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# CHARACTERIZATION OF VOLCANIC ASH SOILS IN SOUTHWESTERN TANZANIA: MORPHOLOGY, PHYSICOCHEMICAL PROPERTIES, AND CLASSIFICATION

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ABSTRACT This study examined the characteristics of volcanic ash soils in southwestern Tanzania. Twelve pedons of volcanic origin were studied, and 66 soil samples were analyzed. Soil morphology revealed volcanic ash layers of varying thicknesses. Most pedons had a dark thick humus surface and buried A, AB, and BA horizons with melanic indices of 1.7 or less. Except in two pedons, the NaF pH was 9.4 or more, reflecting an exchange complex dominated by amorphous materials and/or Al–humus complexes. The phospate-retention capacity ranged from 65 to 100%, except in two pedons, and was positively correlated with NaF pH. Both Tanzanian and Japanese volcanic ash soils showed comparable ranges of base saturation (BS) values, but the distribution patterns of BS basic cations, for example, showed some differences. Some Tanzanian volcanic ash soils had higher BS values than their Japanese counterparts. While the Japanese soils were generally more calcic and magnesic, the Tanzanian soils were more potassic and sodic than their counterparts, most likely reflecting lithological differences among parent materials in the two study areas. According to the USDA Soil Taxonomy, nine pedons satisfied the requirements for andic properties and were classified as Andisols at the order level, whereas according to FAO World Reference Base (WRB) soil classification, eight pedons were classified as Andosols at the level of reference soil groups.

Key Words: Soil classification; Morphology; Physicochemical characteristics; Tanzania; Volcanic ash soils.

## INTRODUCTION

Soils developed from volcanic parent materials such as ash and pumice have unique morphological, physical, and chemical attributes. They are characterized by properties such as low bulk density, high water-retention capacity, an exchange complex dominated by variable charge surfaces, and high anion-retention capacity. Pedological surveys in Rwanda (Mizota & Chapelle, 1988) have indicated the presence of volcanic ash soils derived dominantly from basic ashes. In Tanzania, some reconnaissance studies (Msanya et al., 2002) found similar soils in the Rift Valley area of the Southern Highlands between Mbeya and Lake Nyasa. Like in Rwanda, these soils are highly dependable for human use and support high densities of human population.

Numerous volcanoes have produced ejecta carried southeastward by winds and deposited in many tephra layers over the geomorphologically stable plateau of the Southern Highlands (Stockley, 1948; Harkins, 1960). Among these, Mt. Rungwe and Mt. Poroto are the largest known calderas to have produced cyclic depositions of loamy volcanic ash and pumice. The volcanic soils in this area, unlike others in Africa and particularly those in Kenya and the Tanzanian Northern Rift Valley, are characterized by thick humus-rich horizons that look quite similar to those in Japan.

In-depth studies on the potential of these soils and data needed for their sound management and use are lacking. The main objective of this study was to characterize the soils based on their morphology, physicochemical properties, and taxonomy, and to compare them with Japanese volcanic ash soils to provide a basis for agricultural and other technology transfers.

## MATERIALS AND METHODS

### I. Field Methods

Using standard procedures (FAO, 1990; Munsell Color Co., 1992), 12 pedons were examined and sampled in a southeastward direction from Mbeya. Sample sites were located by international coordinates determined by a Sony Global Positioning System (GPS) receiver (Fig. 1). The total mean annual rainfall of the study area ranges from 900 to slightly more than 2,000 mm, and tempera-

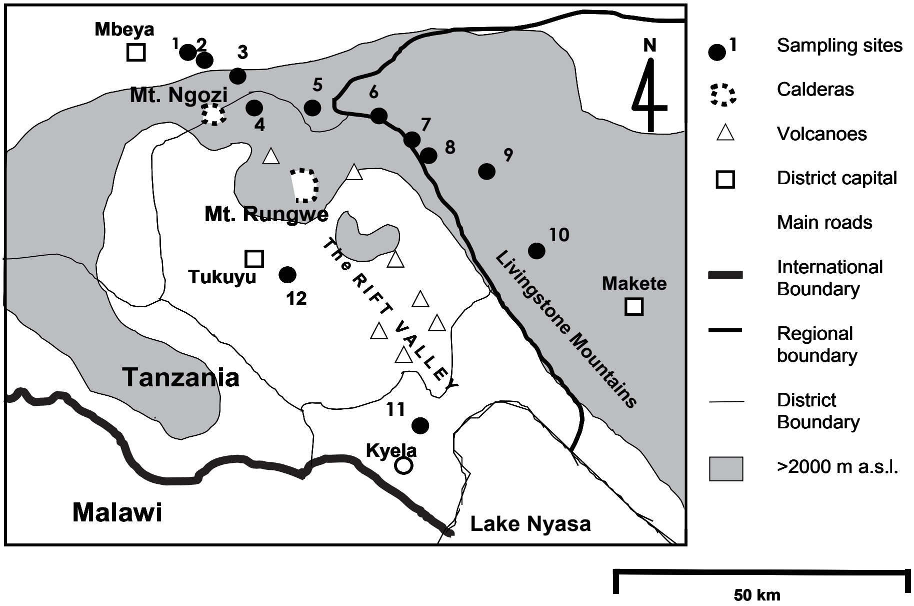

**Fig. 1.** Location of the studied pedons

**Table 1.** Site characteristics of the studied soils

| Pedon No. | Site name | Location | Altitude (m asl) | Landform | Vegetation / Land use | STR* | SMR* |
|---|---|---|---|---|---|---|---|
| 1 | Uyole-1 | S 08° 54′ 25"<br>E 33° 31′ 33" | 1792 | Alluvio-colluvial plain | Maize, wheat, beans | isothermic | udic |
| 2 | Uyole-2 | S 08° 55′ 16"<br>E 33° 32′ 06" | 1836 | Alluvio-colluvial plain | Grazing land (grasses mainly *Cynodon* spp., *Chloris gayana, Digitaria* spp. and *Hyperrhenia* spp.) | isothermic | udic |
| 3 | Galijembe | S 08° 57′ 43"<br>E 33° 36′ 02" | 2180 | Hilland-backslopes | Irish potatoes, wheat, maize, peas, pyrethrum | isothermic | udic |
| 4 | Isyonje | S 09° 00′ 16"<br>E 33° 37′ 37" | 2313 | Hilland-backslopes | Irish potatoes, maize, cabbage, pyrethrum | isomesic | udic |
| 5 | Nyalwela | S 09° 00′ 10"<br>E 33° 43′ 26" | 2657 | Hilland-backslopes | Forest reserve with *Hagenia abyssinica* | isomesic | udic |
| 6 | Ilala | S 09° 01′ 17"<br>E 33° 49′ 01" | 2792 | Hilland-backslopes | Grazing land (grasses mainly *Cynodon* spp., *Chloris gayana,* and *Digitaria* spp.) | isomesic | udic |
| 7 | Kitulo Comworks | S 09° 03′ 35"<br>E 33° 52′ 10" | 2870 | Hilland-summit | Grazing land (short grasses locally called *wasumba*) | isomesic | udic |
| 8 | Kitulo Central | S 09° 05′ 27"<br>E 33° 54′ 30" | 2749 | Hilland-backslopes | Grazing land with scattered Cypress trees (*Cupressus* spp.), and grasses mainly *wasumba* | isomesic | udic |
| 9 | Ujuni | S 09° 07′ 07"<br>E 33° 59′ 45" | 2607 | Hilland-backslope | 2 years fallow (normally under potatoes, maize and peas) | isomesic | udic |
| 10 | Luvulunge | S 09° 14′ 49"<br>E 34° 04′ 22" | 2348 | Hilland, backslope | Planted pines (*Pinus patula*) and bamboo (*Oxytenanthera abyssinica*) | isomesic | udic |
| 11 | Mwaya | S 09° 34' 25"<br>E 33° 52' 34" | 480 | Alluvial plain | Paddy rice | isohyper-thermic | aquic |
| 12 | Pakati | S 09° 17' 30"<br>E 33° 40' 26" | 1260 | Ridge summit | Banana garden | isothermic | udic |

*STR: soil temperature regime, SMR: soil moisture regime

tures range from slightly less than 10 to about 20°C. The altitude varies from 480 m (Lake Nyasa) to 2,900 m (Southern Plateau). Table 1 lists general site characteristics.

## II. Laboratory Methods

Physical and chemical analyses were conducted as follows. The bulk density was ascertained by the core method (Black & Hartge, 1986), and texture was determined by the hydrometer method (Day, 1965) after dispersing soil with sodium hexametaphosphate. Soil moisture characteristics were measured by pressure plate and membrane apparatuses (Klute, 1986).

The melanic index (the ratio of humic and fulvic acids) was calculated according to the method of Honna et al. (1988). The pH was measured potentiometrically in water and 1 M KCl at a ratio of 1:2.5 soil–water and soil–KCl, respectively (McLean, 1986), and at a ratio of 1:50 soil–NaF, with measurements taken after 2 min (Fieldes & Perrot, 1966; National Soil Service (NSS), 1990). The phosphate-retention (P-retention) capacity was determined according to the method of Blakemore et al. (1981). Organic carbon was ascertained by the wet oxidation method (Nelson & Sommers, 1982) and converted to organic matter by multiplying by a factor of 1.724. The Kjeldahl method (Bremner & Mulvaney, 1982) was used to determine total nitrogen. Phosphorus was extracted by the Bray and Kurtz-1 method (Bray & Kurtz, 1945) and determined spectrophotometrically (Murphy & Riley, 1962; Watanabe and Olsen, 1965). Acid-oxalate-extractable Al, Fe, and Si were determined by single extraction using 0.2 M ammonium oxalate at pH 3 (Soil Survey Staff, 1999) and measured using an inductively coupled plasma spectrometer (ICPS). Sodium-pyrophosphate-extractable Al was measured by single extraction using 0.1 N solution at pH 10 (Soil Survey Staff, 1999) and the ICPS. Cation exchange capacity (CEC) and exchangeable bases were extracted by saturating soil with neutral 1 M $NH_4OAc$ (Thomas, 1982); the adsorbed $NH_4^+$ was displaced with $K^+$ using 1 M KCl and determined by the Kjeldahl distillation method for estimating the CEC of soil. The bases $Ca^{++}$, $Mg^{++}$, $Na^+$, and $K^+$ displaced by $NH_4^+$ were measured by an atomic absorption spectrophotometer.

### III. Soil Classification

Using both field and laboratory data, the soils were classified according to the United States Department of Agriculture (USDA) Soil Taxonomy up to the subgroup level (Soil Survey Staff, 1999) and up to the second categorical level of the FAO World Reference Base (WRB) for Soil Resources (FAO et al., 1998).

## RESULTS AND DISCUSSION

### I. Soil Morphology

Table 2 presents some key morphological properties of the studied soils as revealed by the pedons. The soils were deep to very deep with friable to very friable moist consistency. The topsoils were very dark colored with color values of 2 or less in all pedons except Uyole-1. Most pedons contained buried horizons, including A, AB, BA, and B alternating with layers of volcanic ashes and pumiceous materials, a morphology reflecting the cyclic deposition of volcanic ejecta. The textures were variable within and among pedons, but were gener-

**Table 2.** Some morphological characteristics from soil profile descriptions

| Pedon | Horizon | Depth (cm) | Texture[1)] | Moist color[2)] | Consistence[3)] | Structure[4)] | Hor. boundary[5)] |
|---|---|---|---|---|---|---|---|
| 1 | Ap | 0 - 33 | SL | vdg (10YR3/1) | vfr, ss&sp | w, sbk | cs |
| | C | 33 - 47 | LS | gb (2.5Y5/2) | fr, ns&np | mass. | cs |
| | 2Cb | 47 - 56 | gSL | lbg (2.5Y6/2) | vfr, ns&np | mass. | as |
| | 3Bwb | 56 - 131 | gCL | dyb (10YR4/4) | fr, s&p | w, sbk | cs |
| | 3BCtb | 131 - 185+ | CL | b (10YR4/3) | fr, s&p; | w, sbk | - |
| | Pumice | 131 - 185+ | gL | lbg(2.5YR6/2) | ns&np | s-grain. | - |
| 2 | Ap | 0 - 41/45 | gCL | vdb (10YR2/2) | fr, ss&sp | w-m, sbk | cw |
| | C | 41/45 - 50 | gL | g (10YR6/1) | fr, ss&sp. | mass. | cs |
| | 2Bwb | 50 - 115 | CL | bl (7.5YR2.5/1) | fr, s&p. | w, sbk | cs |
| | 2C/Bwb | 115 - 200+ | SL | w (2.5Y8/1) | fr, ss&sp | mass. | as |
| | 3BCtb | >200 | CL | b (10YR4/3) | fr, s&p | w, sbk | - |
| 3 | Ap | 0 - 54 | CL | bl (10YR2/1) | vfr, ss&sp | w, sbk | gs |
| | AB | 54 - 80/95 | C | vdg (10YR3/1) | fr, s&p | w, sbk | cw |
| | 2Ahb | 80/95 - 155 | CL | b (10YR2/1) | fr, s&p. | m, sbk | as |
| | 2C | 155 - 178 | LS | oy (2.5Y6/6) | ns&np. | s-grain. | as |
| | 3Btb | 178 - 234 | C | vdgb (2.5Y3/2) | fr, s&p. | m, sbk | as |
| | 3Cb | 234 - 244 | SL | lob (2.5Y5/6) | ss&sp. | mass. | as |
| | 4Btb | 244 - 255+ | C | db (10YR3/3) | fr, s&p. | m, sbk | - |
| 4 | Ap1 | 0 - 18 | gSL | db (10YR3/3) | fr, ns&np. | s-grain. | cs |
| | Ap2 | 18 - 78/82 | L | bl (10YR2/1) | vfr, ss&sp | w, cr | cw |
| | C | 78/82 - 88/90 | gSCL | yb (10YR5/8) | fr, ss&sp. | w, sbk | aw |
| | 2Bwb | 88/90 - 134 | C | dyb (10YY3/6) | fr, s&p. | w, sbk | as |
| | 2Cb | 134 - 156 | S | yb (10YR5/6) | ns&np | s-grain. | as |
| | 3Bwb | 156 - 171 | C | dyb (10YR4/6) | fr, s&p. | w, sbk | as |
| | 3Cb | 171 - 220 | SL | yb (10YR6/6) | ns&np | s-grain. | - |
| 5 | Ah1 | 0 - 12/18 | SL | bl (10YR2/1) | vfr, ss&sp | s, cr | cw |
| | Ah2 | 12/18 -77/92 | SCL | vdb (10YR2/2) | vfr, s&p. | m, sbk | aw |
| | C | 77/92 - 175 | LS | yb (10YR5/6) | ns&np. | s-grain. | - |
| 6 | Ap | 0 - 33/50 | SL | bl (10YR2/1) | vfr, ss&sp. | m, cr | cw |
| | C | 33/50 - 53/60 | SL | sb (7.5YR5/6) | ns&np | s-grain. | cw |
| | 2Cb | 53/60 - 90 | LS | gb (10YR5/2) | ns&np. | s-grain. | aw |
| | 3Ab | 90 - 122/140 | gSCL | bl (10YR2/1) | fr, s&p. | w, sbk | aw |
| | 3Cb | 122/140 - 143 | gSCL | b (7.5YR4/4) | ns&np. | s-grain. | cs |
| | 4Cb | 143 - 185+ | gL | b (7.5YR4/4) | ns&np | s-grain. | - |
| 7 | Ap | 0 - 32/42 | SL | bl (10YR2/1) | vfr, ss&p. | s, cr | aw |
| | C | 32/42 - 80/89 | SL | dyb (10YR3/4) | ns&np | s-grain. | aw |
| | 2Cb | 80/89 - 100/105 | SL | bl (10YR2/1) | fr, s&p. | w, sbk | gw |
| | 3Ab | 100/105 - 141 | LS | dyb (10YR3/4) | ns&np. | s-grain. | as |
| | 3Cb | 141 - 180+ | SCL | db (10YR3/3) | ns&np | s-grain. | - |

(*continued*)

(*continued*)

| Pedon | Horizon | Depth (cm) | Texture1) | Moist color2) | Consistence3) | Structure4) | Hor. boundary5) |
|---|---|---|---|---|---|---|---|
| 8 | Ap | 0 - 40/47 | SL | bl (10YR2/1) | vfr, ss&sp | m, cr | aw |
| | C | 40/47 - 55/60 | SL | yb (10YR6/8) | fr, ss&sp | mass. | aw |
| | 2Ab | 55/60 - 75/89 | SCL | bl (10YR2/1) | fr, s&p | w, sbk | cw |
| | 2Cb | 75/89 - 110/116 | SL | yb (10YR5/4) | ns&np | s-grain. | aw |
| | 3Bwb | 110/116 - 130/138 | C | vdgb (10YR3/2) | fr, s&p | w, sbk | aw |
| | 3BCb | 130/138 - 160/165 | L | b (7.5YR4/4) | fr, s&p | w, sbk | aw |
| | 3Cb | 160/165 - 174/180 | SL | sb (7.5YR5/8) | ns&np | mass. | aw |
| | 4Ab | 174/180 - 190/202 | SL | vdgb (10YR3/2) | fr, s&p | w, sbk | aw |
| | 4Bwb | 190/202 - 220 | L | b (10YR4/3) | fr, s&p | m, sbk | - |
| 9 | Ap | 0 - 38/51 | SL | bl (10YR2/1) | vfr, ss&sp | s, cr | aw |
| | Bw | 38/51 - 75/85 | SCL | vdb (10YR2/2) | fr, s&p | w-m, sbk | aw |
| | C | 75/85 - 98 | SCL | b (10YR4/3) | vfr, s&p | mass. | as |
| | 2Ab | 98 - 110 | CL | vdgb (10YR3/2) | vfr, s&p | w, sbk | cs |
| | 2BAtb1 | 110 - 145/154 | SCL | db (10YR3/3) | fr, s&p. | w, sbk | cw |
| | 2BAtb2 | 145/154 - 180+ | CL | dyb (10YR3/4) | fr, s&p | w, sbk | - |
| 10 | Ah | 0 - 30/35 | SL | bl (10YR2/1) | vfr, ns&sp | m, cr | cw |
| | C | 30/35 - 49 | LS | dyb (10YR3/4) | vfr, ss&sp | w, sbk | as |
| | 2Ab | 49 - 98 | SL | db (10YR3/3) | fr, s&p | m, sbk | cs |
| | 2BAb | 98 - 120/125 | SCL | db (7.5YR3/4) | fr, s&p | m, sbk | gw |
| | 2Btb | 120/125 - 180/195 | C | yr (5YR4/6) | fr, s&p | w, sbk | cw |
| | 2BCb | 180/195 - 215+ | gSiCL | yr (5YR5/6) | fr, s&p | w, sbk | - |
| 11 | Ap | 0 - 17/20 | C | bl (10YR2/1) | vfr, s&p | m, sbk | aw |
| | Bwg1 | 17/20 - 30 | gSC | gb (10YR5/3) | fr, s&p | m, sbk | cs |
| | Bwg2 | 30 - 80+ | gSC | pb (10YR 6/3) | fr, s&p | w, sbk | - |
| 12 | Ap | 0 - 27 | CL | bl (10YR2/1) | vfr, ss&sp | m, gr | cs |
| | Ah | 27 - 50 | CL | bl (10YR2/1) | fr, ss&sp | m, sbk | as |
| | CB | 50 - 100+ | SL | by (10YR6/8) | fr, ss&sp | w, sbk | - |

1) S=sand; LS=loamy sand; gSL=gravelly sandy loam; SL=sandy loam; gSCL=gravelly sandy clay loam; SCL=sandy clay loam; gL=gravelly loam, L=loam; gCL=gravelly clay loam; CL=clay loam, gSiCL=gravelly silty clay loam; gSC=gravelly sandy clay; C=clay

2) vdg=very dark gray; gb=grayish brown; lbg=light brownish gray; dyb=dark yellowish brown; b=brown; vdb=very dark brown; g=gray; bl=black; w=white; oy=olive yellow; vdgb=very dark grayish brown; lob=light olive brown; yb=yellowish brown; sb=strong brown; db=dark brown; yr=yellowish red; pb=pale brown; by=brownish yellow

3) fr=friable; vfr=very friable; ns=nonsticky; ss=slightly sticky; s=sticky; np=nonplastic; sp=slightly plastic; p=plastic

4) mass.=massive, s-grain.=single grained; w, sbk=weak subangular blocky; w-m, sbk=weak to moderate subangular blocky; m, sbk=moderate subangular blocky; w, cr=weak crumby; m, cr=moderate crumby; s, cr=strong crumby; m, gr=moderate granular

5) a=abrupt; c=clear; g=gradual; s=smooth; w=wavy

ally loamy or coarser. Clayey textures were observed in some horizons of the Isyonje, Kitulo Central, Luvulunge, and Mwaya pedons. The structures of the A and B horizons were better developed (granular, crumby, or subangular blocky) than those of the C horizons, which had mostly single-grained or massive structures. Soil horizon boundaries were quite distinct, ranging mostly from clear to abrupt with either smooth or wavy horizon topography. The Mwaya pedon was situated in an alluvial plain characterized by waterlogging and the presence of common, distinct Fe mottles and coarse Mn concretions.

## II. The Analytical Data

Table 3 shows some chemical characteristics essential for defining volcanic ash soils. The organic carbon (OC) varied within and among pedons, rating as high to very high in the surface A horizons and buried A, AB, and BA horizons. These horizons also had low Melanic index (MI) values (≤1.7), corresponding to their intense dark colors. Bulk density (BD) values for all pedons were lower than 0.85 g/cc except in the Uyole and Galijembe pedons. The water pH values for most pedons ranged between medium acidic and mildly alkaline, with Uyole pedons having the highest pH values. Values of KCl pH were, on average, 1.5 units lower than the pH values for water; this difference became high when an appreciable amount of exchangeable Al was dissolved.

NaF pH values were generally greater than 9.4 for all pedons except those from Uyole. This suggests that in most pedons, exchange complexes are dominated by short-range ordered minerals and/or Al– and Fe–humus compounds (Wada, 1980; Shoji et al., 1993; Barreal et al., 2001; Camps Arbestian et al., 2001). The P-retention capacity for all pedons except those from Uyole ranged from 65 to 100%. Most of the studied pedons thus met the P-retention capacity requirements of 85% (USDA Soil Taxonomy) and 70% (FAO WRB) for the definition of andic properties. The Alo + 0.5 Fe values were generally greater than 2.0 in all pedons except the Uyole pedons and a Mwaya pedon. The high values point to andic properties. Except for the Uyole pedons and the Mwaya pedon, the other pedons had Sio contents of 0.6% or more or Alp/Alo ratios of less than 0.5 in all or most of their horizons. These values indicate the dominance of allophane and similar minerals (FAO et al., 1998). According to the ratings by Baize (1993), Landon (1991), and Msanya et al. (1996), the CEC values (except for those of the Uyole pedons), ranged from high to very high [25 to >40 cmol(+)/kg]. The Uyole pedons had medium to high CEC values. The values were highest in the surface A horizons and buried A, AB, and BA horizons. KCl-extractable Al contents were very low in all pedons. Base saturaion (BS) was high (50% or more) in the Uyole pedons but low (<50%) in the rest of the pedons. Because Uyole is situated in the Rift Valley, its pedons may have received fresher materials from volcanic eruptions, which would explain the higher BS.

## III. Correlation among Some Physical and Chemical Characteristics

Table 4 presents a Pearson correlation matrix for selected properties of the studied soils. Clay and silt contents were negatively correlated with sand. Texture is a composite of the coarse fraction (sand) and the finer fraction (silt and clay), and increasing or decreasing one component imparts the opposite effect on the other. Total nitrogen (TN) and OC were positively correlated, indicating that OC is the main source of TN. OC and TN were negatively correlated with water pH, suggesting that carboxyl groups associated with organic matter contributed to lowering the water pH. The water pH and KCl pH were pos-

**Table 3**. Some chemical characteristics of the studied soils

| Pedon | % OC | MI | BD g/cc | 1500 kPa $H_2O$ | pH $H_2O$ | pH KCl | pH NaF | % P ret. | Alo + 0.5Feo | Sio | Alp /Alo | CEC* | TEB* | Al* | % BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Ap | 1.9 | 1.6 | 1.1 | 14.1 | 6.6 | 5.0 | 8.6 | 18 | 0.5 | 0.10 | 0.46 | 16.5 | 10.20 | 0.01 | 61.8 |
| C | 0.3 | 1.6 | - | - | 7.3 | 5.0 | 8.0 | 15 | 0.2 | 0.05 | 0.48 | 17.5 | 8.90 | 0.01 | 50.9 |
| 2Cb | 0.3 | 1.5 | 1.2 | 20.4 | 7.2 | 5.1 | 8.0 | 4 | 0.2 | 0.03 | 0.42 | 13.9 | 11.54 | 0.01 | 83.0 |
| 3Bwb | 1.0 | 1.8 | 1.2 | 25.5 | 7.1 | 5.2 | 8.6 | 26 | 0.7 | 0.17 | 3.41 | 16.1 | 9.74 | 0.01 | 60.5 |
| 3BCtb | 0.8 | 1.8 | - | - | 7.4 | 5.1 | 8.8 | 35 | 0.8 | 0.27 | 2.08 | 20.3 | 12.99 | 0.01 | 64.0 |
| Pumice | 0.4 | 1.5 | - | - | 7.5 | 5.3 | 8.7 | 44 | 0.9 | 0.26 | 1.74 | 22.3 | 7.45 | 0.01 | 33.4 |
| 2. Ap | 3.2 | 1.6 | 1.0 | 19.3 | 6.8 | 5.1 | 8.7 | 39 | 1.2 | 0.28 | 1.20 | 22.7 | 14.95 | 0.02 | 65.9 |
| C | 0.5 | 1.5 | 1.0 | 21.3 | 7.1 | 5.1 | 8.5 | 14 | 0.4 | 0.10 | 1.04 | 29.8 | 14.83 | 0.01 | 49.8 |
| 2Bwb | 1.2 | 1.6 | 1.1 | 25.0 | 6.7 | 5.2 | 8.8 | 42 | 0.9 | 0.27 | 1.88 | 21.5 | 14.04 | 0.02 | 65.3 |
| 2C/Bwb | 0.3 | 1.6 | - | - | 7.0 | 5.2 | 8.7 | 37 | 0.9 | 0.33 | 0.97 | 28.9 | 8.00 | 0.01 | 27.7 |
| 3BCtb | 0.8 | 1.8 | - | - | 7.1 | 5.0 | 8.8 | 21 | 0.2 | 0.03 | 1.91 | 20.3 | 12.61 | 0.01 | 62.1 |
| 3. Ap | 7.1 | 1.7 | 1.1 | 30.4 | 6.0 | 4.8 | 9.7 | 65 | 2.8 | 0.72 | 0.48 | 32.5 | 15.24 | 0.03 | 46.9 |
| AB | 3.8 | 1.6 | 0.9 | 33.6 | 6.5 | 5.0 | 9.3 | 58 | 2.3 | 0.81 | 0.61 | 31.7 | 15.41 | 0.02 | 48.6 |
| 2Ahb | 3.2 | 1.5 | 0.9 | 28.8 | 6.7 | 5.2 | 9.1 | 60 | 2.3 | 0.96 | 0.73 | 31.5 | 18.43 | 0.02 | 58.5 |
| 2C | 0.6 | 1.8 | - | - | 6.8 | 5.0 | 9.7 | 39 | 2.7 | 1.34 | 0.05 | 25.5 | 7.81 | 0.00 | 30.6 |
| 3Btb | 1.2 | 1.6 | - | - | 6.7 | 5.1 | 9.1 | 53 | 2.0 | 0.73 | 0.97 | 30.2 | 14.88 | 0.01 | 49.3 |
| 3Cb | 0.7 | 1.8 | - | - | 7.0 | 4.9 | 9.4 | 57 | 2.8 | 1.61 | 0.20 | 23.3 | 11.90 | 0.00 | 51.1 |
| 4Btb | 1.1 | 1.7 | - | - | 6.9 | 5.0 | 9.0 | 58 | 2.0 | 0.86 | 0.89 | 35.7 | 10.01 | 0.00 | 28.0 |
| 4. Ap1 | 7.0 | 1.7 | 0.7 | 31.8 | 6.5 | 5.0 | 9.8 | 65 | 2.6 | 1.09 | 0.30 | 20.3 | 10.48 | 0.01 | 51.6 |
| Ap2 | 8.2 | 1.6 | 0.8 | 45.5 | 6.3 | 4.9 | 10.5 | 88 | 4.2 | 1.18 | 0.40 | 27.8 | 14.20 | 0.03 | 51.1 |
| C | 2.8 | 1.5 | 0.9 | 44.8 | 6.4 | 4.8 | 11.0 | 82 | 3.7 | 1.80 | 0.29 | 17.9 | 4.73 | 0.02 | 26.4 |
| 2Bwb | 2.7 | 1.8 | - | - | 6.5 | 4.8 | 9.8 | 78 | 2.8 | 0.87 | 0.61 | 28.1 | 9.21 | 0.02 | 32.8 |
| 2Cb | 0.5 | 1.6 | - | - | 6.7 | 5.0 | 10.7 | 82 | 3.6 | 2.40 | 0.10 | 14.9 | 1.55 | 0.01 | 10.4 |
| 3Bwb | 1.5 | 1.8 | - | - | 6.5 | 4.7 | 9.3 | 74 | 2.3 | 0.83 | 0.58 | 29.9 | 8.12 | 0.01 | 27.2 |
| 3Cb | 0.6 | 1.7 | - | - | 6.7 | 4.9 | 10.5 | 97 | 5.3 | 3.91 | 0.07 | 28.6 | 3.05 | 0.02 | 10.7 |
| 5. Ah1 | 10.2 | 1.7 | 0.6 | 28.6 | 5.8 | 4.6 | 10.4 | 93 | 3.8 | 0.89 | 0.63 | 40.1 | 7.32 | 0.08 | 18.3 |
| Ah2 | 8.8 | 1.7 | 0.8 | 41.6 | 6.0 | 4.5 | 11.2 | 98 | 5.1 | 2.09 | 0.42 | 31.5 | 4.92 | 0.14 | 15.6 |
| C | 0.3 | 2.2 | 0.5 | 38.6 | 6.9 | 4.7 | 10.5 | 70 | 3.2 | 2.52 | 0.07 | 9.9 | 2.45 | 0.01 | 24.9 |
| 6. Ap | 6.4 | 1.7 | 0.8 | 13.2 | 6.2 | 5.0 | 11.1 | 100 | 7.6 | 4.28 | 0.27 | 41.8 | 7.98 | 0.02 | 19.1 |
| C | 1.7 | 1.9 | 0.8 | 5.5 | 6.4 | 5.2 | 10.8 | 100 | 7.6 | 3.28 | 0.07 | 27.3 | 2.29 | 0.00 | 8.4 |
| 2Cb | 0.3 | 1.8 | - | - | 6.7 | 4.8 | 10.6 | 84 | 3.7 | 2.85 | 0.07 | 28.3 | 4.36 | 0.02 | 15.4 |
| 3Ab | 1.6 | 1.5 | 1.1 | 49.8 | 6.6 | 5.0 | 9.1 | 70 | 2.9 | 2.03 | 0.21 | 19.9 | 6.11 | 0.00 | 30.7 |
| 3Cb | 0.9 | 1.8 | - | - | 6.7 | 4.7 | 10.3 | 95 | 4.4 | 3.14 | 0.08 | 36.7 | 12.80 | 0.02 | 34.9 |
| 4Cb | 0.5 | 1.8 | - | - | 6.7 | 4.6 | 10.2 | 96 | 5.1 | 3.05 | 0.06 | 35.9 | 10.95 | 0.06 | 30.5 |
| 7. Ah | 6.7 | 1.5 | 0.7 | 32.9 | 6.2 | 5.0 | 11.3 | 100 | 7.3 | 4.00 | 0.26 | 37.5 | 5.76 | 0.01 | 15.4 |
| C | 0.7 | 1.9 | 0.4 | 28.2 | 6.6 | 4.9 | 10.6 | 98 | 5.9 | 2.67 | 0.06 | 29.3 | 2.82 | 0.01 | 9.6 |
| 2Cb | 1.5 | 1.6 | 1.2 | 29.5 | 6.8 | 5.0 | 9.8 | 64 | 2.8 | 1.66 | 0.13 | 10.5 | 4.99 | 0.00 | 47.5 |
| 3Ab | 1.5 | 1.7 | - | - | 6.6 | 5.0 | 9.9 | 81 | 4.5 | 2.52 | 0.08 | 18.7 | 3.99 | 0.00 | 21.3 |
| 3Cb | 1.0 | 1.9 | - | - | 6.8 | 4.9 | 10.3 | 100 | 7.1 | 4.08 | 0.08 | 20.5 | 9.71 | 0.06 | 47.4 |

(*continued*)

(*continued*)

| Pedon | % OC | MI | BD g/cc | 1500 kPa $H_2O$ | pH $H_2O$ | pH KCl | pH NaF | % P ret. | Alo + 0.5Feo | Sio | Alp /Alo | CEC* | TEB* | Al* | % BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8. Ap | 6.4 | 1.6 | 0.6 | 35.7 | 4.9 | 4.6 | 11.2 | 100 | 7.4 | 4.47 | 0.37 | 41.9 | 4.87 | 0.03 | 11.6 |
| C | 1.3 | 1.9 | 0.4 | 35.0 | 6.0 | 5.1 | 10.9 | 100 | 7.2 | 5.77 | 0.09 | 30.7 | 4.53 | 0.00 | 14.8 |
| 2Ab | 5.0 | 1.6 | - | - | 6.6 | 5.2 | 11.1 | 100 | 7.3 | 5.78 | 0.15 | 43.7 | 6.44 | 0.00 | 14.7 |
| 2Cb | 0.5 | 1.9 | 0.5 | 37.1 | 6.5 | 4.7 | 10.2 | 90 | 5.9 | 2.75 | 0.06 | 31.3 | 8.60 | 0.04 | 27.5 |
| 3Bwb | 2.0 | 1.6 | - | - | 6.7 | 5.0 | 9.8 | 87 | 4.6 | 2.29 | 0.27 | 33.7 | 14.14 | 0.00 | 42.0 |
| 3BCb | 1.3 | 1.7 | - | - | 6.6 | 5.1 | 10.4 | 98 | 7.4 | 5.25 | 0.05 | 34.6 | 4.66 | 0.00 | 13.5 |
| 3Cb | 0.5 | 1.7 | - | - | 6.7 | 4.9 | 10.1 | 96 | 5.8 | 2.93 | 0.05 | 31.9 | 5.40 | 0.02 | 16.9 |
| 4Ab | 2.6 | 1.6 | - | - | 6.7 | 5.1 | 10.4 | 95 | 6.7 | 4.42 | 0.07 | 44.3 | 5.42 | 0.00 | 12.2 |
| 4Bwb | 2.5 | 1.6 | - | - | 6.6 | 5.0 | 10.2 | 100 | 7.3 | 4.85 | 0.07 | 41.7 | 10.59 | 0.00 | 25.4 |
| 9. Ap | 6.8 | 1.5 | 0.6 | 22.7 | 6.3 | 5.1 | 11.3 | 100 | 8.7 | 3.96 | 0.20 | 39.1 | 5.47 | 0.00 | 14.0 |
| Bw | 4.4 | 1.7 | 0.6 | 40.6 | 6.4 | 5.1 | 11.1 | 100 | 8.5 | 5.24 | 0.12 | 34.1 | 3.52 | 0.00 | 10.3 |
| C | 2.4 | 1.7 | - | - | 6.1 | 5.0 | 10.9 | 100 | 9.5 | 5.86 | 0.08 | 33.3 | 8.83 | 0.00 | 26.5 |
| 2Ab | 3.9 | 1.6 | 0.5 | 43.4 | 6.3 | 4.9 | 10.6 | 100 | 7.3 | 4.53 | 0.15 | 43.1 | 9.35 | 0.00 | 21.7 |
| 2BAtb1 | 3.5 | 1.6 | - | - | 6.2 | 5.0 | 10.7 | 100 | 9.1 | 5.96 | 0.12 | 41.2 | 7.50 | 0.00 | 18.2 |
| 2BAtb2 | 3.4 | 1.6 | - | - | 6.1 | 5.2 | 10.8 | 100 | 12.5 | 7.58 | 0.08 | 44.3 | 5.00 | 0.00 | 11.3 |
| 10. Ah | 7.6 | 1.7 | 0.7 | 15.4 | 5.6 | 4.7 | 11.4 | 99 | 7.8 | 3.05 | 0.30 | 34.7 | 1.15 | 0.10 | 3.3 |
| C | 3.4 | 1.8 | - | - | 6.3 | 5.6 | 11.2 | 100 | 10.9 | 5.86 | 0.06 | 9.6 | 0.83 | 0.00 | 8.6 |
| 2Ab | 5.3 | 1.7 | 0.6 | 52.1 | 6.1 | 5.2 | 11.1 | 100 | 9.8 | 5.27 | 0.10 | 31.1 | 1.10 | 0.00 | 3.5 |
| 2BAb | 3.4 | 1.7 | 0.6 | 45.0 | 6.2 | 4.9 | 10.9 | 100 | 6.1 | 2.67 | 0.20 | 22.7 | 1.12 | 0.00 | 4.9 |
| 2Btb | 0.6 | 2.1 | - | - | 6.1 | 5.1 | 9.4 | 74 | 0.8 | 0.18 | 3.77 | 7.2 | 2.15 | 0.00 | 29.9 |
| 2BCb | 0.3 | 1.6 |  | - | 6.1 | 5.5 | 8.8 | 24 | 0.1 | 0.07 | 1.85 | 6.1 | 1.97 | 0.00 | 32.3 |
| 11. Ap | 4.4 | 1.6 | 0.8 | 42.9 | 4.8 | 4.0 | 11.1 | 69 | 1.6 | 0.29 | 1.02 | 21.2 | 5.33 | 0.96 | 25.1 |
| Bwg1 | 0.8 | 2.0 | 1.0 | 38.2 | 5.2 | 3.8 | 10.4 | 45 | 0.5 | 0.13 | 2.05 | 17.9 | 6.68 | 0.29 | 37.3 |
| Bwg2 | 0.7 | 2.2 | 1.0 | 38.7 | 6.9 | 4.0 | 9.8 | 43 | 0.4 | 0.16 | 2.44 | 18.6 | 7.78 | 0.17 | 41.8 |
| 12. Ap | 7.7 | 1.7 | 0.8 | 33.7 | 6.4 | 5.2 | 11.2 | 100 | 7.5 | 2.98 | 0.21 | 26.3 | 8.28 | 0.00 | 31.5 |
| Ah | 1.2 | 1.7 | 0.8 | 32.9 | 6.0 | 5.0 | 10.9 | 94 | 12.3 | 5.77 | 0.07 | 22.9 | 8.05 | 0.00 | 35.2 |
| CB | 1.1 | 1.9 | 1.1 | 28.2 | 6.7 | 5.6 | 11.1 | 100 | 1.2 | 0.33 | 1.08 | 17.7 | 8.51 | 0.00 | 48.1 |

OC=Organic carbon; MI=Melanic index; BD=Bulk density; 1500kPa $H_2O$=Water retention at 1500 kPascal; P-ret.=P-retention; Alo=Acid oxalate extractable $Al_2O_3$; Feo=Acid oxalate extractable $Fe_2O_3$; Sio=Acid oxalate extractable $SiO_2$; Alp=Na-pyrophosphate extractable $Al_2O_3$; CEC=Cation exchange capacity; TEB=Total exchangeable bases; BS=Base saturation

*units in cmol(+)/kg

itively correlated but not significantly. This is a normal trend reported elsewhere for Andisols and similar soils (Breimer et al., 1986). The OC, TN, and sand content were positively correlated with the NaF pH, indicating that both the organic matter and sand fraction were sources of the active hydroxyl-Al(Fe) compounds involved in the NaF reaction that releases OH ions.

In addition, this strongly suggests that the sand fraction is mainly composed of short-range ordered materials resulting from the weathering of volcanic glass, forming pseudo-sand. However, the silt content was negatively correlated with NaF pH and the P-retention capacity, indicating that this fraction, among the three, contributed the least to the characterization of these soils as Andisols. Water pH was negatively correlated with both NaF pH and the P-retention capacity, which were positively correlated with each other. The high P retention implies the presence of large amounts of hydroxyl-Al(Fe) compounds in the soil that react with NaF to release OH, which would consequently cause a high NaF pH. The P retention was also positively correlated with CEC because the presence of organic matter helped to increase both CEC

**Table 4.** Pearson correlation matrix for various physical and chemical characteristics of the studied soils

| | clay | silt | sand | OC | TN | $pHH_2O$ | pHKCl | pHNaF | Pret | CEC | Ca | Mg | K | Na | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| silt | 0.01 | | | | | | | | | | | | | | |
| sand | -0.82** | -0.59** | | | | | | | | | | | | | |
| OC | -0.05 | -0.15 | 0.13 | | | | | | | | | | | | |
| TN | -0.01 | -0.15 | 0.10 | 0.97** | | | | | | | | | | | |
| $pHH_2O$ | -0.15 | 0.25 | -0.02 | -0.54** | -0.54** | | | | | | | | | | |
| pHKCl | -0.17 | 0.18 | 0.04 | -0.11 | -0.13 | 0.43** | | | | | | | | | |
| pHNaF | -0.19 | -0.51** | 0.45** | 0.50** | 0.50** | -0.62** | -0.18 | | | | | | | | |
| Pret | -0.09 | -0.45** | 0.33 | 0.41 | 0.41 | -0.46** | -0.02 | 0.88** | | | | | | | |
| CEC | -0.04 | -0.01 | 0.04 | 0.44 | 0.39 | -0.23 | -0.08 | 0.39 | 0.53** | | | | | | |
| Ca | 0.22 | 0.29 | -0.34 | 0.26 | 0.26 | 0.07 | -0.03 | -0.29 | -0.25 | 0.21 | | | | | |
| Mg | 0.54** | 0.37 | -0.65** | -0.10 | -0.11 | 0.24 | -0.06 | -0.48** | -0.35 | 0.09 | 0.58** | | | | |
| K | 0.13 | 0.38 | -0.33 | -0.31 | -0.30 | 0.55** | 0.06 | -0.66** | -0.51** | 0.04 | 0.38 | 0.51** | | | |
| Na | 0.17 | 0.22 | -0.63** | -0.26 | -0.24 | 0.41 | 0.18 | -0.34 | -0.25 | -0.03 | 0.24 | 0.50** | 0.60** | | |
| Al | 0.23 | 0.02 | -0.20 | 0.12 | 0.19 | -0.50** | -0.62** | 0.16 | -0.06 | -0.09 | 0.02 | 0.05 | -0.16 | -0.17 | |
| BS | 0.24 | 0.39 | -0.42 | -0.26 | -0.25 | 0.46** | 0.08 | -0.75** | -0.75** | -0.42 | 0.61** | 0.61** | 0.67** | 0.53** | -0.03 |

**significant at the 0.01 probability level (n=66) and P retention. Mg was positively correlated with clay because clay is part of the soil's colloidal fraction, which holds and exchanges cations.

The correlation between the other cations (K, Na, Ca, and Al) and clay was positive but not significant. Cations and BS were negatively correlated with sand content, but the correlation was only significant for Mg and Na. The negative correlation occurred because the higher the sand content is, the smaller the surface area of the soil's colloidal fraction for holding and exchanging cations. Water pH was significantly positively correlated with K and BS but negatively correlated with Al. Normally, a higher pH will cause the amounts of basic cations to be higher and the acidic cations, including Al, to be lower. Water pH and KCl pH were negatively correlated with Al because the higher the pH is, the lower the amounts of acidic cations including Al. Negative correlations were also found for Mg, K, and BS with NaF pH. The high NaF pH implies a preponderance of hydroxyl-Al(Fe) groups in the soil and thus low levels of basic cations and BS. The P-retention capacity was negatively correlated with cations, but the correlation was significant only for K and BS. Basic cations were positively correlated among each other and with BS.

## IV. Comparison between Tanzanian and Japanese Volcanic Ash Soils

Some chemical properties were used to compare the Tanzanian and Japanese volcanic ash soils. Data on Japanese volcanic ash soils were derived from the work of Wada (1986).

### *1. BS and distribution of basic cations*

Figures 2 through 5 show the relationship between BS and basic cations for both Tanzanian and Japanese volcanic ash soils. The pertinent observations follow.

1) BS values for both Tanzanian and Japanese volcanic ash soils show comparable ranges. However, the distribution patterns of BS basic cations, for example, are somewhat different.
2) Some Tanzanian volcanic ash soils have higher BS values than their Japanese counterparts. The Uyole pedons have the highest BS values (see also Table 3). The higher BS in the Rift Valley can be explained by the greater likelihood of receiving fresh materials from volcanic eruptions.
3) Japanese volcanic ash soils are generally richer in Ca and to a certain extent Mg than their Tanzanian counterparts. However, Tanzanian volcanic ash soils are generally richer than their Japanese counterparts in K and Na.
4) The observations in number 3 above may reflect differences in parent materials (lithology) as associated with differences in magma characteristics in the two areas.

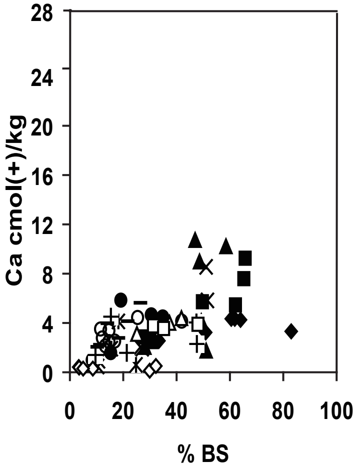

**Fig. 2.1.** Relationship between BS and Ca for Tanzanian volcanic ash soils

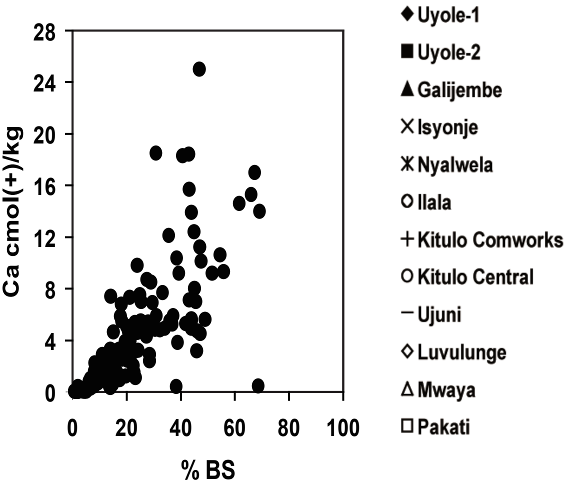

**Fig. 2.2.** Relationship between BS and Ca for Japanese volcanic ash soils

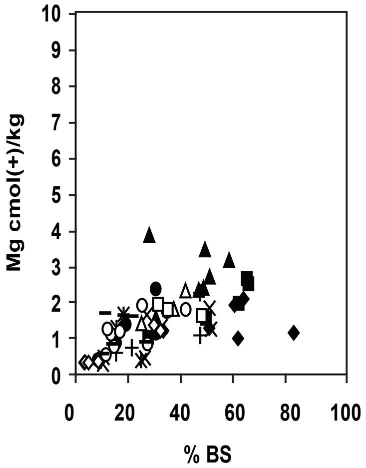

**Fig. 3.1.** Relationship between BS and Mg for Tanzanian volcanic ash soils

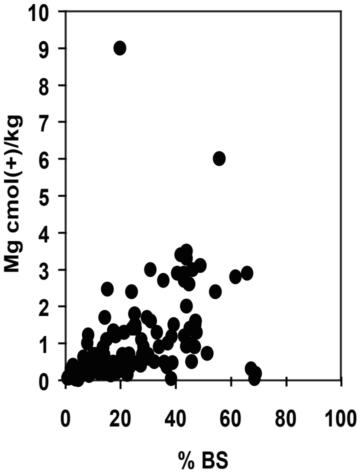

**Fig. 3.2.** Relationship between BS and Mg for Japanese volcanic ash soils

### *2. NaF pH and P-retention capacity*

Figures 6.1 and 6.2 show the relationship between NaF pH and P-retention capacity for Tanzanian and Japanese volcanic ash soils, respectively. The distribution patterns for the two areas were generally similar. In both cases, relatively more soils were concentrated in region I, characterized by a NaF pH greater than 9.4 and P-retention capacity greater than 85%. Region II, having soils with a NaF pH greater than 9.4 and P-retention capacity of less than 85%, was similarly represented in both areas. However, for Tanzanian volcanic ash soils, relatively more soils were concentrated in region III (NaF pH 8.5

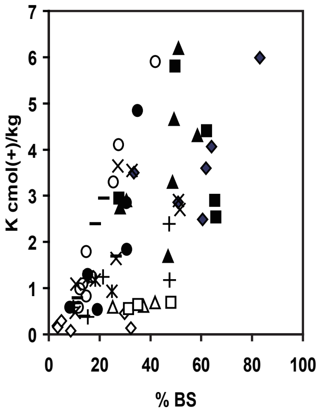

**Fig. 4.1.** Relationship between BS and K for Tanzanian volcanic ash soils

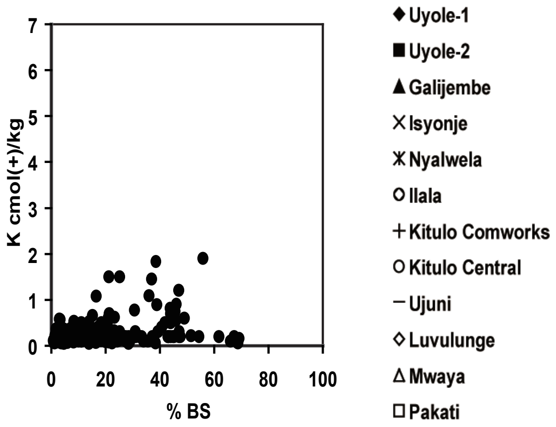

**Fig. 4.2.** Relationship between BS and K for Tanzanian volcanic ash soils

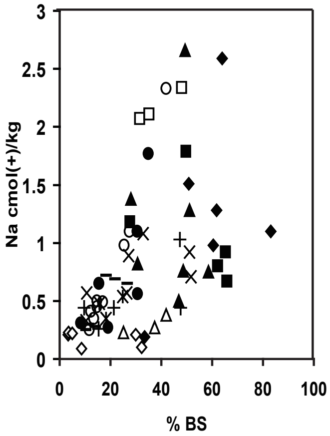

**Fig. 5.1.** Relationship between BS and Na for Tanzanian volcanic ash soils

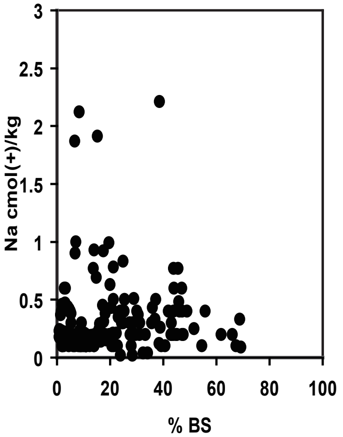

**Fig. 5.2.** Relationship between BS and Na for Tanzanian volcanic ash soils

–9.4 and P-retention capacity <85%) when compared to Japanese soils. In both cases, very few soils were in region IV (NaF pH <8.5 and P-retention capacity <85%). Few Japanese soils fell in region V (NaF pH 8.5–9.4 and P-retention capacity >85%), while none of the Tanzanian study soils were in that region.

## V. Soil Classification

Both morphological (Table 2) and analytical data (Table 3) were used to classify the study soils. Table 5 presents the soil names. According to the USDA Soil Taxonomy, nine pedons satisfied the diagnostic criterion for andic properties and were classified as Andisols at the order level. Pedons Uyole-1, Uyole-2, and Mwaya, which did not wholly satisfy the requirements for Andisols, showed andic properties only at the subgroup level. Udic soil moisture regime

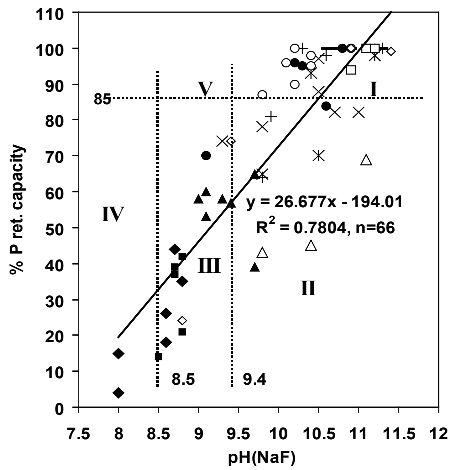

**Fig. 6.1.** Relationship between pH(NaF) and P retention capacity for Tanzanian volcanic ash soils*
* For legend, see Fig. 2

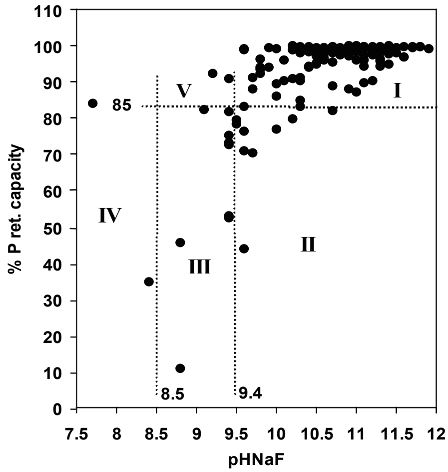

**Fig. 6.2.** Relationship between pH(NaF) and P retention capacity for Japanese volcanic ash soils

**Table 5.** Classification of the studied pedons

| Pedon | USDA Soil Taxonomy | FAO-WRB |
|---|---|---|
| 1. Uyole-1 | *Vitrandic Hapludoll* | *Tephri-Vitric Phaeozem* |
| 2. Uyole-2 | *Vitrandic Eutrudept* | *Molli-Vitric Cambisol (Endoeutric}* |
| 3. Galijembe | *Pachic Melanuadand* | *Cutani-Vitric Luvisol (Thaptomollic and Epidystric)* |
| 4. Isyonje | *Hydric Pachic Melanudand* | *Melani-Silandic Andosol (Thaptocambic and Dystric)* |
| 5. Nyalwela | *Hydric Pachic Melanudand* | *Melani-Silandic Andosol (Hyperdystric}* |
| 6. Ilala | *Vitric Melanudand* | *Melani-Silandic Andosol (Thaptoumbric and Hyperdystric)* |
| 7. Kitulo Comworks | *Vitric Melanudand* | *Melani-Silandic Andosol (Hyperdystric)* |
| 8. Kitulo Central | *Hydric Melanudand* | *Melani-Silandic Andosol (Thaptoumbric and Hyperdystric)* |
| 9. Ujuni | *Hydric Pachic Melanudand* | *Melani-Silandic Andosol (Thaptoumbric and Hyperdystric)* |
| 10. Luvulunge | *Acrudoxic Hydric Melanudand* | *Melani-Silandic Andosol (Thaptoumbric and Hyperdystric}* |
| 11. Mwaya | *Aquandic Epiaquept* | *Gleyi-Fluvic Cambisol (Hyperdystric)* |
| 12. Pakati | *Typic Hapludand* | *Orthidystri-Silandic Andosol* |

(SMR) was characteristic of all the pedons, except Mwaya, which had aquic SMR. These regimes were used to assign names at the suborder level. Eight of the 12 pedons had melanic epipedons and were classified as Melanudands at the great group level.

Table 5 also gives the taxonomic names of the studied pedons according to the FAO WRB. The diagnostic criterion used in this system to classify soils at the first category (Andosol) was the presence of an andic or vitric horizon starting within 25 cm from the soil surface. Based on this criterion, all except four pedons (Uyole-1, Uyole-2, Galijembe, and Mwaya) were classified as Andosols. At a lower level, all of the Andosols were classified as Silandic Andosols, with andic properties having an acid oxalate extractable Si of 0.6 or more or a Na-pyrophosphate-extractable Al/acid oxalate-extractable Al ratio of less than 0.5. More qualifiers can be employed to indicate other subordinate properties of the soils. Note that the diagnostic criteria used in the two systems of classification were not exactly identical, and direct correlation of soil names was not possible. For example, a soil classified as an Andisol in the USDA Soil Taxonomy will not always translate to Andosol in the FAO WRB.

The two systems have different parameters for defining andic properties and an andic horizon. The P-retention capacity of 85%, BD of 0.9 g/cc used in the Soil Taxonomy versus the 70% and 0.85 g/cc in the FAO WRB can create a big difference when classifying soils.

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## REFERENCES

Baize, D. 1993. *Soil Science Analyses. A guide to Current Use*. John Wiley & Sons Ltd., West Sussex.

Barreal, M., M. Camps Arbestian, F. Macias & A.E. Fertitta 2001. Phosphate and sulphate retention by nonvolcanic soils with andic soil properties. *Soil Science,* 166 (10): 691-707.

Black, G.R. & K.H. Hartge 1986. *Bulk Density*. In (A. Klute, ed.) *Methods of Soil Analysis, part 1, 2nd edition*, *Agronomy Monograph No. 9,* pp. 364-376. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Blakemore, L.C., P.L. Searle & B. K. Daly 1981. *Methods for Chemical Analysis of Soils, New Zealand Soil Bureau Scientific Report 10A*. Department of Scientific and Industrial Research, New Zealand.

Bray, R.H. & L.T. Kurtz 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Science,* 59: 39-45.

Breimer, R.F., A.J. van Kekem & H. van Reuler 1986. *Guidelines for Soil Survey and Land Evaluation in Ecological Research*, *MAB Technical Notes 17.* UNESCO, Rome.

Bremner, J.M. & C.S. Mulvaney 1982. Total nitrogen. In (L.A. Page, R.H. Miller & D.R. Keeney, eds.) *Methods of Soil Analysis, Part 2, 2nd Edition, Agronomy Monograph no. 9,* pp. 595-624. American Society of Agronomy, Madison, Wisconsin.

Camps Arbestian, M.E., M.E. Barreal & F. Macias 2001. Sulfate sorption in nonvolcanic Andisol from Galicia, NW Spain. *Geoderma* 104: 75-93.

Day, P.R. 1965. Particle fractionation and particle size analysis. In (C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger & F.E. Clark, eds.) *Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods,* pp. 545-566. American Society of Agronomy, Madison, Wisconsin.

FAO 1990. *Guidelines for Soil Profile Description. 3rd Edition.* Food and Agriculture Organization of the United Nations, Rome.

——— International Soil Reference and Information Centre (ISRIC) & International Society of Soil Science (ISSS) 1998. *World Reference Base for Soil Resources*, *World*

*Soil Resources Report 84*. FAO, Rome.

Fieldes, M. & PK.W. Perrot 1966. The nature of allophone in soils: III. Rapid field and laboratory test for allophane. *New Zealand Journal of Science,* 9: 623-629.

Harkins, D.A. 1960. *The Rungwe Volcanics at the Northern End of Lake Nyasa. Geological Survey of Tanganyika. Memoir II.* Government Printer, Dar es Salaam.

Honna, T., S. Yamamoto & K. Matsui 1988. A simple procedure to determine melanic index that is useful for differentiating melanic from fulvic Andisols. *Pedologist,* 32: 69-78.

Klute, A. 1986. Water retention. In (A. Klute, ed.) *Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. 2nd Edition*, *Agronomy Monograph No. 9*, pp. 635-662. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Landon, J.R. 1991. *Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*. John Wiley & Sons, Inc., New York.

McLean, E.O. 1986. Soil pH and lime requirement. In (A.L. Page, R.H. Miller & D.R. Keeny, eds.) *Methods of Soil Analysis, part 2, Chemical and Mineralogical Properties, 2nd Edition. Agronomy Monograph no. 9,* pp. 199-223. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Mizota, C. & J. Chapelle. 1988. Characterization of some andepts and andic soils in Rwanda, Central Africa. *Geoderma,* 41: 193–209.

Msanya, B.M., J.M. Wickama, D.N. Kimaro, J.P. Magoggo & J.L. Meliyo 1996. *Investigation of the Environmental Attributes for Agricultural Development in Kitanda village, Mbinga District, Tanzania. Technical Report No 5*. Department of Soil Science, Faculty of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania and Ministry of Agriculture, National Soil Service, Agricultural Research Institute, Mlingano, Tanga, Tanzania.

——— J.P. Magoggo & H. Otsuka 2002. Development of soil surveys in Tanzania. *Pedologist,* 46(2): 79-88.

Munsell Color Company 1992. *Munsell Soil Color Charts.* Baltimore, Maryland.

Murphy, J. & J.P. Riley 1962. A modified single solution method for determination of phosphate in natural waters. *Analytica Chimica Acta*., 27: 31-36.

National Soil Service 1990. *National Soil Service Laboratory Procedures for Routine Soil Analysis. Third edition. Miscellaneous Report, M13*. Mlingano, Tanga, Tanzania.

Nelson, D.W. & L.E. Sommers 1982. Total carbon, organic carbon and organic matter. In (L.A. Page, R.H. Miller & D.R. Keeny, eds.) *Methods of Soil Analysis, part 2, 2nd edition, Agronomy Monograph no. 9*, pp. 539-579. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Shoji, S., M. Nanzyo & R.A. Dahgren 1993. *Volcanic ash Soils. Genesis, Properties and Management.* Elsevier, Amsterdam.

Soil Survey Staff 1999. *Soil Taxonomy 2nd Edition. A Basic System of Soil Classification for Making and Interpreting Soil Surveys, Agricultural Handbook No. 436.* United States Department of Agriculture, Natural Resources Conservation Service, Washington D. C.

Stockley, G.M. 1948. *Geology of North, West and Central Njombe District, Southern Highlands Province, Bulletin No. 18.* Department of Lands and Mines, Geological Division, Tanganyika Territory.

Thomas, G.W. 1982. Exchangeable cations. In (L.A. Page, R.H. Miller & D.R. Keeny, eds.) *Methods of Soil Analysis, part 2, 2nd edition, Chemical and Mineralogical Properties, Agronomy Monograph No. 9*, pp. 595-624. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Wada, K. 1980. Mineralogical characteristics of Andisols. In (B.K.G. Theng, ed.) *Soils with*

*Variable Charge*, pp. 87-107. New Zealand Society of Soil Science, Lower Hutt.

——— (ed.) 1986. *Ando Soils in Japan*. Kyushu University Press, Fukuoka.

Watanabe, F.S. & S.R. Olsen 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from Soil. *Soil Science Society of America Proceedings,* 29: 677-678.

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