Pedological characteristics and implication on soil fertility of selected soils of Mbeya Region, Tanzania

The 3rd RUFORUM Biennial Conference, 24th – 28th September 2012

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Background

Understanding the soil origin and its fertility in a given climatic conditions is important for efficient and sustainable utilization of soils. The composition of parent material determines the mineral nutrient content (Nube and Voortman, 2006), and sorption of nutrients, other chemicals and soil organic matter. A recent study in China demonstrated that available Fe and Zn in Xichang city soils differed depending on the nature of the parent rock (Zhang et al., 2012). Time is also essential in determining the stage of weathering, and hence soil properties. The soils of the surveyed areas are derived from volcanic tephra deposits of which are reported to be from relatively old (Upper Miocene to Lower Pleistocene Kitulo and Ngozi volcanoes) to most recent eruptions (Middle Pleistocene to Holocene Rungwe and Kyejo Volcano) (Fontijn et al., 2010). Information on the differences in chemical and other characteristics of the soils derived from these chronologically variable deposits of the area is limited.

Mbeya region is among the four regions of Southern Highlands of Tanzania with high agricultural production, supplying major staple food in the country. However, crop yields are still low despite use of NPK fertilizers, contributing to food insecurity in Tanzania. Copper and Zn deficiencies were reported in this area's volcanic soils about three decades ago, which was associated with nutrient mining (Kamasho, 1980). Yet, to date there is no follow-up studies on the status of these micronutrients in soils. Therefore, there is a need to determine the properties of soils of Mbeya region in relation to their origin and genesis.

Mineral malnutrition is also wide spread and it is estimated that about 66% of world population is Fe deficient, over 30% is Zn deficient, 30% is iodine deficient and 15% is selenium deficient (White and Broadley, 2009). In Tanzania about 65% of children under 5 years of age are iron deficient (Fortifying African's Future, 2009), 58.2% of pregnant women are anemic and 23% of the population are at risk of Zn deficiency (TFNC, 2009). These nutritional health problems can be attributed to low soil mineral content and/or availability to crops (Welch and Graham, 2002). Adequate levels of essential minerals in food crops to satisfy human health requirement is referred to as crop nutritive quality. One way to curb mineral malnutrition is fortification of some staple food with these essential minerals. However, food fortification cannot be expected to reach all populations deficient in essential micronutrients, especially in developing countries, and have challenge of low bioavailability (Hurrell, 1997; Mehasho, 2006). Therefore, there is a need to investigate, systematically, the relationship between soil nutrient contents (both macro- and micro-nutrients) and crop quality as might be related to the potential for agronomic biofortification to improve human nutrition and health.

This study was therefore conducted as a contribution to efforts by national and international programs and strategies to attain not only high yields but also nutritional health for poverty alleviation. Therefore, the objective of this study was to determine and assess the pedological characteristics of soils and their influence on soil fertility and crop quality in selected physiographic units of Mbeya region. Specifically, i) to determine the morphological and physico-chemical characteristics of the soils ii) to determine the mineralogical composition of the soils iii) to determine the extent of weathering, and iv) to determine the implication of soil characteristics on nutrient availability, agricultural productivity and crop nutritive quality.

Study description

Study Site Description:

The study was conducted in three districts of Mbeya region, covering a southward transect from Mbeya town to Lake Nyasa. The study area is located between longitudes 33^0 38’ and 33^0 53’ E and between latitudes 8^0 50’ and 9^0 33’ S covering Mbeya rural, Rungwe, and Kyela districts which represent different physiographic units in the area. The location of the study sites and their characteristic land form and climate are shown in Table 1.

Soil Profile Description

Excavated profile (to depth of 2 m or to a lithic or paralithic contact) representing the dominant soils of each sites selected (Table 1) were described based on the FAO guidelines for soil description (FAO, 2006). Soil color was determined by using Munsell Color Chart (Munsell Color Co, 1992). Each site profile was located by international coordinates using Global Positioning System (GPS) (model OREGON 400t).

Soil and Grain Sampling and Sample Preparation

Soil samples were taken from each horizon of each profile pit for laboratory physical and chemical analysis for pedological characterization. Composite surface soil samples (0 to 20-cm depth) were also taken in each site for soil fertility evaluation. After planting, surface (0 to 15-cm depth) soils from farmers’ fields were sampled around selected and tagged plants in four replicates. Crop grains (maize, groundnuts and rice) samples were collected from the tagged plants at crop maturity. Soil samples were air dried and ground to pass through 2-mm sieve and grain samples were air dried and oven dried at 60 ^oC and ground using plant sample grinder for chemical analysis.

Routine Soil Analyses

Soil physical and chemical analyses were done using standard analytical methods. Particle size analysis was done by the hydrometer method after dispersion with 5% sodium hexametaphosphate while water dispersible silt and clay contents were determined by both pipette and hydrometer methods (NSS, 1990). Soil pH was determined potentiometrically in water and 1 *N* KCl at 1:2.5 soil:water/KCl ratio (McLean, 1986). Delta pH to characterize charge was obtained by the equation DeltapH = pH (KCl) – pH (H_2O). Cation exchange capacity (CEC) and exchangeable bases were determined by neutral 1M NH_4OAc (ammonium acetate), and CEC was determined by Kjeldahl distillation of the adsorbed NH_4^+. Exchangeable bases displaced by 1M KCl (Chapman, 1965) were determined using atomic absorption spectrophotometer (Ca, Mg) and flame photometer (K and Na). Organic carbon was determined by Walkey and Black wet oxidation method of Nelson and Sommers (1982). Total N was determined using micro-Kjeldahl digestion-distillation method as described by Bremner and Mulvaney (1982). Extractable P was determined by Bray 1 method using 0.03M NH_4F and 0.025M HCl extraction solution (Bray and Kurtz, 1945) and molybdenum blue method (Murphy and Riley, 1962). The extractable P was determined by a spectrophotometer at the wavelength of 884 nm. Extractable micronutrients (Zn, Cu, and Fe) were extracted by 0.005 M DTPA (diethylenetriamine pentaacetic acid), 0.01M $CaCl_2.2H_2O$ and 0.1M TEA (triethanolamine) adjusted to pH 7.3 (Lindsay and Norvel, 1978) and determined by atomic absorption spectrophotometer.

Table 1: Salient characteristics of the studied sites

Site/village name	Profile	District	Coordinates	Altitude m (a. s. l.)	Rainfall mm/year	Physiography	SMR
Makwenje	MKW	Mbeya Rural	E 33^0 38' 37'' S 08^0 50' 43''	1514	650-2700	Plateau/plain	Ustic
Ifiga	IFIG	Mbeya Rural	E 33^0 33' 58'' S 08^0 55' 44''	1882	650-2700	Foot slope	Udic
Mkuyuni	MKY	Mbeya Rural	E 33^0 41' 21'' S 08^0 54' 55''	1839	650-2700	Upper slope of the ridge	Udic
Mwanzazi	MWZ	Mbeya Rural	E 09^0 0' 26'' S 33^0 39' 49''	2357	650-2700	Crest of the ridge	Udic
Ndembela	NDE	Rungwe	E33^0 36' 54'' S 09^0 16' 7''	1371	650-2700	Upper slope of the ridge	Udic
Tenende	KYE	Kyela	E 33^0 53' 13'' S 09^0 33' 50''	493	1000-2400	Alluvial Plain	Aquic

SMR: soil moisture regime

The presence and amount of active Al and Fe in each horizon samples were determined using NaF pH in a 1:50 soil:NaF ratio and pH was measured potentiometrically after 2 min (NSS, 1990). Aluminium (for MWZ 04 profile only), Fe, and Mn from amorphous minerals and organic/humic-bound were extracted by 0.2 M ammonium oxalate at pH 3 (Al_o, Fe_o, Mn_o) (McKeague and Day, 1966) and 1 N Sodium-pyrophosphate pH 10 (Fe_p, Mn_p) (McKeague, 1967), respectively. The crystalline and non-crystalline Fe and Mn were extracted by single extraction using 0.68 M sodium dithionite-citrate (Fe_d and Mn_d) (Soil Conservation Service USDA, 1972). The extracted Al, Fe, and Mn were determined by atomic adsorption spectrophotometer and were converted to percentage oxides by multiplying by a factor of 1.43, 1.58 and 1.89 respectively (Pansu and Gautheyrou, 2006). Phosphate-retention capacity was determined according to the method of Blakemore et al. (1981).

Ground plant samples (0.5 g) were digested using H_2O_2-$HClO_4^-$HF in tubes, and heated in a block digester at 200 ^oC for 2 hours. The digest were cooled and made up to 50-ml volume plants extract used to determine nutrients contents as for soils.

Soil Classification

Field and laboratory data were used to classify soils to tier-2 of the FAO World Reference Base (FAO-WRB, 2006).

Research Application

Soil Morphology

All the studied soils are very deep with profile thickness of at least 200 m, and are well drained, except Tenende plain soil (profile KYE) with water table around 170 cm. Some profiles have buried horizons such as 2BC (IFIG), 2Bwb, and 3Bwb (MWZ). The soils differed significantly in soil color, structure, consistence and bulk densities. The moist soil color of Ap horizons of all soils ranges from very dark brown (7.5YR2.5/6 to 10YR2/3) for MKW, MKY and NDE soils to black (10YR2/1 to 10YR2/2) for IFIG. Topsoil of MWZ 04 is dark brown (10YR3/3) while that of KYE is black (2.5YR2.5/1). Down the profiles, there is decrease in yellow hue (becoming redder) and darkness, but increase in color intensity (chroma) for MKW, IFIG and MKY profiles. The profile NDE also showed similar soil color trend, but the more yellow hue did not change down the profile, and there was a yellowish weathered pumice layer (5cm thick at 78-cm depth). Profile MWZ and KYE Ap horizons were darker than all the C horizons, which also had high color intensity (more yellow). In KYE 01 the C3 horizon becomes gray where there is water table, due to reduced Fe and Mn. The decrease in darkness and increase in color intensity down the profile indicate the decrease in SOM and stable goethite (darkness agent) and increase in coloring agents (free iron oxides and hydroxides).
The topsoil structures of all the soils range from weak, moderate, to strong structure with friable moist consistence. Moderate to strong structure and weak development of fine or granular structure are common morphological features of volcanic soils (Ugolini and Zasoski, 1979; Gama-Castro et al., 2000).

The presence of buried horizons and pumice layers in some of the profiles is an indication of different layers of volcanic ashes and pumiceous materials, a unique morphological characteristic reflecting cyclic deposition of volcanic ejecta. Unlike other volcanic soils, profiles MKW, MKY and NDE have considerably marked B horizon, with some extent of illuviation indicating that these soils are more developed (more weathered) than IFIG and MWZ. Profile MWZ shows less weathered volcanic materials mainly pumice, probably due to age (younger) at which the eruption of the materials was deposited and high silica, low aluminum and iron contents. Lack of clear B horizon in KYE is due to alluvial deposits and paddling of the Ap horizon. The studied soils have low bulk densities of 0.7 g/cm^3 for MWZ, 0.91 g/cm^3 for KYE, and 0.91 g/cm^3 NDE, 1.13 g/cm^3 IFIG, 1.16 g/cm^3 for MKY and 1.26 g/cm^3 MKW (Munishi, 2012). Thus, the soils of MWZ, KYE and NDE have bulk densities common for most soils derived from tephra (i.e 0.1 to 0.9 g/cm^3) (Ugolini and Zasoski, 1979; Gama-Castro et al., 2000).

Chemical Properties

The top soil pH (water) ranges from 4.0 to 6.6 (Table 2). The soil pH in water slightly increases with soil depth for all profiles except NDE, which showed a decrease in soil pH. The soil pH(KCl) values are lower than the soil pH (water) in all horizons of the studied profiles with delta pH range of -0.5 to -1.7, and the change becomes greater (i.e more negative) with increasing soil depth, expect in NDE 01 profile. All studied soils had delta pH of -0.5 or greater indicating the dominance of negatively charged exchange complex (Van Wambeke, 1991; Nanzyo et al., 1993; Fiantis et al., 2011). These results differ from those of Fiantis et al. (2011) who observed small delta pH of -0.09 on weathered volcanic ash of Mt Talang, Indonesia which was attributed to simultaneous increase in negative ($\equiv SiO^-$) and positive ($=AlOH_2^+$ and/or $FeOH_2^+$) charges of noncrystalline minerals in 1M KCl.

Active Al and Fe

Presence of active Al-OH and Fe-OH groups in soil particles can be deduced using pH in NaF test, where the exchange of OH- by F- reaction tends to increase pH values (Fiantis et al., 2011). The NaF pH of >9.4 indicates presence of significant amounts of active Al and Fe (Fiantis et al., 2011), and helps to predict the tendency of soil to retain P (Gama-Castro et al., 2000). The NaF pH of the soils studied ranges from 9.7 to 11.0 in the surface horizons and from 9.8 to 11.6 in the subsurface horizons (Table 2). These results indicate that all soils have considerable amount of active Al and Fe. Generally, the soil NaF pH slightly increase with increase in soil depth in all soil profiles except NDE 01 profile (Table 2), suggesting that these soils developed from old volcanic materials. This is because soils developed from volcanic ash are characterized by in situ accumulation of active Al and Fe, which increase as they weather (Nanzyo et al., 2002). Therefore, increase in NaF pH down the profile indicates that the volcanic ash from which these soils formed are weathered because it is estimated that the parent materials of these soils are of Mid Pleistocene (0.6 Ma) to late Miocene (8.6 to 5.4 Ma) eras (Fontijn et al., 2010). These results differed from those of Gama-Castro et al. (2000) who reported NaF pH > 9.5 in the Ap horizons but < or = 9.5 in the subsurface horizons (C) in two young volcanic soils developed on Holocene (0 to 0.0117 Ma) volcanogenic pumiceous alluvia of West Nayarit, Mexico. Therefore, all horizons of these soils contain active Al and Fe, of which active Al can be in the form of allophones, imogolites, Al-humus, while active Fe is mainly Ferrihydrite (Nanzyo et al., 2009).

Amorphous Materials

The ammonium oxalate extracts poorly crystalline Fe and Mn from their oxides (Fe_o and Mn_o) in soils (Schwertmann, 1973). The Fe_o of the studied soils ranges from 0.28% in KYE to 3.91% in MKY in the surface horizons, and from 0.31 in KYE to 4.36 in NDE (Table 2). On average, the Fe_o increases with depth in all the profiles except MKY (Table 3). Fiantis et al. (2011) reported an increase in Fe_o and Al_o at the initial weathering stage of the volcanic ash from Mt. Talang volcanic ash of West Sumatra, suggesting that Fe and Al are relatively immobile, hence accumulates as the soil weathers. Therefore, the amorphous materials in the subsoil horizons are mainly Ferrihydrite, while in the topsoil is mostly Fe/Al-humus.

The ammonium oxalate extractable Al and Fe were determined only for profile MWZ. This is because the profile showed typical and unique layers of volcanic ashes and pumiceous materials, a morphology reflecting the cyclic deposition of volcanic ejecta (Msanya *et al*., 2007). Profile MWZ had Al_o contents of 2.24 and 3.64% in topsoil and subsoil respectively and have $Al_o + 0.5\ Fe_o$ values of 2.61% and 4.19% in topsoil and subsoil respectively. The values (Al_o + 0.5 Fe_o) for MWZ are > 2.0, which according to Soil Survey Staff (1999) indicate the presence of andic properties.

The sodium pyrophosphate extractable Fe (Fe_p), Mn (Mn_p) and Al (Al_p) represent the organically bound Fe, Mn and Al of soils (McKeague, 1967). The Fe_p and Mn_p values of the studied soils range from 0.09 to 0.52% and 0.01 to 0.06%, respectively, where all C horizons had low Fe_p and Mn_p (Table 3). The trend corresponds with the distribution of soil organic matter. The values of Fe_o and Mn_o are greater than Fe_p and Mn_p, suggesting that there are more mineral amorphous Fe and Mn than organic/humus Fe and Mn, which increase with soil depth.

Dithionite-citrate extracts both crystalline and non-crystalline iron oxide minerals (McKeague *et al.*, 1971), but partly dissolves allophane, goethite and hematite in a single extraction. The Fe_d ranges from 0.11 (KYE) to 0.51% (MWZ), while Mn_d ranges from 0.14 (KYE) to 0.43 (MKW) (Table 3). The Fe_d and Mn_d generally increase with soil depth except for the profiles KYE and MWZ for Fe_d and KYE for Mn_d (Table 2). The Fe_d and Mn_d values are lower than Fe_o and Mn_o values, suggesting dominance of amorphous than crystalline Fe and Mn minerals in all the studied soils.

Indices of Weathering

Iron oxide crystallinity index

Sodium dithionite extractable iron (Fe_d) is used to determine the proportion of crystalline iron oxides while acidified ammonium oxalate extractable iron (Fe_o) is used to determine the proportion of non crystalline (amorphous) iron oxides (Sheldrick, 1984). Difference in amounts of dithionite extractable iron (Fe_d) and oxalate extractable iron (Fe_o) indicates the distribution of amorphous and crystalline forms of iron in the soils. In all the studied soils, the values of Fe_d-Fe_o are negative (Table 2), indicating that Fe_o was higher than Fe_d. This indicates that amorphous iron oxides dominate in the studied soils. Since high amount of crystalline Fe is an indication of high degree of soil weathering (Jackson, 1965; Schulze, 1989), then none of the studied soils can be categorized as highly weathered.

Degree of Fe oxide crystallinity

Degree of crystallinity is also used to determine the proportion of crystalline iron oxides (Fe_d) compared to non-crystalline oxides of iron (Fe_o). The Fe_o/Fe_d ratios become smaller with advanced crystallinity which reflects an advanced level of weathering or maturity of crystallinity of free iron oxides in a soil material (Blume and Schwertmann, 1969). Values of Fe_o/Fe_d of less than 0.1 indicate that crystalline iron oxides (commonly goethite and hematite) are dominant in the soil (Fitzpatrick and Schwertmann, 1982). In this study all the soils have large Fe_o/Fe_d ratios ranging between 1.71 and 5.08 (Table 2), indicating that the soils have less crystalline iron and therefore moderately to slightly weathered.

Silt/clay ratio

Silt/clay ratios in the topsoils range from 0.27 to 1.36 and in subsoils from 0.22 to 4.56, and the ratios decrease with depth in all profiles except profile MWZ (Table 2). According to van Wambeke (1962) and Barshad (1965) soils having silt/clay ratio of less than 0.2 are considered to be highly weathered. So the soils in the study areas are moderately to slightly weathered. Higher silt/clay ratio in the topsoil than subsoil can be explained by lessivage of clay down the profile resulting to lower proportion of clay in topsoils compared to the subsoils. The translocation of clay is also a good index of soil development (Zonn, 1986). The general trend of silt/clay ratios of the studied soil is as follows: MWZ 04> KYE 01> IFIG 02> MKW 01> MKY 03> NDE 01.

Soil Classification of the Studied Soil Profiles

The TIER-1 category of the soils in the study areas are Haplic Cutanic Alisols (Profondic, Clayic) in Makwenje (MKW), Vitric Fluvic Cambisols (Humic, Eutric) in Ifiga (IFIG), Umbric Cutanic Alisols (Hyperdystric, Clayic) in Mkuyuni (MKY), Melanic Silandic Andosols (Dystric, Siltic) in Mwazazi (MWZ), Vitric Cutanic Alisols (Profondic, Clayic) in Ndembela (NDE) and Vitric Endogleyic Umbrisols (Humic, Clayic) in Tenende plain Kyela (KYE).

Table 2. Extractable Fe and Mn and weathering indices of some selected soils of Mbeya region

Site	Hor	pH H_2O	pH KCl	Fe_o	Mn_o	Fe_p	Mn_p	Fe_d	Mn_d	Fe_d-Fe_o	Fe_o/Fe_d	Silt/clay
MKW	Ap	5.1	3.7	0.47	0.2	0.23	0.04	0.22	0.43	-0.25	2.14	0.59
	Bt_1	5.4	4.0	1.32	0.85	0.25	0.01	0.31	0.44	-1.01	4.26	0.40
	Bt_2	5.5	4.2	1.19	0.59	0.31	0.01	0.35	0.39	-0.84	3.40	0.38
	Bt_3	5.9	4.2	0.96	0.5	0.33	0.01	0.32	0.40	-0.64	3.00	0.38
	Bt_4	5.9	4.2	1.73	0.6	0.25	0.01	0.27	0.40	-1.46	6.41	0.45
	BC	5.8	4.1	0.5	0.32	0.33	0.01	0.19	0.29	-0.31	2.63	0.27
IFIG	Ap	5.8	4.6	1.45	0.34	0.09	0.04	0.20	0.17	-1.25	7.25	0.59
	AB	6.1	4.6	1.89	0.35	0.15	0.01	0.30	0.18	-1.59	6.30	0.44
	Bw	6.3	4.6	0.48	0.1	0.14	0.01	0.28	0.15	-0.20	1.71	0.49
	C	6.4	4.5	1.59	0.19	0.03	tr	0.09	0.10	-1.50	17.67	0.26
	2BC	6.5	4.6	1.89	0.43	0.02	tr	0.24	0.17	-1.65	7.88	0.51
	2C	6.6	4.6	2.31	0.4	tr	tr	0.07	0.11	-2.24	33.00	0.85
MKY	Ap	6.1	4.4	3.91	0.87	0.13	0.04	0.18	0.24	-3.73	21.72	0.42
	BA	6.0	4.3	1.81	0.53	0.18	0.01	0.25	0.26	-1.56	7.24	0.39
	Bt_1	5.9	4.2	2.06	0.49	0.2	0.01	0.32	0.26	-1.74	6.44	0.40
	Bt_2	6.2	4.2	1.88	0.38	0.38	0.01	0.37	0.23	-1.51	5.08	0.40
	BC	6.2	4.2	0.94	0.3	0.14	tr	0.35	0.20	-0.59	2.69	0.40
MWZ	Ap1	6.3	5.0	0.75	0.42	0.52	0.06	0.51	0.20	-0.24	1.47	1.00
	Ap2	6.2	4.9	1.1	0.13	0.48	0.04	0.55	0.19	-0.55	2.00	4.56
	C	6.5	4.8	1.36	0.17	0.57	0.03	0.63	0.21	-0.73	2.16	0.70
	2Bwb	6.5	4.8	0.88	0.26	0.34	0.01	0.49	0.16	-0.39	1.80	0.51
	2Cb	6.8	5.0	0.53	0.03	tr	tr	0.03	0.04	-0.50	17.67	0.86
	3Bwb	6.5	4.7	1.3	0.05	0.11	tr	0.25	0.16	-1.05	5.20	0.48
	3Cb	6.7	4.9	0.66	0.05	0.07	tr	0.01	0.05	-0.65	66.00	3.57
NDE	Ap	6.6	4.9	0.79	0.19	0.12	0.01	0.23	0.20	-0.56	3.43	0.33
	Bt_1	6.3	4.7	4.36	0.45	0.14	tr	0.50	0.23	-3.86	8.72	0.22
	Bt_2	5.8	4.2	2.96	0.28	0.07	tr	0.75	0.26	-2.21	3.95	0.26
KYE	Ap_1	4.0	3.6	0.28	0.01	0.24	0.01	0.11	0.14	-0.17	2.55	0.27
	Ap_2	4.4	3.8	0.31	tr	0.13	tr	0.10	0.03	-0.21	3.10	1.24
	AC	4.7	3.5	0.46	0.01	0.09	tr	0.12	0.12	-0.34	3.83	0.72
	C_1	5.8	3.8	Tr	0.01	0.09	tr	0.03	0.08			0.54
	C_2	5.9	3.8	0.31	0.13	0.02	tr	0.01	0.08	-0.30	31.00	0.44
	C_3	6.1	3.8	0.35	0.12	tr	0.03	tr	0.10			0.43

tr = traces, MKW= Makwenje, IFIG= Ifiga, MKY= Mkuyuni MWZ= Mwazazi, KYE= Tenende Plain NDE= Ndembela

Influence of Pedological Properties on Soil Fertility and Crop Quality

Soil fertility status

The physical and chemical properties of soils determine the content and availability of essential plant nutrients. The soil physical properties determined (soil texture and bulk density) are adequate for agricultural crop production. The soil pH in water of all studied soils is acidic ranging from 4.9 to 5.9 (Table 3), of which soils from KYE, MKW, MKY, and IFIG are categorized as strongly acidic (pH < 5.5) while those of MWZ and NDE are medium acidic (Landon, 1991). Lowest soil pH of KYE soil is due to exchangeable Al^{3+} > 1.0 cmolc/kg (Munishi, 2012). All soils that are strongly acidic require liming to improve crop growth and yield as well as response to fertilizers to minimize risks of low profit crop production. Soil organic C in these soils ranges from 0.1 to 4.4% (Table 3), rated as low (<1.25%) in MKW and KYE soil, medium (1.26 to 2.50) in IFIG and NDE soils, and very high (> 3.5) in MKY and MWZ soils (Landon, 1991). The CEC values of the soils range from 20.2 to 38.5 cmolc/kg (Table 3), and are rated as medium in MKW, but high (> 25 cmolc/kg) in all other studied soils. The medium to high CEC further shows that although these soils are dominated by noncrystalline minerals, the negative charges are dominant in the exchange complex. The CEC of these soils may be due to both dominance of negatively charged amorphous $\equiv SiO^-$ and highly negatively charged humic materials. Therefore, both physical and most of the chemical properties of the soils studied are adequate for crop production, except for the strongly acidic soil, that needs liming to optimize crop production.

Table 3. Soil chemical properties and some nutrient contents of soils of study areas in Mbeya region

Site	pH	OC	TN	P	Exchangeable cations and CEC (cmol (+)/kg					Extractable micronutrients (mg/kg)		
	H_2O	%	%	mg/kg	K	Ca	Mg	Na	CEC	Fe	Cu	Zn
MKW	5.1	1.2L	0.1L	10.2L	0.6H	1.0L	0.4M	0.1L	20.2M	35.22H	0.34L	1.17H
IFIG	5.5	2.5M	0.2M	8.5VL	1.2H	6.5H	0.9H	0.2L	29.4H	38.65H	0.44L	4.17H
MKY	5.1	4.4VH	0.2M	6.6VL	1.1H	3.4M	1.1H	0.1L	27.8H	25.91H	0.29L	1.41H
MWZ	5.7	3.4VH	0.3H	6.7VL	0.7H	4.3H	0.8H	0.2L	37.2H	27.53H	0.29L	2.97H
NDE	5.9	1.5M	0.2M	4.3VL	1.7H	2.3M	0.9H	0.1L	31.1H	18.32H	0.31L	0.93L
KYE	4.9	0.1L	0.2M	6.0VL	0.6H	0.9L	0.2L	0.3L	26.6H	33.22H	0.29L	0.74L

Note: TN = OC = organic carbon, total nitrogen, CEC = cation exchange capacity, the rating of the soil parameters were according to Landon (1991) and Tandon (1995). Where VL = very low, L = low, M = medium, H = high and VH = very high

Levels of Some Essential Nutrients in Soils

The level of essential plant nutrients in soils determines their availability and crop yields if physical and chemical properties affecting availability are not limiting. The total nitrogen (TN) of the studied soils ranges from 0.1 to 0.3% (Table 3), where all soils have medium TN level, except MWZ soil which had high and MKW which had low TN values (Landon, 1991). Total N estimates N in both organic and inorganic form, and since plants absorb N in form of NH_4^+ or NO_3^- (inorganic) (Harvlin et al., 2005), all low and medium TN soils will require additional N to ensure adequate growth and yield of crops. The available P values in the soil range from 4.3 to 10.2 mg/kg (Table 3), and are all rated as low (<15 mg/kg) (Landon, 1991). Low available P can be explained by the inherently low P containing minerals in these soils, as demonstrated by low <0.1% total P_2O_5 in these soils (Table 3). The P retention of the soils studied ranges from 35 to 85%, and increases with increase in NaF pH (Fig 1). Thus, presence of active Al/Fe/Mn in all soils and exchangeable Al in KYE might have contributed to low available P observed.

Therefore, P fertilization is inevitable for sustainable and profitable crop productivity in the study area. Exchangeable K levels range from 0.6 to 1.2 cmolc/kg (Table 4), which are adequate (> 0.4 cmolc/kg) for most crop. (Landon, 1991). High exchangeable K can also be explained by the K-rich volcanic ash from which these soils developed (Funtijn et al., 2010). However, the preliminary results showed that the K content in leaves of wheat, beans and rice grown in MKY, MKW, NDE and KYE, were below the critical limit (<1.5 to 3.0%) for these crops (Mhoro, 2012), indicating that most of the soil K is not available for plant uptake. Thus, K application to improve availability and replenish K removal will help to sustain high yields for long time. Exchangeable Ca and Mg range from 0.9 to 6.5 and 0.2 to 0.9 cmolc/kg, respectively. Soils of MKW and KYE had low Ca (<2.0 cmolc/kg), while only KYE soil had low Mg (< 0.2 cmolc/kg) (Landon, 1991). The rest of the soils had medium to high Ca and Mg levels. Low exchangeable Ca and Mg may be due to excessive leaching of these cations especially in the low pH soils of MKW and KYE. Therefore, all the soils are deficient in N and P, and have low K availability, hence require fertilization to supply and improve availability of these essential macronutrients.

Although required in very small quantities, micronutrients are equally essential for adequate growth and yield of agricultural crops. This study revealed that available Fe is sufficient (> 10 mg/kg) according to Motsara and Roy (2008), while available Cu is deficient (>0.5 mg/kg) according to Tandon (1995) for crop production in all soils studied (Table 3). Available Zn is sufficient (> 1.0) in all soils, except in NDE and KYE soils (Table 3). These results show that all soils in the study area require Cu fertilization and soils in KYE and NDE require Zn fertilization, in addition to NPK for optimum crop production.

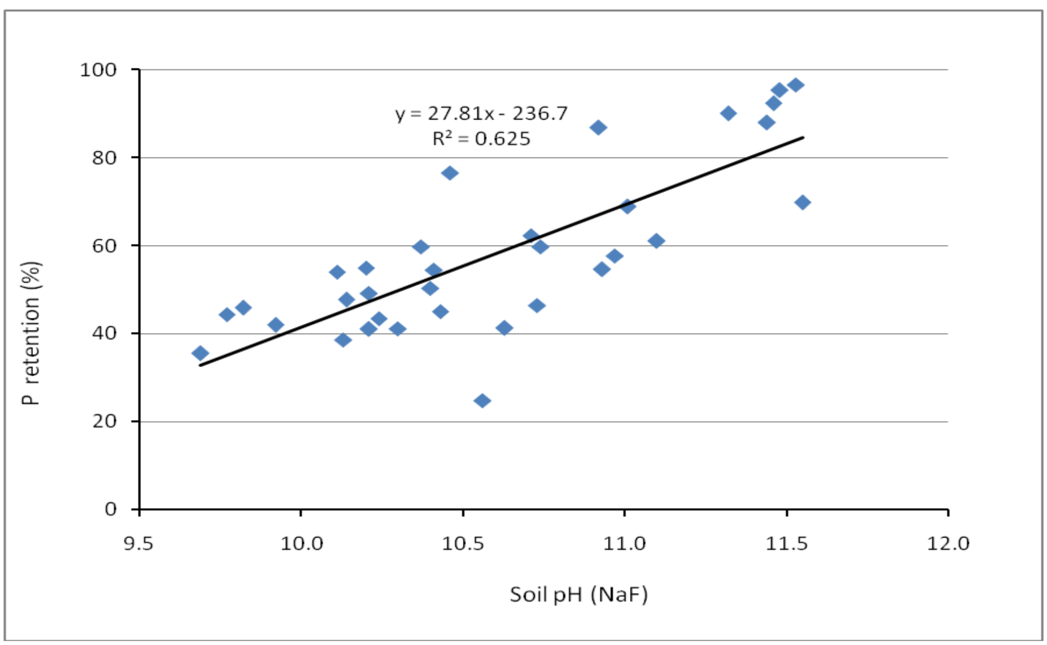

Figure 1. Relationship between NaF pH and P retention of some volcanic soils of Mbeya region

Soil Fertility and Crop Nutritive Quality

The mineral nutritional quality of the crop depends on the nutrient content of the soil if the edible part is leaves and both soil nutrient content and partitioning of the element for other edible parts of the plants. The Zn and Cu contents of all soils in the present study were marginal for crop production, and Zn contents were below human and livestock dietary requirements of 56.0 mg/kg for Zn (Welch and Bouis, 2009) and Cu contents were below 10 mg/kg for Cu in all grain samples (Table 4).

Table 4. Micronutrient contents and correlation coefficients of the soils and crops grains from farmers' fields in some areas of Mbeya region

Site	Crop	Zn (mg/kg)			Cu (mg/kg)		
		Soil	Grains	r	Soil	Grains	r
MKW	Maize	2.54±0.32M	17.46±1.61L	-0.976*	0.70±0.04M	9.93±0.19L	0.680^{ns}
MKY	Maize	2.82±0.15M	13.89±1.42L	-0.435^{ns}	0.13±0.04L	5.06±0.25L	0.252^{ns}
NDE	Groundnuts	2.86±0.5M	13.34±2.92L	0.063^{ns}	0.24±0.06L	4.56±0.33L	0.852^{ns}
KYE	Rice	1.56±0.41M	12.35±2.23L	-0.989*	0.02±0.003VL	5.43±0.77L	0.183^{ns}

Note: r = correlation coefficient, * = Significant (*P*= 0.05), the rating of the soil parameters i.e. VL = very low, L = low and M =medium, were according to Motsara *et al.* (2008) and Havlin *et al.* (2005) for plant parameters, ns = not significant (*P* = 0.05)

Simple correlations analysis revealed that the soil DTPA-extractable Zn and grain Zn contents were significantly (*P* = 0.05) negatively correlated (r = -0.976*) and (r = -0.989*) for MKW and KYE, respectively (Table 4). The correlations of soil and plant Zn for NDE and Cu for all soils soil were not significant (Table 4). These results suggest the other factors such as the concentration of Zn in solution, ion speciation and the interaction of Zn with other macronutrient and/or micronutrient elements control the availability in the soil, and/or uptake, and/or partitioning of Zn to seeds (Cox and Kamprath, 1972). Copper contents of the soils in all locations are positively correlated with copper contents of the plants, though not significantly *(P* = 0.05) (Table 4). Therefore, Zn and Cu fertilization and improvement of their availability to plant, and ensuring nutrients balance is essential for improvement of mineral nutritive quality and yields of crops.

Conclusions

The studied soils of Mbeya region are slightly to moderately weathered, and derived from basaltic and basaltic-andesitic volcanic materials rich in K and Na feldspars with adequate physical conditions for crop production. The exchange complex of these soils are dominated by amorphous, variable charged minerals with active Fe or Al and Mn, contributing to high CEC and high P retention. The soils are acidic with deficiencies of N, P, K, Cu and Zn in some locations. The crops produced in the area have Zn and Cu levels below the dietary requirements of human and livestock health. Therefore, soil fertility management to improve availability of all deficient nutrients are necessary for sustainable high yields and good crop mineral nutritive quality. In the light of the results obtained in this study, all the studied sites were rated as moderately suitable for maize, beans, wheat and potatoes except Tenende plain (KYE 01). Tenende plain (KYE 01) on the other hand was rated as moderately suitable for paddy rice and marginally suitable for the other crops.

Acknowledgements

This work was funded by the Regional University Forum for Capacity Building in Agriculture (RUFORUM) through Competitive Grant Award 2009-2011. Field technical assistance by Mr. J. Meliyo is acknowledged.

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