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Morphology, Genesis, Physico-chemical Properties, Classification and Potential of Soils Derived from Volcanic Parent Materials in Selected Districts of Mbeya Region, Tanzania

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Authors' contributions

This work was carried out in collaboration between all authors. Author BMM designed and supervised the field work. Author JAM did field work, managed soil analyses and literature search and wrote the first draft of the manuscript. Authors NA, ES, LM and ZM supervised the laboratory protocols. All authors read and approved the final manuscript.

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ABSTRACT

This study clarifies the morphology, genesis, physico-chemical properties and classification of soils developed from volcanic parent materials of Mbeya Region, Tanzania. Six typical pedons (MWK 01, IFIG 02, MKY 03, MWZ 04, KYE 01 and NDE 01), were identified, described and 33 soil samples analyzed for physical and chemical characteristics. Results indicate that all pedons were very deep, with textures ranging between fine and coarse. Soil moisture retention ranged between low and medium (78 - 101 mm/m). Some pedons had volcanic ash layers of varying thicknesses and buried 2BC, 2Bwb or 3Bwb horizons, typical of recent volcanic soils. Topsoils had low bulk and particle densities ranging between 0.70 to 1.26 g cm^{-3} and 1.95 to 2.55 g cm^{-3}, respectively.

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Organic carbon (OC) content ranged from medium to very high (1.29 to 5.58%). The studied pedons had extremely acidic to very slightly acidic pH ranging from 4.02 to 6.58. Cation exchange capacity (CEC) ranged from medium to very high (16.8 - 41 cmol(+) kg^{-1} soil for topsoils and 21 - 42.6 cmol(+) kg^{-1} for subsoils). All studied pedons had pH_{NaF} > 9.5, reflecting an exchange complex dominated by amorphous Fe and Al oxides and/or humus complexes. Phosphate retention capacity (PRC) ranged from 25 to 97% and one pedon (MWZ 04) met the *andic properties* requirement of PRC ≥ 85%. SiO_2, Al_2O_3 and Fe_2O_3 ranged from 46.5 to 62.1%, 26.3 to 38.4% and 4.0 to 9.8%, respectively. On the basis of computed *Chemical Index of Alteration (CIA),* the degree of weathering of the studied pedons followed the trend NDE 01>MKY 03>MKW 01>KYE 01>IFIG 02>MWZ 04. According to USDA Soil Taxonomy, the studied pedons were classified as *Alfisols* (pedons MKW 01, MKY 03 and NDE 01), *Inceptisol* (pedon IFIG 02), *Andisol* (pedon MWZ 04) and *Entisol* (Pedon KYE 01), respectively correlating to *Alisols, Cambisol, Andosol* and *Umbrisol* of WRB for Soil Resources. The studied soils were generally rated as having low to medium fertility.

Keywords: Soil morphology; soil genesis; physico-chemical properties; nutrient balance; total elemental composition; chemical index of alteration; soil classification; Tanzania.

1. INTRODUCTION

Different soils show diverse behaviour owing to differences in pedogenic pathways they have gone through in the course of pedogenesis. The pedogenic pathways are reflected in the morphological, physico-chemical, mineralogical and other soil properties. Collecting soil information through systematic soil survey is a prudent way of registering the holistic picture about the behaviour of soils of an area and requires knowledge about soil morphology, genesis, properties and classification. Soil and related land resources inventory data are basic in guiding and enabling forecast of land use potential and management requirements for sustained agricultural production. The knowledge of soil physical and chemical properties together with other ecological conditions is a basic requirement to enable prediction of types of crops to grow. The types and amount of fertilizers to be applied for economic and sustained crop productivity also depend on knowledge about the soil. Moreover, soil fertility specialists need well characterized soils and well defined ecological conditions in order to carry out meaningful fertilizer trials to enhance transferability of information from one place to another [1].

With regard to the availability of soil information in Tanzania, there is a big gap between need for pedological soil characterization and actual work that has already been done. Soils and other land resources in a greater part of Tanzania are still largely unknown in terms of their properties. Some studies [2] reported that only about 3% of soil resources of Tanzania were mapped at detailed and semi-detailed scales to allow proper planning at village and farm level. Since then, not much has been registered in the area of soil characterization at the stated scales; only sporadic soil/land resource inventories have been made here and there. A national soil-terrain (SOTER) inventory was produced at a scale of 1:2 000 000 [3], but this is mostly suited for planning at national level. Therefore, it can be said that the available soil information is inadequate for most planning purposes to allow land users to use their land holdings properly and sustainably. Such vital information is mostly lacking for most parts of Tanzania including Mbeya Region where this study was conducted. Mbeya is complex in terms of its geomorphology, vegetation and soils [4]. The volcanic soils in Mbeya are highly dependable for human use and support high densities of human population in terms of food and income [5]. Moreover, Mbeya Region is known to be among the four regions of Southern Highlands of Tanzania with high agricultural production, supplying staple foods in the country [6,7]. However, not much is known in terms of soils and their physical, chemical and mineralogical properties to allow ranking of their potential for various agricultural and other uses.

In an effort to increase knowledge on soils and related land resources of Mbeya Region, Tanzania, this study was initiated to cover areas of Mbeya Rural, Rungwe and Kyela Districts. The study was aimed at identifying, characterizing and classifying major soils of the areas according to the USDA Soil Taxonomy and the FAO World Reference Base for Soil Resources. It was envisaged that soil characterization data accruing from the study would provide users the needed information on soils and related attributes of their land holdings.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The study was carried out in Mbeya Region, Tanzania, with representative soil pedons located in Mbeya Rural, Rungwe and Kyela Districts. Table 1 and Fig. 1 present location details of the study sites. The pedons were developed from volcanic rocks / materials i.e. basaltic lavas (Pedon MWZ 04), phonolites / basalts (Pedon NDE 01), older basalts (Pedons MKY 01, MKY 03, IFIG 02) and alluvium derived from diverse volcanic materials (Pedon KYE 01). Apart from the influence of parent rocks/materials, soil formation has also been influenced by other factors notably relief and climate. Altitude across the study areas ranges from about 500 to 2400 m a.s.l. Whereas rainfall ranges from 650 – 2700 mm for MKW 01, IFIG 02, MKY 03, MWZ 04 and NDE 01 sites, it ranges from 1000 – 2400 mm for KYE 01 site. With the exception of Pedon KYE 01 which has isohyperthermic soil temperature regime (STR) (mean annual soil temperature of 22ºC or more), the rest have isothermic STR (mean annual soil temperature ranging between 15 and 22ºC).

2.2 Field Work

Reconnaissance field survey involving transect walks, auger observations and descriptions was carried out to establish representative study sites for soil characterization on the basis of landforms and other physiographic attributes. Six representative soil profiles namely Makwenje (MKW 01), Ifiga (IFIG 02), Mkuyuni (MKY 03) and Mwanzazi (MWZ 04) in Mbeya Rural District, Ndembela (NDE 01) in Rungwe District and Kyela (KYE 01) in Kyela District were identified and excavated to represent the major soil types. The six profile pits were dug to a depth of at least 170 cm. Soil profiles were studied, described and sampled according to FAO Guidelines for Soil Profile Description [9]. Soil colour was determined using Munsell Colour Chart [10]. Geo-referencing of soil profiles was done using Global Positioning System (GPS) Model OREGON 400t. From each profile pit, disturbed (bulk) and undisturbed (core samples) were taken from each horizon for physical and chemical analysis in the laboratory. Thirty three (33) soil samples representing genetic soil horizons of six profiles were collected and prepared for analysis.

2.3 Physical and Chemical Analyses

Undisturbed core samples were used for determination of bulk density (BD), porosity and soil moisture retention characteristics. Bulk density was determined by weighing soil cores after drying overnight at 105ºC [11]. Particle density (PD) of soils was determined using water pycnometer method as described by [12]. Mass of solid particles was obtained by weighing solid particles and likewise volume from mass and density of water displaced by soil samples. Soil moisture retention characteristics were studied using sand kaolin box for low suction values and pressure apparatus for higher suction values [13]). Available water capacity of soils was calculated as the difference in water retention between the -33 kPa and -1500 kPa suctions. Disturbed soil samples were used for determination of other physical and chemical properties after air-drying, gently crushing and sieving to 2 mm. Particle size analysis was determined by hydrometer method after dispersion with 5% sodium hexametaphosphate [13]. Textural classes were determined using the USDA textural class triangle [14]. Soil pH was measured potentiometrically in water and in 1 N KCl at the ratio of 1:2.5 soil:water and soil:KCl [15], respectively. As an indicator of amorphous material, the soil pH was also measured after 2 minutes of stirring in a 1 M NaF solution (w/v 1:50) according to [16]. Organic carbon (OC) was determined by the Walkley and Black wet oxidation method [17]). Organic carbon values obtained were converted to organic matter (OM) by multiplying by a factor of 1.724 [18]. Total N was determined using the micro-Kjeldahl digestion-distillation method as described by [19]. Available phosphorus was determined using filtrates extracted by the Bray and Kurtz-1 method [20] and determined by spectrophotometer at 884 nm wavelength following colour developed by the molybdenum blue method [21,22]. 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 NH_4^+ were displaced using 1 M KCl and then determined by Kjeldahl distillation method for estimation of CEC of the soil [23]. The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) were measured by atomic absorption spectrophotometer (AAS) [24]. Total exchangeable bases (TEB) were calculated as sum of exchangeable bases Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}. Total exchangeable acidity was determined by 1 M KCl extraction solution and the soil extract titrated with sodium hydroxide. A second titration with 1 M HCl after addition of sodium fluoride was used to obtain exchangeable aluminium [13]. Phosphate retention capacity (PRC) was determined following the method by [25]. Determination of multi-element oxides for selected soil horizons was done as follows: 200 g of fine earth soil samples were weighed and open air dried by using Infra-Red lamps for two hours. Samples were then ground to particle size ≤ 177 µm (80 Mesh) using swing mill pulverizer. Powdered samples were pressed into XRF sample cups and mounted with PANalytical B.V. X-Ray film-polyester PETP (Polyethylene Terephthalate Polyester). Elemental oxides were measured using PANalytical, Minipal 4 Energy Dispersive X-Ray Fluorescence Spectrometer (ED-XRF) Model PW4030/45B. From the total elemental composition, chemical index of alteration (CIA) as an indicator of degree of weathering was calculated for selected horizons using the formula by [26] given as: $CIA = \{Al_2O_3 / (Al_2O_3 + K_2O + Na_2O + CaO)\} * 100$.

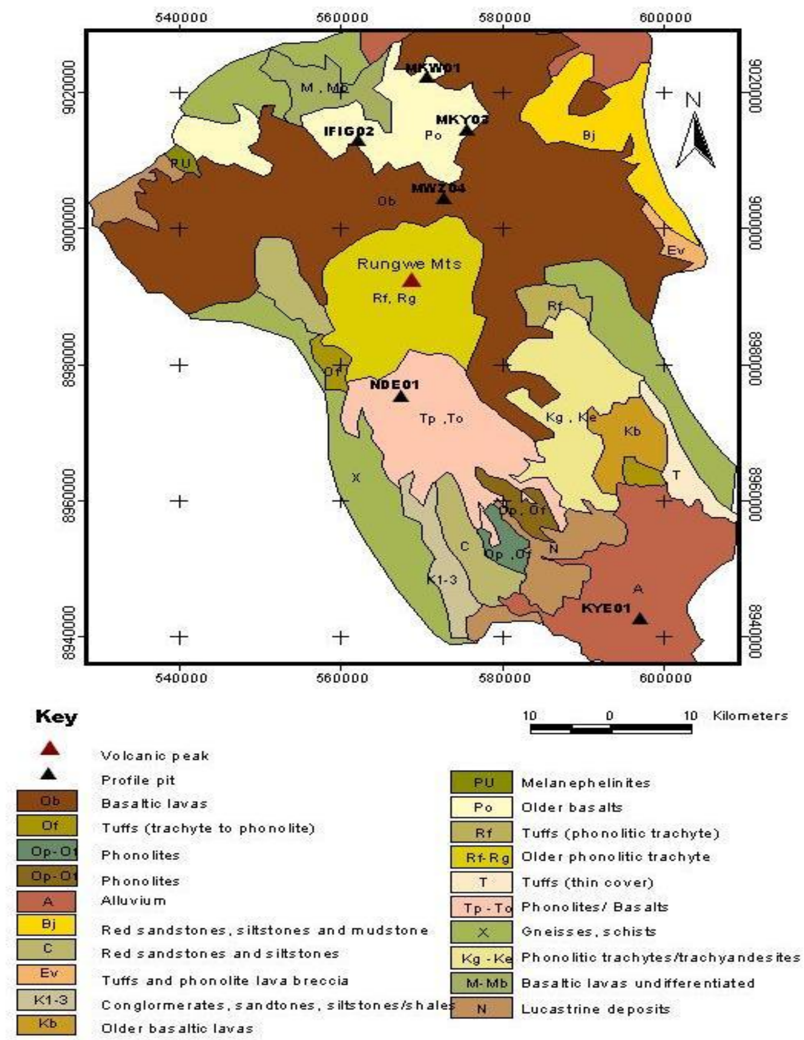

Fig. 1. Geological map of the study area in Mbeya Region, Tanzania, showing soil profile sites
Source: Modified from geological survey map [8]

Table 1. Location and other salient features of the studied sites in Mbeya Region, Tanzania

Soil pedon	District	Coordinates	Altitude m a.s.l.	MAR[1)] mm	Landform	#Parent rock / material	STR[2)]
Makwenje soil pedon (MKW 01)	Mbeya Rural	E 33º 38' 37" S 08º 50' 43"	1514	650 - 2700	Plateau / plain	Phonolites / basalts	Isothermic
Ifiga soil pedon (IFIG 02)	Mbeya Rural	E 33º 33' 58" S 08º 55' 44"	1882	650 - 2700	Footslope	Older basalts	Isothermic
Mkuyuni soil pedon (MKY 03)	Mbeya Rural	E 33º 41' 21" S 08º 54' 55"	1839	650 - 2700	Upper slope of the ridge	Older basalts	Isothermic
Mwanzazi soil pedon (MZW 04)	Mbeya Rural	E 09º 00' 26" S 33º 39' 49"	2357	650 - 2700	Ridge crest	Basaltic lava	Isothermic
Kyela soil pedon (KYE 01)	Kyela	E 33º 53' 13" S 09º 33' 50"	493	1000 - 2400	Alluvial plain	Alluvium derived from a mix of volcanic materials	Isohyper-thermic
Ndembela soil pedon (NDE 01)	Rungwe	E33º 36' 54" S 09º 16' 07"	1371	650 - 2700	Upper slope of the ridge	Phonolite / basalts	Isothermic

[1)]MAR = mean annual rainfall; [2)]STR: soil temperature regime
 # Source: [8]

2.4 Classification of Soils

Using field and laboratory data, soil pedons were classified to family level of USDA Soil Taxonomy [27] and to tier-2 of FAO World Reference Base for Soil Resources [28].

3. RESULTS AND DISCUSSION

3.1 Soil Morphology and Genesis in the Study Area

Some key morphological properties of the studied soils are presented in Appendix 1. Generally, the soils are very deep (> 150 cm) and well drained, except Pedon KYE 01 in which water table was observed around 170 cm. Soil colours of the pedons were quite variable among and within studied pedons. Redder hues were observed more in pedons MKW 01 and MKY 03, which are apparently more advanced in terms of pedogenesis. All studied pedons had friable moist consistence throughout their profile depths. Some pedons had buried horizons; such as 2BC (IFIG 02), 2Bwb, and 3Bwb (MWZ 04). In Pedon NDE 01 there was a 5 cm thick yellowish weathered pumice layer. The presence of buried horizons and pumice layers is diagnostic of volcanic soils, reflecting cyclic deposition of volcanic ejecta [29]. This phenomenon was more typical for Pedon MWZ 04, and to a lesser extent Pedon IFIG 02, both representing relatively younger volcanic materials than the rest. Pedon KYE 01 showed stratification more typical of alluvial formation. Pedons MKW 01, MKW 03 and NDE 01 showed morphology more of in-situ and relatively older pedogenesis. Soil structures varied widely among and within pedons, with topsoils being dominantly granular and subsoils dominantly subangular blocky except in the case of C horizons which were mostly structureless single-grained. The subsoils of Pedons MKW 01, MKY 03, MWZ 04 and KYE 01 had redoximorphic features in form of common, distinct Fe and coarse Mn concretions/nodules reflecting former reducing/waterlogged conditions.

3.2 Physico-chemical Properties of the Studied Soil Pedons

3.2.1 Physical properties

The results of particle size distribution are shown in Appendix 2. Pedons MKY 03 and NDE 01 are clayey throughout their profile depths, while pedons MKW 01 and KYE 01 have loamy topsoils overlying clayey subsoils. On the contrary, Pedons IFIG 02 and MWZ 01 had variable textures within their profiles, reflecting lithological discontinuity. These are the pedons where relatively younger volcanic materials were observed. Volcanic soils show a wide variation in soil texture depending on the type and particle size of tephras, mode and degree of weathering [29]. Clay content increased regularly with depth in Pedons MKW 01, MKY 03 and NDE 01, in which clay eluviation-illuviation was evident as indicated by presence of clay cutans in varying amounts. However, in the rest of pedons, variation in texture with depth was irregular; with the most irregular pattern in Pedon MWZ 04 followed by Pedon IFIG 02 and then Pedon KYE 01. Generally, sand contents were higher in topsoils than in subsoils, and this was attributed to migration of finer soil particles from topsoils to subsoils. Silt contents of the studied soils were generally lower than sand and clay contents.

Topsoil bulk density (BD) ranged from 0.7 to 1.26 g cm^{-3} while subsoil BD ranged from 0.8 to 1.46 g cm^{-3} for all soil profiles (Appendix 2). The BD values suggest that studied soils were not compact; hence plant roots can penetrate easily and movement of air between soil and atmosphere would be unhindered. According to [30], these values are within the common range for tropical soils and would favour crop growth. Pedons MWZ 04 and NDE 01 had low BD in both topsoils and subsoils, ranging from 0.70 to 0.80 g cm^{-3} and 0.91 to 0.98 g cm^{-3}, respectively. Low BD and high macro-porous subsoils provide excellent medium for plant root penetration where root hairs can extend relatively freely in a well aerated soil searching for water and plant nutrients. Pedon MWZ 04 had the lowest BD values (less than 0.9 g cm^{-3}) meeting the criterion for Andisols (Andosols). Such low BD values imply low cohesion and weak soil strength, meaning that soils with this attribute would compact very easily under pressure [31]. Particle density (PD) of the studied soils ranged from 1.95 to 2.55 g cm^{-3} for topsoils and from 2.14 to 2.46 g cm^{-3} for subsoils. Generally, there was an increase in particle density with soil depth, except in pedon MKW 01. Normally, PD of mineral soils varies between 2.60 and 2.75 g cm^{-3} [32]. All the studied pedons had PD values of < 2.60 g cm^{-3} (Appendix 2). This is probably because of the high content of organic matter in both topsoils and subsoils. According to [36], PD values observed in this study suggest that the soils have relatively low amounts of quartz and feldspars.

Total porosity (% vol/vol) of the studied soils ranged from 47.40 to 59.30% in topsoils and from 41.15 to 61.45% in subsoils. The higher values of total porosity in topsoils as compared to subsoils for the respective pedons were attributed to relatively higher soil organic matter content. Moreover, the lower total porosity in subsoils may be due to higher clay content responsible for increase in soil compaction. Available water capacity (AWC) of most topsoils range from 7.14% to 12.7% by volume while values of intermediate horizons ranged from 4.5% to 10.40% by volume (Appendix 2). The AWC values of surface horizons were generally higher than those of the intermediate horizons and subsoils. The variation of AWC within soil horizons and profiles was comparatively small. The AWC values of intermediate and subsoil were generally lower than those of surface soil despite higher clay contents in subsoils. Pedons MKY 03 and KYE 01 had relatively higher AWC in surface horizons than the rest, probably due to higher organic matter (OM) content. Organic matter has been reported to influence soil water holding capacity [33]. Available water capacity (mm per meter) of the studied soils range from 78 to 101 mm/m, which is low to medium. Data presented in Appendix 2 clearly indicate that the soils had low AWC values, despite their relatively high clay content. Similar results showing low AWC for clayey soils developed on basalt or andesitic soils have been reported in New Zealand [34] and in volcanic soils of Jos Plateau, Nigeria [35]. These observations may explain why some crops like wheat and maize experience periodic moisture stress in cropping seasons whenever there is a break in rainfall even for short periods [35]. Soil moisture characteristic (SMC) curves of the studied pedons indicate actual trend of soil moisture behaviour in the soils (Fig. 2). The SMC curves show that subsoils and intermediate soils retained more water than topsoils of Pedons MKW 01, MKY 03, KYE 01 and NDE 01 (Fig. 2). This is probably due to the fact that these layers contain substantial amounts of clay, which has ability to hold more water. In addition, subsoil and intermediate horizons of Pedon NDE 01 retained almost the same amount of water and there was a big gap between the amount of water retained by both the topsoils and intermediate soils as compared to those in subsoils in the pedon. On the other hand, topsoils of Pedon IFIG 02 retained more water than intermediate soil layers (Fig. 2). This is because of the high OM content in topsoils while below 50 cm depth the pedon was dominated by coarse grains/gravels.

3.2.2 Chemical properties

Appendix 3 presents some selected chemical properties of the studied pedons. The soil reaction varied slightly between and among pedons. The lowest pH value was observed in profile KYE 01, with values of 4.02 for topsoils and 4.41 for subsoils. This is probably because the studied soils have high amounts of exchangeable Al which can enter the soil solution and react with water to form hydroxy Al compounds and free hydrogen ions that can make the soil acidic [36]. Other profiles had topsoil and subsoil pH values ranging from 5.10 to 6.58 and from 5.38 to 6.28, respectively. The increasing trend of soil pH with profile depth may be attributed to high accumulation of organic matter. According to [15], organic matter has a tendency of accumulating acid (low pH)-dependent cations on the exchange sites. Profiles MKW 01, MWZ 04 and KYE 01 had soil pH of less than 5.5 for both topsoils and subsoils. Soil pH(KCl) values of all the studied pedons were consistently lower than pH(H_2O) values, indicating that the soils have net negative charge [37]. According to [12], most plants thrive well in soils of pH 6.5 to 7.5. From this point of view, most of the studied soils may present some limitations to crop production. According to [38], low pH may adversely affect availability of various plant nutrients such as phosphorus and basic cations like Ca and Mg.

Soil pH in NaF (pHNaF) 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 [39]. The pHNaF values of studied soils range from 9.69 to 11.01 in topsoils and from 10.03 to 11.44 in subsoils. The close relationship between extractable forms of Al with pHNaF indicates that for these soils, pHNaF is primarily a measure of abundance of OH ions associated with extractable Al compounds [39]. A soil pHNaF ≥ 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-aluminum complexes [28].

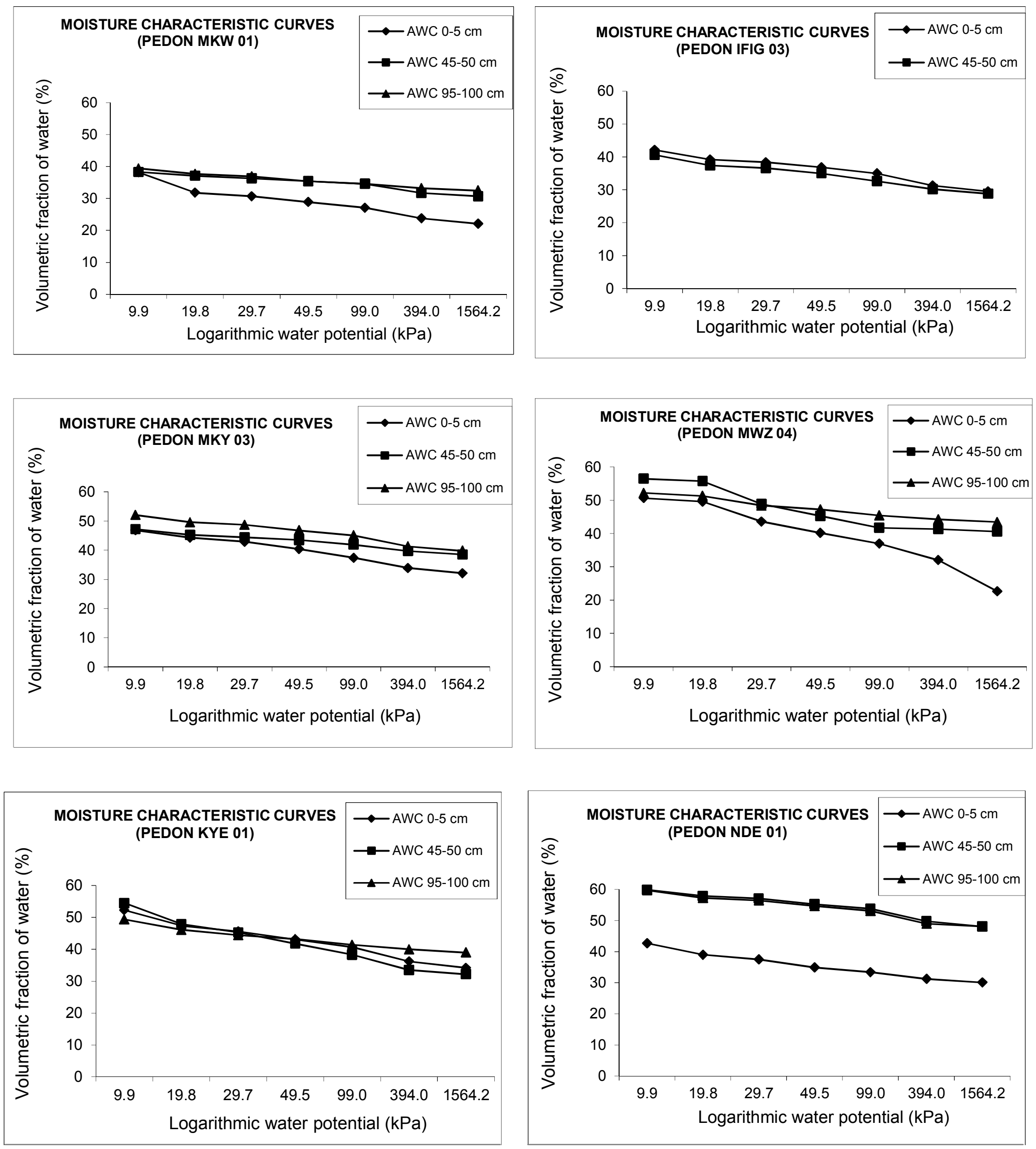

Fig. 2. Moisture characteristic curves of the studied soil pedons of Mbeya Region, Tanzania

Amorphous material is usually an early product of weathering of pyroclastic material in a humid climate [16]. All studied pedons had pHNaF values greater than 9.5, suggesting that they have varying amounts of amorphous materials. pHNaF values in the studied pedons were highest in MWZ 04 followed by KYE 01, NDE 01, MKY 03, IFIG 02 and lastly MKW 01. Electrical conductivity (EC) values of all the studied pedons were very low (much less than 1.7 dS/m), indicating that the soils have no problems of salinity [40]. Topsoil OC contents ranged from medium (1.29%) in Pedon MKW 01 to very high (7.30%) in Pedon MWZ 04 corresponding, respectively, to 2.22 - 12.60% OM. The relatively high OM content, particularly at the surface, could be linked to the continuous addition of crop residues on the surface of cropped fields and their decomposition under the favourable climatic conditions.

The AB, Bw horizons (Pedon IFIG 02) and C, 2Bwb horizons (Pedon MWZ 04) also had relatively high OC content. Topsoil total nitrogen (TN) content ranged from 0.11% (low) in Pedon MKW 01 to 0.46% and 0.49% (medium) in

Pedons MWZ 04 and KYE 01. The relatively higher levels of TN observed in these pedons may be attributed to decomposition of plant litter as well as crop residues, and application of both organic manure and inorganic fertilizers [41]. The low values of TN in topsoils of the other profiles may be due to continuous cultivation of high N demanding crops without replenishment of that nutrient element [41]. According to [42], the quality of organic matter in topsoils of studied soils was good (C/N ratios 8 -13), except for Pedon IFIG 02 whose topsoil C/N value was rated as moderate (C/N ratios 14 - 20). In subsoils, C/N ratios indicated good quality (values 8-13), except for pedons IFIG 02, MWZ 04 and NDE 01 whose values were 14.33, 14.9 and 7.12, implying moderate to poor quality. According to [42], C/N ratios greater than 12 and/or less than 10 indicate that nitrification is inhibited.

Phosphorus is commonly the growth limiting nutrient element in soils derived from volcanic materials [36]. Topsoil available phosphorus in the studied soils range from 0.80 in Pedon MKW 03 to 20.02 mg P/kg soil in Pedon IFIG 02, while subsoil values range from 0.07 in Pedon NDE 01 to 3.79 mg P/kg soil in Pedon IFIG 02. According to [43], the available P values can be rated as ranging from very low to high for topsoils and from very low to low for subsoils. Pedon IFIG 02 had topsoil phosphorus level of 20.02 mg P/kg soil which is considered to be high [40]. The high level of P in this pedon may be attributed to anthropogenic activities; including addition of manure, farm residues and P fertilizer use, resulting in increased P in surface layers of the soil [41]. The low P contents in the other pedons may be due to low pH values responsible for fixation of P by oxides and hydroxides of iron, aluminum and manganese, thereby forming compounds which are not readily available to plants [38]. The P-retention capacity (PRC) values for Pedons MWZ 04, KYE 01, MKY 03 and NDE 01 were generally higher than those of Pedons MKW 01 and IFIG 02. The high PRC values of volcanic ash soils are related to the contents of active Al and allophane [36]. The trend of PRC was as follows for the studied pedons: MZW 04>NDE 01>KYE 01>MKY 03>MKW 01>IFIG 02, with % PRC pedon mean values of 85, 64, 61, 55, 44 and 39, respectively. Only Pedon MWZ 04 had PRC value squarely meeting the requirement of 85% or more for andic properties used in the definition of Andisols/Andosols [27,28]. Cation exchange capacity (CEC) of the studied pedons range from medium to very high (16.8 - 41 cmol(+) kg^{-1} soil for topsoils and 21 - 42.6 cmol(+) kg^{-1} for subsoils). The high CEC values of studied pedons may be attributed to high organic matter content and nature of clay mineralogy of the soils, most likely illites and chlorites [41]. The exchangeable bases Ca^{2+} and Mg^{2+} ranged from medium to high, while K^{+} content ranged from medium to very high and exchangeable Na^{+} from low to very high. Percent base saturation (PBS) of the studied pedons ranged from 7.88 to 72.65 and from 7.80 to 62.69 in topsoils and subsoils, respectively. Most topsoils had PBS of above 20, implying good soil fertility for crop production. It also implies low or no intensive leaching of bases from topsoils to subsoils.

3.2.3 Nutrient balance

In general, values of exchangeable cations in the study areas followed the trend: Ca>Mg>K>Na. A similar trend was observed in soils of other parts of Tanzania [44-46]. In addition to the absolute amounts of Ca, Mg and K in soils, relative amounts of these nutrients are a measure of their availability [47]. In particular, the ratios Ca:Mg, Mg:K and K:TEB (where TEB is total exchangeable bases) are important. The Ca/TEB ratios for studied pedons range from 0.36 to 0.87 (Table 2). According to [42], Ca/TEB ratios of more than 0.5 may affect the uptake of other bases, particularly Mg and/or K, as calcium induced deficiency of Mg and/or K may appear. According to this author, the Ca/Mg ratios in Pedons IFIG 02 and KYE 01 range between 2 and 4 (Table 2) and are thus considered optimal for most crops. The Ca:Mg ratios for Pedons MKW 01, MWZ 04 and NDE 01 are outside the optimal range and are hence unfavourable. The Mg/K ratios in Pedons IFIG 02 and MKY 03 were about 1.50, which is within the recommended range of 1 to 4 for optimal nutrient uptake by plants [42]. Pedons MKW 01, MWZ 04, KYE 01 and NDE 01 had topsoil Mg/K ratios ranging from 0.15 to 0.94. These ratios are below the optimal minimum level of 1, implying that K in some horizons is greater than Mg in those pedons and this will likely reduce uptake of Mg from soil by plants. The K/TEB ratios, expressed as percent, for all the studied pedons were above 2% (Table 2), which is considered favourable for most tropical crops according to [42].

Table 2. Nutrient ratios for topsoils and subsoils of the studied soil pedons of Mbeya Region, Tanzania

Pedons	Soil Depth Section	Ca/TEB	Ca/Mg	Mg/K	% (K/TEB)
Makwenje soil pedon (MKW 01)					
	Topsoil	0.63	3.95	0.92	17.43
	Subsoil	0.65	2.86	2.77	9.65
Ifiga soil pedon (IFIG 02)					
	Topsoil	0.87	11.37	1.49	5.13
	Subsoil	0.72	6.95	0.71	15.95
Mkuyuni soil pedon (MKY 03)					
	Topsoil	0.77	6.01	1.50	8.62
	Subsoil	0.62	3.75	0.94	19.83
Mwanzazi soil pedon (MWZ 04)					
	Topsoil	0.56	4.70	0.46	25.76
	Subsoil	0.42	3.29	0.47	30.93
Kyela soil pedon (KYE 01)					
	Topsoil	0.36	5.00	0.15	47.43
	Subsoil	0.57	11.22	0.34	23.98
Ndembela soil pedon (NDE 01)					
	Topsoil	0.63	3.62	0.94	18.57
	Subsoil	0.49	2.22	0.90	26.03

Topsoil = 0 - 20 cm Subsoil = 30 - 150 cm

3.2.4 Total elemental composition and chemical index of alteration

The total elemental oxides of topsoils and subsoils of studied pedons are presented in Table 3. The most abundant oxide was SiO_2, which range from 46.54 to 62.06%, and was the highest of all oxides determined. The high SiO_2 content is an indication of existence of amorphous silica. The SiO_2 content decreased in the order Pedon MWZ 04>Pedon KYE 01>Pedon IFIG 02>Pedon MKY 03>Pedon MKW 01>Pedon NDE 01, with pedon mean values of 59.96, 59.30, 57.28, 54.91, 52.77, and 49.00. Contents of Al_2O_3 varied among pedons and ranged from 26.25% to 38.36%, while Fe_2O_3 contents ranged from 3.99% to 9.78%. The narrow SiO_2/Al_2O_3 ratio insinuates the presence of gibbsite in the studied pedons. Similar observations have been made in other studies by [8] and [48] for soils of Mbeya in Tanzania, and for soils of Samar in Philippines, respectively. Generally, high concentrations of SiO_2 and Al_2O_3 in volcanic soils are contributed by quartz and clay minerals such as vermiculite and illite whereby clay minerals originate from the hydrolysis of plagioclase in the rocks [49]. The elemental oxides MnO, Na_2O, CaO, MgO, K_2O, TiO_2, and P_2O_5 in the studied pedons were in low concentrations, below 4.5%. According to [49], low levels of these element oxides in the studied soils are associated with leaching during weathering process and also due to low concentrations of these elements in parent rocks/minerals. Parent rocks in the study areas include older basalts, basaltic lavas, trachyandesites and alluvium superficial deposit [8]. Higher concentrations of K_2O in all studied pedons as compared to other elements apart from SiO_2, Al_2O_3 and Fe_2O_3 may be contributed by illite minerals [41].

In the current study, a weathering index referred to as *"Chemical Index of Alteration" (CIA)* was applied on total elemental composition data, and accruing values used to determine degree of weathering of studied pedons. The CIA has been widely used as a quantitative indicator for estimating degree of weathering of silicates [50,51] on grounds that feldspars are the most abundant reactive minerals in earth's crust and that calcium, sodium and potassium are removed from feldspars during weathering by aggressive soil solutions. They further argued that during weathering, proportion of alumina to alkalis would typically increase in the weathered product and that a good measure of degree of weathering could be obtained by the "Chemical Index of Alteration", defined as:

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

In this study, CIA values varied somehow among studied soil pedons, with the trend NDE 01>MKY 03>MKW 01>KYE 01>IFIG 02>MWZ 04 with mean pedon values of 94.61, 87.94, 87.23, 86.59, 83.82, and 79.01, respectively. According to studies elsewhere [51], the trend shown here suggests that degree of weathering decreases in the same direction from Pedon NDE 01 to MWZ 04. Pedon MWZ 04 had the smallest CIA value implying that it is the youngest of the studied soil pedons in terms of degree of weathering and age

Table 3. Total elemental composition of the studied soil pedons of Mbeya Region, Tanzania

Pedons	Al_2O_3	SiO_2	Fe_2O_3	MnO	Na_2O	CaO	MgO	K_2O	TiO_2	P_2O_5	#CIA
					% wt.						%
Makwenje soil pedon (MKW 01)											
Topsoil	27.09	54.59	9.77	0.58	2.42	0.35	0.00	2.75	2.45	0.11	83.07
Subsoil	33.40	50.94	9.49	0.55	0.00	0.28	0.79	2.89	8.09	0.11	91.33
Ifiga soil pedon (IFIG 02)											
Topsoil	28.30	57.99	7.51	0.47	1.02	0.83	0.00	4.2	1.34	0.13	82.39
Subsoil	29.16	56.57	6.69	0.38	0.67	0.70	0.45	3.68	1.17	0.12	85.24
Mkuyuni soil pedon (MKY 03)											
Topsoil	32.27	52.57	7.23	0.39	1.39	0.41	1.28	2.41	1.60	0.10	88.46
Subsoil	27.84	57.25	6.89	0.32	1.88	0.19	1.99	1.94	1.29	0.09	87.41
Mwanzazi soil pedon (MWZ 04)											
Topsoil	26.25	62.06	6.70	0.39	0.93	0.46	0.00	3.1	1.17	0.13	85.39
Subsoil	23.45	57.85	4.21	0.19	1.77	1.06	3.82	6.01	1.08	0.11	72.62
Kyela soil pedon (KYE 01)											
Topsoil	26.76	61.71	3.99	0.05	1.69	0.37	1.69	1.93	1.28	0.12	87.02
Subsoil	28.86	56.89	5.54	0.10	1.65	0.34	1.97	2.65	1.31	0.10	86.15
Ndembela soil pedon (NDE 01)											
Topsoil	38.36	46.54	9.26	0.35	1.11	0.15	1.30	0.96	1.61	0.09	94.53
Subsoil	32.82	51.46	9.78	0.36	0.79	0.16	1.53	0.89	1.83	0.10	94.69

#CIA = Chemical index of alteration = $\{Al_2O_3 / (Al_2O_3 + K_2O + Na_2O + CaO)\} * 100$

of formation. This pedon was developed on basaltic lavas (Fig. 1) which represent rather recent volcanic eruption. Pedon NDE 01, developed on phonolites, had the highest CIA value implying higher degree of weathering, followed by Pedons MKY 03, MKW 01, KYE 01 formed on older basalts and having comparable CIA values, and then IFIG 02 formed from alluvium of mixed origin.

3.2.5 Soil classification

Soil morphological and laboratory analytical data were used to define diagnostic horizons and other features for classifying the soils. Appendix 4 presents a summary of the classification. According to USDA Soil Taxonomy, soils of study area were classified as *Alfisols* (Pedons MKW 01, MKY 03 and NDE 01), *Inceptisol* (pedon IFIG 02), *Andisol* (Pedon MWZ 04) and *Entisol* (Pedon KYE 01), respectively correlating to *Alisols*, *Cambisol*, *Andosol* and *Umbrisol* of FAO WRB system. At the first level of both systems of classification, the taxa correspond very well with their pedogenetic definitions. Thus, soils which are relatively well developed and having clay enriched B-horizons keyed out as *Alfisols/(Alisols)*; moderately developed soil with cambic B-horizon as *Inceptisol (Cambisol)*; typically volcanic ash soil with melanic epipedon and andic properties as *Andisol (Andosol)*; and relatively young soil with dark coloured A-horizon (umbric epipedon) resting on C materials and having no B-horizon as *Entisol (Umbrisol)*. Only Pedon (MWZ 04) qualified as *Andisol (Andosol)*. According to [29] soils developed from volcanic materials are generally classified as *Andosols* (or *Andisols* according to the USDA Soil Taxonomy), but not all volcanic soils are *Andosols,* depending on weathering and soil formation processes. *Andosols* are characterized by high organic carbon content, low bulk density, high P retention, high CEC [52], high pHNaF, and high oxalate-extractable Al and Si contents [53], and presence of large amounts of short-range-order minerals such as allophane [54,36].

4. CONCLUSIONS

The studied pedons exhibit varying morphological, physical and chemical properties and are likely to behave differently in terms of use and management. All pedons have properties of volcanic soils in terms of their morphological, physical and chemical properties; only the degree of expression of these attributes varies from one pedon to another. Generally, the soils are of low to medium fertility on the basis of levels of N, OM, pH and available P. The soils may exhibit some problems of nutrient imbalance due to unfavorable Ca/Mg, Ca/TEB and Mg/K ratios. Sustainable cropping on the soils can be achieved with introduction of technologies suitable for rejuvenating soil fertility such as manuring, crop rotation, proper management of crops residues, fallow periods, and introduction of leguminous cover crops in the farming system and use of fertilizers, particularly non- acidifying types of fertilizers. Pedon MWZ 04, developed on more recent volcanic parent rocks (basaltic lava), is the least weathered when compared to those developed on older basalts/phonolites (Pedons IFIG 02, MKY 03, MKW 01, NDE 01) and on alluvium (Pedon KYE 01). On the basis of chemical index of alteration, the degree of weathering of studied pedons follows the trend NDE 01>MKY 03>MKW 01>KYE 01>IFIG 02>MWZ 04. Although all studied pedons exhibit properties of volcanic soils in varying degrees, only Pedon MWZ 04 squarely fitted to be classified as *Andisol* (USDA Soil Taxonomy) or *Andosol* (FAO WRB for Soil Resources).

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Msanya BM, Kaaya AK, Araki S, Otsuka H, Nyadzi GI. Pedological characteristics, general fertility and classification of some benchmark soils of Morogoro District, Tanzania. African Journal of Science and Technology (AJST) Science and Engineering Series. 2003;4(2):101-112.
2. Msanya BM, Magoggo JP, Otsuka H. Development of soil surveys in Tanzania. Pedologist. 2002;46(2):79-88.
3. National Soil Service. Soils of Tanzania and their potential for agriculture development. Draft Report. Mlingano Agricultural Research Institute. Department of Research and Training. Ministry of Agriculture, Food Security and Co-operatives. Tanga, Tanzania. 2006;35.
4. Karlsson I, Messing I. A reconnaissance soil survey in parts of the Mbeya Region in Tanzania. Rural Development Studies no. 9, Swedish University of Agricultural Science. 1980;8-19.
5. Msanya BM, Otsuka H, Araki S, Fujitake N. Characterization of volcanic ash soils in southwestern Tanzania: Morphology, physicochemical properties, and classification. African Study Monographs. 2007;Suppl.34: 39-55.
6. Amuri N, Semu E, Msanya BM, Mhoro L, Munishi JM. Evaluation of the soil fertility status in relation to crop nutritive quality in selected physiographic units of Mbeya Region, Tanzania. Second RUFORUM Biennial Meeting 20 - 24 September, Entebbe, Uganda; 2010.
7. Amuri N, Mhoro L, Munishi JA, Msanya BM, Semu E, Malley Z. Pedological characteristics and implications on soil fertility of selected soils of Mbeya Region, Tanzania. The 3rd RUFORUM Biennial Conference, 24th – 28th September; 2012. Entebbe, Uganda.
8. Harkin DA. The Rungwe volcanics at the Northern End of Lake Nyasa. Geological Survey of Tanganyika. Dar es Salaam, Tanzania. Memoir No. II. 172 pp. Accompanied by geological map of Mbeya at scale of 1:250 000; 1960.
9. FAO. Guidelines for Soil Description. 4th Edition. Food and Agriculture Organization of the United Nations Rome. 2006;97.
10. Munsell Color Company. Munsell Soil Color Charts. Baltimore, Maryland. Lincoln, NE; 1992.
11. Blake GR, Hartge KH. Particle density. In: Methods of soil analysis, physical and mineralogical methods Part 1, 2nd Edition. Edited by Klute A. Agronomy Monograph No. 9. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin. 1986;364-376.
12. Baize D. Soil science analysis. A guide to correct use. John Wiley and Sons Ltd. West Sussex. 1993;192.
13. National Soil Service. Laboratory procedures for routine analysis, 3rd edition. Agricultural Research Institute, Mlingano Tanga, Tanzania. 1990;212.
14. United States Department of Agriculture. Soil Taxonomy. A basic system of soil classification for making and interpret soil survey. Agriculture Handbook no. 436. US Government Printing Office. Washington D.C. 1975;754.
15. McLean EO. Soil pH and lime requirement. In: Methods of Soil Analysis, Chemical and Mineralogical Properties, Part 2, 2nd Edition. Edited by Page AL, Miller RH, Keeney DR. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin. Agronomy Monograph. 1986;9:99-223.

16. Fieldes M, Perott KW. The nature of allophane in soils. Part 3: Rapid field and laboratory test for allophane. N.Z. J. Soil Sci. 1966;9:623-629.
17. Nelson DW, Sommers LE. Total carbon. In Methods of Soil Analysis, Chemical and Microbiological Properties, Part 2. Edited by Page AL, Miller RH, Keeney DR. American Society of Agronomy. Madison. 1982;539-579.
18. Duursma EK, Dawson R, (Eds). Marine organic chemistry: Evolution, composition, interactions and chemistry of organic matter in seawater. Elsevier. 1981;521.
19. Bremner JM, Mulvaney CS. Total nitrogen. In: Methods of Soil Analysis, Chemical and Microbiological Properties, Part 2, 2nd Edition. Edited by Page AL, Miller RH, Keeney DR. American Society of Agronomy. Madison. 1982;539-579.
20. Bray RH, Kurtz LT. Determination of total, organic and available forms of phosphorus in soils. Soil Sci. 1945;58:39-45.
21. Murphy J, Riley JP. Modified single solution method for determination of phosphate in natural waters. Analytica Acta. 1962;27;31-36.
22. Watanabe FS, Olsen SR. Test of an ascorbic acid method for determining phosphorus in Central Illinois: Midwest Friends of the Pleistocene 26th Field Conf., Campaign, IL, Illinois Geol. Surv., Guidebook 1965;13:29-134.
23. Chapman HD. Cation exchange capacity. In: Methods of Soil Analysis. Edited by Black CA. Am. Inst. Agronomy, Madison, Wisconsin. 1965;9:891-901.
24. Thomas GW. Exchangeable cations. In: Methods of Soil Analysis, Chemical and Mineralogical Properties Part 2, 2nd Edition. Edited by Page LA, Miller RH, Keeney DR. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin. Agronomy Monograph No. 9. 1982;595-624.
25. Blakemore LC, Searle PL, Daly BK. Methods for chemical analysis of soils, New Zealand Soil Bureau Scientific Report 10A. Department of Scientific and Industrial Research, New Zealand; 1981.
26. Evans LJ, Cameron BH. A chrono-sequence of soils developed from granite morainal material, Baffin Island NWT. Canadian Journal of Soil Science. 1979;59:203-210.
27. Soil Survey Staff. Keys to Soil Taxonomy. United States Department of Agriculture. 11th Edition. Natural Resource Conservation Service. 2006;346.
28. IUSS Working Group WRB. World Reference Base for Soil Resources 2014, update. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. FAO, Rome; 2015.
29. Shoji S, Nanzyo M, Dahlgren RA. Volcanic ash soils – Genesis, properties, and utilization. Developments in Soil Science 21. Elsevier, Amsterdam; 1993.
30. Zonn SV. Tropical and subtropical soil science. Mir Publishers. Moscow. 1986;422.
31. Craigg TL, Howes SW. Assessing quality in volcanic ash soils. USDA Forest Service Proceedings RMRS-P-44; 2007.
32. Brady NC. The Nature and Properties of Soils.10th Ed. Macmillan Publishing Co., New York. 1990;620.
33. Klute A. Water retention. In: Methods of Soil Analysis, Physical and Mineralogical Methods. Part 1, 2nd Edition. Edited by Klute A. Agronomy Monograph No. 9. 1986:635-662.
34. Warkentin BP, Maeda T. Physical and chemical characteristics of andosols. In: Soils with Variable Charges. Edited by Theng BKG. N.Z. Soil Sci. Lowers Hutt, New Zealand. 1980;281-301.
35. Olowolafe EA, Nyagba JL. Soils constraints to sustainable crop production in the volcanic areas of Jos Plateau, Nigeria. Journal of Environmental Sciences. 1999;3(2):160-168.
36. Yatno E, Zauyah S. Properties and management implications of soils formed from volcanic materials in Lembang area, West Java. Indonesian Journal of Agricultural Science. 2008;9(2):44-54.
37. Bohn HJ, McNeal BL, O'Connor G.A. Soil Chemistry. 2nd edition. Wiley Interscience Publication. New York. 1985;341.
38. Marschner H. Mineral nutrition of higher plants. Academic Press. Harcourt Brace Jovanovich Publisher, London. 1990;674.
39. Gilkes RJ, Hughes JC. Sodium fluoride pH of south-western Australian soils as an indicator of P sorption. Australian Journal of Soil Research. 1994;32:755-766.
40. Msanya BM, Kimaro DN, Kimbi G.G, Kileo EP, Mbogoni JDJ. Land resources inventory and suitability assessment for the major land use types in Morogoro Rural District, Tanzania. Soils and Land

Resources of Morogoro Rural and Urban Districts. 2001;4. Department of Soil Science, Faculty of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania.

41. Munishi JA. Pedological characterisation of soils and assessment of their agricultural potential in selected Districts of Mbeya Region, Tanzania. MSc (Soil Science and Land Management) dissertation. Department of Soil Science, Sokoine University of Agriculture, Morogoro, Tanzania. 2012;136.
42. Landon JR, (Editor). Booker Tropical Soil Manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman Scientific & Technical Publishers, Essex. 1991;474.
43. EUROCONSULT. Agriculture Compendium for Rural Development in the Tropics and Sub-Tropics. 3rd Revised edition. Elsevier, Amsterdam. Oxford. New York. Tokyo. 1989;740.
44. Msanya BM, Kimaro DN, Magoggo JP. Characteristics of two pedons and their implication for environmental management in parts of Mbinga District, Tanzania. Paper presented at the first annual Faculty of Agriculture Research Conference. August 28-30th. Sokoine University of Agriculture, Morogoro, Tanzania; 1995.
45. Meliyo JL. Pedological investigation and characterization in Litembo village, Mbinga District, Tanzania. MSc (Agric). Dissertation, Sokoine University of Agriculture, Morogoro, Tanzania. 1997;113.
46. Wickama JMW. Pedological investigation and characterization in Kitanda village, Mbinga District, Tanzania. MSc Dissertation. Sokoine University of Agriculture, Morogoro, Tanzania. 1997;93.
47. Magoggo JP, Msanya BM, Kimaro DN. Environmental profile for agricultural production and development of conservation strategies in Mahenge Village, Mbinga District, Tanzania. Miombo Woodland Research Project, Natural Resources Study Team Technical Report 3. Department of Soil Science, Sokoine University of Agriculture, P.O. Box 3008, Morogoro, Tanzania & Ministry of Agriculture, National Soil Service, ARI Mlingano, P.O.Box 5088 Tanga, Tanzania. 1996;38.
48. Navarrete IA, Asio VB, Reinhold J, Tsutsuki K. Characteristics and genesis of two strongly weathered soils in Samar, Philippines. Australian Journal of Soil Research. 2007;45:153-163.
49. Baba M, Hennie FW, Soehady E, Sanudin T. Geochemical characterization of volcanic soils from Tawau, Sabah. Geological Society of Malaysia. Bulletin. 2008;54:33-36.
50. Nesbitt HW, Young GM. Early Proterozoic climates and plate motions inferred from major element chemistry of Lutites. Nature. 1982;299:715-717.
51. Young GM, Nesbitt HW. Paleoclimatology and provenance of the glaciogenic Gowganda Formation (Paleoproterozoic), Ontario, Canada: A chemostratigraphic approach. Geological Society of America Bulletin. 1999;111:264-274.
52. Otawa M. Morphology and classification. In: Ando Soils in Japan. Edited by Wada K. Kyushu University Press, Japan. 1986;3-20.
53. Balsem T, Buurman P. Chemical and physical analyses required for soil classification. Technical Report No. 11. Version 2. LREP Project, Center for Soil and Agro climate Research, Bogor; 1990.
54. Mizota C, Van Reeuwijk LP. Clay mineralogy and chemistry of soils formed in volcanic material in diverse climatic region. Soil Monograph 2; 1989. ISRIC, Wageningen.

APPENDICES

Appendix 1. Some morphological properties of the studied soil pedons of Mbeya Region, Tanzania

Pedons	Horizon	Depth (cm)	Dry color [1)]	Moist color[2)]	Consistence[3)]	Structure[4)]
Makwenje soil pedon (MKW 01)						
	Ap	0 - 15/20	rb (5YR4/3)	vdb (7.5YR2.5/3)	fr, st & spl	w, gr
	Bt1	15/20 - 34/40	drb (5YR3/4)	db (7.5YR3/4)	fr, st & pl	mo-str, sbk & ab
	Bt2	40 - 70	drb (5YR3/4)	drb (5YR3/4)	fr, st & pl	str, sbk & ab
	Bt3	70 - 130	drb (5YR3/4)	drb (5YR3/4)	fr, st & pl	str, sbk & ab
	Bt4	130 - 160	rb (5YR4/4)	drb (5YR3/4)	fr, st & pl	str, sbk & ab
	BC	160 - 200	rb (5YR4/4)	drb (5YR3/3)	fr, st & pl	str, sbk & ab
Ifiga soil pedon (IFIG 02)						
	Ap	0 - 25	dgb (10YR4/2)	bl (10YR2/1)	fr, st & pl	mo, gr
	AB	25 - 42/45	db (10YR3/3)	vdb (10YR2/2)	fr, st & pl	mo, gr
	Bw	42/45 - 60/75	db (7.5YR4/2)	vdb (7.5YR3/3)	fr, st & pl	mo, sbk
	C	60/75 - 120	pg (7.5YR7/2)	db (7.5YR3/3)	-	s-grain
	2BC	120 - 170/184	db (7.5YR4/2)	vdb (7.5YR2.5/3)	fr, st & pl	mo, sbk
	2C	170/184 - 200	pb (10YR6/3)	sb (7.5YR4/6)	-	s-grain
Mkuyuni soil pedon (MKY 03)						
	Ap	0 - 26	drb (5YR3/3)	vdb (10YR2/2)	fr, st & pl	w, gr & sbk
	BA	26 - 40	drb (5YR3/4)	vdb (7.5YR2.5/2)	fr, st & pl	w-mo, sbk & ab
	Bt_1	40 - 95	drb (5YR3/4)	vdb (7.5YR2.5/3)	fr, st & pl	str, sbk & ab
	Bt_2	95 - 145	rb (5YR4/4)	db (7.5YR3/4)	fr, st & pl	str, sbk & ab
	BC	145 - 210+	rb (5YR5/4)	vdb (7.5YR2.5/3	fr, st & pl	mo, sbk
Mwanzazi soil pedon (MWZ 04)						
	Ap_1	0 - 18	vdgb (10YR3/2)	db (10YR3/3)	fr, st & spl	mo, gr
	Ap2	18 - 78/82	vdgb (10YR3/2)	bl (10YR2/1)	fr, nst & npl	mo, gr
	C	78/82 - 88/90	dib (10YR4/4)	by (10YR5/8)	fr, st & spl	w, sbk
	2Bwb	88/90 - 134	db (10YR4/3)	dib (10YY3/6)	fr, st & spl	mo, sbk
	2Cb	134 - 156	vpb (10YR7/4)	yb (10YR5/6)	-	s-grain
	3Bwb	156 - 171	dyb (10YR4/4)	dyb (10YR4/6)	fr, st & pl	w, sbk
	3Cb	171 - 220	vpb (10YR7/3)	yb (10YR6/6)	-	s-grain
Kyela soil pedon (KYE 01)						
	Ap_1	0 - 17/22	dg (5YR4/1)	bl (2.5YR2.5/1)	fr, st & spl	w, gr
	Ap_2	17/22 - 36/40	dg (5YR4/1)	bl (2.5YR2.5/1)	fr, st & spl	w, gr
	AC	36/40 - 51	db(7.5YR4/2)	vdb (10YR2/2)	fr, st & spl	w, sbk
	C_1	51 - 90	vpb (10YR7/3)	yb (10YR5/4)	fr, st & spl	w-mo, sbk
	C_2	90 - 125	vpb (10YR7/3)	lyb (10YR6/4)	fr, st & pl	w-mo, sbk
	C_3	125 - 170	lg (10YR7/2)	lbg (10YR6/2)	fr, st & pl	w-mo, sbk

Pedons	Horizon	Depth (cm)	Dry color [1)]	Moist color[2)]	Consistence[3)]	Structure[4)]
Ndembela soil pedon (NDE 01)						
	Ap	0 - 22/26	drb (5YR3/3)	vdb (7.5YR2.5/3)	fr, st & pl	mo, gr
	Bt_1	22/26 - 78	drb (5YR3/4)	db (7.5YR3/4)	fr, st & spl	mo, sbk & ab
	Bt_2	78 -220+	rb (5YR4/4)	db (7.5YR4/4)	fr, st & spl	mo-str, ab & sbk

[1 & 2]) lbg = light brownish gray; dyb = dark yellowish brown; vdb = very dark brown; db = dark brown; drb = dark red brown; bl = black; vdgb = very dark grayish brown; yb = yellowish brown; sb = strong brown; pb = pale brown; by = brownish yellow; rd = reddish brown; dgb = dark grayish brown; pg = pinkish gray; rb = reddish brown; vdgb = very dark grayish brown; vpb = very pale brown; dg = dark gray; lg = light gray; lyb = light yellowish brown.

[3)] fr = friable; nst = nonsticky; sst = slightly sticky; st = sticky; npl = nonplastic; spl = slightly plastic; pl = plastic

[4)] Grade: w=weak; mo= moderate; st=strong;

Type: s-grain = single grained; gr= granular; sbk = subangular blocky; ab= angular blocky

Appendix 2. Selected physical properties of the studied soil pedons of Mbeya Region, Tanzania

Pedons	Horizon	Depth	Particle size distribution (%)			Textural class	Bulk density	Particle density	#Total Porosity	##Available water capacity
		(cm)	Sand	Silt	Clay		g cm^{-3}		%	% vol/vol
Makwenje soil pedon (MKW 01)										
	Ap	0 - 15/20	38	23	39	CL	1.26	2.55	47.4	10.8
	Bt_1	15/20 - 34/40	26	21	53	C	nd	2.46	nd	nd
	Bt_2	40 - 70	24	21	55	C	1.46	2.49	41.2	9.2
	Bt_3	70 - 130	24	21	55	C	1.45	2.45	41.4	6.7
	Bt_4	130 - 160	26	23	51	C	nd	2.50	nd	nd
	BC	160 - 200	20	17	63	C	nd	2.55	nd	nd
Ifiga soil pedon (IFIG 02)										
	Ap	0 - 25	38	23	39	CL	1.13	2.36	50.8	9.2
	AB	25 - 42/45	38	19	43	C	nd	2.36	nd	nd
	Bw	42/45 - 60/75	42	19	39	CL	1.19	2.42	49.2	8.8
	C	60/75 - 120	76	5	19	SL	nd	2.53	nd	nd
	2BC	120 - 170/184	38	21	41	C	nd	2.37	nd	nd
	2C	170/184 - 200	50	23	27	SCL	nd	2.45	nd	nd
Mkuyuni soil pedon (MKY 03)										
	Ap	0 - 26	36	19	45	C	1.16	2.36	51.1	11.4
	BA	26 - 40	32	19	49	C	nd	2.41	nd	nd
	Bt_1	40 - 95	26	21	53	C	1.1	2.34	51.9	6.2
	Bt_2	95 - 145	20	23	57	C	0.97	2.22	57.6	9.1
	BC	145 - 210+	26	21	53	C	nd	2.29	nd	nd

Pedons	Horizon	Depth	Particle size distribution (%)			Textural class	Bulk density	Particle density	#Total Porosity	##Available water capacity
		(cm)	Sand	Silt	Clay		g cm^{-3}		%	% vol/vol
Mwanzazi soil pedon (MWZ 04)										
	Ap_1	0 - 18	62	19	19	SL	0.7	2.02	65.3	12.7
	Ap_2	18 - 78/82	50	41	9	L	0.8	2.14	62.6	nd
	C	78/82 - 88/90	61	16	23	SCL	0.8	2.20	63.6	4.5
	2Bwb	88/90 - 134	32	23	45	C	0.8	2.19	63.5	nd
	2Cb	134 - 156	87	6	7	LS	1.0	2.47	59.5	nd
	3Bwb	156 - 171	29	23	48	C	0.9	2.31	61.0	3.2
	3Cb	171 - 220	66	27	7	SL	nd	1.71	nd	nd
Kyela soil pedon (KYE 01)										
	Ap_1	0 - 17/22	58	9	33	SCL	0.95	1.95	55.4	11.5
	Ap_2	17/22 - 36/40	44	31	25	L	nd	2.16	nd	nd
	AC	36/40 - 51	26	31	43	C	1.02	2.26	54.9	10.4
	C_1	51 - 90	16	29	55	C	nd	2.33	nd	nd
	C_2	90 - 125	30	21	49	C	1.06	2.39	53.1	5.7
	C_3	125 - 170	36	19	45	C	nd	2.35	nd	nd
Ndembela soil pedon (NDE 01)										
	Ap	0 - 22/26	30	17	53	C	0.91	2.33	59.3	7.1
	Bt_1	22/26 - 78	16	15	69	C	0.98	2.36	61.5	8.8
	Bt_2	78 - 220+	16	17	67	C	0.93	2.30	62.7	7.9

nd= not determined #Total porosity = {1 - BD/PD}x100; ## AWC = water retained betn. -33 kPa and -1500 kPa suctions

Appendix 3. Some chemical properties of the studied soil pedons of Mbeya Region, Tanzania

Pedons	Horizon	pH			ΔpH	EC	OC	OM	TN	C/N	Avail. P	*PRC	CEC	Ca	Mg	K	Na	H^+	Al^{3+}	TEB	BS
		H_2O	KCl	NaF		dS/m		%		ratio	mg/kg	%				cmol(+)/kg soil					%
Makwenje soil pedon (MKW 01)																					
	Ap	5.1	3.7	9.7	-1.4	0.01	1.29	2.22	0.11	12.3	2.19	35.6	17.6	2.22	0.56	0.61	0.11	0.37	0.17	3.50	19.9
	Bt_1	5.4	4.0	10.2	-1.4	0.01	0.59	1.01	0.06	9.3	0.80	49.2	24.6	4.54	1.21	0.30	0.12	0.13	0.13	6.17	25.1
	Bt_2	5.5	4.2	10.1	-1.3	0.01	0.41	0.71	0.06	6.5	0.65	47.7	32.6	4.54	1.59	0.47	0.26	0.03	0.17	6.86	21.0
	Bt_3	5.9	4.2	9.9	-1.7	0.01	0.21	0.37	0.04	5.1	0.10	42.0	51.4	3.71	1.50	0.72	0.27	0.20	0.07	6.20	12.1
	Bt_4	5.9	4.2	9.8	-1.7	0.01	0.02	0.03	0.04	0.6	0.15	44.4	22.4	2.89	1.23	0.77	0.16	0.20	0.03	5.04	22.5
	BC	5.8	4.1	9.8	-1.7	0.01	0.12	0.20	0.03	4.2	0.00	45.9	24.2	3.83	1.75	1.01	0.17	0.13	0.13	6.76	27.9

Pedons	Horizon	pH			ΔpH	EC	OC	OM	TN	C/N	Avail. P	*PRC	CEC	Ca	Mg	K	Na	H^+	Al^{3+}	TEB	BS
		H_2O	KCl	NaF		dS/m		%		ratio	mg/kg	%				cmol(+)/kg soil					%
Ifiga soil pedon (IFIG 02)																					
	Ap	5.8	4.6	10.1	-1.2	0.03	3.16	5.45	0.19	16.7	20.02	38.6	34.0	18.76	1.65	1.11	0.14	0.07	0.03	21.65	63.7
	AB	6.1	4.6	10.3	-1.5	0.01	1.40	2.42	0.10	14.3	3.79	41.2	25.8	13.47	1.59	1.59	0.15	0.17	0.03	16.80	65.1
	Bw	6.3	4.6	10.4	-1.7	0.01	2.98	5.14	0.07	42.6	2.34	45.1	32.8	10.32	1.56	1.93	0.17	0.10	0.03	13.99	42.6
	C	6.4	4.5	10. 6	-1.9	0.01	0.14	0.24	0.02	6.5	6.87	24.9	20.5	5.28	0.82	1.69	0.19	0.23	0.03	7.98	38.9
	2BC	6.5	4.6	10.2	-1.9	0.01	0.47	0.81	0.11	4.2	0.50	41.0	29.2	8.42	1.34	2.41	0.28	0.17	0.03	12.45	42.6
	2C	6.6	4.6	10.2	-2.0	0.01	0.31	0.54	0.03	11.1	2.14	43.5	26.4	6.03	1.14	1.69	0.25	0.17	0.03	9.11	34.5
Mkuyuni soil pedon (MKY 03)																					
	Ap	6.1	4.4	10.4	-1.7	0.01	1.81	3.13	0.15	12.3	0.80	59.8	48.8	9.08	1.51	1.01	0.12	0.00	0.17	11.72	24.0
	BA	6.0	4.3	10.4	-1.7	0.01	1.19	2.05	0.10	12.1	0.05	50.4	34.6	8.34	1.77	1.25	0.14	0.07	0.10	11.50	33.2
	Bt_1	5.9	4.2	10.4	-1.7	0.01	0.80	1.38	0.08	10.4	0.00	54.5	52.0	6.44	1.73	1.64	0.28	0.13	0.07	10.09	19.4
	Bt_2	6.2	4.2	10.1	-2.0	0.01	0.25	0.44	0.04	6.0	0.15	54.0	29.6	6.11	1.80	2.61	0.23	0.13	0.10	10.75	36.3
	BC	6.2	4.2	10.2	-2.0	0.01	0.10	0.17	0.04	2.3	0.00	55.0	37.4	7.18	2.27	3.77	0.28	0.17	0.13	13.50	36.1
Mwanzazi soil pedon (MWZ 04)																					
	Ap_1	6.3	5.0	10.9	-1.3	0.02	2.30	4.90	0.22	10.2	1.05	86.8	20.3	5.83	1.24	2.70	0.71	0.43	0.10	10.48	51.6
	Ap_2	6.2	4.9	11.3	-1.3	0.02	7.30	12.60	0.49	15.0	0.30	90.0	24.9	8.55	1.83	2.90	0.92	0.23	0.33	14.20	57.0
	C	6.5	4.8	11.5	-1.7	0.01	2.50	4.30	0.22	11.6	0.05	92.4	17.9	2.06	0.46	1.60	0.57	0.27	0.20	4.69	26.2
	2Cb	6.8	5.0	11.6	-1.8	0.01	0.40	0.77	0.08	5.5	0.15	69.8	14.9	0.45	0.29	0.48	0.33	0.13	0.07	1.55	10.4
	2Bwb	6.5	4.8	11.5	-1.7	0.01	2.40	4.20	0.19	13.3	1.47	96.7	28.1	3.26	1.32	3.50	1.08	0.03	0.13	9.16	32.6
	3Bwb	6.5	4.7	11.5	-1.8	0.01	1.30	2.23	0.15	9.3	1.50	95.4	29.9	1.93	1.65	3.65	0.89	0.13	0.03	8.12	27.2
	3Cb	6.7	4.9	11.1	-1.8	0.00	0.50	0.86	0.06	8.3	0.25	61.4	30.7	0.92	0.47	1.09	0.57	0.10	0.17	3.05	9.9
Kyela soil pedon (KYE 01)																					
	Ap_1	4.0	3.6	10.5	-0.4	0.19	5.07	8.74	0.46	10.97	3.64	76.6	57.4	0.90	0.18	1.20	0.25	0.37	1.40	2.53	4.4
	Ap_2	4.4	3.8	11.4	-0.6	0.03	3.86	6.66	0.32	11.99	0.30	88.0	40.8	0.24	0.02	0.37	0.15	0.03	1.17	0.78	1.9
	AC	4.7	3.5	10.9	-1.2	0.02	2.15	3.70	0.18	12.26	2.09	54.7	33.2	1.56	0.07	0.41	0.39	0.23	1.50	2.43	7.3
	C_1	5.8	3.8	11.0	-2.0	0.00	0.68	1.18	0.07	9.75	0.20	57.8	28.6	3.38	0.37	1.06	0.65	0.10	0.53	5.46	19.1
	C_2	5.9	3.8	10.7	-2.1	0.01	0.39	0.67	0.06	6.96	0.40	46.5	35.4	5.78	0.85	1.74	0.75	0.23	0.67	9.12	25.8
	C_3	6.1	3.8	10.6	-2.3	0.01	0.39	0.67	0.04	11.14	0.90	41.3	22.8	7.10	1.21	1.88	0.79	0.30	0.43	10.98	48.2
Ndembela soil pedon (NDE 01)																					
	Ap	6.6	4.9	11.0	-1.7	0.10	1.77	3.06	0.17	10.56	1.89	68.9	30.6	8.51	2.35	2.51	0.15	0.07	0.03	13.52	44.2
	Bt_1	6.3	4.7	10.7	-1.6	0.00	0.45	0.77	0.06	7.12	0.07	59.8	27.2	3.96	1.61	2.56	0.15	0.00	0.20	8.28	30.4
	Bt_2	5.8	4.0	10.7	-1.8	0.00	0.16	0.27	0.04	4.46	0.00	62.3	19.8	3.38	1.70	1.45	0.33	0.27	0.03	6.86	34.6

*Soil Pedons: MKW 01=Makwenje; IFIG 02=Ifiga; MKY 03=Mkuyuni; MWZ 04=Mwanzazi; KYE 01=Tenende plain; NDE 01= Ndembela; ΔpH= pH_{KCl} - pH_{H2O}; *PRC= Phosphate retention capacity*

Appendix 4. Classification of the studied soil pedons of Mbeya Region, Tanzania

USDA soil taxonomy (Soil Survey Staff, 2006)						WRB for soil resources (IUSS Working Group WRB, 2015)	
Diagnostic horizons	**Order**	**Suborder**	**Greatgroup**	**Subgroup**	**Family**	**Reference Soil Group (Tier-1)**	**WRB soil name (Tier-2)**
Makwenje soil pedon (MKW 01)							
Ochric epipedon; Argillic horizon	Alfisols	Ultalfs	Haplustalfs	Ultic Haplustalfs	*Very deep, clayey, acid, isothermic, Ultic Haplustalfs*	Alisols	*Haplic Cutanic Alisols (Profondic, Clayic)*
Ifiga soil pedon (IFIG 02)							
Mollic epipedon; Cambic horizon	Inceptisols	Udepts	Eutrudepts	Vitrandic Eutrudepts	*Deep, loamy, acid, isothermic, Vitrandic Eutrudepts*	Cambisols	*Vitric Fluvic Cambisols (Humic, Eutric)*
Mkuyuni soil pedon (MKY 03)							
Umbric epipedon; Argillic horizon	Alfisols	Udalfs	Hapludalfs	Typic Hapludalfs	*Very deep, clayey, acid, , isothermic, Typic Hapludalfs*	Alisols	*Umbric Cutanic Alisols (Hyperdystric, Clayic)*
Mwanzazi soil pedon (MWZ 04)							
Melanic epipedon; Cambic horizon	Andisols	Udands	Melanudands	Hydric Pachic Melanudands	*Very deep, loamy, acid, isothermic, Hydric Pachic Melanudands*	Andosols	*Melanic Silandic Andosols (Dystric, Siltic)*
Kyela soil pedon (KYE 01)							
Umbric epipedon	Entisols	Fluvents	Udifluvents	Aquic Udifluvents	*Deep, loamy, acid, isohyperthermic, Aquic Udifluvents*	Umbrisols	*Vitric Endogleyic Umbrisols (Humic, Clayic)*
Ndembela soil pedon (NDE 01)							
Umbric epipedon; Argillic horizon	Alfisols	Udalfs	Hapludalfs	Andic Hapludalfs	*Very deep, clayey, acid, isothermic, Andic Hapludalfs*	Alisols	*Vitric Cutanic Alisols (Profondic, Clayic)*

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