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RESEARCH ARTICLE

PEDOLOGICAL CHARACTERIZATION OF SOILS DEVELOPED ON GNEISSIC - GRANITES IN THE CONGO NILE WATERSHED DIVIDE AND CENTRAL PLATEAU ZONES, RWANDA

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ABSTRACT

Pedological characterization was carried out on soils developed on gneissic granites of Southern Province of Rwanda. Three representative soil profiles (GSK-P1, GSK-P2 and TMB-P1) were identified, described and sampled using standard manuals. A total of nineteen soil samples were analyzed in the laboratory for physico-chemical properties. Soil classification was carried out using two international systems of classification. The potentials and limitations of the soils were also identified. All studied pedons were very deep, well drained with loamy to clayey topsoil textures overlying dominantly clayey subsoil textures. The deeper subsoil of Pedon TMB-P1 consisted of loamy and sandy textures. Pedons GSK-P1 and GSK-P2 depicted eluviation-illuviation process as indicated by presence of clay cutans in subsoils. Analytical data showed low bulk and particle densities and high porosity in topsoils ranging from 1.02 to 1.34 g/cm^3, from 2.18 to 2.59 g/cm^3 and from 48.34 to 53.23%, respectively. Topsoilsof studied soils were strongly to slightly acidic with pH ranging from 5.49 to 6.59 while subsoils were strongly acidic to medium acidic with pH range between 5.13 and 5.86. The studied pedons had very low to medium total nitrogen and organic carbon respectively ranging from 0.15 to 0.24% and from 1.6 to 2.5%, both decreasing with depth. Topsoil and subsoil cation exchange capacity of the soils respectively ranged from low (9.8 - 21.6 cmol (+)/kg) to medium (4.2 - 13.2 cmol (+)/kg). Base saturation of the studied pedons was rated as low (< 50%) throughout all horizons of studied pedons. Whereas topsoil available phosphorus ranged from low to medium (6.4 - 15.7 mg/kg) and decreased with depth, phosphorus retention capacity was < 50% and increased with depth in Pedons GSK-P1 and GSK-P2 but didnot show any definite trend in PedonTMB-P1. All studied pedons indicated suboptimal nutrient ratios with reference to the basic cations, implying potential nutrient imbalance and toxicity of these nutrients. SiO_2, Al_2O_3 and Fe_2O_3 ranged from 45.4 to 58.4%, 17.0 to 27.0% and 16.7 to 24.3%, respectively. On the basis of silt/clay ratios, the degree of weathering of the studied pedons followed the trend GSK-P1>GSK-P2>TMB-P1. According to USDA Soil Taxonomy, the studied pedons classified as Ultisols (GSK-P1 and GSK-P1) and Inceptisols (TMB-P1), respectively, correlating to Alisols and Cambisols of WRB for Soil Resources. The studied soils were generally rated as having low fertility and only marginal suitability for the major crops of the area. Specific land management and cropping systems were recommended for sustainable utilization of soils.

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INTRODUCTION

Pedological characterization is defined as the gathering of soil information by systematic identification, grouping and delineation of different soils occurring in the locality (Tan, 1995; Kebeney *et al*., 2015). According to Jenny (1941), cited by (Munishi, 2010), soil forming factors namely climate, parent material, biota, relief and time influence the morphological, physical, chemical and biological characteristics of soil. Understanding soil genesis, morphology and other key properties is a prerequisite to sustainable use of soil resources and thus detailed knowledge about them is essential (Msanya *et al*., 2003). In Rwanda soil survey works were carried out between 1990-2002 years which led to creation of Carte pedologique du Rwanda (CPR) database covering the whole country (Van Wambeke, 1963). Since many years ago, due to increasing population of Rwanda, coupled with high rainfall, steep slopes and various human activities (bench terraces, deforestation, over cultivation and overgrazing), erosion rate increased (Bizoza and Degraaf, 2010). Thus soils have been much disturbed in terms of morphology and physico-chemical properties (Rushemuka *et al*., 2014; Olsen *et al*., 1994c; Verdoodt and Van Ranst,

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2006). Nyamagabe and Huye Districts are no exception in terms of land degradation. Demographic pressure with mean annual growth rate of 0.5% in 1991-2002 and grew to 2% in 2002- 2012 with densities which increased from 386 in 2002 to 565 inhabitants/km2 in 2012 (National Institute of Statistics of Rwanda-NISR, 2012). This problem has led to cultivation periods to be extended up to two or three times per year and this has contributed to the highly acidic soils (< 5.5), deficient in phosphorus (P) and nitrogen (N)and with aluminium toxicity which affects crops (Roose and Barthes, 2001; Rutunga, 2006). Moreover, the nutrient status of the soils is poor because of the low CEC of the clay fraction and the rapid decomposition of OM (Rutunga, 2006). Heavy rains which frequently occur in these mountainous regions cause serious erosion and subsequent soil sedimentation in the lower parts of the hillsides, often causing significant damage to crops and deposition of new materials (mineral and organic) from the upper part (soil truncation) to the lower part (soil aggradation). This resulted in shallow, acidic and less fertile soils in upper parts of the hillside whereas, soils in lower part, are deeper, less acidic and more fertile (Aleyamahu, 2007; Msanya, 2015). The soil profiles we see today are thus no longer the soils that were mapped before. Therefore, pedological characterization to update current situation of soils is important for improved soil management and productivity for specific crops.

MATERIALS AND METHODS

Description of the study area

The study was carried out in Nyamagabe District situated in Congo Nile Watershed Divide Zone (CNWD) with pedons designated as GSK-P1 and GSK-P2 and Huye District situated in Central Plateau Zone(CP) with a pedon designated as TMB-P1in Southern Province of Rwanda. Table 1 and Figure 1 present location details of the study area. The three profiles have developed on Precambrian metamorphic complexes of Butare including alternation of granite, gneissic granite, quartzitic and mica-schistose meta-sediments, amphiboles and some mylonites (Theunissen *et al*., 1991). The altitude across the study area ranges from 1624m.a.s.l. to 2128m.a.s.l. In terms of physiography, the soils are formed on steep slopes with gradient ranging from 30 - 60%. Surface characteristics illustrated severe gully and interill/sheet erosion with no deposition, but with rapid infiltration and rapid runoff in the identified sites. The climatic condition of the study area is summarized in Figure 2. The area is characterized by high rainfall averaging 1124.32 mm per annum and mean annual temperature of 19.81oC. In addition, the study sites experience bimodal rainfall pattern with long rains having their peak in March-April whereas the short rains having their peak in November. The maximum temperatures vary between 26.20C and 22.70C and minimum temperatures range between 13.40C and 14.80C (Huye and Nyamagabe District reports, 2013). The maximum temperature is within the rating of land use requirements for rainfed beans, maize and cowpeas production (EUROCONSULT, 1989; Landon, 1991; Raemaeker, 2001).

Field methods

Through a reconnaissance field survey using transect walks, auger observation and descriptions, the representative study sites on the basis of altitudes, landforms and other physiographic attributes were established. Soil profile pits were dug; geo-referenced using global positioning system (model GARMIN etrex 20), studied and described according to the FAO guidelines for soil description (FAO, 2006). Site characteristics such as slope gradient, erosion, natural drainage, elevation, parent material, natural vegetation and land use were recorded. Soil morphological characteristics including soil color, texture, consistence, structure, porosity, and effective depth were also determined. Soil color was determined by using Munsell Color Chart (Munsell Color Company, 1992).

From each profile pit, disturbed (bulk) and undisturbed (core samples) samples were taken from each genetic soil horizon for physical and chemical analysis in the laboratory.

Laboratory methods

Pedological characterization

Undisturbed core samples were used for the determination of bulk density, particle density, porosity and moisture retention characteristics. Bulk density was determined by the core method (Black and Hartge, 1986). Soil moisture retention characteristics were determined using sand kaolin box for low suction values and pressure apparatus for higher suction values (NSS, 1990). The collected disturbed soil samples were air-dried and ground to pass through a 2-mm sieve for determination of physical and chemical properties. Particle size analysis was determined by Bouyoucos hydrometer method after dispersion with 5%sodium hexametaphosphate (NSS, 1990) and textural classes were determined using the USDA textural class triangle (USDA, 1975). Soil pH was measured potentiometrically in water and 1N KCl at a ratio of 1:2.5 soil: water and KCl (Okalebo, 2002). Potentiometric method was used to determine electrical conductivity of soil samples (Okalebo, 2002). Total exchangeable acidity was determined using 1M KCl extraction solution and the soil extract titrated with sodium hydroxide. A second titration with 1M HCl after addition of sodium fluoride was used to obtain the exchangeable aluminium (NSS, 1990).

Organic carbon was determined by the Walkley and Black wet oxidation method (Nelson and Sommers, 1982) and OC was converted to organic matter (OM) by multiplying by a factor of 1.724 (Duursma and Dawson, 1981).Total nitrogen was determined using micro-Kjeldahl digestion-distillation method (Bremmer and Mulvaney, 1982). Available P was extracted using Bray no.1 solution and determined by spectroscopy at 882nm following color development by the molybdenum blue method (Okalebo, 2002). Phosphate-retention capacity was determined according to the method of Blakemore (Blackmore *et al*., 1981). The CEC and exchangeable bases were extracted by saturating soils with neutral 1M NH4OAc (ammonium acetate) (Thomas, 1982) and the absorbed NH4+ displaced by K+ using 1M KCl and then determined by Kjeldahl distillation method for the estimation of CEC of the soil. The bases Ca2+, Mg2+, K+ and Na+ displaced by NH4+ were measured by atomic absorption spectrophotometer (Thomas,1982). The total exchangeable bases (TEB) were calculated arithmetically as a sum of the four exchangeable bases (Ca2+, Mg2+, Na+ and K+) for a given soil sample. Cation Exchange Capacity of clay (CECclay) was calculated using the formula outlined by Landon, 1991:

CECclay= (CECsoil /% Clay)*100

Table 1. Salient characteristics of the studied sites in Nyamagabe and Huye Districts, Rwanda

Pedon no.	Coordinates	AEZs1	Altitude m asl	Lithology/parent materials	Landform	Land use/vegetation	STR2	SMR3
GSK-P1	029o32′20.7″E 02o27′58.6″S	CNWD	2128	Precambrian metamorphic complexes of Butare including alternation of granite, gneissic granite, quartzitic and mica-schistose metasediments, amphiboles and some mylonites.	Mountainous	Agriculture/banana, sweet, potatoes, beans, coffee, wheat and peas	Isohyperthermic	Udic
GSK-P2	029o35′23.0″E 02o29′59.0″S	CNWD	1768	As above	As above	Agriculture/beans and banana	Isothermic	Udic
TMB-P1	029o44′07.8″E 02o38′23.8″S	CP	1624	As above	Hill bordering a U-shaped valley	Agriculture/rice maize and banana	Isothermic	Udic

1) AEZs: Agro-Ecological Zones:
CNWD: Congo Nile Watershed Divide, the fifth largest agro-ecological zone, occupying the highland area of Rwanda. In this region the altitude varies between 1,900-2,500 m while the annual rainfall varies between 1,300 and 1,800 mm/year. This abundant rainfall has totally leached the soils that were developing from poor parent material such as mica-schistose, gneissic granites.
CP: Central Plateau, Large region of hills and valleys between the Congo-Nile mountain chain and the Granitic Ridge zones, at the centre of the country. At an average altitude of 1,700 m, the annual rainfall amounts to 1,200 mm and the average temperature attains 19 °C. If the humus-bearing horizons are conserved, the soils can be used for the cultivation of a whole range of climatically adapted crops.
2) STR= Soil Temperature Regime
3) SMR = Soil Moisture Regime

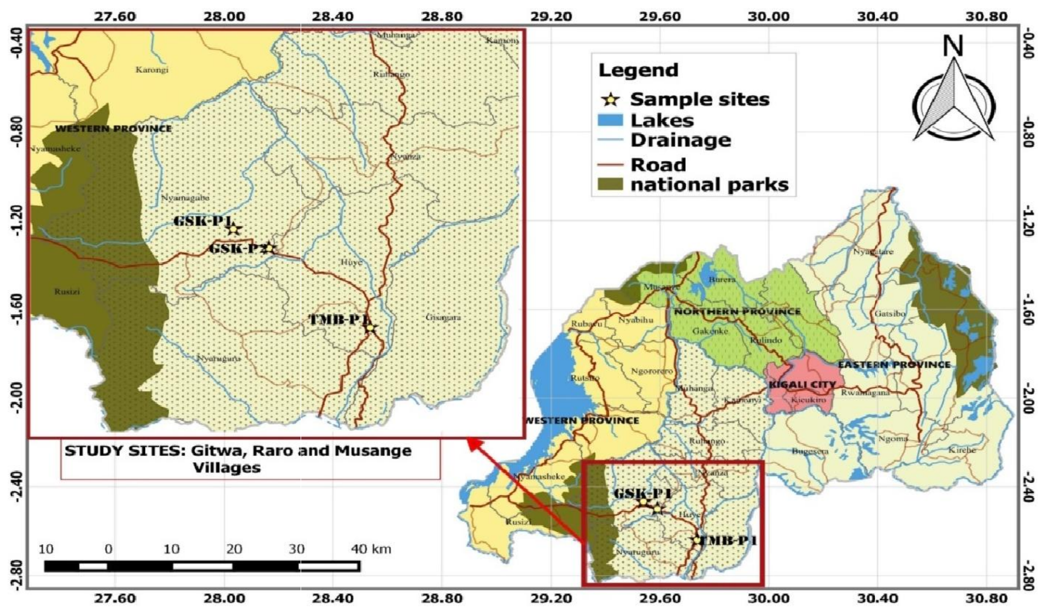


Figure 1. Map of study area in Nyamagabe and Huye Districts with location of soil profile sites

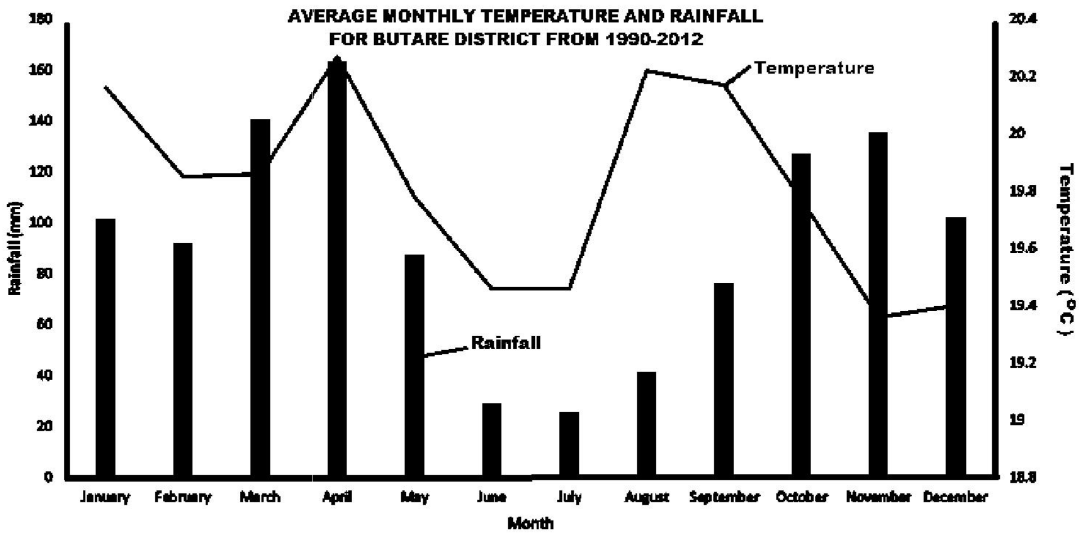


Figure 2. Average monthly rainfall and temperature data of the study areas

Determination of multi-element oxides for selected soil horizons was done by X-Ray Fluorescence. Portions of 60 g of air dried (fine earth fraction) soil samples were open air dried by using Infra-Red lamps for two hours. Samples were ground to particle size ≤ 177 µm (80 Mesh) using swing mill pulverizer. Powdered samples were then pressed into XRF sample cups and mounted with PANalytical B.V X-Ray filmpolyesterpetp. Elemental oxides were measured using PANalytical, Minipal 4 Energy Dispersive X- Ray Fluorescence Spectrometer (ED-XRF) Model PW4030/45B. The degree of weathering of the soils was assessed based on the silt/clay ratioand silica sesquioxide ratio.

Data Analysis

MS-Excel software was employed to construct graphs (Microsoft Excel, 2010) and Pearson's rank correlation was used to assess correlation between soil parameters.

Classification of soils

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

Determination of potentials and limitations of soils for the production of major crops

Using field and laboratory data, rating of potentials and limitations of soils was done using known guidelines (EUROCONSULT, 1989; Landon, 1991; Raemaeker, 2001). The 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.

RESULTS AND DISCUSSION

Morphological characteristics

Key morphological properties of the profiles in the study areas are presented in Table 2. GSK-P1 and GSK-P2 profiles are very deep (>150 cm), well drained with dark yellowish brown sand clay and clay loamtopsoils, overlying reddish brown, yellowish brown to brown clayey subsoils. Many distinct clay cutans were observed in subsoil, indicating that illuviation-elluviation has been a dominant pedogenetic process in the area. The clay cutans are rich in sesquioxides as indicated by red subsoil colours. Profile TMB-P1 is also very deep, well drained and has moderate, fine to medium crumby structure in topsoil. Subsoil is characterized by weak fine subangular blocky structure in Bw and BC horizons and structure less single grained in the rest of the horizons. The profile has brown clay loam topsoils overlying reddish brown, dark yellowish brown, yellowish red, red and yellow subsoils having respectively sandy clay, gravely sand clay, gravely loam, loamy sand and gravely clay textures. All soil profiles have pores ranging from few to many, fine and very fine, pores, and very few to many, fine to coarse roots in the topsoil and few to common, medium to fine roots in subsoils. Artifacts in the form of pieces of bricks and charcoal were observed in the profiles indicating anthropogenic activities in the study area.

Soil physical characteristics

Soil particle size distribution

Particle size distribution and textural classes of the studied soils are presented in Table 3. Figure 2 gives the size particle distribution in relation to depth, clearly indicating that the distribution patterns of the textural separates are similar for Pedons GSK-P1 and GSK-P2. This supports the fact that the two pedons have developed largely under same soil forming factors and have attained comparable degree of pedogenesis (Kebeney *et al*., 2015). Although Pedon GSK-P1 has sandy clay topsoil and GSK-P2 has clay loam topsoil, subsoils of the pedons are dominantly clayey. The silt/clay ratios of subsoils of the two pedons are very low, indicating that the two pedons are highly weathered (Msanya *et al*., 2016). The silt/clay ratios in GSK-P2 are relatively lower than those in GSK-P1 indicating that the former pedon is slightly more weathered than the latter (Uwingabire, 2016). Pedon TMB-P1 is more heterogeneous in terms of texture when compared to the previous two pedons. It has clay loam topsoil overlying different coarse textures in subsoils such as sand clay, gravely sand clay, gravely loam, loamy sand, and gravely clay. This coarse textures control the variability of nutrient storage capacity, and this will likely limit the water holding capacity of the soil implying that roots may grow under suboptimal soil water due to water deficits (Lar and Shukla, 2005).

Bulk density, particle density and total porosity

The analytical results on bulk density (BD), particle density (PD) and total soil porosity (TSP) of the studied profiles are given in Table 3. Bulk density affects infiltration, rooting depth, available water capacity, soil porosity, plant nutrient availability, and soil microbial activity, which in total influence key soil processes and productivity (Lar and Shukla, 2005). According to Hunt and Gilkes (1992) topsoil bulk densities were rated as low and ranged from 1.02 to 1.34 g/cm3 while subsoil bulk densities were medium, ranging from 1.30 to 1.55 g/cm3 for all soil profiles. According to Zonn (1986), cited by Msanya *et al*. (2016) the values of BD are within the common range for tropical soils. These values suggest that the studied soils were not compact, hence plant roots can penetrate easily and movement of air between soil and atmosphere would be unhindered. Soil particle density values ranged from 2.18 to 2.59 g/cm^3 in topsoils and from 2.56 to 2.66 g/cm^3 insubsoils. Low particle density values of <2.6 g/cm^3 (Brady and Weil, 1990) show that there is no restriction to crop growth since they indicate that there is no soil compaction; roots can penetrate without difficulty, and there is adequate aeration and water storage within the soil (Gachene *et al*., 2003). TSP ranged from 48.34 to 53.25 % in topsoil and 41.42 to 51.27 % in subsoils. The high porosity > 40% in all the horizons as previously reported by Gachene*et al*. (2003), indicate that there is no restriction of crop growth since it indicates no soil compaction, root penetration without difficulty, adequate aeration and water storage within the soil. The values of topsoil BD and PD of the studied soils are lower than those of subsoils. This is due to higher content of OM in topsoils and also, to increasing contents of clay, free oxides of iron, aluminum and manganese in subsoils which act as cementing agents in soil, responsible for binding strongly together individual soil particles in subsoils (Mullins *et al*., 1992; Karuma *et al*., 2015).

Table 2. Main morphological characteristics of the studied soil pedons in Nyamagabe and Huye Districts, Rwanda

Pedon no.	Horizon	Depth (cm)	Texture 1	Moist color 2	Moist and wet consistence 3	Structure 4	Cutans 5	Horizon boundary 6
GSK-P1	Ap	0 - 10/16	SC	dyb(10YR4/4/)	vfr,st&pl	mo,f,cr	-	cw
	Bt1	10/16 -69	gSC	r(2.5YR4/6)	fr,vst&vpl	mo,m+c,sbk	m,d,cs	ds
	Bt2	69 - 139	C	yb(10YR5/6)	fr,vst&vpl	mo-s,m,sbk	m,d,cs	ds
	Bt3	139 - 172	C	b(7.5YR5/4)	fr,vst&vpl	mo-s,c,sbk	m,d,cs	cs
	Bt4	172 - 195/208	C	dyb(10YR4/6)	fr,st&pl	mo,c,sbk	m,d,cs	cw
	CBt	195/208 - 251+	vgC	yb(10YR5/6)	fr,st&spl	w,m-c,sbk	f,f,cs	-
GSK-P2	O	0 - (-4/13)	L	dyb(10YR4/4)	vfr,nst&spl	mo,m,cr	-	cw
	Ap	0 - 13/34	CL	b(7.5YR5/4)	fr,sst&spl	mo,f+m,sbk	-	cw
	BA	13/34 - 38/51	CL	b(10YR4/3)	fr,sst&spl	w-m,f+m,sbk	-	cw
	Bt1	38/51 -75/122	C	yr(5YR4/6)	f,vst&vpl	mo,m+c,sbk	m,d,ch	gw
	Bt2	75/122 - 183	C	rb(5YR5/4)	f,vst&vpl	s,m+c,sbk	m,d,cs	ds
	Bt3	183 - 223+	C	yr(5YR5/6)	fr,st&pl	s,m+c,sbk	m,d,cs	-
TMB-P1	Ah	0 - 8	CL	b(10YR4/3)	vfr,sst&spl	mo,f+m,cr	-	cw
	Bw	8 - 48/68	SC	rb(5YR4/4)	fr,st&pl	w,m+c,sbk	-	cw
	BC	48/68 - 55/87	gSC	dyb(10YR3/4)	fr,sst&spl	w,f,sbk	-	dw
	CB	55/87 - 100/130	gL	yr(5YR4/6)	fr,sst&spl	ss	-	cw
	C1	100/130 - 148/174	LS	r(2.5Y5/6)	f,sst&spl	ss	-	cw
	C2	148/174 - 188/200	gC	yb(10YR5/6)	f,st&pl	ss	-	aw
	C3	188/200 - 240+	LS	y(10YR8/8)	fr,sst&spl	ss	-	-

Soil pedons: GKS-P1=Gasaka; TMB-P1=Tumba

1) Texture: SC= sand clay; gSC = gravely sand clay; C = clay; vgC = very gravely clay; L = loam; CL = clay loam; gL = gravely loam; LS = loamy sand;gC = gravely clay.

2) Color:dyb = dark yellowish brown; r=red; yb = yellowish brown; b=brown; yr = yellowish red; rb =reddish brown;y=yellow

3) Consistence:vfr = very friable; s = sticky; p = plastic; vs = very sticky; vp = very plastic; f = firm

4) Structure:Grade: s=strong; mo=moderate; w=weak; m-s=moderate to strong; w-m=weak to moderate;
Size: c=coarse; m=medium; f=fine; f+m=fine and medium; m+c=medium and coarse;
Form:cr=crumby; sbk=subangular blocky; ss=structure less single-grained

5)Cutans:Quantity: m=many; f=few; v=very few; Thickness: d=distinct; f=faint;
Type: cs=clay+ sesquioxides; ch=clay and humus (organic matter).

6) Horizon boundary: Width: c=clear; d=diffuse; a=abrupt; g=gradual;Topography: w=wavy; s= smooth

Table 3. Soil physical properties of pedons from selected districts, Southern Region (Nyamagabe and Huye Districts), Rwanda

Pedon no.	Horizon	Depth (cm)	Particle size distribution					Bulk density (g/cm3)	Particle density (g/cm3)	Soil Porosity %	Penetration resistance kg/cm2
			Sand %	Clay %	Silt %	Silt / clay ratio	Textural classes				
GSK-P1	Ap	0 - 10/16	47	39	14	0.36	Sandy clay	1.34	2.59	48.34	1.60
	Bt1	10/16 - 69	47	41	12	0.29	Sandy clay	1.43	2.61	45.36	5.69
	Bt2	69 - 139	41	49	10	0.20	Clay	1.37	2.61	47.69	4.91
	Bt3	139 - 172	43	47	10	0.21	Clay	nd	nd	nd	7.50
	Bt4	172 - 195/208	37	53	10	0.18	Clay	nd	nd	nd	8.54
	CBt	195/208 - 251+	45	49	5.6	0.11	Clay	nd	nd	nd	5.16
GSK-P2	O	0 - (-4/13)	46	25	29	1.16	Sandy loam	1.02	2.18	53.23	0.78
	Ap	0 - 13/34	39	37	24	0.65	Clay loam	nd	nd	nd	4.45
	BA	13/34 - 38/51	39	47	14	0.30	Clay loam	1.3	2.66	51.27	5.69
	Bt1	38/51 - 75/122	39	55	6	0.11	Clay	1.35	2.58	47.67	16.68
	Bt2	75/122 - 183	41	53	6	0.11	Clay	nd	nd	nd	13.19
	Bt3	183 - 223+	35	57	8	0.14	Clay	nd	nd	nd	14.81
TMB-P1	Ah	0 - 8	48	38	14	0.37	Clay loam	1.06	2.21	52.19	0.92
	Bw	8 - 48/68	47	46	7	0.15	Sandy clay	1.55	2.64	41.42	5.55
	BC	48/68 - 55/87	47	48	5	0.10	Gravely sand clay	1.31	2.56	49.01	6.78
	CB	55/87 - 100/130	45	28	27	0.96	Gravely loam	nd	nd	nd	7.51
	C1	100/130 - 148/174	74	6	20	3.33	Loamy sand	nd	nd	nd	37.73
	C2	148/174 - 188/200	43	56	1	0.02	Gravely clay	nd	nd	nd	13.97
	C3	188/200 - 240+	80	9	11	1.22	Loamy sand	nd	nd	nd	22.87

GSK-P1&P2: Soil profiles in Gasaka Sector; TMB-P1: Soil profile in Tumba Sector;nd: not determined

Table 4. Chemical properties of pedons from selected areas in Nyamagabe and Huye Districts, Rwanda

Pedon no.	Horizon	Depth(cm)	pH			EC (dS/m)	OC %	OM %	TN %	C/N ratio	Avail.P (mg/kg)	P retention capacity%
			H2O	KCl	NaF							
GSK-P1	Ap	0-10/16	5.49	4.75	9.07	0.06	1.99	3.43	0.16	12.44	6.44	30.6
	Bt1	10/16–69	5.61	4.72	9.06	0.03	1.20	2.07	0.14	8.57	4.83	38.3
	Bt2	69–139	5.64	4.72	8.68	0.03	0.90	1.55	0.13	6.92	4.63	35.8
	Bt3	139–172	5.42	4.68	9.18	0.02	1.02	1.76	0.15	6.73	5.62	33.2
	Bt4	172-195/208	5.23	4.68	9.05	0.03	0.85	1.47	0.12	7.08	4.38	39.9
	CBt	195/208-251+	5.13	4.68	9.20	0.03	0.44	0.76	0.08	5.55	1.45	40.8
GSK-P2	O	0 - (-4/13)	6.36	5.59	8.75	0.10	3.00	5.17	0.26	8.35	16.24	25.6
	Ap	0-13/34	5.43	4.63	9.46	0.06	1.43	2.47	0.16	8.93	8.36	38.3
	BA	13/34 - 38/51	5.2	4.77	10.01	0.03	1.72	2.97	0.14	12.29	9.40	35.5
	Bt1	38/51 - 75/122	5.51	4.815	9.44	0.03	1.06	1.83	0.12	8.83	10.63	28.2
	Bt2	75/122 - 183	5.42	4.725	8.75	0.03	0.60	1.03	0.09	6.66	7.33	30.6
	Bt3	183-223+	5.3	4.84	9.27	0.05	0.56	0.97	0.08	7.00	6.33	20.5
TMB-P1	Ah	0 – 8	6.59	5.14	9.56	0.06	2.50	4.31	0.24	12.66	15.70	10.2
	Bw	8 - 48/68	5.41	4.81	9.65	0.02	1.59	2.74	0.13	12.23	4.50	7.7
	BC	48/68 - 55/87	5.79	4.83	10.2	0.02	1.38	2.38	0.12	11.50	4.92	2.6
	CB	55/87 - 100/130	5.86	4.83	9.69	0.01	0.34	0.59	0.07	4.86	5.04	3.1
	C1	100/130 - 148/174	5.5	4.85	10.09	0.02	0.21	0.36	0.06	3.50	8.92	10.1
	C2	148/174 - 188/200	5.4	4.74	9.58	0.02	0.39	0.67	0.07	5.57	6.23	17.7
	C3	188/200 - 240+	5.2	4.90	9.51	0.02	0.18	0.31	0.06	3.00	6.87	7.54

GSK-P1&P2: Soil profiles in Gasaka Sector, Nyamagabe DistrictTMB-P1: Soil profile in Tumba Sector, Huye District

Table 5. Exchangeable cations and related chemical properties of the studied soils in Nyamagabe and Huye Districts, Rwanda

Pedon no.	Horizon	Depth (cm)	Exchangeable bases cmol(+)kg-1				TEB	CECsoil	CECclay	Exchangeable acidity		PBS
			Ca2+	Mg2+	K+	Na+				Exch. Al3+	Exch. H+	
GSK-P1	Ap	0 - 10/16	2.01	0.045	0.080	0.089	2.22	9.8	25.13	1.05	0.20	22.69
	Bt1	10/16 – 69	1.38	0.012	0.014	0.064	1.47	11.0	26.83	0.80	0.15	13.36
	Bt2	69 – 139	1.36	0.034	0.014	0.081	1.49	8.0	16.32	0.65	0.10	18.61
	Bt3	139 – 172	1.69	0.017	0.014	0.089	1.81	11.6	24.68	2.25	0.10	15.60
	Bt4	172 - 195/208	1.31	0.009	0.014	0.081	1.41	10.6	20.00	2.35	0.10	13.34
	CBt	195/208 - 251+	0.82	0.004	0.004	0.072	0.90	10.0	20.41	2.55	0.10	9.00
GSK-P2	O	0 - (- 4/13)	2.02	0.085	0.494	0.115	2.71	21.6	86.40	0.25	0.20	12.56
	Ap	0 - 13/34	1.15	0.006	0.105	0.106	1.37	16.8	45.41	1.65	0.20	8.14
	BA	13/34 - 38/51	1.25	0.005	0.055	0.089	1.40	11.0	23.40	2.25	0.20	12.72
	Bt1	38/51 - 75/122	0.82	0.007	0.070	0.081	0.98	11.6	21.09	2.70	0.05	8.43
	Bt2	75/122 – 183	0.82	0.003	0.004	0.072	0.90	8.2	15.47	2.35	0.10	10.96
	Bt3	183 - 223+	0.83	0.002	0.004	0.098	0.93	6.8	11.92	1.00	0.10	13.73
TMB-P1	Ah	0 – 8	2.24	0.063	0.292	0.089	2.68	14.2	37.37	0.20	0.00	18.90
	Bw	8 - 48/68	0.85	0.018	0.019	0.098	0.98	12.4	26.96	2.05	0.10	7.94
	BC	48/68 - 55/87	0.82	0.002	0.004	0.081	0.91	13.2	27.50	2.90	0.10	6.87
	CB	55/87 - 100/130	0.56	0.003	0.004	0.098	0.67	12.8	45.71	0.40	0.50	5.20
	C1	100/130 - 148/174	0.92	0.002	0.004	0.072	1.00	11.4	190.00	1.05	0.05	8.77
	C2	148/174 - 188/200	0.81	0.002	0.004	0.072	0.99	8.4	15.00	1.40	0.25	11.71
	C3	188/200 - 240+	0.92	0.011	0.004	0.072	1.01	4.2	46.67	1.45	0.35	23.97

GSK-P1&P2: Soil profiles in Gasaka Sector, TMB-P1: Soil profile in TumbaSector

Table 6. Nutrient balance in the studied pedons in Nyamagabe and Huye Districts, Rwanda

Pedon no.	Horizon	Depth(cm)	%Ca/TEB	Ca/Mg	Mg/K	% (K/TEB)
GSK-P1	Ap	0 - 10/16	0.91	43.60	0.57	3.60
	Bt1	10/16 – 69	0.94	114.80	0.82	0.95
	Bt2	69 – 139	0.93	51.72	2.4	0.93
	Bt3	139 – 172	0.93	95.95	1.22	0.77
	Bt4	172 - 195/208	0.92	130.80	0.66	0.99
	CBt	195/208 - 251+	0.91	211.70	0.94	0.44
GSK-P2	O	0 - (- 4/13)	0.74	23.06	0.17	18.23
	Ap	0 - 13/34	0.84	185.90	0.06	7.66
	BA	13/34 - 38/51	0.89	171.70	0.13	3.93
	Bt1	38/51 - 75/122	0.84	300.00	0.04	7.14
	Bt2	75/122 - 183	0.91	514.20	0.39	0.44
	Bt3	183 - 223+	0.83	12.76	15.6	0.43
TMB-P1	Ah	0 – 8	0.85	119.00	0.06	10.90
	Bw	8 - 48/68	0.87	514.20	0.08	1.94
	BC	48/68 - 55/87	0.90	300.00	0.66	0.36
	CB	55/87 - 100/130	0.89	581.90	0.39	0.60
	C1	100/130 - 148/174	0.92	581.90	0.39	0.40
	C2	148/174 - 188/200	0.91	163.60	1.22	0.40
	C3	188/200 - 240+	0.91	86.66	2.60	0.40

GSK-P1&P2: Soil profiles in GasakaSectorTMB-P1: Soil profile in TumbaSector

Table 7. Correlation among physic-chemical properties of the studied pedonsin Nyamagabe and Huye Districts, Rwanda

	Horizon	% Clay	% Sand	pHwater	Exch. Al	% OM	% OC	%TN	% PRC	CEC	Exch. Ca	Exch. Mg	Exch. K	Exch. Na
Horizon	1													
% Clay	0.02	1												
% Sand	0.26	-0.858**	1											
pHwater	-0.635**	-0.238	-0.014	1										
Exch. Al	0.742**	0.347	-0.031	0.551*	1									
% OM	-0.874**	0.072	-0.262	0.637**	-0.633**	1								
% OC	-0.874**	0.017	-0.273	0.615**	-0.633**	0.928**	1							
% TN	-0.835**	0.004	-0.269	0.699**	-0.633**	0.923**	0.940**	1						
% PRC	-0.08	0.43	-.502*	-0.35	0.067	0.049	0.121	0.195	1					
CEC	-0.691**	-0.085	-0.222	0.579**	-0.641**	0.667**	0.789**	0.789**	0.13	1				
Exch. Ca	-0.661**	-0.074	-0.092	0.542*	-0.534*	0.737**	0.710**	0.844**	0.303	0.447	1			
Exch. Mg	-0.3	-0.043	-0.166	0.381	-0.219	0.346	0.526*	0.518*	0.134	0.316	0.561*	1		
Exch. K	-0.592**	-0.239	-0.061	0.769**	-0.572*	0.708**	0.810**	0.853**	-0	0.775**	0.645**	0.628**	1	
Exch. Na	-0.494*	0.103	-0.325	0.246	-0.41	0.609**	0.721**	0.684**	0.165	0.680**	0.458*	0.611**	0.628**	1

Pearson's rank correlation at 95% confidence level,*** signifies P<0.001, ** signifies P<0.

Table 8. Total elemental composition of the studied pedons in Nyamagabe and Huye Districts,Rwanda

Pedon no.	Horizon	Depth (cm)	Al_2O_3	SiO_2	Fe_2O_3	MnO	Na_2O	CaO	MgO	K_2O	$V2O_5$	TiO_2	Total
								%					
GSK-P1	Ap	0 - 10/16	19.00	52.20	21.38	0.11	0.002	0.45	0.001	3.38	0.08	2.36	99.0
	Bt2	69 - 139	20.00	51.50	21.49	0.08	0.004	0.42	0.001	3.08	0.07	2.28	98.5
	Bt4	172 - 195/208	20.00	49.30	23.14	0.07	0.002	0.33	0.001	3.31	0.07	2.27	99.4
	CBt	195/208 - 251+	21.00	48.40	29.12	0.06	0.003	0.28	0.003	2.61	0.07	1.90	97.8
GSK-P2	Ap	0 - 13/34	21.00	53.20	18.55	0.07	0.008	0.30	0.008	2.29	0.06	2.29	98.8
	Bt2	75/122 - 183	17.00	58.20	20.77	0.04	0.002	0.26	0.001	1.16	0.04	1.40	98.7
	Bt3	183 - 223+	22.00	59.90	21.05	0.06	0.002	0.28	0.008	2.03	0.06	2.33	99.3
TMB-P1	Ah	0 - 8	19.00	58.40	16.70	0.14	0.001	0.47	0.003	1.93	0.07	2.58	99.3
	Bw	8 - 48/68	21.00	53.30	19.00	0.13	0.005	0.30	0.009	1.47	0.08	2.54	97.8
	CB	55/87 - 100/130	24.00	45.40	24.30	0.06	0.004	0.26	0.009	1.38	0.09	2.26	97.8
	C2	1448/174 - 188/200	27.00	46.30	19.85	0.05	0.005	0.26	0.007	1.94	0.09	2.30	97.8

GSK-P1&P2: Soil profiles in Gasaka Sector, Nyamagabe DistrictTMB-P1: Soil profile in Tumba Sector, Huye District

Table 9. Parameters showing weather ability of soils in studied pedonsinNyamagabe and Huye Districts, Rwanda

Pedon no.	Horizon	Depth	SiO_2 / Al_2O_3	[SiO2 /(Al_2O_3 + Fe_2O_3)]*	Silt/clay ratio
GSK-P1	Ap	0 - 10/16	2.75	1.29	0.34
	Bt2	69 - 139	2.58	1.24	0.19
	Bt4	172 - 195/208	2.47	1.14	0.18
	CBt	195/208 - 251+	2.59	1.36	0.11
GSK-P2	Ap	0 - 13/34	2.53	1.35	0.64
	Bt2	75/122 - 183	3.42	1.54	0.11
	Bt3	183 - 223+	2.31	1.18	0.14
TMB-P1	Ah	0 - 8	3.07	1.64	0.36
	Bw	8 - 48/68	2.07	1.33	0.15
	CB	55/87 - 100/130	1.89	0.94	0.96
	C2	1448/174-188/200	1.71	0.99	0.01

GSK-P1&P2: Profiles in Gasaka Sector, Nyamagabe District, Rwanda
TMB-P1: Profile in Tumba Sector, Huye District, Rwanda
*Also referred to as silica/sesquioxide ratio

Table 10. Soil classification of the studied soils of Nyamagabe and Huye Districts, Rwanda

Pedon no	USDA Soil Taxonomy(Soil Survey Staff,2014)					World Reference Base for Soil Resources (IUSS Working Group WRB,2015)	
	Order	Suborder	Greatgroup	Subgroup	Family	Reference Soil Group-Tier1	TIER2-WRB Soil name
GSK-P1	Ultisols	Humults	Palehumults	TypicPalehumults	Mountainous, very deep, clayey, medium acid, udic, thermic, TypicPalehumults	Alisols	HaplicAlisols (Clayic, Cutanic, Hyperdystric, Humic, Profondic
GSK-P2	Ultisols	Humults	Palehumults	TypicPalehumults	Mountainous, very deep, loamy over clayey, strongly acid, udic, thermic, TypicPalehumults	Alisols	HaplicAlisols (Clayic, Cutanic, Hyperdystric, Humic, Profondic)
TMB-P1	Inceptisols	Udepts	Dystrudepts	TypicDystrudepts	Steeply dissected, very deep, clayey over loamy, medium to strongly acid, udic, thermic,TypicDystrudepts	Cambisols	DystricCambisols (Loamic, Humic)

GSK-P1&P2: Soil profiles in Gasaka Sector, Nyamagabe District, RwandaTMB-P1: Soil Profile in Tumba Sector, Huye District, Southern Province, Rwanda

Table 11. Overall land suitability classification for the representative areas of Nyamagabe and Huye Districts, Rwanda

Land area/ Studied sites	Rainfed crops				
	Maize	Beans	Sweet potatoes	Pea	Wheat
GSK-P1	S3x,nr,na,e	S3x,nr,e	S3m,c,x,na,nr,e	S3na,x,nr,e	S3m,c,na,nr,e
GSK-P2	S3x,nr,e	S3 x,nr,e	S3m,c,x,na,nr,e	S3x,nr,e	S3m,c,na,nr,e
TMB-P1	S3x,nr,e	S3 x,nr,e	S3x,nr,e	S3x,nr,e	S3m,c,na,nr,e

GSK-P1&P2: Soil profiles for Gasaka Sector, Nyamagabe DistrictTMB-P1: Soil profile in Tumba Sector, Huye District
Limitations to suitability:
x=toxicities, na= nutrient availability, nr= nutrient retention capacity, m= moisture availability, c=temperature regime, e= erosion hazard

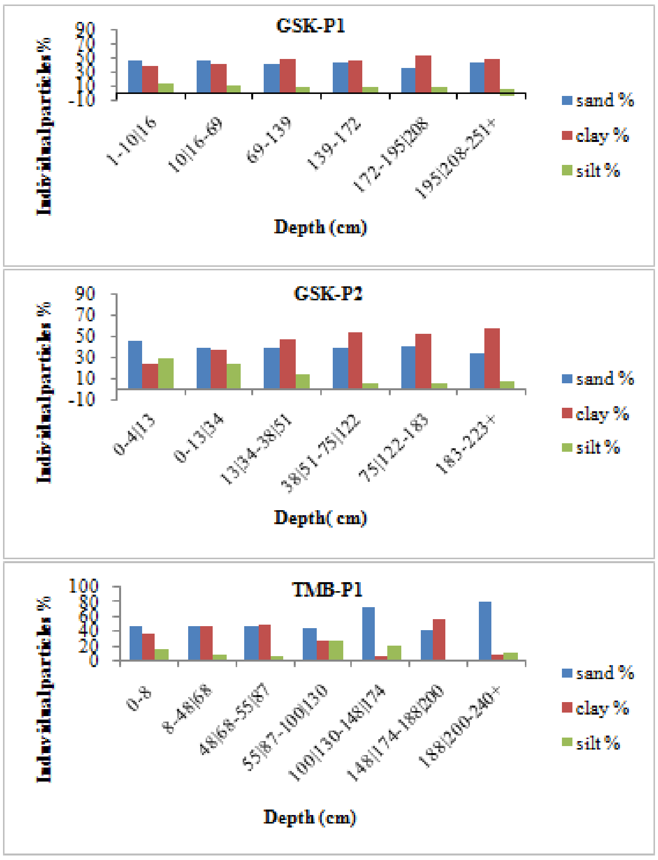


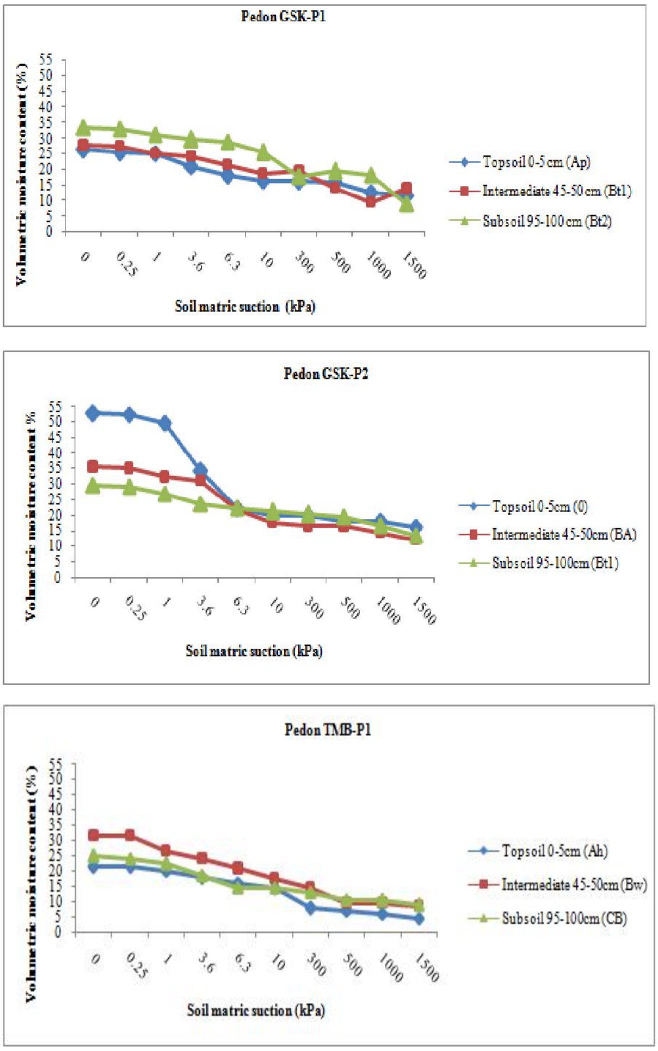
Figure 3. Particle size distribution against soil depth for the studied pedons

Penetration resistance

Table 3 presents the penetration resistance of the three studied pedons. Topsoil penetration resistance values of the studied pedons ranged from 1.60 - 5.20 kg/cm2while those of subsoils ranged from 0.8 - 16.68 kg/cm2. This depicts low soil compaction in topsoils which is attributed to low bulk density and high porosity (Whaley, 2006). All studied pedons had penetration resistance of <30 kg/cm^2; this implies possible low levels of soil compaction in the profile horizons which is likely not to impair growth and development of crops in the study area (Busscher *et al*., 2000; Kebeney *et al*., 2015).

Soil moisture retention characteristic curves

Figure 4 presents results on soil moisture retention characteristics for Gitwa (GSK-P1), Raro (GSK-P2) and Musange (TMB-P1) sites. At low soil matric potentials, PedonGSK-P2 retained more water than the other two pedons which showed similar moisture release patterns. Topsoil of the same pedon retained more water than intermediate and subsoil layers because of its high OM content (5.17% OM) which has a natural attraction for water (Klute, 1986). There was a drastic decrease in soil moisture with increasing suction for topsoil of PedonGSK-P2 implying an effect of drastic dryness of field crops whenever there is a dry spell during the rainy season, consequently causing plants to experience temporal wilting (Kebeney *et al*., 2015). Subsoil horizon (Bt2) of PedonGSK-P1, retained much more water than topsoil and intermediate horizons, because this horizon had more clay than the overlying horizons, and thus could hold more moisture at any suction.The higher retention of water in the case of the intermediate horizon in PedonTMB-P1 compared to the other horizons in the same pedon was attributed to higher clay content.



GSK-P1&P2: Gasaka profilesTMB-P1: Tumba profile

Figure 4. Soil moisture retention characteristic curves of the studied pedons

Soil chemical properties

Soil pH and exchangeable acidity

The pH of the studied soils varied slightly between and among profiles (Table 4). According to the ratings by ILACO (1991), Landon (1991), Baize (1993) and Msanya *et al*. (2001), topsoils of all three pedons had moderate to slightly acidic conditions (5.49-6.49) while subsoils had moderate to strongly acidic conditions (5.13-5.86). Exchangeable aluminum values ranged from 0.20 to 1.05 cmol(+)/kg in the topsoil and from 0.40 to 2.55 cmol(+)/kg in the subsoil (Table 5). According to Brady and Weil (2002) and Jamieson *et al*. (1995), the values of exchangeable Al3+ in topsoils were rated as low whereas in subsoils were rated as medium to high. These results indicated that the acidity of these soils is mostly contributed by exchangeable Al and to a less extent by hydrogen (Munishi, 2010). Aluminum ions are released from clay lattices at pH values of about below 5.5 and become exchangeable in the clay complex (Landon, 1991). They can also enter into soil solution and get hydrolyzed to form hydroxylAl compounds and free H+ that make the soil acidic (Yatno and Zauyah, 2008) as cited by Munishi (2010). Low pH of soils in the study area is probably induced by acidifying nitrogen fertilizers, nitrate leaching, removal of bases through crop harvests and the farming practices (Brady and Weil, 2002; Landon, 1991; Mackenzie *et al*., 2004). The results imply that application of liming materials is inevitable to raise soil pH to the optimal levels of about 6.5 to 7.5. This will minimize nutrient imbalances, toxicity and nutrient unavailability since low soil pH values below pH < 5.5 have potential to cause toxicity problems and deficiency of some essential plant nutrients as well as negative effects on soil microbial activities (Adamchuk and Mulliken, 2005). Also soil pH < 5.5 could cause dissolution of aluminum and iron minerals which precipitate with phosphorus effectively causing its fixation and further lowering the soil pH (Brady and Weil, 2002).

Organic carbon, total nitrogen, C/N ratio and organic matter

According to ILACO (1991), Landon (1991), Baize (1993) and Msanya *et al*. (2001), Pedon GSK-P1 had very low to medium organic carbon (OC) content and very low to medium total nitrogen (TN) ranging from 1.99 to0.44% for OC and from 0.16 to 0.08% for TN (Table 4). Pedon GSK-P2 had low to high OC content and very low to medium TN ranging between 3.00 - 0.56% and 0.2 - 0.08% respectively (Table 4). Pedon TMB-P1 had low to mediumOC, very low to medium TN ranging from 2.50-0.18% and 0.24-0.06%, respectively (Table 4). Low content of OC and TN levels may be attributed to low pH which restricts microbial activities (Landon, 1991). Low levels of OC and TN in PedonGSK-P1 may be due to continuous cultivation without replenishment of organic residues (Kebeney *et al*., 2015). Topsoils of all pedons under study had C/N values ranging from 8.4 - 12.5 which are within the rating of good quality organic matter (ILACO 1991; Landon, 1991; Baize 1993; Msanya *et al*., 2001). The values of OM in topsoils of all pedons in the study area ranged between 3.43 and 4.31% which are rated as medium to high (Table 4) (ILACO 1991; Landon1991; Baize 1993; Msanya *et al*., 2001). High amount of OM was observed in TMB-P1 which was kept as fallow, while relatively low amounts were observed in GSK-P1and GSK-P2. Johnsons (2002) observed higher concentration of OM in the surface soil under no-tillage systems since less disruption resulted in greater accumulation of surface residue carbon. Moreover, the roots of fodder crops and the slower rate of organic matter decomposition might have contributed to the buildup of organic matter in soil with zero tillage treatment (Uwingabire, 2016). Tillage treatment enhanced decomposition of OM thereby reducing its content in Gitwa (GSK-P1) site, because any mixing of residue with soil would allow residue to remain wetter and, therefore, provide ideal conditions for microbial decomposition that leads to loss of surface residues (Hasinur *et al*., 2008).

Available phosphorus and phosphorus retention capacity of soils

According to ILACO (1991), Landon (1991), Baize (1993) and Msanya*et al*. (2001), Pedon GSK-P1 had very low available phosphorus (P) (<7 mg/kg) (Table 4). This is probably due to continuous cultivation without replenishment of P from different P fertilizers (Kebeney *et al*., 2015). Pedons GSK-P2 and TMB-P1 had medium levels of available P (7-20 mg/kg). This might be because these areas have been kept fallow (Uwingabire, 2016). Low available phosphorus in subsoil layers of the pedons may be attributed to low soil pH (<5.8) and could react with iron (Fe) and aluminium (Al) to produce insoluble Fe and Al phosphates that are not readily available for plant uptake (Hodges,2007).Available P level of 7 - 15 mg/kg is generally considered as the critical level below which P deficiency symptoms are likely to occur in many crops (Landon, 1991; Hodges, 2007; Msanya *et al*., 2016; ILACO, 1991). The P-retention capacity (PRC) of the soils under study ranged from 33.25 to 40.80% for Pedon GSK-P1, 20.48 to 38.3% for Pedon GSK-P2 and 2.56 to 17.75% for Pedon TMB-P1. PRC increased with depth for Pedons GSK-P1 and GSK-P2, while for Pedon TMB-P1 there was no well-defined trend of PRC with depth. The increase of PRC with depth could be attributed to increase in clay content, Al and Fe hydrous oxides such as hematite and goethite (Adam *et al*., 2007). Clay and Al and Fe hydrous oxides have high affinities for phosphorus, hence the amount of P retained. High affinities of clay and oxides could be attributed to high specific surface area and the existence of variable charges (pH-dependent charges) on their exposed surfaces. Low values of PRC in topsoils may be attributed to high OM in topsoils than subsoils since soil OM competes with P for the ion retention sites of the inorganic soil colloids, hence low P retention capacities of the surface soil (Perez *et al*., 2014). From the data (Table 4), pH decreases with depth with clear trend particularly for Pedons GSK-P2 and TMB-P1. The decrease in pH increases concentration of hydrogen ions in soil solutions which protonates exposed OH- groups on the surface of soil colloids (both organic and inorganic), hence increasing the magnitude of positive charges on soil colloids consequently increasing adsorption of phosphate ion species in solution (Li *et al*., 2013).

Exchangeable bases, cation exchange capacity and base saturation

According to ILACO (1991, Landon (1991), Baize (1993) and Msanya *et al*. (2001), all the studied pedons had low to medium cation exchange capacity (CEC) in topsoils (9.8 - 16.8 cmol(+)/kg) and very low to medium CEC in subsoils (4.2 - 13.2 cmol (+)/kg) (Table 5). The low CEC values are contributed by kaolinite and sesquioxide or oxidic clays which are dominant clay minerals in highly weathered soils. The CEC values of the pedons implied possible negative influence on the buffering capacity of the soils and reduced retention of base cations by the studied soils (Kebeney *et al*., 2015; Brady and Weil, 2002). Exchangeable cations were low to very low in all studied pedons and this has direct implication on the cation exchange capacity (CEC), soil pH and ultimately plant nutrient imbalances, unavailability and nutrient induced deficiencies. The level of exchangeable bases in soils is actually a measure of the availability of bases for plant uptake. Percent base saturation (PBS) of the studied pedons ranged from 8.14 to 22.69 % and from 5.20 to 23.97% in topsoils and subsoils, respectively. PBS values can be rated as very low (much less than 50%) in all the studied pedons. Low PBS levels may result in very acid soils and potentially toxic cations such as Aluminium and Manganese from the soil (Hodges, 2007). Poor cultivation practices, poor soil and water conservation and inadequate supply of fertilizer to replenish nutrients removed by crops are reported to contribute to low levels of bases in most soils (Ellenkamp, 2004; Jones *et al*., 2013).

Nutrient balance in studied pedons

Nutrient ratios of the studied pedons are presented in Table 6. The ratios of Ca/TEB of the studied pedons ranged from 0.74 to 0.91% (Table 6). According to Landon (1991 and Msanya *et al*. (2016), Ca/TEB of more than 0.5 may affect the uptake of other bases, particularly Mg and/or K as Ca induced deficiency of Mg and/or K may appear. The ratios of Ca/Mg in studied topsoils ranged from 43.60 to 185.90. These values are not within the optimum range of 2 - 4 favorable for plant growth and development (Table 6) (Landon, 1991). The Mg/K ratios in topsoils ranged from 0.06 to 0.57 for all pedons and were below the recommended range of 1 to 4 for optimum nutrient uptake by plants (Table 6) (Landon, 1991; Msanya *et al*., 2016), implying potential nutrient imbalance and toxicity. In addition because these ratios are below the optimum minimum level of 1, it implies that K in some horizons is greater than Mg in these pedons and this is likely to reduce uptake of Mg from the soil by plants. The overall K/TEB ratios (expressed as percentage) in topsoils of studied pedons ranged between 3.6 and 18.23 % (Table 6). These ratios are above 2% which is said to be favorable for most tropical crops (Karuma *et al*., 2015; Kebeney *et al*., 2015; Landon, 1991). From these results, it is apparent that, nutrient imbalances observed in this study will influence nutrient availability. As a matter of fact nutrient availability determines the yield potential of crops and can be improved by manuring, application of inorganic fertilizers and crop rotation (Karuma *et al*., 2015; Jones *et al*., 2013).

Correlation among some chemical characteristics of the studied soils

Table 7 shows correlations among soil chemical and physical properties of the studied soils. The pH, OM, OC, TN, CEC and exchangeable Ca were strongly and negatively correlated with horizon depth with correlation coefficients of 0.64, 0.87, 0.87, 0.84, 0.69, and 0.64 respectively. This means that the mentioned attributes decreased with depth. Soil pH water was weakly and positively correlated with OM; with a correlation coefficient of 0.64. This is because the presence of OM helped to raise pH water but its contribution was not significant as the acidity of soils in these areas was much correlated with exchangeable aluminium. Al3+ ions enter into soil solution and get hydrolyzed to form hydroxy Al compounds and free H+ions which tend to make the soil acidic (Yatno and Zauyah, 2008). Also the pH was strongly and positively correlated with OC, TN, CEC and exchangeable bases. This is because pH contributes to the availability of macro and micro nutrients, as pH is lowered, the availability of those nutrients (macro and micro) will be low for uptake by crops (Adamchuk *et al*., 2005). CEC provides a buffering effect to changes in pH, available nutrients and calcium levels. As such it is a major controlling agent of stability of soil structure and nutrient availability for plant growth. Also as soils become more acidic, exchangeable cations are replaced by H+, Al3+ and Mn2+, thus lowering the CEC of the soil (Pam and Brian, 2007). Organic matter was strongly and positively correlated with OC, TN, CEC and exchangeable bases. CEC of soil was strongly and positively correlated with OM, with a correlation coefficient of 0.67 (Table 7). High content of OM and clay contribute to high CEC values because both have a large number of negative charges on their surface which attract and hold cations (Tomašić *et al*., 2013). All exchangeable cations Mg, Ca, K and Na were weakly and positively correlated with percentage BS of the studied soils with correlation coefficients of 0.37, 0.31, 0.01 and 0.39 respectively. This observation suggests that, these cations contributed little to the BS of the studied soils.

Pedogenesis, weathering index and total elemental composition of the studied pedons

Pedogenesis can be defined as the process of soil development. It is largely determined by five interrelated factors: climate, living organisms, parent material, topographyand time (Landon, 1991). There are different pedogenic processes observed to have operated and differentiated the soils in the study area. The consistently low OM of the soils is presumed to be a result of rapid humification and mineralization as conditioned by high radiation in the area (Uwingabire, 2016). The low amounts of exchangeable bases and the predominance of exchangeable acidity on the exchange complex in all the soils, is an indication of leaching and erosion processes as indicated by a lot of gullies and rills in the sites (Foth *et al*., 1998). The increase in clay content with depth in the soils of Gitwa and Raro villages (GSK-P1 and GSK-P2 pedons) as indicated by clay cutans in subsoils evidently indicates the process of lessivage (eluviation-illuviation) (Msanya *et al*., 2016). Ferralitization is also common in the study area. It is defined as accumulation of hydro (oxides) of Fe, Mn and Al, involving strong depletion of basic cations resulting low pH and dominance of low activity clays and hydroxydes (Dey, 1999). As a result it forms inherently poor soils with unfavorable chemical properties for agriculture use. The total elemental composition of the studied soils (Table 8) revealed that SiO2 was the most abundant among all determined oxides (45.4 - 58.4%) followed by Al_2O_3 (17-27%) and Fe_2O_3(16.7-24.3%). According to Yanai*et al*. (2012) the other elements i.e. MnO, Na2O, CaO, MgO, K2O, TiO2, and V2O5 were in low concentrations (<4.5%). Generally, the relatively high Si, Al and Fe concentrations and extremely low Na, Ca and Mg concentrations in the soils under study, reflect their high degree of weathering (Takeda *et al*., 2004). Silica/alumina (SiO_2/Al_2O_3) ratios in the soils decrease with depth and are generally moderate indicating that subsoils are more weathered than topsoils (Yanai *et al*., 2012; Takeda *et al*., 2004). As presented in Table 9, silica/sesquioxide ratios within pedons were < 1.6 indicating the predominance of kaolinite and considerable percentages of gibbsite, or aluminum oxides (Foth *et al*., 1998). Kaolinite as elaborated by Buol *et al*. (2003) is the most common clay mineral in acid, highly weathered soils.

Silt/clay ratios were slightly >0.2in topsoils but generally <0.2 in subsoils (Table 9) of the studied pedons, implying that subsoil horizons were more weathered than topsoils (Yanai *et al*., 2012). On the basis of silt/clay ratios, the degree of weathering followed the trend Pedon GSK-P1 >Pedon GSK-P2>Pedon TMB-P1 with mean silt/clay ratios of 0.21, 0.30 and 0.37 respectively.

Soil classification

Based on the field and laboratory data, the soils have been classified up to the family level of Soil Taxonomy (Soil Survey Staff, 2014) (Table 10) and up to the TIER-2 of the FAO World Reference Base for Soil Resources Classification Scheme (IUSS Working Group WRB (2015) (Table10). At order level of USDA Soil Taxonomy, the soils have been classified as Ultisols (Pedons GSK-P1 and GSK-P2) and Inceptisol (Pedon TMB-P1). According to the FAO-WRB for Soil Resources, the soils of the study area have been classified at TIER 2 as Alisols (Pedons GSK-P1 and GSK-P2), and Cambisols (Pedon TMB-P1).

Potentials and limitations of the studied soils for the production of maize, sweet potato, beans and wheat

Potential of the soils in the study areas was assessed by combining main ecological requirements of the selected crops with land qualities of the study areas (Landon, 1991; Raemaekers, 2001; EUROCONSULT, 1989). All the sites under study were marginally suitable for the major crops of the area i.e. maize, cowpeas, beans, sweet potatoes and wheat (Table 11). Major limitations of the area include erosion hazards, nutrient availability, nutrient retention capacity and toxicity (Al).

Conclusions and Recommendations

The areas under study are susceptible to high soil erosion due to their steep slopes and heavy rains. Thus, permanent crops such as coffee, banana and tea or agroforestry and fodder crops should be planted in these areas. This will help in stabilizing the soil from erosion by their extended roots and reduce leaching of cations. Moreover, the use of progressive and bench terraces should be promotedfor soil and water conservation particularly in the highly mountainous areas of Rwanda. From the fertility point of view, the studied soils represent a fragile ecosystem that requires a careful management. The soils are highly weathered, characterized by low TN, low OC and low OM, low pH, low available P, low levels of CEC and exchangeable bases, and low base saturation, thus necessitating immediate attention to revert the already depleted soils. Promotion of efficient use, types and application rates of fertilizers to replenish deficient nutrients is inevitable. To achieve increased sustainable crop yields, soil management practices that will increase nutrient availability and enhanced uptake are required. Aluminum toxicity appears to be a serious problem in the study areas. This should be corrected by liming to pH >5.5. Alternatively, OM addition can be used to reduce Al toxicity by binding the Al ions in OM complexes.

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