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Physicochemical, Geochemical and Mineralogical Aspects of Agricultural Soils in Limpopo Province, South Africa

K. J. Molepo[1*], G. I. E. Ekosse[2] and V. M. Ngole-Jeme[3]

[1, 2]Directorate of Research and Innovation, University of Venda, Private Bag X5050,
Thohoyandou 0950, Limpopo Province, South Africa
[3]Department of Environmental Sciences, College of Agriculture and Environmental Sciences,
University of South Africa, Florida, Private Bag X6, Roodepoort 1710,
Gauteng Province, South Africa

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ABSTRACT Soil samples were collected from three selected sites (uncultivated, cultivated and grazing land) at University of Limpopo Experimental Farm (Syferkuil) in Mankweng area to characterise their physicochemical, geochemical and mineralogical properties and their influence on soil fertility for agriculture. Soil textural triangle using Texture Auto Lookup Software (TAL 4.2) Package was used to determine particle sizes of samples which were all dominated by a loamy texture. Chemical characterisation carried out included determination of exchangeable cations, major elemental oxides and trace elements. Silica was the dominant oxide with the highest weight percentage values ranging from 75.99 to 83.45. Chemical index of alteration values of 66 to 75 depicted moderate silica weathering with depletion of soil nutrients due to leaching. Seven minerals were identified in soil samples which were dominated by kaolinite. The presence of mica and smectites in the soils displayed properties typical of soils rich in exchangeable cations compared to those with mineral assemblage dominated by kaolinite and quartz. The overall findings indicated moderate concentrations of nutrient elements and favorable plant growing conditions, where addition of adequate nutrient fertilizers would potentially optimize crop yield.

INTRODUCTION

Scotney and Dijkhuis (1990) and Bernard et al. (2000) have identified declining soil fertility as the fundamental agronomic cause for declining food productivity in Africa and particularly in South Africa. The Limpopo Province has a diversity of soils and climatic conditions permitting a variety of different forms of agriculture (Joseph and Botha 2012; Petja et al. 2012; Nesamvuni et al. 2003). This has given rise for the expansion of arable agricultural lands. The soils at the University of Limpopo Experimental Farm particularly, have being reported to be vulnerable to various forms of degradation (physical, chemical and biological) (Mashamaite 2014). Therefore, appropriate management strategies are critical for sustainable improvement of the soils' productivity. Previous studies have confirmed that soils at the University Farm are formed in situ on basalt, sandstone and biotic gneiss, and therefore generally characterised by poor fertility status (Phefadu and Kutu 2016; FAO 2009). There is a general global concern of soil fertility management especially with the recent increases in food prices (FAO 2012).

Soil physicochemical, chemical and mineralogical properties have strong bearings on soil fertility. Soil mineralogy exerts control on both soil chemical and physical properties (Woodruff et al. 2015). It is also an essential determinant of most soil functional properties, such as nutrient quantities and intensities, pH, anion and cation exchange capacity, aggregate stability, soil carbon protection, dispersion, and resistance to erosion. In support of food security, it is strategically important for any area to have available information on the relative suitability of their soils for agriculture. This view is confirmed by land suitability studies conducted at the University Farm by Moshia et al. (2008).

A variety of elemental concentrations and mineralogical composition of selected soils in the Limpopo Province were therefore investigated to ascertain their influence on the fertility in selected areas. The main objective of this study was to characterise the soil's physicochemical, geochemical and mineralogical aspects of selected uncultivated and cultivated soils in selected areas of the University of Limpopo Exper-

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Address for correspondence:
E-mail: kjmolepo@gmail.com

imental Farm. A related objective was to determine these soil properties' influence on soil fertility. The aim is to expand arable agricultural lands in Limpopo, particularly Mankweng area which in turn will improve people's livelihoods by alleviating food insecurity and poverty.

MATERIAL AND METHODS

Study Area

The University of Limpopo Agricultural Experimental Farm is located in Mankweng township, under the jurisdiction of the Capricorn District Municipality, Limpopo Province of South Africa (23°49'S; 29°41'E) illustrated in Figure 1. The farm is about 1 650ha and serves as the University's agricultural experiential farm for students, agronomic and plant nutrition research as well as animal production studies. The farm's 50ha has been allocated for rainfed crops, 80ha for irrigated crops and 40ha is used for rotation of winter and summer crops.

The climate is semi-arid with annual precipitation of roughly ±495mm per annum. The mean annual temperatures are 25±1°C (max) during summer and 10±1°C (min) during winter. The farm is bordered by five populated rural farming communities, where local farmers have always relied on the agricultural research outputs and agricultural extension services from the farm due to the same climate and parent material.

Soil Sampling and Analyses

Twenty-seven soil samples were collected from the three sites (Site UL -uncultivated land, CL - cultivated land and GL - Grazing land being the control site) of the study area. Site UL was uncultivated land which was previously used to grow maize, but had been left fallow for a period of 3 years prior to sampling for this research. Site CL was chosen due to its intensive cultivation while Site GL was an uncultivated site used for grazing and had the same lithology with the two other study sites. Nine soil samples were collected per site. Random sampling technique at a depth of 30cm, which constitutes most of plants rooting zone was used. The collected samples were air dried at room temperature, disaggregated and sieved through a 2mm sieve, until ready for analysis.

Physicochemical tests carried out included particle size distribution (PSD), soil pH, soil electrical conductivity (EC) and exchangeable cations. The PSD of the samples were determined using the hydrometer method as described by Van Reeuwijk (2002). A Texture Auto Lookup

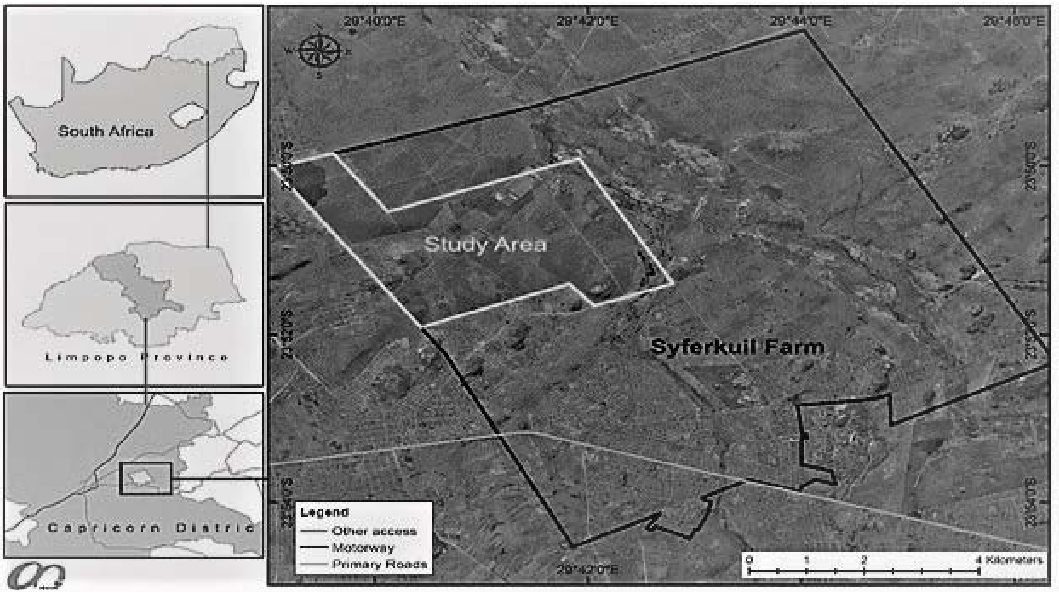

Fig. 1. Location of the study area

Software Package (TAL Version 4.2) was used to obtain texture of each sample with values obtained from PSD. Soil pH was measured in water at a ratio of 1:2.5, using digital electronic pH metre (Ngole 2011; Van Reeuwijk 2002).

Exchangeable cations were determined using ammonium acetate (NH_4OAc) method as described by Van Reeuwijk (2002). A Flame Emission Spectrophotometer (FES) was used to determine K and Na, a Flame Atomic Absorption Spectrophotometer (AAS) (Perkin Elmer 3300) was employed in the detection of Ca and Mg.

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The elemental concentrations of selected samples were determined by X-Ray Fluorescence (XRF) Spectrophotometer (Phillips X'Unique II XRF Spectrometer), as described by Van Reeuwijk (2002) and according to instruction as described in methods set by Council for Geosciences (2011).

The mineral compositions of the soil samples were identified by X-ray diffractometry. The oven dried soil samples were crushed to fine powder and mounted on the sample holder with little pressure. They were then scanned with a Philips PW 3710 XRPD equipment operated at 41kV and 40mA, having a Cu-Kα radiation and a graphite monochromator. Samples were scanned from 2 to 70° 2ϴ Cu-Kα radiation at a speed of 0.02° 2ϴ steps size/ 0.2 sec. Philips X'PERT Graphics and Identify Software package (1999 version) was used for qualitative and quantitative identification of the minerals according to methods described by Ekosse (2000).

RESULT AND DISCUSSION

Soil Physicochemical Composition

Soil samples resulting from the three sites had weight percentage of sand which ranged from 68 to 86 shown in Table 1 and Figure 2. Results revealed that the samples from the three sites had high weight percentage of sand especially from the control site. The overall soil texture according to the soil textural triangle illustrated by Figure 3 ranged from sandy clay loam,

Table 1: Physicochemical parameters

Sample ID	*Particle size distribution (wt%)*			*pH $(H_2 0)$*	*EC (µS/cm)*	*Exchangeable cations (meq/100)*			
	Sand	*Silt*	*Clay*			*K*	*Ca*	*Mg*	*Na*
UL1	75	12	13	7.7	13	484	1482	903	1885
UL2	80	8	12	8.0	40	471	1406	865	1337
UL3	79	6	15	8.0	29	478	1288	826	1834
UL4	83	4	13	8.3	29	432	1580	954	3427
UL5	82	5	13	8.0	42	385	1361	810	2112
UL6	83	4	13	7.6	40	743	1253	923	1285
UL7	82	3	15	8.0	28	250	1224	1224	678
UL8	85	2	13	7.6	28	421	1222	736	1298
UL9	78	7	15	8.0	29	452	1300	779	2061
CL1	79	8	13	9	43	716	2047	1015	1041
CL2	72	9	19	7.7	16	383	1912	951	773
CL3	68	5	27	7.7	26	437	1742	1090	936
CL4	74	13	13	7.7	24	515	1874	1136	1186
CL5	70	9	21	7.5	33	577	2013	943	617
CL6	73	12	15	7.2	16	480	1965	1036	1659
CL7	68	11	21	7.4	11	477	1819	1165	1368
CL8	68	15	17	7.5	27	928	1592	1228	889
CL9	74	5	21	7.3	12	509	1472	854	648
GL1	84	3	13	7	21	613	969	268	486
GL2	82	4	14	6	6	296	653	534	487
GL3	84	4	12	6	17	353	711	334	480
GL4	81	8	11	7	24	355	751	385	555
GL5	77	6	17	6	10	701	1046	578	992
GL6	86	2	12	7	13	351	797	446	534
GL7	80	2	18	7	16	525	1298	819	583
GL8	79	10	11	7	17	636	1766	965	743
GL9	79	6	15	7	85	702	1298	518	1162

Note: Site UL – Uncultivated Fallow Land; Site Y – Intensively Cultivated Land and Site Z - Grazing Land

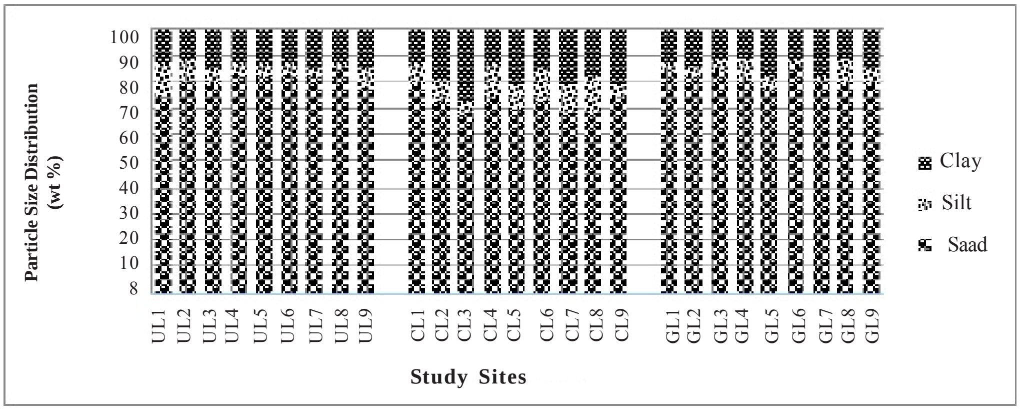

Fig. 2. Soil particle distribution of soil samples from the study area

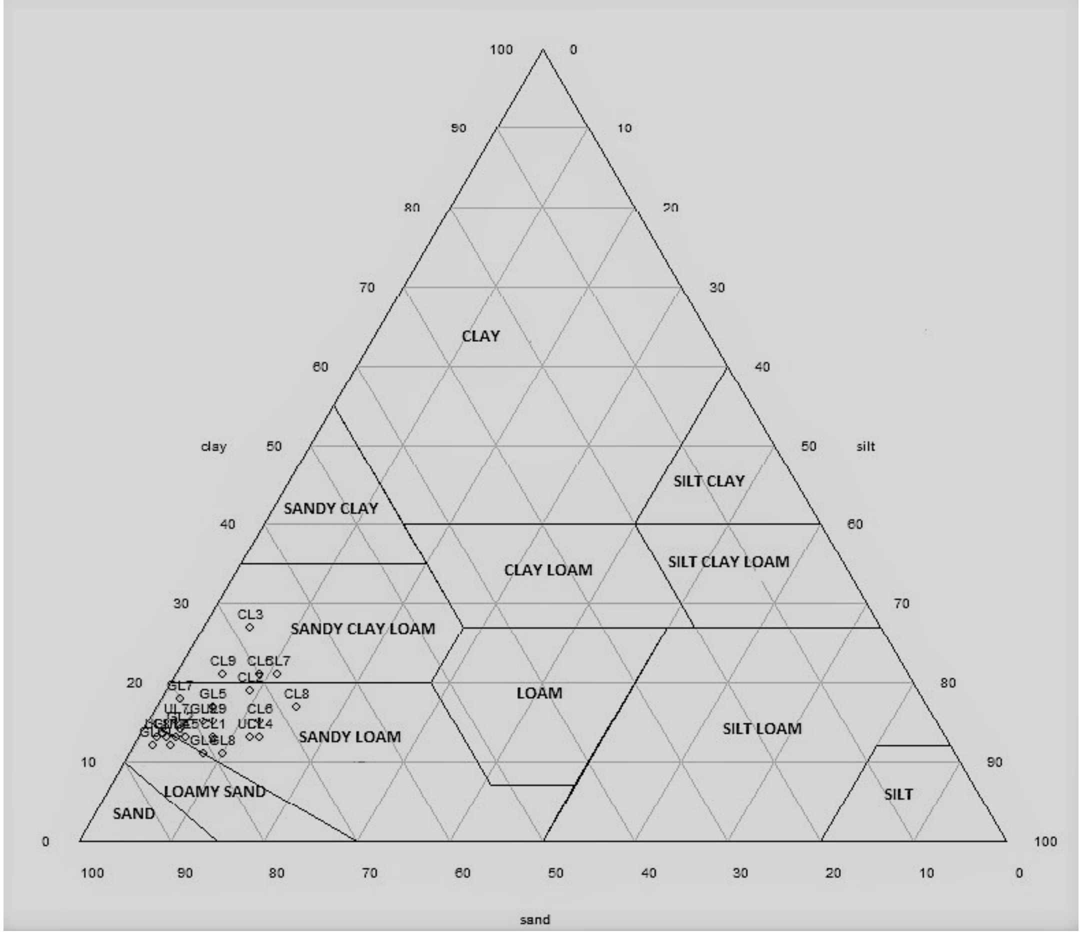

Fig. 3. Soil texture of samples from the study area

loamy sand to sandy loam, these results are also in agreement with findings from the same Farm by Phefadu and Kutu (2016). Sandy loam soils which were generally classified in the whole study area, but mostly in the fallow and intensively cultivated field, are generally well balanced soils dominated by sand particles, with low to moderate water-holding capacity, nutrient retention and good permeability and contains enough clay particles to provide good soil structure and fertility and these soils are generally good for vegetable production (Lerner 2000; Miles and Brown 2003).

Sandy clay loam samples were dominantly classified in the field under intensive cultivation and are categorized as having a moderately slow permeability. This is also confirmed by Russell (2005). The loamy sand soil is classified sparingly only at the grazing field, having a rapid permeability due to its coarser texture. Since all the analyzed soil samples contained a loamy texture, they could therefore be favorable for crop production with additional adequate fertilisers (Lerner 2000). Loamy soils are considered ideal for gardening and agricultural uses because of their capacity to retain nutrients and water, while allowing excess water to drain away (Lerner 2000). As a result of these qualities, the studied soils are a good medium for maize and vegetable production.

The soil pH measured in water ranged from 6.0-9.0 from all sites shown in Table 1. The range of the pH values from the three sites generally depicted a slightly acidic to alkaline environment. Plant nutrient availability is greatly influenced by soil pH (Liu and Hanlon 2012; Ronen 2007) and most plants grow best at pH values between 5.5 and 7.0 where availability for most nutrients is optimal (Ronen 2007). The presence of micronutrients such as Ni and Cu occur within the pH range of 6 and 7 (Liu and Hanlon 2012). This was also observed in most samples from the study area. The high pH levels (>8) from the site under intensive cultivation could hinder the availability of some essential crop nutrients such as iron and manganese, especially for vegetables (Fageria and Zimmermann 1998; Osakia et at. 1997). The resulting situation would have to be corrected to modify the alkaline content of the soils.

The electrical conductivity (EC) values ranged from 11.0 - 85.00 μS/cm for all sites shown in Table 1. The optimum EC as reported by Smith and Doran (1996) is generally between 2dS/m-4dS/m for most grains and vegetables. The salinity conditions of the study area would be less harmful for crop growth, especially for vegetables such as tomatoes, green beans and cowpeas, and maize which are mostly grown in the area, as they all constituted concentration levels of less than 2 dS/m. These findings are in agreement with findings by Phefadu and Kutu (2016) and Waskom et al. (2014).

In case of unbalanced plant nutrients in the soil, plant nutrients deficiency may occur due to competition for plant nutrient uptake (Marx 1999). The values of exchangeable potassium in the samples ranged from 250 meq/100g to 928 meq/100g and such levels could result in detrimental conditions for crop growth as they are higher than the optimum range of 80-160 meq/100g for grains and 120-140 meq/100g for vegetables. This is a point also illustrated by Marx (1999). The exchangeable calcium ranged from 854 meq/100g to 2047 meq/100g at the sites. The results indicated Ca concentration where growing conditions are favourable, which is within the optimum range of 300-2000 meq/100g for grains and 400-2500 meq/100g for vegetables as described by Marx (1999). The exchangeable magnesium values from the study area ranged from 268 meq/100g to 1228 meq/100g. Results indicate a low to extreme Mg concentrations which according to Marx (1999) should have ranges of 80-300 meq/100g for grains and 100-400 meq/100g for vegetables. The soils with Mg concentration of Â 400g meq/100g will provide favorable growing conditions for the crops being planted, except for higher Mg concentrations revealed on fallow and grazing site, which could lead to detrimental effects for crop growth and cause loss of soil structure (Rengasamy et al. 1986). Exchangeable sodium concentrations ranged from 480 meq/100g to 3427 meq/100g. Sodium is not a plant nutrient and is therefore unnecessary for plant growth. Moreover, high levels of sodium, are detrimental to soil tilth and plant growth. The reclamation of land affected should therefore involve establishment of drainage followed by gypsum application and leaching with low-sodium water (Rayment et al. 1992).

Geochemical Composition

The major oxides were dominated by silica (Si_2O) with the highest weight percentage (wt%)

ranging from 75.99 to 83.45 shown in Table 2. The overall alumina concentration of the samples in weight percentages ranged from 7.25 to 10.44 among other oxides. Major elements such as Al_2O_3, Na_2O, K_2O, P_2O_5, SiO_2, are associated with feldspathic clays and mafic volcanic rocks; whereas MgO, TiO_2, Fe_2O_3, H_2O, CaO are usually associated with felsic volcanic rocks (Drew et al. 2010).

The chemical index of alteration (CIA) which assumes that the dominant process during chemical weathering is the degradation of K-feldspar and the formation of clay minerals (Goldberg and Humayun 2010) were calculated as illustrated in Table 2 as well as chemical index of weathering (CIW). The inclusion of CIA and CIW were done to explain the clayey soil formation from the study area. The CIA could be used to study the degree of alteration of sediments (Eriksson et al. 2004) and it is based on the following equations 1 and 2:

$$CIA = [Al_2O_3/ (Al_2O_3 + CaO + Na_2O + K_2O)] \times 100 \ldots \quad .[1]$$

Where CaO considered is that which is incorporated into silicate structure (Harnois 1988), and

$$CIW = [Al_2O_3/ (Al_2O_3 + CaO + Na_2O)] \times 100 \quad ....[2]$$

Alteration of primary minerals to secondary minerals as weathering progresses, results in an increase of CIA values because of a decrease in primary mineral content and accumulation of secondary minerals (Nesbitt and Wilson 1992). According to Depetris and Probst (1998), the CIA values of 45 to 55 are indicative of low or no weathering, whereas CIA values of between 60 and 80 depicts moderate chemical weathering, and those greater than 80 indicates intense chemical weathering of the source rock (Fedo et al. 1995). The studied soil samples are characterized by dominance of SiO_2 with average value of 79.70 wt% (Fig. 4) which is higher than the Upper Continental Crust (UCC) value of 66.6 wt% as reported by Taylor and McLennan (1985). This also might have attributed to the sandy nature of the soils in the study area as classified by the soil textural triangle for soil texture of the studied soils. Aluminum oxide followed in abundance with an average value of 8.65 wt% which is lower than the corresponding UCC value of 15.40 wt% as shown in Figure 4. The higher the CIA, the higher the nutrient depletion in the soil, thus nutrients are leached on the soil studied due to higher CIA. The CIW values ranged from 83 to 91, which were higher than the CIA values of the same samples (Figure 4). Increase in values of CIW corresponds with an increase in the degree of weathering (Ekosse et al. 2011; Price and Velbel 2003). The CIA values of soils studied inferred moderate silica weathering, with depletion of soil nutrients due to leaching.

The concentrations of trace elements are presented in Figure 5. Essential trace elements which are important for agriculture such as Zn, Mo and Cu were detected in the studied soils utilising procedures described by Uchida (2000). The presence of other trace elements which are favorable for plant development and profitable for crop production further confirm the fertility of the soils. The concentration of trace elements of the soils studied were compared to the UCC values of the corresponding element as recorded by Taylor and McLennan (1985). Figure 5 illustrates the trace elements enrichment and depletion in selected soil samples, where Ba, Cr, Ni, Sr, V, Zr, Ce, Co, Cu, Ga, La, Nd, Pb, Rb, Sc,

Table 2: Major oxides (wt%) concentrations

Major elements	*Sample no (wt%)*									
	UL1	*UL2*	*UL3*	*CL1*	*CL2*	*CL3*	*GL1*	*GL2*	*GL3*	*UCC*
SiO_2	80.3	80.3	78.5	80.2	76.0	77.3	83.5	82.5	78.7	66.6
TiO_2	0.4	0.4	0.5	0.3	0.4	0.4	0.3	0.3	0.4	0.6
Al_2O_3	8.5	8.2	9.4	8.6	10.4	9.8	7.3	7.4	8.3	15.4
Fe_2O_3	3.2	3.0	3.4	3.2	4.1	3.8	2.3	2.4	2.9	5.0
MnO	0.1	0.04	0.1	0.04	0.04	0.1	0.04	0.04	0.1	0.1
MgO	0.7	0.7	0.7	0.7	1.1	1.1	0.7	1.3	1.5	2.5
CaO	0.4	0.4	0.5	0.4	0.5	0.5	0.43	0.6	0.6	3.6
Na_2O	0.8	0.8	1.0	0.5	0.7	0.7	0.8	1.0	1.0	3.3
K_2O	2.3	2.3	2.4	2.3	2.3	2.3	2.5	2.3	2.5	2.8
P_2O_5	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.2
CIA	71	70	71	73	75	74	66	66	67	-
CIW	88	87	86	91	90	90	86	83	84	-

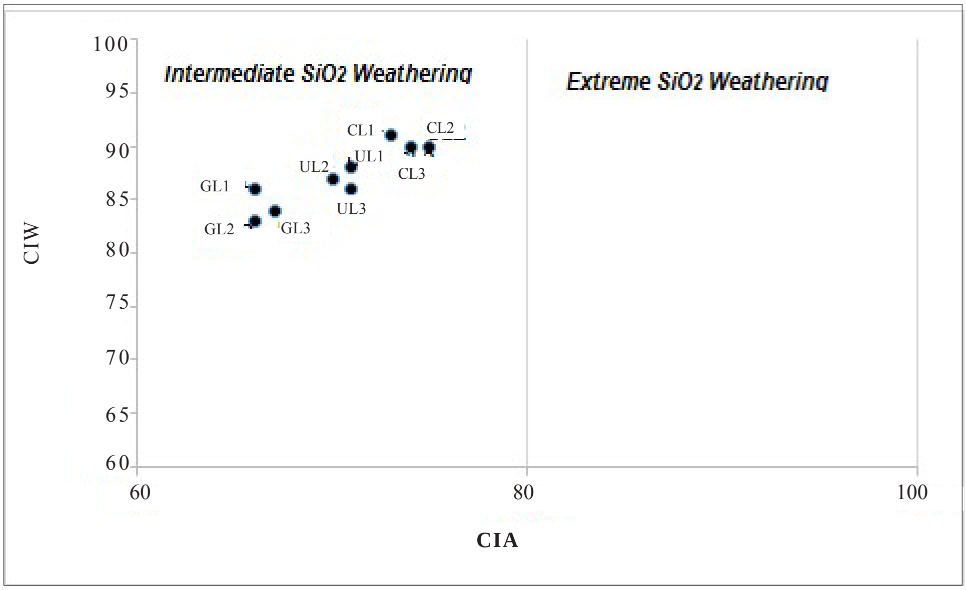

Fig. 4. Chemical Index of Weathering (CIW) versus Chemical Index of Alteration (CIA) of the soil samples for major elements

Sm, V and Zn were enriched. The Cr and Ni elements were greatly enriched and the enrichment of these elements was also recorded for the geochemistry of shales by EL-Wekeil and Abou El-Anwar (2013). Slight enrichment of Ba, Br, Cs, Ga, Hf, Nb, Sc, Th, U, W, Y, Yb was also recorded. Depletion of Ta, Ti and slight depletion Bi, Se was recorded from the studied soils and the relative depletion in these elements could be related to their high mobility during weathering processes. Neither Mo nor Ge were enriched or depleted. Essential agricultural trace elements concentrations found in the studied soils were Zn, Cu, Mo among others such as Fe, Mn, and Cl and B. These observations are in line with Ronen's (2007) and Borggaard et al.'s (2012) descriptions.

Soil Mineralogical Composition

Seven minerals were identified in the soil samples as illustrated in Table 3, which included K-feldspar, plagioclase, quartz, amphibole, kaolinite, talc and interstratified illite/smectite; dominated by quartz and interstratified I/S. All samples from the three sites contained K-Feldspar, plagioclase and quartz, whereas over seventy percent of the selected soil samples had minor quantities of kaolinite, talc and interstratified illite/smectite. Several studies of soil clays and

Table 3: Minerals identified in selected bulk soil samples by XRD expressed in relative weight percentage (wt%)

Sample	*K-feldspar*	*Plagioclase*	*Quartz*	*Kaolinite*	*Amphibole*	*Talc*	*Interstratified I/S*
UL1	9	6	75	5	-	-	5
UL2	10	6	76	4	-	-	5
UL3	7	9	66	4	4	4	4
CL1	10	8	70	4	-	4	5
CL2	23	26	31	5	4	4	8
CL3	13	6	66	3	3	4	5
GL1	15	9	63	3	4	4	3
GL2	6	7	70	-	10	6	-
GL3	6	12	67	2	2	7	4

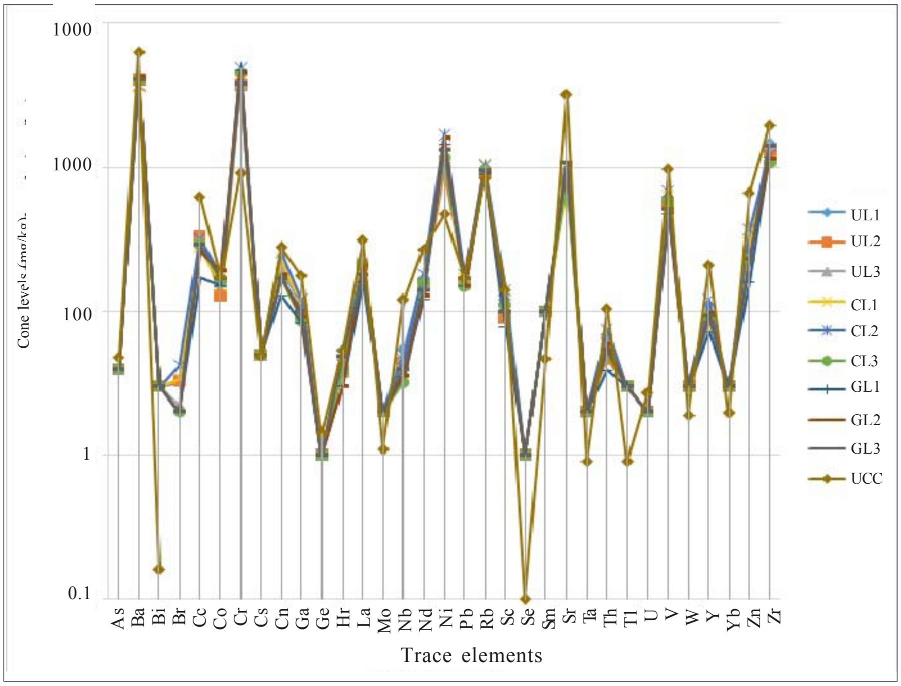

Fig. 5. Trace elements concentrations enrichment and depletion of selected soil samples from the study area

clay minerals (Tucker 1999; Ekosse et al. 2011) have also shown that soil clays and clay minerals influence agricultural land use, soil fertility and soil productivity. Clay minerals have a lot of benefits to soil fertility as they increase the soil's cation exchange capacity (CEC), enhance water holding capacity, provides elasticity, acts as a binding agent for the non-clay components, and reduce nutrient loss through leaching (Churchman and Lowe 2012). The mineralogical composition of the studied soils was dominated by kaolinite, indicating that there would be less effect of CEC in the soils studied and higher levels of aluminum hydroxide species, thereby allowing anion exchange. In addition, lower CEC in the soil possibly influences the presence of soil nutrients.

Interstratified illite/smectite clay minerals contained in the soils have a great capacity to retain and supply large quantities of nutrients, such as Ca, Mg, K, and NH_4 which tend to favor high soil fertility (Gilkes and Prakongkep 2016; Sandler et al. 2015; Churchman and Lowe 2012). Kaolinite in the soils with added nutrient supplementation from manure and fertilizer could enhance soil productivity of the studied soils (Gilkes and Prakongkep 2016). Quartz would prevent clogging, and promote soil aeration and porosity. The presence of smectites in the soils may have resulted in the soil displaying properties typical of soils rich in exchangeable cations, as also described by Gilkes and Prakongkep (2016) and Missana et al. (2008). These soils have a great capacity to retain and supply large quantities of nutrients as compared to those with mineral assemblage dominated by kaolinite and quartz. Where soils are dominated by kaolinite and quartz which result in low release of plant nutrients in soils for plant uptake, as also described by Gilkes and Prakongkep (2016) and Bühmann et al. (2006), corrective measures should be taken and K nutrient fertilizers in addition to other necessary soil nutrients must be applied.

CONCLUSION

The findings illustrate moderate concentrations of nutrient elements essential for plant growth, which are mostly within the optimum ranges for maize and vegetable production. The soils could perform better and become more profitable for agricultural production if adequate nutrient fertilizers or manure were added in the soil. This is because concentrations of the nutrient elements and soil clay minerals were found in moderate amounts. The Site-Specific Nutrient Management plan may be implemented in this regard. Further findings from the study revealed that the soil in the study area was adequate for sustainable production of dominant crops such as maize, spinach and soybeans. Physicochemical, geochemical and mineralogical aspects clearly have an impact on soil fertility for agriculture. The expansion of agricultural land in the region is therefore possible and an effective strategy in promoting smallholder agricultural growth to reduce poverty and income inequality.

RECOMMENDATIONS

In view of the above findings, the following recommendations are made in order to enhance agricultural practices around Mankweng area to alleviate poverty. Authorities are encouraged to initiate various farming systems on uncultivated potential arable lands around the area with reference to the studied soils. In this way, individual soils could be utilized for the type of agricultural production for which they are best suited. This exercise would expand agricultural lands in the area and improve people's livelihoods as a result of an increased food and income availability. The uncultivated lands around the area must be carefully managed if any agricultural activities are initiated and relevant nutrient fertilizers should be adequately applied to keep the soils fertile.

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