	9.74	0.06	0.94	1.62	0.13	7.23	8.43	42.00
	2CB	105/120-119/134	7.25	5.68	9.50	0.06	0.22	0.38	0.06	3.67	3.93	16.75
	3Bw3	119/134-140/151	7.51	5.68	9.49	0.06	0.43	0.74	0.06	7.17	4.27	27.76
	3C	140/151-160	7.44	5.61	9.08	0.04	0.00	0.00	0.04	0.00	tr	6.25
	4Bw4	160-180+	7.48	5.63	9.32	0.05	0.18	0.31	0.04	4.50	1.46	14.75

KNG-P1 = Kinigi pedon 1 KNG-P2 = Kinigi pedon 2 GHNG-P1 = Gahunga pedon 1tr = Trace

A soil $pH_{NaF} \geq 9.5$ is a strong indicator that amorphous material dominates the soil exchange complex. Such pH values indicate the presence of allophane and/or organo-aluminium complexes (IUSS Working Group WRB, 2015). The high values of pH_{NaF} in studied topsoils and subsoils pedons may be attributed to the presence of large amounts of hydroxyl-Al (Fe) compounds in the soil that react with NaF to release OH (Shoji *et al*., 1993, Msanya *et al.,* 2007). High pH_{NaF} values may also be associated with the presence of allophane (Yatno and Zauyah, 2008), attributes which are closely linked to soils developed from volcanic parent materials (Shoji *et al*., 1993; Msanya *et al.,* 2007; Yatno and Zauyah, 2008; IUSS Working Group WRB, 2015 Msanya *et al.,* 2016).

Electrical conductivity (EC)

Electrical conductivity ranged from 0.13to 0.20 dS/m in studied topsoils and it ranged from 0.08 to 0.13 dS/m in subsoils, respectively (Table 5). Electrical conductivity (EC) values studied pedons were very low (much less than 1.7 dS/m), indicating that the soils have no problems of salinity (Msanya *et al*., 2001).

Organic carbon

Analytical results on organic carbon and soil organic matter are presented in Table 4.Organic carbon ranged from 0.53 to 11.67% (0.91 to 20.12% SOM) inPedon KNG-P1; 9.64 to 13.03% (16.61 to 22.46% SOM) inPedon KNG-P2 and from 0 to 3.97% (0 to 6.84% SOM) in Pedon GHNG-P1. The organic carbon (OC) varied within and among pedons. The organic carbon (OC) contents in the topsoils ranged from 3.97 to 13.03 %, while the subsoils' organic carbon ranged from 1.89 to 12.54%. According to Msanya *et al*. (2001) topsoils organic carbon was rated as high to very high while the subsoils were rated as medium to very high. High values of organic carbon content in the topsoils may be attributed to the continuous addition of crop residues on the surface of cropped fields

and their decomposition under the favourable climatic conditions, but it may also originate from the decomposition of roots and plant residue remaining after the crops were harvested. Organic carbon content was very high in almost all horizons of Pedons KNG-P1 and KNG-P2. This may be attributed to volcanic soils' habit of accumulating organic matter (Ugolini, 2002). Kinigi site is relatively cool, because of its high elevation. Cool temperatures retard SOM decomposition and mineralization, which favours appreciable accumulation of organic carbon in the soils (Dejarme-Calalang and Colinet, 2014).

Generally organic carbon contents decrease with soil depth in all studied pedons except in Pedon GHNG-P1 where there is no clear trend of OM variation with depth. This was probably due tothe continuous deposition of new materials from the surrounding area on top of soilswhich were on the surface.

Total nitrogen

Total Nitrogen contentresultsof the studied pedons are presented in Table 4. Total N ranged from 0.06 to 1.13%,0.89 to 1.62%, and from 0.04 to 0.36% inPedons KNG-P1,KNG-P2, and GHNG-P1, respectively. Total Nitrogen (TN) content in topsoils of the studied sites ranged from 0.36% to 1.62% rated as medium to highsame as in subsoils, it was rated as medium (0.22%) to high (1.45%)(Msanya *et al*.,2001). The relatively higher levels of totalNitrogenobserved in topsoils and subsoils of Pedons KNG-P1, KNG-P2may be attributed to decomposition of plant litter such as crop residues and application of organic manure. That may also be attributed to the volcanic soil property of accumulating organic matter which is the main source of Nitrogen andother various plant nutrients. High N content may also be attributed to slow mineralization. The medium and low values of TN content inPedon GHNG-P1 may be attributed to plant uptake especially sorghum or may be due to continuous cultivation without replenishment of organic residues.

C/N ratio in soils helps to determine the rate of organic materials decay, the level of total organic matter and the amount of nitrogen available to plant. The C/N ration of the studied soils ranged from 8.83 to10.33, 8.04 to 10.83 and from 0 to 11.03 inPedons KNG-P1, KNG-P2 and GHNG-P1, respectively (Table 4). The C/N ratioof the studied pedons ranged from 8.04to 11.03 and from 8.59 to 9.75, respectively for topsoils and subsoils.According to EUROCONSULT (1989),the C/N ratios of the studied topsoil and subsoils wererated as low to medium,andlow, respectively. The C/N ratio ranging from 8to13 indicates good quality of organic matter (Msanya *et al*., 2001). Therefore, topsoils' and subsoils' C/N ratios revealed that the soils had good quality of organic matter.

Available phosphorus

The analytical results on soil available phosphorous are presented in table 4. Available P ranged from 3.28 to 6.70 mg P/kg, 3.49 to 4.39 mg P/kg and from 1.46 to 65.14mg P/kg inPedons KNG-P1, KNG-P2 and GHNG-P1, respectively. According to EUROCONSULT (1989), available P was low in studied horizons of KNG -P1 and KNG-P2 pedons. Theobserved results may be attributed to adsorption of phosphorus by amorphous oxides (iron and aluminium oxide) and allophane, resulting in the formation of insoluble phosphorus compounds, making it sparingly available for plant uptake phosphate (Shoji *et a1*.,1993), or/and it may be attributed to the nature of rocks and minerals that made the parent materials (Brady and Weil, 2008). Available P content in Pedon GHNG-P1 ranged from low to high (Landon, 1991). The high value of available P on this site may be attributed to anthropogenic activitiessuch the application ofP fertilizers(DAP and NPK fertilizers). The observed phosphorus levels in the studied soils (Pedons KNG-P1 and KNG-P2), suggests that these soils require either organic or inorganic P fertilization for optimum crop yield.

Phosphorus retentioncapacity

P retention capacity ranged from 98 to 99.58% in PedonKNG-P1, 96.58 to 99.42% inPedonKNG-P2 and 6.25 to 49% inPedon GHNG-P1 (Table 4). The high P retention values in pedons KNG-P1 and KNG-P2 may be related to the high content of active Al and active Fe(Shoji *et al*., 1993; Nanzyo, 2002; Yatno and Zauyah, 2008).The capacity of soil material to retain large amounts of phosphate is also due to the very high specific surface of the amorphous minerals (van Wambeke, 1992). Pedon GHNG-P1 had low values of P retention capacity (< 50%).According toSoil Survey Staff (2014) and IUSS Working Group WRB (2015), Pedons KNG-P1and KNG-P2 met the P-retention capacity requirement for the definition of andic properties. The results suggest that high rates of P fertilizers should be applied in orderto correct the amount of P that would be fixed by the soil and leave amounts that would be available to plants.

Cation exchange capacity (CEC)

Analytical results on cation exchange capacity (CEC) are presented in Table 5. The studied soils CEC ranged from 32.2 to 61.6cmol(+)/kg inPedon KNG-P1, 50.40 to 61.6cmol(+)/kg inPedon KNG-P2 and from11.4 to 32cmol(+)/kg inPedon GHNG-P1. Topsoil CEC ranged from 31.40 to 56.80 cmol(+)/kg rated as high to very high according to Landon (1991). The high CEC found in studied topsoils and subsoils ofPedons KNG-P1 and KNG-P2 and in topsoils ofPedon GHNG-P1 may be attributed to high content of soil organic matter. The CEC levels observed in studied topsoils indicate that the soils have high nutrient retention capacity, therefore soluble cations are protected from leaching out of the plant root zone and it helps soils resist changes in pH (Brady and Weil, 2008).

Table 5: Exchangeable cations and related properties and micronutrient contents of the studied soils

Pedon No.	Horizons	Exchangeable bases					CEC_{soil}	BS	Extractable micronutrients				Melanic index
		Ca	Mg	K	Na	TEB			Fe	Cu	Zn	Mn	
		(cmol(+)/kg)						%	mg/kg soil				
KNG-P1	Ap1	6.63	1.34	0.05	0.12	8.14	56.6	14.38	54.74	0.87	1.78	2.62	2.55
	Ap2	9.92	0.83	0.00	0.09	10.84	52.4	20.69	56.49	0.64	2.24	2.62	2.73
	Ap3	15.32	1.64	0.03	0.11	17.10	57.6	29.69	78.07	0.87	4.17	4.48	2.71
	Bw	9.28	2.06	0.00	0.10	11.44	61.6	18.57	60.53	0.52	0.35	2.62	2.91
	CR	3.24	1.08	0.11	0.09	4.52	32.2	14.04	56.14	0.52	0.66	2.19	3.27
KNG-P2	Ap1	6.31	0.61	0.34	0.14	7.40	56.8	13.03	78.07	1.11	2.54	1.61	2.23
	Ap2	6.42	0.25	0.14	0.12	6.93	50.4	13.75	51.75	0.64	0.91	1.04	2.29
	RA	4.09	0.40	0.04	0.11	4.64	61.6	7.53	33.25	0.64	0.2	0.61	2.72
GHNG-P1	Ap	16.17	3.04	5.09	0.11	24.41	31.4	77.74	68.33	1.58	7.08	7.2	nd
	Bw1	14.79	1.94	5.35	0.14	22.22	32.0	69.44	82.46	1.58	2.13	3.05	nd
	BC	7.16	1.39	2.62	0.20	11.37	18.6	61.13	42.98	0.87	1.01	1.76	nd
	2Bw2	12.78	2.87	1.91	0.24	17.80	26.6	66.92	6.49	2.53	1.73	2.04	nd
	2CB	6.00	1.79	1.96	0.17	9.92	16.0	62.00	34.21	1.46	0.81	1.61	nd
	3Bw3	7.69	2.22	2.87	0.18	12.96	26.6	48.72	42.98	1.58	0.35	1.61	nd
	3C	2.82	0.70	1.40	0.09	5.01	11.4	43.95	11.75	0.28	0.5	0.75	nd
	4Bw4	5.57	1.64	3.02	0.11	10.34	16.8	61.55	30.61	1.11	0.71	1.04	nd

KNG-P1 = Kinigi pedon 1 KNG-P2 = Kinigi pedon 2 GHNG-P1 = Gahunga pedon 1 nd: not determined

Exchangeable bases

Exchangeable Ca, Mg, K, and Na in the soils studied are presented in Table 5. Pedons KNG-P1, KNG-P2 and GHNG-P1 had exchangeable Mg of 1.34, 0.61 and 3.04 cmol(+)/kg in the topsoils, respectively. According to Metson (1961) topsoil Mg is rated as low to high. Exchangeable Mg in the subsoils ranged from very low (0.25 cmol(+)/kg) to moderate (1.94 cmol(+)/kg). The relatively high values of exchangeable Mg in the topsoils may be attributed to low mining by cropping systems and low leaching and washing by run-off. It has been reported by Sanchez (1976) that 0.2 to 0.64 cmol(+)/kg levels of exchangeable Mg are sufficient for most crops. Therefore, soils of the study areas had sufficient levels of exchangeable Mg for crop production.

The topsoil exchangeable K levels in the studied area ranged from 0.05 to 5.09cmol(+)/kg whilein the subsoils it ranged from 0 to 5.35cmol(+)/kg whichwere rated as very low to very high for both topsoils and subsoils (Metson, 1961). K is one of the major nutrient elements required in large amounts by the plants. The availability of K in volcanic ash soils is influenced by the mineralogical properties of the tephras, chemical weathering regime, vegetation and cropping practices (Shoji *et al.,*1993).The low values of exchangeable K in PedonsKNG-P1 and KNG-P2 may be attributed to the selectivity of cations by allophanic soils.Allophanic soils exhibit low K selectivity and K deficiencies are the first ones to appear among the cations(Van Wambeke,1992). It may also be attributed to the mineralogical properties of the tephras, chemical weathering regime, vegetation and cropping practices (Shoji *et al.,*1993). The high values of exchangeable K found in Pedon GHNG-P1 may be attributed to K fertilizer application in form of NPK (Niyitanga *et al*., 2015). Topsoilsexchangeable Na was 0.12, 0.14 and 0.11cmol(+)/kg inPedonsKNG-P1,KNG-P2 and GHNG-P1, respectively. Exchangeable Na was low in all topsoils and subsoils of the studied pedons.Low levels of exchangeable Na may be

attributed to its solubility and mobility when soils are sufficiently moist which leads to removal of sodium out of the soil (Zonn, 1986).The topsoils exchangeable Ca levels were 6.63, 6.31 and 16.17cmol(+)/kginPedonsKNG-P1, KNG-P2 and GHNG-P1, respectively, which were rated as moderate to high (Metson, 1961).Generally,PedonsKNG-P1 and KNG-P2 showed low level of base content; this may be attributed to their being developed on young volcanic parent materials (Poudel and West, 1999).

Base saturation

Percent base saturations(PBS) of the studied pedons are presented in Table 5.PBS of the studied pedons ranged from 14.04 to 29.69%, 7.53 to 13.75% and from43.95 to 77.74% respectively,inPedons KNG-P1, KNG-P2 and GHNG-P1.Topsoil PBS ranged from 13.03 to 77.74% while it ranged from 13.75 to 69.44 in subsoils which were rated as very low to high(Metson, 1961). There was no clear trend of base saturation with soil depth. The low PBS values observed in Pedons KNG-P1 and KNG-P2 may be attributed to poor cultivation practices, poor soil and water conservation and inadequate supply of fertilizer to replenish nutrients removed by crops(Vanlauwe *et al*., 2006).Thereforeapplication of limiting nutrients is encouraged. In Pedon GHNG-P1, thePBS was rated as medium to high (Landon, 1991). The PBS of above 50 implies good soil fertility for crop production. It also implies low or no intensive leaching of bases from topsoils to subsoils (Msanya *et al*., 2016).

Extractable micronutrients

Micronutrient contents of the studied soils are given in Table 5.Micronutrients are defined as those elements required in small quantities for higher plantgrowth and reproduction (Landon, 1991). The exact quantity needed varies with plant species and the specific element (Brady and Weil, 2008). Deficiencies of micronutrients may be related to low

contents of these elements in the parent rocks or transported parent material and the toxicity are sometimes related to abnormally large amounts in the soil forming rocks and minerals. However deficiency and toxicity of these elements may result from certain soil conditions such as soil pH, redox potential, texture, organic matter and environmental factors which either increase or decrease the solubility and the availability of these elements (EUROCONSULT, 1989; Landon, 1991; Brady and Weil, 2008).

Extractable Fe of the studied soils ranged from 54.74 to 78.07mg Fe /kg soil, 33.25 to 78.07 mg Fe /kg soil and from 6.49 to 82.46 mg Fe /kg soil inPedons KNG-P1, KNG-P2, and GHNG-P1, respectively. Topsoils' extractable Fe of the studied pedons ranged from54.74 to 78.07mg Fe /kg soil whereas it ranged from 51.75 to 82.46mg Fe /kg soilin subsoils. According to FAO (2008) topsoils and subsoils extractable Fe was very high in studied pedons.High amount of extractable Fe may be attributed to the nature of soil forming rocks and minerals.Extractable Cu of the studied soils ranged from 0.52 to 0.87 mg Cu/kg soil, 0.64 to 1.11 mg Cu/kg soil and from 0.28 to 2.53mg Cu/kg soil inPedons KNG-P1, KNG-P2, and GHNG-P1, respectively. The topsoils extractable Cu of the studied pedons ranged from 0.87 to 1.58mg Cu/kg soil and from 0.64 to 1.58mg Cu/kg soil in subsoils.Extractable Cu in the topsoils was high while in subsoil, it ranged from medium to high(FAO, 2008). According to Landon (1991), the deficiency level of Cu in soils is 0.75 mg/kg. Therefore the topsoils of studied pedons were not deficient in Cu.

Extractable Zn of the studied soils ranged from 0.35 to 4.17mg Zn/kg soil, 0.20 to 2.54 mg Zn/kg soil and from 0.35 to 7.08mg Zn/kg soil inPedons KNG-P1, KNG-P2, and GHNG-P1 respectively.The topsoils extractable Zn ranged from 1.78 to 7.08mg Zn/kg soil which rated as medium to very high while it rated as low(0.91 mg Zn/kg soil) to medium(2.24mg Zn/kg soil) in subsoils in all studied pedons. Extractable Mn of the studied soils ranged

from 2.19 to 4.48mg Mn/kg soil, 0.61 to 1.61 mg Mn/kg soil and from 0.75 to 7.20mg Mn/kg soil inPedons KNG-P1, KNG-P2, and GHNG-P1, respectively.Topsoils extractable Mn was rated as medium(1.61mg Mn/kg soil) to very high(7.20mg Mn/kg soil) while it was low(mg Mn/kg soil) to medium(3.05 mg Mn/kg soil) in subsoils in all studied pedons. There was no clear trend of extractable micronutrients with soil depth except in Pedon KNG-P2 where the extractable micronutrients decreased with soil depth. Generally extractable micronutrients were high in topsoils, and deficiency or toxicity of these elements may result from certain soil conditions and environmental factors which either increase or decrease the availability of these elements to plants.

Melanic Index

The Melanic Indexvalues of the studied pedons are presented in Table 5**.** Melanic Index helps to differentiate melanic from fulvic Andosols (Honna *et al*., 1988). The melanic index of the studied pedons in topsoil and subsoils of KNG-P1 and KNG-P2 Pedons (soils which showed andic properties) were much greater than 1.7 indicating that the studied soilsare dominated by fulvic acid (Soil Survey Staff, 2014, IUSS Working Group WRB, 2015).

Nutrient balance

The soil nutrient ratios in the studied pedons are presented in Table 6.The effects of the major cations in soils on plant growth are often closely interlinked (Landon, 1991).Nutrient imbalances influence nutrient uptake by inducing deficiencies of nutrients which may be present in the soil in good quantities (Edem and Ndaeyo, 2009).Ca/Mg ratio of the studied pedons ranged from 3 to 11.95, 10.23 to 25.68 and from 3.35 to 7.62 inPedons KNG-P1, KNG-P2 and GHNG-P1, respectively. The topsoils and subsoils' Ca/Mg ratio ranged from 4.95 to 10.34and from 7.62 to 25.68 respectively.

Table 6: Nutrient ratios of the studied soils, Northern Province, Rwanda

Profile	Horizons	Ca/TEB	Ca/Mg	Mg/K	% (K/TEB)
KNG-P1	Ap1	0.81	4.95	26.80	0.61
	Ap2	0.92	11.95	-	0.00
	Ap3	0.90	9.34	54.67	0.18
	Bw	0.81	4.50	-	0.00
	CR	0.72	3.00	9.82	2.43
KNG-P2	Ap1	0.85	10.34	1.79	4.59
	Ap2	0.93	25.68	1.79	2.02
	RA	0.88	10.23	10.00	0.86
GHNG-P1	Ap	0.66	5.32	0.60	20.85
	Bw1	0.67	7.62	0.36	24.08
	BC	0.63	5.15	0.53	23.04
	2Bw2	0.72	4.45	1.50	10.73
	2CB	0.60	3.35	0.91	19.76
	3Bw3	0.59	3.46	0.77	22.15
	3C	0.56	4.03	0.50	27.94
	4Bw4	0.54	3.40	0.54	29.21

KNG-P1=Kinigi pedon 1 KNG-P2=Kinigi pedon 2 GHNG-P1= Gahunga pedon 1

According to Landon (1991), the presence of Mg deficiency in crop may not only be associated with low Mg content in soil, it may also be attributed to the presence of large amount of other cations particularly Ca and K. The optimum range of Ca/Mg ratio for mostcrops is 2 to 4 (Msanya *et al*., 2001). Topsoils and subsoils of the studied pedon were above the optimal levels. This may limit the uptake of Mg by plants. If the Ca/Mg exceeds 5:1, the availability of Mg and P is reduced (Landon, 1991). This is the cases of Pedon KNG-P2, and some horizons of Pedons KNG-P1 and GHNG-P1. Ca/TEB of the studied soils ranged from 0.72 to 0.92, 0.85 to 0.93 and from 0.54 to 0.72 in Pedons KNG-P1, KNG-P2, and GHNG-P1, respectively. Topsoils Ca/TEB ratio of the studied soils ranged from 0.66 to 0.85 while it ranged from 0.67 to 0.93 in the subsoils. Studied pedons have Ca/TEB ratio of more than 0.5 in both topsoils and subsoils. This may affect the uptake of otherbases particularly Mg and/or K due to Ca induced deficiency (Landon, 1991). Mg/K

of the studied pedons ranged from 9.82 to 54.67, 1.79 to 10.00 and from 0.36 to 1.50 in pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. The studied topsoil Mg/K ranged from 0.60 to 26.80 while in subsoils, it ranged from 0.36 to 1.79.According to Msanya *et al.* (2001), 1 to 4is the optimum range of Mg/K for nutrient uptake by plants. Pedons KNG-P1 and GHNG-P1 topsoils were within the optimum range.

The %K/TEB of the studied soils ranged from 0 to 2.43% in Pedon KNG-P1,0.86 to 4.59% inPedon KNG-P2 and from 10.73 to 29.21% in Pedon GHNG-P1.The topsoils K/TEB ranged from 0.61 to 20.85% while it ranged from 0 to 24.08% in subsoils.Landon (1991) reported that the favourable K/TEB ratio for most tropical crops is 2% or more. Therefore soils represented by Pedons KNG-P2 and GHNG-P1 are in favourable range of K/TEB ratio for most tropical crops. On the overall, nutrient ratios observed in the studied pedons indicate nutrient imbalance and will thus affect negatively nutrient availability.Application ofmanures and inorganic fertilizers, adoption of crop rotationcan improve nutrient availability (Jones*et al*., 2013).

4.1.4 Correlation among some physical and chemical properties of the studied soils

Table 7 presents a Pearson correlation matrix focusing on selected soil properties of the studied pedons. Clay and silt contents showed negative correlation but significant with sand indicating that an increase or decrease of the coarse fraction (sand) imparts the opposite effect on finer fraction (silt and clay). Phosphorus retention capacity and pH_{NaF}were strongly and positively correlated, with a correlation coefficient of 0.98. High P retention indicates the presence of large amounts of hydroxyl-Al (Fe) compounds in the soil that react with NaF to release OH, which would consequently cause a high pH_{NaF}

Table 7: Pearson correlation among some physical and chemical soil properties of the studied soils

	Sand	Silt	Clay	pH_{water}	pH_{NaF}	OM	TN	CEC	PRC	BS	Ca	Mg	Na	K
Sand	1													
Silt	-0.911**	1												
Clay	-0.887**	0.618*	1											
pH_{water}	-0.106	-0.177	0.402	1										
pH_{NaF}	0.093	0.117	-0.31	-0.911**	1									
OM	-0.106	0.347	-0.188	-0.949**	0.846**	1								
TN	-0.107	0.354	-0.193	-0.927**	0.797**	0.988**	1							
CEC	-0.08	0.283	-0.165	-0.896**	0.945**	0.905**	0.868**	1						
PRC	0.064	0.161	-0.303	-0.891**	0.975**	0.823**	0.795**	0.921**	1					
BS	-0.433	0.121	0.692**	0.871**	-0.833**	-0.728**	-0.719**	-0.769**	-0.844**	1				
Ca	-0.769**	0.575*	0.824**	0.128	0.02	0.081	0.049	0.14	0.014	0.464	1			
Mg	-0.615*	0.313	0.824**	0.597*	-0.432	-0.487	-0.513*	-0.333	-0.438	0.731**	0.673**	1		
Na	-0.496	0.428	0.466	0.415	-0.469	-0.364	-0.324	-0.381	-0.409	0.511*	0.191	0.452	1	
K	-0.494	0.223	0.693**	0.792**	-0.706**	-0.610*	-0.602*	-0.619*	-0.704**	0.892**	0.467	0.630**	0.322	1

* significant at the 0.05 probability level,** significant at the 0.01 probability level (n=16)

(Shoji *et al*., 1993; Msanya *et al*., 2007). Sand content showed a weak positive correlation with pH_{NaF} and the correlation was not significant, indicating that sand fraction was not the source of the active hydroxyl-Al (Fe) compounds involved in the NaF reaction that releases OH ions. The P retention was also positively correlated with CEC, with a correlation coefficient of 0.92 indicating that the presence of organic matter helped to increase both CEC and P retention (Msanya *et al*., 2007). Organic matter and CEC were positively correlated, with a correlation coefficient of 0.91 because the presence of organic matter helped to increase CEC. Soil pH_{water} was negatively correlated with OM with correlation coefficient of 0.95. The negative correlation is probably due to high accumulation of OM which has a tendency of accumulating acid-dependent cations on the exchange site (McLean, 1986). The correlation between pH water and BS was positive and significant because high pH causes the amounts of basic cations to be high.

TN was positively correlated with OM with correlation coefficient of 0.99. It implies that the high values of TN observed in the studied areas are highly contributed by OM of the soil. Total nitrogen was positively correlated with pH_{NaF} with correlation coefficients of 0.80. This indicatesthat organic matter is the sources of the active hydroxyl-Al (Fe) compounds involved in the NaF reaction that releases OH- ions (Msanya *et al*., 2007). Exchangeable Mg was positively correlated with percentage BS of the studied soils with correlation coefficient of 0.73 while exchangeable Ca was positively correlated with BS but with a correlation coefficient of 0.46. Exchangeable Na was positively correlated with percentage BS of the studied soils with correlation coefficient of 0.51 while exchangeable K was positively correlated with BS with a correlation coefficient of 0.89.This observation suggests that, Mg, Ca,Na and K contributed to amount of BS of the studied soils. Basic cations were positively correlated among each other.Cations and BS were negatively correlated with sand content, but the correlation was only significant for Mg and Ca. The

negative correlation is attributed to the fact that sand content possesses small surface area for holding and exchanging cations.

4.1.5 Total elemental content of the selected soil and rock samples

Analytical results of total oxides of elements in the studied areas are presented in Table 8.Fe_2O_3, SiO_2 and Al_2O_3 were the most abundant oxide among all oxides in all studied pedons.Fe_2O_3concentration of the studied soils ranged from37.09 to 40.17%, 38.07 to 45.88% and from 26.27 to 29.86% in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. Fe_2O_3 concentration of the studied rock in Pedons KNG-P1, KNG-P2 and GHNG-P1 was 29.98%, 29.98% and 28.58%, respectively. The Fe_2O_3 content decreased in the order Pedon KNG-P2> Pedon KNG-P1> Pedon GHNG-P1 with pedon mean values of 41.98, 38.36 and 27.81%. High value of Fe_2O_3 probably derived from hematite or it may indicate the presence of iron oxides like goethite. The SiO_2 levelin studied soils ranged from 23 to 29%, 17 to 37.2% and from 31 to 36.6% in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively.

SiO_2 level in the studied rocks was 27.7% in Pedons KNG-P1, KNG-P2 and 39% in Pedon GHNG-P1. The presence of SiO_2 indicates the existence of amorphous silica and quartz content (Msanya *et al*., 2016). Al_2O_3 in the studied soils ranged from 15 to 21%, 8 to 19% and from 12 to 15% in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. Al_2O_3 concentration in studied rocks was 13%, 13% and 0% in Pedons KNG-P1, KNG-P2 and GHNG-P1, respectively. The high values of Al_2O_3 may be due to the presence of gibbsite. High concentrations of SiO_2 and Al_2O_3 in volcanic soils are probably contributed by quartz, amorphous clay minerals namely vermiculite and illite whereby clay minerals originate from the hydrolysis of plagioclase in the rocks (Baba *et al*., 2008). The studied soils showed higher level of CaO and K_2O in Pedon GHNG-P1 compared to Pedons KNG-P1 and KNG-P2.

Table 8: Total elemental concentrations of the studied soil and rock samples, Northern Province of Rwanda

Profile	Horizon	Depth	SiO_2	Al_2O_3	Fe_2O_3	K_20	CaO	TiO_2	MnO	P_2O_5	MgO	Na_2O	Total	CIA
		cm	%											
KNG-P1	Ap1	0-35/47	29	18	37.09	0.79	3.98	6.92	0.74	1.4	0.01	0.01	97.94	79.01
KNG-P1	Bw	136/140-166/210	23	21	40.17	0.76	4.39	7.56	0.71	1.4	0.02	0.02	99.03	80.26
KNG-P1	CR	166/210-280	26	15	37.81	0.71	10.5	7.96	0.62	0	0.08	0.01	98.69	57.20
KNG-P2	Ap1	0-24	37.2	8	38.07	1	4.55	6.81	0.51	1.5	0.01	0.02	97.66	58.98
KNG-P2	RA	40-93	17	19	45.88	0.68	5	8.3	0.69	1.2	0.01	0.01	97.77	76.95
GHNG-P1	Ap1	0-31/40	32.2	13	28.03	3.29	12.7	6.14	0.55	1.9	0.06	0.03	97.89	44.80
GHNG-P1	Bw1	31/40-52/65	31	13	29.86	3.28	11.9	6.49	0.57	1.6	0.01	0.02	97.72	46.11
GHNG-P1	2Bw2	71/73-105/120	33.7	14	28.24	3.03	11.8	6.16	0.53	1.2	0.04	0.07	98.77	48.45
GHNG-P1	3Bw3	119/134-140/151	36.6	15	26.65	3.12	10.9	5.77	0.39	0	0.06	0.01	98.50	51.67
GHNG-P1	3C	140/151-160	34.9	12	26.27	4.26	14.6	6.21	0.44	0	0.09	0.02	98.79	38.87
	Rocks samples													
KNG-P1	_	_	27.7	13	29.98	2.69	18.3	7.13	0.43	0	0.09	0.03	99.35	38.21
KNG-P1	_	_	27.7	13	29.98	2.69	18.3	7.13	0.43	0	0.09	0.03	99.35	38.21
GHNG-P1	_	_	39	0	28.58	6.32	16.9	6.85	0.46	0	0.08	0.02	98.21	0.00

KNG-P1= Kinigi pedon 1 KNG-P2= Kinigi pedon 2 GHNG-P1= Gahunga pedon1

This may be attributed to anthropogenic activities such as application of fertilizers (K fertilizer) and liming material and/or the nature of the parent rock. The level of MgO and Na_2O were less than 0.1 in all studied soils and rocks, the low values may be attributed to low concentration of these elements in the parent material. $P_2O_5$was not found in all studied rocks while P_2O_5 levels ranged from 0 to 1.9 % in all studied soils and decreased with soil depth. The higher level of P_2O_5 in topsoils compared to subsoils may be attributed to anthropogenic activities such as application of P fertilizers, manures and incorporation of crop residues, a common practice in these areas.

4.1.6 Pedogenesis

Enrichment or addition of organic and mineral materials was the dominant soil forming process in the studied area. Dark coloured surface horizons observed in studied soils indicate melanisation and humification processes. Oxido-reduction cycles have been localised in concretions and nodules in Pedon KNG-P1. This process may be related to soil management, temperature and soil moisture regime(Lindbo *et al*., 2010) Oxido-reduction conditions are responsible for release of free oxides of iron, aluminium and manganese from primary minerals.Erosion, which is the deposition of new soil materials from other sites,was observed in PedonsGHNG-P1 and KNG-P1. Different buried horizons 2Bw2, 2CB, 3Bw3,3C, 4Bw4 observed in PedonGHNG-P1 indicate different cycles of deposition of soil materials from the surrounding areas. The presence of a thick Ap horizon in Pedon KNG-P1 indicated the deposition of soil materials from the upper part of the mountain. Pedoturbation of soils through human activities such as ploughing, addition of organic and mineral materials has been observed in the studied areas. Transformation, which is the weathering of mineral and organic substance within the soil and translocationof materials from one point to another within the soil,have been observed in the studied areas.

4.1.7 Indices of degree of weathering

Exposed rocks are affected to variable degrees by a combination of chemical and physical weathering.Silt/clay ratio and Chemical Index of Alteration (CIA) are used in this study as indices to assess the degree of weathering.

Silt/clay ratio

Silt/clay ratio of the studied pedons ranged from 0.60 to 1.66 in Pedon KNG-P1, 1.27 to 1.80 inPedon KNG-P2 and from 0.52 to 1.12 inPedon GHNG-P1 (Table 3). There was no clear trend of decease or increase of clay /silt ratio with soil depth. The Silt/clay ratio decreased inthe order Pedon KNG-P2> Pedon KNG-P1> PedonGHNG-P1 with pedon mean values of 1.46, 0.98 and 0.77.Soils withsilt/clay ratio of less than 0.15 are considered to be highly weathered(VanWambeke, 1962). Therefore the studiedsoils were young (Si/C>0.15) in terms of degree of pedogenesis.

Chemical Index of Alteration (CIA)

Chemical Index of Alteration (CIA) was used to determine degree of weathering of studied pedons. The topsoil CIA ranged from 44.80 to 79.01% and from 46.11 to 80.26% in subsoil (Table 8) of studied pedons. CIA values varied somehow among studied soil pedons, with the trend Pedon KNG-P1>Pedon KNG-P2>Pedon GHNG-P1 with mean pedon values of 72.16, 67.97and 45.98%, respectively.Several studies (Nesbitt and Young 1982; Fedo *et al*., 1995)have shown that kaolinite has a CIA value of 100 and represents the highest degree of weathering. Illite lies between 75 and 90, muscovite at 75, and feldspars at 50. Fresh basalts have values between 30 and 45, fresh granites and granidiorites between 45 and 55. The smaller the CIA value, the younger the soils are in terms of degree of weathering and age of soil formation. The study showed that Pedon

GHNG-P1 was less weathered compared to Pedons KNG-P1 and KNG-P2. This may be attributed to different deposition of fresh materials from the surrounding areas.

4.2 Soil Classification

Soil morphological and laboratory analytical data were used to define diagnostic horizons and other features for classifying the soils in the study sites.Table 9 presents the diagnostic horizons and features for classifying the soils according to the Soil Taxonomy and the soils have been classified up to the family level of Soil Taxonomy (Soil Survey Staff, 2014). Table 10 presents a summary of the diagnostic properties of the studied soils and identifies the prefix and suffix qualifiers, which enabled the classification of the soils up to the TIER-2 of the FAO World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Soils' names at the first level of both classification systems correspond with their pedogenetic definitions.

Pedon KNG-P1 has an umbric epipedon and cambic horizon as diagnostic horizons and it has been classified at the first level as *Andisols* or *Andosols* according to the USDA Soil Taxonomy and World Reference Base for Soil Resources, respectively. Pedon KNG-P2 has an umbric epipedon as a diagnostic horizon and it has been classified at the first level as *Andisols* or *Andosols* according to the USDA Soil Taxonomy and World Reference Base for Soil Resources, respectively.

Both Pedons KNG-P1 and KNG-P2 are volcanic ash soils with andic properties and low base saturations. Pedon GHNG-P1 has a mollic epipedon and cambic horizon as diagnostic horizons and it has been classified at the first level as *Mollisols* or *Phaeozems* according to the USDA Soil Taxonomy and World Reference Base for Soil Resources, respectively. It possesses some degree of andic properties particularly in the upper 100 cm and high base saturation.

Table 9: Diagnostic features and classification of the studied soils according to USDA Soil Taxonomy

Pedon No.	Diagnostic horizon(s)	Other diagnostic features	Order	Suborder	Greatgroup	Subgroup	Family
KNG-P1	Umbric epipedon, Cambic horizon	Mountainous (slope >90%), very deep, loamy, medium acid, udic SMR, mesic STR, abundant basaltic scoria, presence of iron nodules, andic properties (very high PRC >85%; very low BD <0.5 g/cc; very high pH_{NaF})	Andisols	Udands	Fulvudands	Pachic Fulvudands	***Mountainous, very deep, loamy, medium acid, udic, mesic, Pachic Fulvudands***
KNG-P2	Umbric epipedon	Steeply dissected to mountainous (slope >45%), shallow (lithic contact at a maximum of 40 cm), loamy, medium acid, udic SMR, mesic STR, abundant basaltic scoria, andic properties (very high PRC >85%; very low BD <0.5 g/cc; very high pH_{NaF})	Andisols	Udands	Fulvudands	Lithic Fulvudands	***Steeply dissected to mountainous, shallow, loamy, medium acid, udic, mesic,Lithic Fulvudands***
GHNG-P1	Mollic epipedon, cambic horizon	Nearly level (1%), very deep, loamy, mildly alkaline, udic SMR, thermic STR; some degree of andic properties particularly in the upper 100 cm (medium levels of PRC, slightly high pH_{NaF} and low BD)	Mollisols	Udolls	Hapludolls,	Andic Hapludolls	***Nearly level, very deep, loamy, mildly alkaline, udic, thermic, Andic Hapludolls***

KNG-P1= Kinigi pedon 1 KNG-P2= Kinigi pedon 2 GHNG-P1= Gahunga pedon1

Table 10: Diagnostic horizons and features and classification of the studied soils according to WRB for Soil Resources

Pedon No.	Diagnostic horizons	Other features / materials	Reference Soil Group (RSG) - TIER1	Principal Qualifiers	Supplementary Qualifiers	WRB soil name - TIER 2
KNG-P1	Umbric horizon, Cambic horizon	Abundant basaltic scoria, presence of iron nodules, andic properties (very high PRC >85%; very low BD <0.5 g/cc; very high pH_{NaF})	Andosols	Vitric, Umbric, Dystric	Loamic, Fulvic, Hyperhumic,	***Dystric Umbric Vitric Andosols (Loamic, Fulvic, Hyperhumic)***
KNG-P2	Umbric horizon	Abundant basaltic scoria, andic properties (very high PRC >85%; very low BD <0.5 g/cc; very high pH_{NaF})	Andosols	Vitric, Leptic, Umbric, Dystric	Loamic, Fulvic, Hyperhumic, Thixotropic	***Dystric Umbric Leptic,Vitric Andosols (Loamic, Fulvic, Hyperhumic, Thixotropic)***
GHNG-P1	Mollic horizon, cambic horizon	Some degree of andic properties particularly in the upper 100 cm (medium levels of PRC, slightly high pH_{NaF} and low BD)	Phaeozems	Cambic, Haplic	Loamic, Humic, Raptic, Vitric	***Haplic Cambic Phaeozems (Loamic, Humic, Raptic, Vitric)***

KNG-P1= Kinigi pedon 1 KNG-P2= Kinigi pedon 2 GHNG-P1= Gahunga pedon1

4.3 Potentials and Limitations of the Studied Soils for the Production of Maize, Potato, Pyrethrum and Beans

A combination of climatic data, soil and land resources data collected from both field and laboratory were used to identify potentials and limitations of the studied areas of Northern Province of Rwanda.

4.3.1 Physical conditions

Pedon KNG-P1 excavated in Musanze District, Kinigi Sector, Nyabigoma Cell, Gahura Village was located at the lower quarter of the mountain, with a slope of more than 90%. The steep slopes in this area pose some limitations for mechanized agriculture and high risk of soil erosion such as landslide and interill in some cases Thixotropic properties also makes this site susceptible to landslide. The soil was very deep, well drained with dark sand loamy texture in surface horizon (Ap) and low bulk density. Low bulk density facilitates easy root development and growth. Considering the agricultural zone, annual rainfall in the area ranges from 1300-1600 mm.Therefore the amount of rainfall required for the production of maize, beans, pyrethrumandpotatoes is adequate.

Pedon KNG-P2was located in Musanze District, Kinigi Sector, Kaguhu Cell, Kabeza Village with a slope of about 45%. This slope steepness poses some limitation for mechanised agriculture and erosion. Thixotropic properties also makes this site susceptible to landslide usually after prolonged heavy rains as the high water holding capacity of andic horizons increases their weight. Soilin the area is rocky and shallow (effective rooting depth< 50 cm) with lithic contact at about 40 cm depth. This affects negatively crops with deep root development and land workability.Soils were not compacted, which facilitate ease movement of water, plant nutrients, and root development.The amount of

rainfall required for the production of maize, beans, pyrethrum andpotatoes was adequate in this region due to its trends of annual total rainfall (1300-1600 mm).

Pedon GHNG-P1 was located in Burera District, Gahunga Sector, Rwasa Cell, Kabindi Village. The landform was colluvio-alluvial plain with a slope of less than 1%.Gentle slope may cause flooding or ponding during the rainy season. Soil was very deep and not compacted which facilitate an easy root growth and development. In this study area,the trends and the amount of rainfall required for the production of maize, beans andpotatoes was adequate.

4.3.2 Chemical properties of the studied soils

Different soil properties are presented inTable 4, 5, 6.The soil pH in all studied soils was medium acid (5.57) to mildly alkaline (7.51). Pedon KNG-P1 was medium acid to neutral, Pedon KNG-P2 was medium acidand Pedon GHNG-P1 was neutral to mildly alkaline.According to EUROCONSULT (1989), most plants thrive well in soils of pH 6 to 7.5. From this point of view, the studied sites do not present any limitation to crop production. Total Nitrogen content was high in almost all horizonsof Pedons KNG-P1 and KNG-P2 due to high organic matter content.In PedonGHNG-P1, TN was medium. From this point of view, Nitrogen is a not limiting factor in the studied soils for the production of maize, beans, pyrethrum and potatoes. Also, organic carbon content was not a limitation for selected crops due its high content in both topsoils and subsoils inPedons KNG-P1 and KNG-P2, and medium to high content in Pedon GHNG-P1.Phosphorus is commonly the growth limiting nutrient element in soils derived from volcanic materials (Yatno and Zauyah, 2008).Available Phosphorus is problematic in Kinigi sector(Pedons KNG-P1 and KNG-P2) due to high P retention capacity inthe soils. Application of high rate P fertilizers; organic and inorganic, at the right place and at the right time is recommendedto

improve P fertility and crops production. InPedon GHNG-P1, available P is very high which is favourable for the production of maize, bean, pyrethrum and potatoes.

Soil salinity in studied soil was very low consequently crops grown in these areas will not be affected.The nutrient balances were mostly not well balanced; the fact that could limit the production of maize, beans, pyrethrum and potatoes. Crop rotation, application of manures and inorganic fertilizers is highly recommended in the studied areas. High cation retention capacity observed in studied topsoils and subsoils implies good soil fertility for crop production. It also implies low or no intensive leaching of bases from topsoils to subsoils.

4.3.3 Land qualities and their rating

According to FAO (1976), land quality is defined as a complex attribute of land which acts in a distinct manner in its influence on the suitability of land for a specific kind of use. Land qualities may be expressed in a positive or negative way. Moisture availability, temperature regime, oxygen availability to roots, rooting conditions,soil fertility,soil salinity, erosion hazard and flooding hazard are the most land qualities considered in this study.A comparison was made between the land use requirements and the actual land qualities of the two major land units to give the partial suitability rankings for each studied area in respect of theLand Utilization Type(LUT)maize, beans, potatoes and pyrethrum (Table 11, 12, 13, 14). The overall suitability assessment was obtained using the “Law of limiting Conditions” whereby the least favourable suitability class is taken as the overall suitability class for a particular land unit. Land suitability is defined as the fitness of a given type of land for a defined use (FAO, 1976; EUROCONSULT, 1989). Land suitability classes reflect degrees of suitability.The suitability classes of the studied soils are described below.

Class 1: Highly suitable land (S1)

Highly suitable land is considered as land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level (FAO, 1976; EUROCONSULT, 1989). None of the studied soils was classified under this class as an overall land suitability

Class 2: Moderately suitable land (S2)

Moderately suitable land is defined as land having limitations which are moderately severe for sustaining a givenuse; inputs are required to increase productivity or benefits but productivity or benefits will be appreciably inferior to that expected on Class S1 land (FAO, 1976; EUROCONSULT, 1989). Pedon GHNG-P1 is moderately suitable for maize, beans, pyrethrum and potatoes production (Table 15).

Class 3: Marginally suitable land (S3)

Land having limitations which in aggregate are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be onlymarginally justified(FAO, 1976). PedonsKNG-P1 and KNG-P2 aremarginally suitable for maize, beans, pyrethrum and potatoes production (Table 15).

Class N: Not suitable land (N)

It reflects land having limitations which may be surmountable in time but which cannot be corrected with existing knowledge at currently acceptable cost or/and land with limitation which appear as severe as to preclude any possibility of successful sustained use of the land in the given manner. None of the studied soils was classified under this class as an overall land suitability.

Table 11:Rating of land use requirements for maize production and partial suitability classification of the studied soils

Land use requirements (Land quality)	Land characteristics (Diagnostic factor)	Optimum range (rate)	Actual field range (rate)			Partial suitability class		
			KNG-P1	KNG-P2	GHNG-P1	KNG-P1	KNG-P2	GHNG-P1
Moisture availability	Total rainfall in growing period	≥500mm in 3-4 months	1400–1800	1400–1800	1400	S1	S1	S1
Temperature regime	Mean temperature in growing period	18 to 32°C	<25°C	<25°C	9-29°C	S1	S1	S1
Oxygen availability to roots	Soil drainage	well drained	well drained	well drained	well drained	S1	S1	S1
Rooting conditions	Effective soil depth	very deep	very deep	shallow	very deep	S1	S3	S1
	Ground water level (cm)	>75	>200	<100	>200	S1	S1	S1
Nutrient availability	Soil texture	Medium	SL	SL	SCL	S1	S1	S1
	Soil reaction (pH:0-25cm)	5.0 - 8	5.6	5.8	7.41	S1	S1	S1
	Topsoil OC%	High	very high	very high	high	S1	S1	S1
	Topsoil TN%	High	very high	very high	medium	S1	S1	S2
	Topsoil Avail P	High	very low	very low	very high	S3	S3	S1
Nutrient retention capacity	BS%	High	very low	very low	high	S2	S2	S1
	CEC cmol(+)/kg	High	very high	very high	high	S1	S1	S1
Salinity	Ece (dS/m)	<1.7	<1.7	<1.7	<1.7	S1	S1	S1
Flooding hazard	Frequency of flooding	none	none	none	once/year	S1	S1	S2
	Duration of flooding	none	none	none	0 - 2 days	S1	S1	S2
Erosion hazard	Slope angle	<6%	>90%	about 45%	< 1%	S3	S3	S1

KNG-P1= Kinigi pedon 1, KNG-P2= Kinigi pedon 2, GHNG-P1=Gahunga pedon 1

Source: EUROCONSULT (1989); Landon (1991); Sys *et al*. (1993); Verdoodt and Van Rant, (2003a)

Table 12: Rating of land use requirements for beans production and partial suitability classification in the studied soils

Land use requirements (Land quality)	Land characteristics (Diagnostic factor	Optimum range and/or rate	Actual field range			Partial suitability class		
			KNG-P1	KNG-P2	GHNG-P1	KNG-P1	KNG-P2	GHNG-P1
Moisture availability	Total rainfall in growing period	≥300mm in 3 months	1400-1800	1400 – 1800	1400	S1	S1	S1
Temperature regime	Mean temperature in growing period	15 to 27°C	<25°C	25°C	9-29°C	S1	S1	S1
Oxygen availability to roots	Soil drainage	well drained	well drained	well drained	well drained	S1	S1	S1
Rooting conditions	Effective soil depth	very deep	very deep	shallow	very deep	S1	S3	S1
	Ground water level (cm)	>50	>200	<100	>200	S1	S1	S1
Nutrients availability	Soil texture	medium and coarse	SL	SL	SCL	S1	S1	S1
	Soil reaction(PH: 0-25cm)	5.5 - 7.5	5.6	5.8	7.41	S1	S1	S1
	OC%	high	very high	very high	high	S1	S1	S1
	TN%	high	very high	very high	medium	S1	S1	S2
	Avail P	high	very low	very low	very high	S3	S3	S1
Nutrients retention capacity	BS%	high	very low	very low	high	S2	S2	S1
	CEC cmol(+)/kg	high	very high	very high	high	S1	S1	S1
Salinity	Ece (dS/m)	< 1.7	<1.7	<1.7	<1.7	S1	S1	S1
Flooding hazard	Frequency of flooding	none	none	none	once/year	S1	S1	S2
	Duration of flooding	none	none	none	0-2days	S1	S1	S2
Erosion hazard	Slope angle	<6%	>90%	45%	<1%	S3	S3	S1

KNG-P1= Kinigi pedon 1, KNG-P2= Kinigi pedon 2, GHNG-P1= Gahunga pedon1

Source: EUROCONSULT (1989), Landon (1991) and Sys *et al*. (1993); (Verdoodt and Van Rant, 2003a)

Table 13: Rating of land use requirements for potatoes production and partial suitability classification of the studied soils

Land use requirements	Land characteristics	Optimum	Actual field range			Partial suitability class		
(Land quality)	Diagnostic factor	Range and/ or rate	KNG-P1	KNG-P2	GHNG-P1	KNG-P1	KNG-P2	GHNG-P1
Moisture availability	Total rainfall in growing period	≥500mm in 3.5 - 5 months	1400–1800	1400–1800	1400	S1	S1	S1
Temperature regime	Mean temperature in growing period	15 to 25°C	<25°C	<25°C	9 - 29°C	S1	S1	S1
Oxygen availability to roots	Soil drainage	well drained	well drained	well drained	well drained	S1	S1	S1
Rooting conditions	Effective soil depth	very deep	very deep	shallow	very deep	S1	S3	S1
	Ground water level (cm)	>30	>200	<100	>200	S1	S1	S1
Nutrient availability	Soil texture	Sand, clay, loam	SL	SL	SCL	S1	S1	S1
	Soil reaction (PH:0-25cm)	4.5 - 6.0	5.6	5.8	7.41	S1	S1	S1
	OC%	high	very high	very high	high	S1	S1	S1
	TN%	high	very high	very high	medium	S1	S1	S2
	Avail P	high	very low	very low	very high	S3	S3	S1
Nutrient retention capacity	BS%	high	very low	very low	high	S2	S2	S1
	CEC cmol(+)/kg	high	very high	very high	high	S1	S1	S1
Salinity	Ece (dS/m)	< 1.7	<1.7	<1.7	<1.7	S1	S1	S1
Flooding hazard	Frequency of flooding	none	none	none	once/year	S1	S1	S2
	Duration of flooding	none	none	none	0-2days	S1	S1	S2
Erosion hazard	Slope angle	<6%	>90%	45%	<1%	S3	S3	S1

KNG-P1= Kinigi pedon 1, KNG-P2= Kinigi pedon 2, GHNG-P1= Gahunga pedon1

Source: EUROCONSULT (1989), Landon (1991) and Sys *et al*. (1993); Verdoodt and Van Rant, (2003a)

Table 14: Rating of land use requirements for pyrethrum production and partial suitability classification of the studied soils

Land use requirements (Land quality)	Land characteristics (Diagnostic factor	Optimum Range and/or rate	Actual field range			Partial suitability class		
			KNG-P1	KNG-P2	GHNG-P1	KNG-P1	KNG-P2	GHNG-P1
Moisture availability	Total rainfall in growing period	>1000mm	1400-1800	1400 – 1800	1400	S1	S1	S1
Temperature regime	Mean temperature in growing period	<15 ^{o}C	<25 ^{o}C	<25 ^{o}C	9-29 ^{o}C	S1	S1	S1
Oxygen availability to roots	Soil drainage	well drained	well drained	well drained	well drained	S1	S1	S1
Rooting conditions	Effective soil depth	very deep	very deep	shallow	very deep	S1	S3	S1
	Ground water level (cm)	>50	>200	<100	>200	S1	S1	S1
Nutrient availability	soil texture	Loamy soil	SL	SL	SCL	S1	S1	S1
	soil reaction(PH)0-25cm	5.5– 7	5.6	5.8	7.41	S1	S1	S1
	Topsoil OC%	high	very high	very high	high	S1	S1	S1
	TN%	high	very high	very high	medium	S1	S1	S2
	Avail P	high	very low	very low	very high	S3	S3	S1
Nutrient retention capacity	BS%	high	very low	very low	high	S2	S2	S1
	CEC cmol(+)/kg	high	very high	very high	high	S1	S1	S1
Salinity	Ece (dS/m)	<1.7	<1.7	<1.7	<1.7	S1	S1	S1
Flooding hazard	Frequency of flooding	None	None	None	once/year	S1	S1	S2
	Duration of flooding	None	None	None	0-2days	S1	S1	S2
Erosion hazard	Slope angle	<6%	>90%	About 45%	<1%	S3	S3	S1

KNG-P1= Kinigi pedon, KNG-P2= Kinigi pedon, GHNG-P1= Gahunga pedon1

Source: Raemaekers (2001)

The overall suitability class for Pedon KNG-P1 is $S3_{e,na}$.The land unit is marginally suitable for maize, beans, potatoes and pyrethrum production, the main limitation being erosion hazard due to high slope steepness and the landform and nutrient availability due to high P retention capacity (Table 15). The overall suitability class for Pedon KNG-P2 is $S3_{s,na,e}$.the land unit is marginally suitable for maize, beans, potatoes and pyrethrum production, the main limitation being the rooting condition, nutrient availability and erosion hazard (Table 15). The overall suitability class for Pedon GHNG-P1 is $S2_{f,na}$.The land unit is moderately suitable for maize, beans, pyrethrum and potatoes productionwith the main limitation being flooding hazard and nutrient availability (low to medium level of OC, TN, cationic imbalance) (Table 15).

Table 15: Overall land suitability for various crops in the studied area, Northern Province of Rwanda

Land unit	Land use	Overallland suitability classes
KNG-P1	Maize	$S3_{e,na}$
	Beans	$S3_{e,na}$
	Potatoes	$S3_{e,na}$
	Pyrethrum	$S3_{e,na}$
KNG-P2	Maize	$S3_{s,na,e}$
	Beans	$S3_{s,na,e}$
	Potatoes	$S3_{s,na,e}$
	Pyrethrum	$S3_{s,na,e}$
GHNG-P1	Maize	$S2_{f,na}$
	Beans	$S2_{f,na}$
	Potatoes	$S2_{f,na}$
	Pyrethrum	$S2_{f,na}$

KNG-P1= Kinigi pedon 1, KNG-P2= Kinigi pedon 2, GHNG-P1= Gahunga pedon1

Limitations to suitability:

na= nutrient availability, e=erosion hazard, f= flooding hazard,s= root zone limitation(depth, stoniness)

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

The study reported herein was carried out in the Northern Province of Rwanda. Based on the findings the following conclusions and recommendations are drawn:

5.1 Conclusions

i. The studied soils showed a delicate ecosystem that requires careful use and management. Morphology and physico-chemical characteristics of studied soils differed from one pedon to another

ii. The studied soils are not highly weathered as indicated by their indices of weathering.

iii. The soil fertility of the studied area is considered to be moderate.The moderaterating of soil fertility is based on the levels of TN, OM, pH, CEC,BS and available P.

iv. Nutrient availability, erosion hazard, flooding hazard and shallow depth are the most limitations that can limit the production of major crops grown in the area

v. The studied pedons were developed on volcanic parent materials but they displayed different degrees of volcanic properties and only soils represented by Pedons KNG-P1 and KNG-P2 classified as *Andisols* or *Andosols* according to USDA Soil Taxonomy and FAO WRB for Soil Resources respectively.

5.2 Recommendations

The following recommendations can be made from the results of the study:

i. To restore natural fertility of the studied soils, use of animal manure and other sources of organic and inorganic fertilizers, crop rotation is recommended. Due

to high P retention capacity of the volcanic soils, high rate of P fertilizers application is highly recommended

ii. Terracing and terraces stabilization are highly recommended in the area susceptible to erosion.Trees, shrubsand other permanent crops should be planted tohelp in stabilizing, throughtheir extended roots, from soil erosion.Areas with very high slope steepness, afforestation, and tea plantation are highly encouraged.

iii. Further research should be carried out in order to assess efficient use, types and application rates of fertilisers to replenish nutrientdeficiencies.

iv. Pedological characterisation and soil classification should be carried out to cover moreareas of Rwanda in order to generate the needed recent database for land use planning

v. In the area with shallow soils, adoption of shallow rooted crops and crop with rooting system that has the capacity of breaking a hardpan (eg. Pigeon pea),is highly recommended so that the crops can make use of nutrients available at shallow depth.

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