

Physico-chemical Findings Related to the Resilience of Different Soils in the Semi-arid Parts of Tanzania and their Implications on Sustainable Agriculture

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Abstract

As part of an interdisciplinary study on Sustainable Agriculture in Semiarid Areas (SASA) in south-central Tanzania, soils from five different locations were investigated for their mineralogical composition and physico-chemical characteristics in order to determine their resilience in relation to land use. The results of the investigation show that soils developed in such areas on sediments of Holocene age to a certain extent are capable of retaining their chemical fertility as long as low intensity agriculture is being practised. The content of weatherable minerals in the quite silt-rich soils is so large that the weathering taking place, seems sufficient under the prevailing semiarid conditions to ensure adequate supply of plant nutrients for low intensity crop production with the exception of N, P and S. The sand and silt fractions contained substantial amounts of mica and plagioclase and smaller amounts of hornblende/pyroxene. In addition to kaolinite and iron oxides, the clay fraction contains illite and smaller amounts of other 2:1 layer silicate clay minerals. The extractable amount of P is low, although the P-retention is expected to be limited, as the content of P-fixing components is limited. In contrast, the soils in the area formed in situ on metamorphic rocks contain only quartz and very small amounts of microcline and muscovite in the sand fraction. The silt fraction is high in quartz too besides having some kaolinite and gibbsite. The clay fraction of these soils is composed mainly of kaolinite with smaller amounts of Fe-oxides and illite. Chemically, the capacity of these soils is so low that they will not to any degree release any plant nutrients by weathering. The extractable P is also low in these soils, as the P present may be considered to be strongly retained due to the mineralogical composition of these soils. Due to their content of stable micropeds the strongly weathered soils developed in situ are more porous than the less strongly weathered soils developed on the Holocene sediments. However, their available water holding capacity may be expected to be lower than that of the soils developed on the sediments, as such soils normally have a limited number of pores in which plant available water is stored.

Key words: different soils, semi arid puts

Introduction

In less advanced countries where subsistence agriculture is commonly practised (Sanchez *et al.*, 1997) sustainable agriculture depends not only on the land use practices (Smaling and Braun, 1996), but also on the physico-chemical and biological properties of the soils, and their resilience as well (Greenland *et al.*, 1994).

Subsistence agriculture, in which a vegetative fallow period is a part, or where a portion of the land is devoted to perennial vegetation, results only in restricted plant nutrient depletion of the soil as long as the population pressure is limited. In that case, the fallow period or the area covered with perennial vegetation is sufficient for the soil to regain its content of most of the plant nutrients removed by the cropping or lost by erosion during that period (Nye and

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Greenland, 1960; Andriasse, 1980). Certain plant nutrients, for instance K, Ca, and Mg (Andriasse, 1989; Mohr *et al.*, 1972) and micro nutrients (Aubert and Pindo, 1977; Cottenie *et al.*, 1981), are removed from the soils. They may be replaced by weathering during the fallow period. Plant nutrients, such as S and to a smaller extent N, lost when the fallow vegetation is burned, may return to the soil in the precipitation and through particulate deposition. The main part of the N accumulated in the soil during the fallow period originate from the air and is fixed by N-fixing micro-organisms in the soil, either symbiotically by rhizobium, or by free living N-fixing organisms (Dommergues *et al.*, 1984; Szott *et al.*, 1991).

Most parent materials only contain small amounts of P (Liebau and Koritnig, 1978) and almost no P is released by weathering in plant available form in well drained, strongly weathered tropical soils. In spite of the strong retention of P in most of such soils and the small amount of P added to the soil from the air in particulate form (Smaling and Braun, 1996), loss of P by leaching and in particulate form through erosion and burning over millenniums, has resulted in widespread P-deficiency in well drained soils of both the humid and semi-arid parts of the tropics under natural conditions. The main part of the small increase in P in plant-available form in well drained soils during the fallow period may be due to slow release of strongly retained P in the soil (Goedert, 1983) through the activity of mycorrhiza living in symbiosis with more deeply penetrating roots of some of the fallow vegetation (Högberg, 1989; Sanchez *et al.*, 1997).

Physically, vegetated fallow will over years result in increase in soil organic matter content (Andriasse, 1989; Andriasse, 1980; Nye and Greenland, 1960). That, together with an increase in more deeply penetrating roots of trees, brush, and other perennials, leads to improved structure and better porosity of the soil, improved infiltration rate, higher hydraulic conductivity and an increase in the available soil water storage capacity.

With decreasing length of the fallow period and reduced growth of woody vegetation soil deterioration is a common feature of low intensity agriculture in the tropics, as it leads not

only to plant nutrient exploitation but also to decline in biological activity in the soil, declining soil porosity, and increasing soil erosion (Lal, 1986).

Biologically, the increase in organic matter, P, and other plant nutrients in available form by plant residue added to the soil during the fallow period result in an improved environment for both soil fauna and micro-organisms (Young, 1989) and thereby to improved chemical and physical conditions in soils.

Presently, the increase in population in the Sub-Saharan Africa results in land use systems with little or no form for fallow. The result is, that more plant nutrients are removed from the soils than returned through farm manure, plant and household residue, etc., and by application of fertilizers. This means, that much of the farming undertaken there today is not sustainable from the soil point of view, neither chemically, nor physically or biologically.

The aim of the present study is to determine the role of the properties and the mineralogical composition of different soils in the semiarid parts of Tanzania on the resilience of the soils, and on the sustainability of the land use systems presently practised in those areas.

The investigation is part of a broader study on sustainable agriculture in semiarid areas of Tanzania carried out in form of an interdisciplinary investigation involving both social, economical, hydrological, and land use aspects, besides soil characteristics reported in this paper.

Materials and Methods

Climate, physiography and materials

The investigation was carried out on the soils located around the Mkulula, Ilambilola, Ikuwala, and Kiponzelo villages in the Iringa Region and near the Rujewa village in the Mbeya Region of the south-central part of Tanzania. A total of nine soil profiles were described and sampled.

Climatically, the area is located in the semi-arid part of the country with a typical monomodal wet season. The annual rainfall varies from 400 - 550 mm in the Rujewa - Mkulula areas up to 700 - 750 mm in the

Ikuwala - Kiponzelo areas (URT/EEC, 1987). It seems least reliable in the areas where the rainfall is lowest.

The origin of the parent material of the soils included in the study, varied substantially from site to site. The geomorphological terms employed are based on the terminology presented by Thomas (1996).

The Mkulula soil has developed on a lower concave part of an alluvial fan from material originating from a gneiss and schist-rich metamorphic rock.

The Ilambilola soils have been formed *in situ* from gneiss and schist-rich metamorphic rocks on an old erosional surface.

The Ikuwala soils are situated on a detrital pediment. The accumulated sediments, on which they are formed, originate from acid gneiss, phyllite, schists, and migmatite-rich metamorphic rocks.

The soils, which are situated on an old eroded surface, have been formed *in situ* on saprolite originating from phyllite and schist-rich metamorphic rocks.

The Rujewa soils are formed on older and younger sediments deposited in the main Eastern Rift Valley north-east of the Rungwe volcanic complex. The sediments are both of volcanic and metamorphic rock origin.

Certain other external features at the location, such as elevation, rainfall and the temperature regime are summarized in Table 1.

Table 2 contains the classification of the nine soils according to the Soil Taxonomy System (Soil Survey Staff, 1997) at family level.

Methods

On field level, one soil sample was collected from each of the horizons recognized in two soil pits from each site, except at the Mkulula site where only one soil pit was sampled.

In the laboratory the following analytical procedures were used:

pH_{H2O} was measured in a 1:2.5 soil/water suspension. The organic C content was determined by dry combustion after removal of CaCO₃, in case this was expected to be present.

Table 1: Location, elevation and climate of the soils.

Soil	Location	Elevation (m)	Rainfall (mm)	Temperature regime
Mkulula	Ismani District ¹	1250-1300	550-600	isohyperthermic
Ilambilola N and S	Iringa District ¹	1390	600-700	isohyperthermic
Ikuwala NW and Centre	Iringa District ¹	1370	700-750	isohyperthermic
Kiponzelo NW and SE	Iringa District ¹	1740	700-800	hyperthermic
Rujewa NW and SE	Rujewa District ²	1070	400-500	isohyperthermic

¹Iringa Region, ²Mbeya Region.

Table 2: Classification of the soils according to the Keys to Soil Taxonomy (Soil Survey Staff, 1997).

Soil	Classification
Mkulula	Typic Paleustalf, fine, mixed, isohyperthermic, semiactive
Ilambilola N	Typic Kandistalf, fine, kaolinitic, isohyperthermic
Ilambilola S	Typic Kandistalf, fine, kaolinitic, isohyperthermic
Ikuwala NW	Typic Haplustalf, fine loamy, mixed, isohyperthermic, subactive
Ikuwala Centre	Kandic Paleustalf, fine, mixed, isohyperthermic
Kiponzelo NW	Typic Kandistox, fine, kaolinitic, hyperthermic
Kiponzelo SE	Aridic Kandistalf, fine, kaolinitic, hyperthermic
Rujewa NW	Typic Haplustalf, fine, mixed, isohyperthermic, semiactive
Rujewa SE	Typic Haplustalf, fine, mixed, isohyperthermic, semiactive

The P content was extracted by 0.5 M NaHCO_3 at pH 8.5 and determined by the ammonium molybdate-ascorbic acid method. In case of the Ilambilola, Ikuwala, and Kiponzelo soils the exchangeable bases were extracted by the NH_4OAc procedure. In case of the Mkulula and Rujewa soils they were extracted by the silver thiourea procedure (ISRIC, 1993), using atomic absorption spectrophotometry (AAS) for measuring the contents of Ca and Mg and flame emission spectrophotometry (FES) for measuring the contents of K and Na. The cation exchange capacity (CEC) was determined by the ammonium acetate method at pH 7 in case of the Ilambilola, Ikuwala, and Kiponzelo soils and by the silver thiourea method buffered at pH 7 by NH_4OAc (ISRIC, 1993) in case of the Mkulula and Rujewa soils. The particle size distribution was determined by the Andreasens pipette method in case of the Ikuwala, Ilambilola and Kiponzelo soils and by the particle size distribution analysis centrifuge in case of the other soils. All the above analyses, except for the silver thiourea extraction and the last one, were carried out according to the methods described by Møberg *et al.* (1994).

The content of free Al-Fe-oxides was determined by the sodium (DCB) method described by Mehra and Jackson (1960).

Both the total elemental analysis (TEA), which was carried out on ammonium acetate saturated, DCB-treated clay fractions from which the organic matter was removed by H_2O_2 treatment, and the mineralogical analysis of the sand and silt fractions were carried out according to the methods described by Møberg *et al.* (1988). XRD was carried out on non-oriented, Ca-saturated silt, and clay samples, which had not been DCB-treated, and on DCB-treated, oriented Ca- and K-saturated clay samples.

In case of the sand fraction, the XRD analysis was carried out on non-magnetic, pulverized sand. A Phillips XRD-unit equipped with a Co-tube was used for all the XRD analysis. Besides the use of XRD, magnetic separation and microscopic analysis were used for the mineral analysis of the sand fraction. All the mineralogical analyses were carried out as described by Møberg *et al.* (1988), except that Ca-saturation of the clay fraction was used in stead of Mg-saturation and no glycerol treatment was

carried out, as no 1.4 nm diffraction peak was detected in any of the XRD analyses on the clay fraction.

The CEC of the clay fraction was both determined directly on the DCB-treated clay fraction by Ca-saturation by CaCl_2 at pH 7 (in the following this value is called CEC_d) and indirectly from the $\text{CEC}_{\text{pH } 7}$ of the soil after adjustment for the CEC of the organic matter (in the following this value is called CEC_c). The direct CEC determination by Ca-saturation was carried out as follows: After Ca-saturation and removal of the Ca in the solution, the exchangeable Ca was extracted by washing with NH_4OAc and the content of Ca in the extract determined by AAS.

Results and Discussion

General characteristics

The results of the general physico-chemical characteristics of some selected horizons are presented in Table 3. Except for the strongly weathered Kiponzelo soil, the soils are slightly acidic to basic in reaction. The saline subsurface horizons of the Mkulula soil may be due to the semiarid climate and its location on a lower concave part of the alluvial fan below a mountain range with very shallow soils causing an influx of groundwater rich in dissolved calcium and magnesium.

The organic matter content is low in all the soils except in the surface horizon of the Kiponzelo soils, to which manure had been applied for a number of years. The high C-content in the subsurface horizons of the Mkulula soil may be due to incomplete removal of dolomite prior to the determination of organic C by dry combustion.

The extractable P content is very low in all the horizons of the soils investigated, except in the surface horizons of the Kiponzelo soils and in the upper horizons of the Rujewa soils. In case of the Kiponzelo soils, the higher content of P may, as in case of the higher organic matter content, be due to application of manure and of P-containing fertilizers in the past.

In relation to subsistence farming, the amounts of exchangeable Ca and Mg in the nine soils may be considered to be in the medium

Table 3: Results of selected physico-chemical analyses of the soils.

Soil	pH _{H2O}	C (%)	Tot. N (%)	P _{2O5} (mg/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)	K _{ex} (cmol(+)/kg)	Na (cmol(+)/kg)	CEC (cmol(+)/kg)	Sand (%)	Silt (%)	Clay (%)
Mkulula												
Ap	8.2	0.41	0.01	8.37	2.87	0.62	0.05	7.6	70	9	21	70
Bt1 ¹	8.6	1.37	0.03	22.0	8.19	0.78	0.03	17.9	28	16	56	28
Bt2 ¹	8.8	1.78	0.03	18.5	14.6	0.60	0.46	18.8	22	29	49	29
Ilambilola N												
Ap	6.3	0.48	0.04	1.39	0.84	0.30	0.03	6.2	81	7	12	81
Bto1	5.1	0.56	0.03	1.9	2.24	0.31	0.24	6.9	40	26	34	36
Bcno	5.4	0.34	0.06	2.26	2.43	0.19	0.08	6.9	54	9	37	30
Ilambilola S												
Ap	5.8	0.65	0.06	1.66	1.30	0.65	0.12	4.1	74	8	18	78
Bto1	5.6	0.34	0.05	1.56	2.48	0.23	0.03	3.6	48	6	46	46
Bto3	5.9	0.38	0.04	1.44	3.22	0.17	0.23	7.8	49	8	43	43
Ikuwala NW												
Ap	6.2	0.87	0.07	2.81	1.15	0.31	0.03	7.8	70	16	14	70
Btm1	6.5	0.50	0.05	4.48	1.86	0.17	0.07	6.9	56	20	24	24
BCm	8.0	0.37	0.02	3.54	1.10	0.14	0.27	5.0	71	8	21	71
Ikuwala Centre												
Ap	6.2	0.98	0.08	4.26	2.02	0.44	0.07	8.7	54	19	27	27
Bt	6.7	0.78	0.06	6.53	2.73	0.19	0.27	9.6	31	21	69	69
Cm3	8.0	0.34	0.01	2.28	0.87	0.12	0.16	4.1	60	7	13	13
Kiponzelo NW												
Ap	5.5	1.39	0.12	0.85	0.59	0.39	0.05	5.0	51	8	41	41
Bt	5.4	0.52	0.04	0.55	0.23	0.18	0.04	2.3	37	4	59	59
Bto2	4.6	0.36	0.11	0.63	0.25	0.17	0.26	2.1	24	8	68	68
Kiponzelo SE												
Ap	6.0	1.40	0.13	1.23	0.90	0.56	0.03	5.0	56	9	35	35
Btm	5.8	0.58	0.03	0.70	0.36	0.28	0.08	3.2	42	4	54	54
Bto2	5.0	0.34	0.02	0.31	0.15	0.16	0.02	3.2	30	7	63	63
Rujewa NW												
Ap	7.9	0.91	0.07	8.50	2.32	0.62	0.11	10.3	50	18	32	32
Bt1	7.6	0.31	0.05	17.1	4.48	0.24	0.22	16.5	15	34	51	51
C	8.1	0.19	0.01	9.86	2.56	0.08	0.23	9.9	47	25	28	28
Rujewa SE												
Ap	7.3	0.90	0.05	7.47	2.26	0.76	0.03	9.8	44	23	33	33
Em	6.8	0.50	0.02	7.07	2.46	0.35	0.06	10.0	55	17	28	28
Bmw	6.9	0.36	0.01	7.37	2.63	0.20	0.1	10.4	52	18	30	30
Bt	7.6	0.46	0.02	13.8	4.32	0.31	0.07	17.6	26	31	43	43
C	8.0	0.14	0.01	7.56	2.08	0.07	0.1	8.6	50	28	28	28

¹ These two horizons contained some poorly crystalline calcite-dolomite, this is no doubt the reason for the high contents of C, Ca and Mg.

range, except in case of the soils, where the contents are low, and in the Mkulula soil, where the contents are in the high range.

The exchangeable K content in the soils is in the medium range. The amount of exchangeable

Na is low in all the soils, even in the Mkulula soil, in spite of the salt accumulation at depth.

Taking into consideration the quite high content of clay in the subsurface horizons of most of these soils their γ_7 is low, especially in the Kiponzelo soils and to some extent in the Ilambilola soils.

In all the soils some of the subsurface horizons are richer in clay than the surface horizon. In case of soils developed on sediments this may be due to selective deposition of clay-rich or clay poor material, as for instance in case of the C horizons in the Rujewa soils. In other cases, selective removal of clay from the surface horizon could have played a role, but also clay eluviation-illuviation may have been involved in the development of such clay-enriched subsurface horizon(s), as clay skins were detected in most of the B horizons.

Mineralogical composition

The investigation of the mineralogical composition of the nine soils gave the results presented in Tables 4 and 5, and in the Figures 1 to 5 which contain diffractogrammes of some of the X-ray diffraction (XRD) analyses.

Table 4 contains the results of the DCB analysis and of the CEC_c and CEC_d . Compared with the amount of DCB-extractable Fe and Al in the well drained soils of the more humid parts of the tropics (Menzies and Gillman, 1997; Moberg *et al.*, 1982) the DCB-extractable Fe and Al of the clay fraction of the nine soils may in all cases be considered to be quite low. This observation holds even for the Kiponzelo soils, although they vary quite substantially from the other soils in mineralogical composition.

The CEC_d is substantially higher than the CEC_c . The difference could be due to the following reasons: (a) When lacking a high-speed centrifuge it is difficult to remove all the non-adsorbed Ca^{2+} ions completely from the soil after its saturation with that ion, (b) that the estimation is based on wrong premises, *e.g.* the CEC allocated to the organic fraction could be too high due to neutralization of the negative charges by complexed Fe-oxides; (c) that in soils containing substantial amounts of iron oxides the CEC_c will be too low because it will be the iron oxide coatings on the layer silicate clay minerals which will determine the charge of the

soil in preference to the layer silicate clay minerals themselves, and (d) that the NH_4^+ , used for saturation and buffering in case of the soil CEC determination, blocks some of the exchange sites of the 2:1 layer silicate clay minerals, so that the method does not give the true CEC -value in case of soils containing such minerals. On the other hand, by using these two different methods one obtain a better picture of the weathering state of the clay fraction in the soils and their weatherability.

The reasons mentioned under (c) and (d) may seem more plausible to be the causes of the differences in values obtained by the two methods. However, in spite of the differences between the results obtained by the two methods the trend is certainly the same for all the soils.

Table 5 contains the results of the total elemental analysis (TEA) of the DCB-treated clay.

The data indicate that there is a detectable difference in mineral composition of the clay fraction in the soils. Taking into consideration that the parent materials of the soils at the different locations have originated from metamorphic rocks of not too different composition, except in the case of the Rujewa soils, the low contents of Ca and Mg in the Kiponzelo soils, and to a certain extent in the Ilambilola soils, indicate, that they are much more strongly weathered than the Mkulula, Ikuwala, and Rujewa soils. The high content of Al in comparison with the Si content in the clay fraction of the Kiponzelo soils show that leaching must have been stronger in these soils at some point in time during their development than in the other soils. The very low contents of K, Mg and Ca in these two soils support that hypothesis.

XRD analyses were carried out on the non-magnetic sand and silt fractions, and on the DCB non-treated and treated clay fractions from five of the nine soils. The results of the analyses are presented in Figures 1 to 5. The results of the microscopic and XRD analyses of the magnetic sand fractions are not presented but were considered together with the evaluation of the XRD analyses when estimating the mineralogical composition of the sand fraction of the different soils. Table 6 contains the results of this estimation.

Quartz was found to be the dominant mineral in the sand fraction of all the soils, as

Table 4: Sodium dithionite-bicarbonate-citrate (DCB) extractable Fe and Al on the clay fraction, CEC_c and CEC_d.

Soil	Fe		Al		CEC _c ¹	CEC _d ^{2,3}
	%	mg/kg clay	%	mg/kg clay	cmol(+)/kg clay	cmol(+)/kg clay
Mkulula						
Ap	3.2	11.5	0.38	1.3	32	51
Bt1	3.6	12.5	0.36	1.2	27	58
Bt2	3.2	11.0	0.38	1.3	31	97
Ilambilola N						
Ap	2.9	10.0	0.31	1.1	19	28
Bto1	2.6	9.0	0.34	1.2	11	15
Bcmo	3.6	12.5	0.42	1.5	17	19
Ilambilola S						
Ap	5.9	20.5	0.63	2.2	16	23
Bto1	5.5	19.5	0.63	2.2	12	13
Bto3	5.9	20.5	0.67	2.4	16	18
Ikuwala NW						
Ap	3.5	12.5	0.42	1.5	43	36
Btm1	3.3	11.5	0.34	1.2	25	32
BCm	3.1	11.0	0.30	1.1	20	34
Ikuwala Centre						
Ap	3.4	12.0	0.34	1.2	25	33
Bt	3.3	11.5	0.31	1.1	12	20
Cm3	3.6	12.5	0.33	1.2	26	31
Kiponzelo NW						
Ap	2.8	10.0	0.82	2.9	57	12
Bt	3.5	12.5	1.03	3.6	2	4
Bto2	3.3	11.5	0.94	3.3	2	3
Kiponzelo SE						
Ap	2.9	10.0	0.81	2.8	6	14
Btm	3.1	11.0	0.94	3.3	4	6
Bto2	3.3	11.5	0.87	3.1	4	7
Rujewa NW						
Ap	3.5	12.5	0.42	1.5	27	39
Bt1	3.1	11.0	0.39	1.4	31	46
C	3.7	13.0	0.41	1.5	34	47
Rujewa SE						
Ap	3.7	13.0	0.49	1.7	24	38
Em	3.7	13.0	0.48	1.7	32	39
Bmw	3.6	12.5	0.50	1.8	32	43
Bt	3.0	10.5	0.40	1.4	39	45
C	3.5	12.5	0.44	1.6	38	45

¹CEC_c = The estimated CEC of the clay fraction from the soil CEC_{pH7} minus the estimated CEC of the organic fraction at pH 7 (200 cmol(+)/kg organic C); ²CEC_d = The CEC determined on the clay fraction at pH 7; ³Problematic due to presence of carbonates

shown in Figure 1. In the Kiponzelo soil the XRD and the microscopic data showed that more than 95% of the sand fraction was quartz. Quartz was also found to be the dominant mineral in the sand fraction of the Ilambilola and the Mkulula soils but the percentage was lower than in the Kiponzelo soil. In contrast, plagioclase and to a smaller extent biotite-rich mica, amphibole/pyroxene, epidote and magnetite/ilmenite formed a substantial part of the sand fraction of the Ikuwala and Rujewa soils. K-feldspar was also present in these soils, but only in small amounts.

Diffraction patterns of the XRD analysis on the silt fraction of five of the nine soils are

shown in Figure 2. Also in this case the Kiponzelo soil is distinct, as its silt fraction contained both kaolinite and gibbsite besides quartz, whereas almost no feldspars were present. The Ilambilola soil varied also from the other soils, as it was found to contain much less weatherable minerals, such as mica and plagioclase in this fraction, than the Ikuwala and Rujewa soils.

The silt fraction of the Ilambilola and Rujewa soils contained larger amounts of both plagioclase and mica and smaller amounts of quartz and K-feldspars.

Table 5: Results of the total elemental analysis (TEA) and the ignition loss (in %), based on air dry, DCB-treated, NH₄⁺-saturated clay samples.

Soil	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	Na ₂ O	TiO ₂	MnO ₂	Ign. loss	Total
Mkulula											
Ap	46.1	24.8	5.65	2.30	0.09	2.30	0.22	0.78		16.7	98.9
Bt1	46.4	22.7	5.48	2.56	0.09	2.68	0.16	0.95	0.04	16.6	97.6
Bt2	52.8	24.3	5.68	3.69	0.16	3.30	0.24	1.03	0.04	7.50	98.4
Ilambilola N											
Ap	47.5	29.5	4.98	0.63	0.03	2.43	0.16		0.02	14.5	99.8
Bto1	44.6	31.0	4.67	0.37	0.02	1.74	0.06		0.02	14.7	97.2
Bemo	45.4	30.8	4.70	0.38	0.01	1.72	0.07		0.01	14.2	97.3
Ilambilola S											
Ap	46.3	30.6	4.43	0.60	0.05	2.06	0.13		0.02	13.2	97.4
Bto1	45.7	32.2	3.98	0.42	0.01	1.55	0.07		0.02	14.7	99.4
Bto3	45.2	32.5	7.34	1.64	0.07	2.29	0.21	0.94	0.06	18.5	102.5
Kiponzelo NW											
Ap	34.1	40.7	4.15	0.05	0.01	0.35	0.04	1.21	0.01	18.7	99.3
Bt	33.5	41.1	3.25	0.04	0.01	0.35	0.03	1.19	0.01	19.1	98.6
Bto2	34.2	40.6	3.27	0.03	0.01	0.35	0.04	1.22	0.01	18.8	98.5
Kiponzelo SE											
Ap	34.8	39.7	3.76	0.05	0.05	0.37	0.03	1.13	0.01	18.2	98.1
Btm	33.3	41.2	3.40	0.05	0.01	0.35	0.03	1.09	0.01	19.6	99.0
Bto2	34.6	40.5	3.53	0.04	0.01	0.36	0.04	1.07	0.01	18.4	98.6
Rujewa NW											
Ap	49.3	28.9	7.71	1.92	0.24	2.36	0.51	1.40		8.99	101.4
Bt1	49.3	29.4	8.22	1.34	0.14	1.54	0.34	1.32		9.33	100.9
C	46.9	27.3	9.47	2.43	0.14	1.76	0.37	1.23		8.99	98.6
Rujewa SE											
Ap	47.0	29.7	7.69	1.57	0.15	2.04	0.40	1.32		9.70	99.0
Em	48.2	29.0	7.73	1.57	0.15	1.91	0.35	1.37		9.59	99.0
Bmw	47.3	28.3	8.45	1.80	0.14	1.83	0.33	1.25		9.82	99.3
Bt	47.8	29.2	8.43	1.18	0.13	1.33	0.30	1.23		9.83	99.4
C	47.9	27.8	8.36	1.57	0.12	1.28	0.30	1.18		9.85	98.4

Ignition

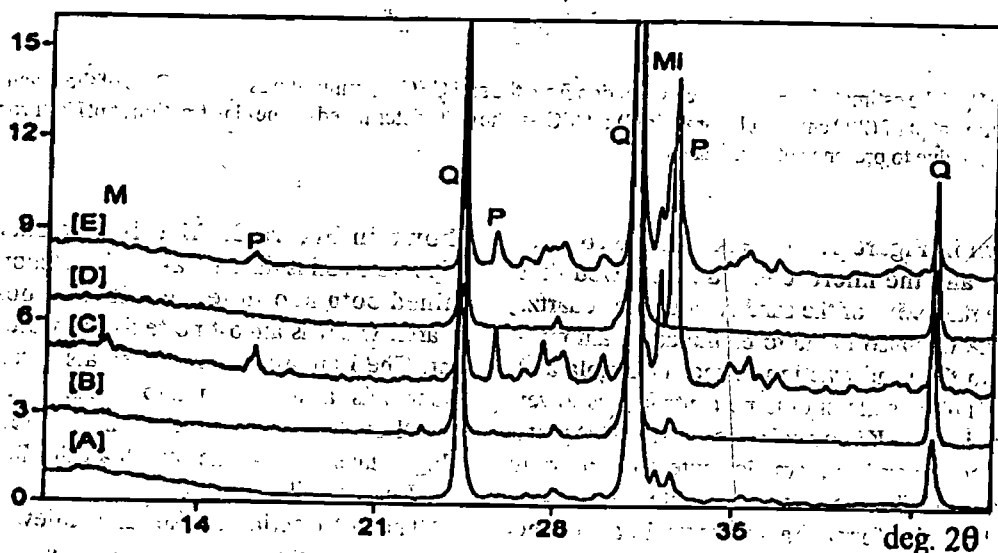


Figure 1: XRD analytical data of the non-magnetic sand fractions in the subsurface horizon at approximately one meter depth. [A] Mkulula, [B] Ilambilola N, [C] Ikuwala NW, [D] Kiponzelo NW, and [E] Rujewa NW. Symbols of the identified minerals: M: Mica; Mi: Microcline; P: Plagioclase; Q: Quartz.

Figure 3 contains the diffractograms of the non-oriented, non DCB-treated clay fraction from the five soils. Besides the minerals identified by XRD on the oriented clay samples goethite was found to be present in all the soils, this was especially the case in the Kiponzelo

soil. Haematite is possibly present too, but in so small an amount that it could not be detected with certainty by the XRD instrument used.

The XRD analysis on the DCB-treated, oriented clay samples from the Ap horizons are presented in Figures 4 and 5. Together with the

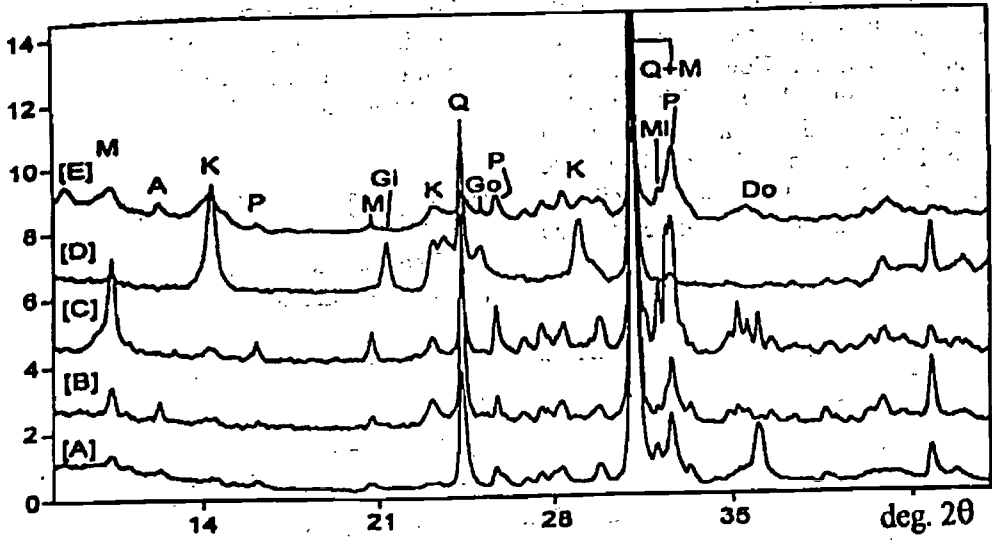


Figure 2: XRD analytical data of the silt fractions in the subsurface horizon at approximately one meter depth. [A] Mkulula, [B] Ilambilola N, [C] Ikuwala NW, [D] Kiponzelo NW, and [E] Rujewa NW. Symbols of the identified minerals: A: Amphibole; Do: Dolomite; Gi: Gibbsite; Go: Goethite; K: Kaolinite; M: Mica; Mi: Microcline; P: Plagioclase; Q: Quartz.

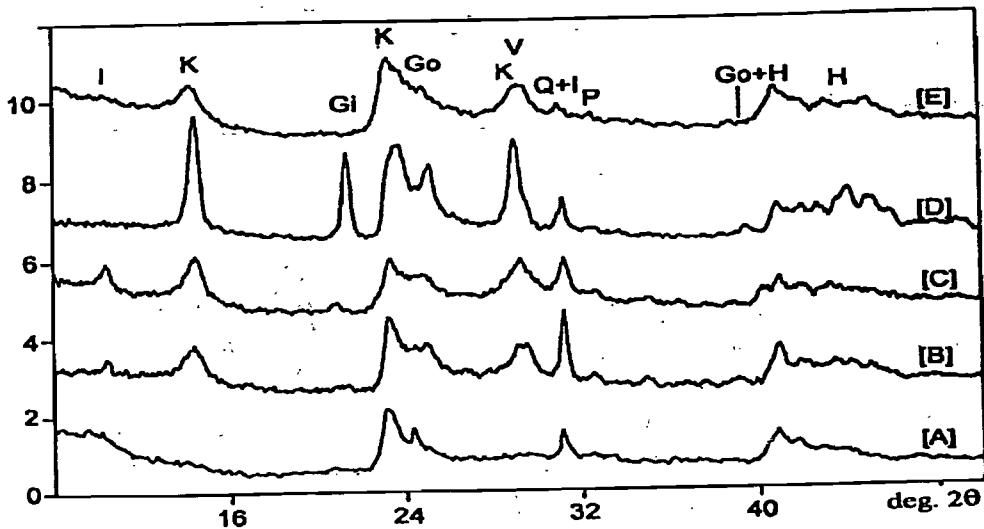


Figure 3: XRD analytical data of the Ca-saturated, non-oriented clay samples in the subsurface horizon at approximately one meter depth. [A] Mkulula, [B] Ilambilola N, [C] Ikuwala NW, [D] Kiponzelo NW, and [E] Rujewa NW. Symbols of the identified minerals: Gi: Gibbsite; Go: Goethite; H: Hematite; I: Illite; K: Kaolinite; P: Plagioclase; Q: Quartz; V: Vermiculite-like.

XRD analyses on the heat-treated samples (not included) the figures indicate that kaolinite and illite were present in all the samples. Kaolinite dominated completely in the Kiponzelo clay fraction. No other minerals were detected in the clay fraction of this soil except illite and gibbsite which were also detected, but only in smaller amounts. Kaolinite dominates over illite in the Rujewa soil, whereas the opposite was the case of the Ikuwala soil. However, both these soils contained some feldspars. The Mkulula and the Ilambilola soils contained substantial amounts of illite and kaolinite and detectable amounts of feldspars. The Ilambilola soil was the only one in which quartz was detected in the oriented clay fraction.

XRD analyses on samples from the deeper horizons of the Rujewa soils (not shown) indicated that a regular interstratified vermiculite-like mineral was present in the clay fraction of these soils, as the Ca-saturated oriented samples had a diffraction top at 1.24 nm. The top disappeared when the samples were heated to 350EC (Righi and Elsass, 1996).

Estimates of the composition of the silt and clay fractions in the five soils considered above are presented in the Tables 7 and 8.

The Resilience of the soils

When considering the connection between the soils included in this investigation and their

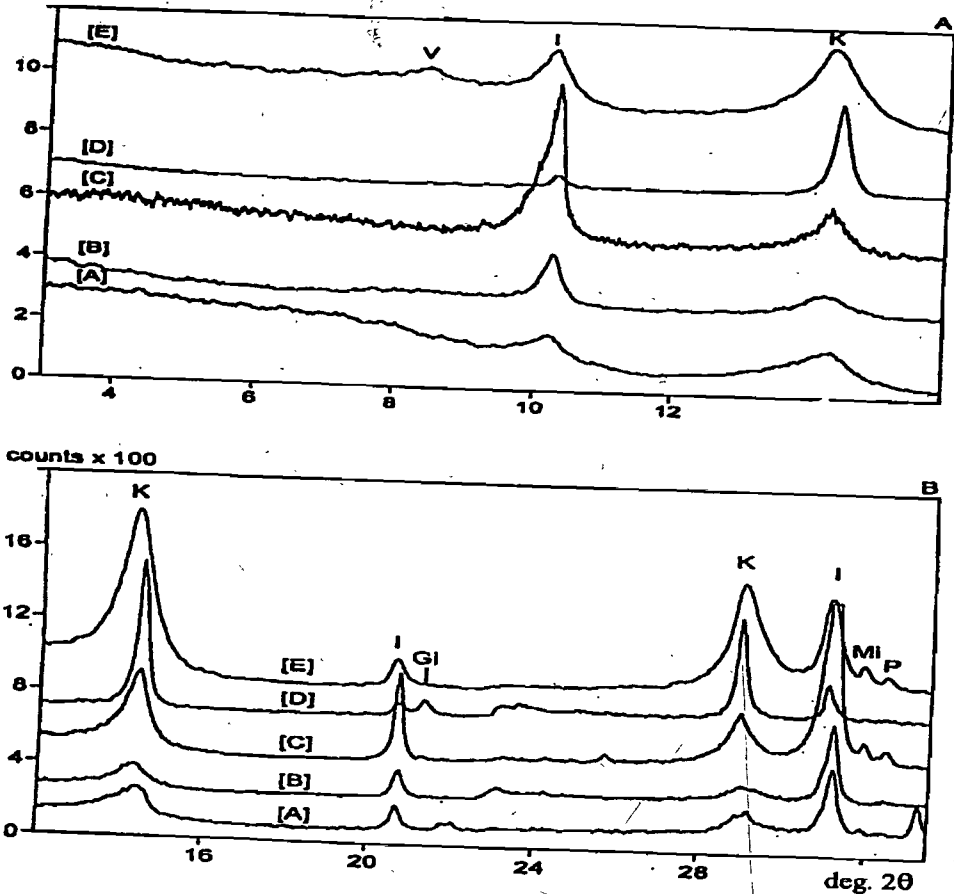


Figure 4: XRD analytical data of the Ca-saturated, DCB-treated, oriented clay samples from the Ap horizon. [A] Mkulula, [B] Ilambilola N, [C] Ikuwala NW, [D] Kiponzelo NW, and [E] Rujewa NW. A: 3-16° 2θ; B: 12-35° 2θ. Symbols of the identified minerals: Gi: Gibbsite; I: Illite; K: Kaolinite; Mi: Microcline; P: Plagioclase; V: Vermiculite-like.

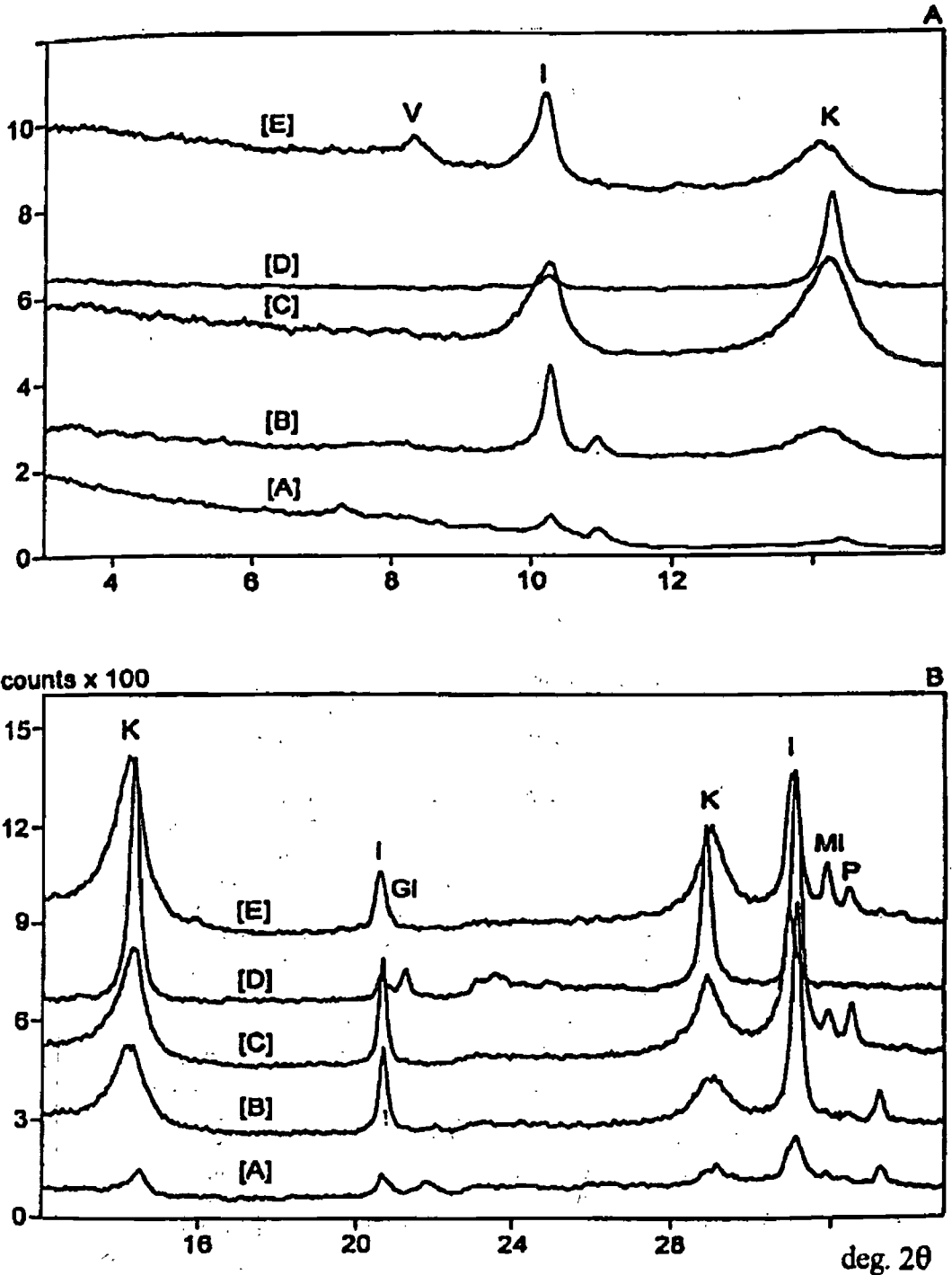


Figure 5: XRD analytical data of the Ca-saturated, DCB-treated, oriented clay samples from the subsurface horizon at approximately one meter depth. [A] Mkulula, [B] Ilambilola N, [C] Ikuwala NW, [D] Kiponzelo NW, and [E] Rujewa NW. A: 3-16° 2 θ ; B: 12-35° 2 θ . Symbols of the identified minerals: Gi: Gibbsite; I: Illite; K: Kaolinite; Mi: Microcline; P: Plagioclase; V: Vermiculite-like.

Table 6. Estimate of the mineral composition of the sand fraction from the surface horizon and the subsurface horizon at approximately one meter depth of the Mkulula, Ilambilola N, Ikuwala NW, Kiponzelo NW, and Rujewa NW soils, based on XRD and microscopic analyses.

Soil	Quartz	K-feldspars	Ca-Na-feldspars	Magnetite/Ilmenite	Amphiboles/Pyroxenes	Mica	Epidote
Mkulula							
Ap	xxxx	xx	xx	(x)	x	tr.	tr.
Bt2	xxxx	x	x	tr.	x	tr.	(x)
Ilambilola N							
Ap	xxxx	-	(x)	tr.	tr.	tr.	tr.
Bt01	xxxx	-	x	tr.	tr.	tr.	tr.
Ikuwala NW							
Ap	xxx	x	xx	tr.	tr.	x	tr.
Btm1	xxx	x	xx	tr.	tr.	x	tr.
Kiponzelo NW							
Ap	xxxxx	-	-	tr.	-	tr.	-
Bt01	xxxxx	-	-	tr.	-	tr.	-
Rujewa NW							
Ap	xxx	xx	xxx	tr.	x	x	(x)
Bt	xxx	x	xxx	tr.	x	(x)	(x)

The intervals are as follows: xxxxx => 90%; xxxx = 90-60%; xxx = 60-30%; xx = 30-10%; x = 10-3%; (x) = 3-1%; tr. = < 1%.

How resilient are these soils towards the impact of cultivation, chemically as well as physically?

Chemically, the substantial to high content of weatherable minerals, such as mica, plagioclase, pyroxene/hornblende and illite reveal, that the Mkulula, Ikuwala, and Rujewa soils seem able through weathering to supply a number of plant nutrients, such as K, Ca, Mg, and certain micro nutrients. The supply will enhance the sustainability of these soils for a much longer time than that of the Kiponzelo and Ilambilola soils. The same holds true for acidification, in case more manure and acidifying fertilizers are applied, the Mkulula soil in particular has a high buffering capacity against acidification. On the contrary, the buffering capacity against acidification of the Kiponzelo soil is low. Based on the composition of the soils, the P-retention is expected to be comparatively weak, except in the Kiponzelo soil, which due to its high content of variable charge compounds and a low pH at depth retain P very strongly, and in case of the Mkulula soil, where the high pH and Ca-Mg carbonate content may cause substantial P retention. The low content of extractable P in the other soils, except in the Rujewa soils, may reflect a low total content of P in these soils.

The mineralogical composition of the Kiponzelo soil indicates, that positively charged plant nutrients can only be stored to a limited extent in that soil. The storage problem is less acute in the Ilambilola soils and is not a serious problem in the other soils, as their mineralogical composition is such that most positively charged plant nutrients can be stored in exchangeable form in these soils, making them quite easily available for the plants.

Physically, the high content of kaolinite and oxides and the very low content of 2:1 layer silicate clay minerals in the Kiponzelo soil indicates, that it has a high amount of stable micropeds which secure good infiltration and drainage. The other soils, especially the Ikuwala and Rujewa soils, have low hydraulic conductivities due to their high amount of illite compared with that of kaolinite and oxides and due to their more silty texture. This, together with their low content of organic matter, leads to surface crusting and formation of a cultivation pan below the Ap horizon.

On the other hand, retention of water in available form is undoubtedly lower in the Kiponzelo soil than in the other soils, due to high content of stable micropeds resulting in a

Table 7: Estimate of the mineral composition of the silt fraction from the surface and subsurface horizon at approximately one meter depth of the Mkulula, Ilambilola N, Ikuwala NW, Kiponzelo NW, and Rujewa NW soils, based on XRD analyses.

Soil	Quartz	K-feldspars	Ca-Na-feldspars	Amph./Pyrox. ¹	Mica	Kaolinite	Gibbsite	Dolomite	Chlorite
Mkulula									
Ap	xxx	x	xx	x	x	-	-	x	-
Bt2	xxx	x	xx	x	xx	-	-	x	-
Ilambilola N									
Ap	xxx	(x)	xx	(x)	x	tr.	-	-	-
Bt01	xxx	(x)	xx	(x)	x	tr.	-	-	-
Ikuwala NW									
Ap	xxx	xx	xx	tr.	xx	-	-	-	-
Btm1	xxx	xx	xxx	tr.	xx	-	-	-	-
Kiponzelo NW									
Ap	xxx	tr.	tr.	-	-	xx	x	-	-
Bt01	xxx	-	tr.	-	-	xx	x	-	-
Rujewa NW									
Ap	xx	x	xxx	x	xx	tr.	-	-	(x)
Bt	xx	x	xxx	x	xx	tr.	-	-	(x)

¹Amphiboles/Pyroxines. The intervals are as follows: XXXXX=>90%; XXXX=90-60%; XXX=60-30%; XX=30-10%; X=10-3%; (X)=3-1%; tr.<1%

Table 8: Estimate of the mineral composition of the clay fraction from the surface horizon and subsurface horizon at approximately one meter depth of the Mkulula, Ilambilola N, Ikuwala NW, Kiponzelo NW, and Rujewa NW soils, based on XRD analyses, TEA, and CEC determinations.

Soil	Quartz	K-feldsp.	Ca-Na-feldsp.	Horn ¹ .	Illite	Illite-Verm ² .	Verm.	Kaol. ³	Fe-oxides	Gibbs ⁴ .	Chlorite
Mkulula											
Ap	x	tr.	tr.	-	xxx	-	x	xxxx	x	-	-
Bt2	xx	tr.	tr.	-	xxx	-	x	xxxx	x	-	-
Ilambilola N											
Ap	-	x	tr.	-	xxxx	tr.	-	xxxx	xx	-	-
Bt01	-	x	tr.	-	xxxx	tr.	-	xxxxx	xx	-	-
Ikuwala NW											
Ap	tr.	tr.	x	-	xxxx	x	-	xxxx	x	-	-
Btm1	tr.	tr.	x	-	xxxx	x	-	xxxx	xx	-	-
Kiponzelo NW											
Ap	tr.	tr.	tr.	-	x	-	-	xxxxx	xx	xxx	-
Bt01	tr.	tr.	tr.	-	xx	-	-	xxxxx	x	xxx	-
Rujewa NW											
Ap	-	xx	x	x	xxxx	x	-	xxxx	xx	-	-
Bt	-	xx	x	x	xxxx	x	-	xxxx	xx	-	-

¹hornblende; ²vermiculite; ³kaolinite; ⁴Gibbsite. The intervals are as follows: XXXXX=>50%; XXXX=50%-20%; XXX=20-10%; XX=10-5%; 5-2%; tr.<2%

the subsurface horizons of the Mkulula soil may

low content of pores in which water available to plants can be stored. The saline properties of

also cause a lower available water storage capacity in that soil than in the other soils.

Biologically, the low content of organic matter in the soils prevents high soil faunal and microbiological activity. Even in the Kiponzelo soil with its higher organic matter content in the surface horizon the biological activity may be limited, as organic matter coated by Fe-oxide complexes makes the humus fraction quite inaccessible for the microbes.

Conclusion

Investigation on the properties and mineralogical composition of five soils from the southern part of the semiarid region of Tanzania indicated that parent material, the climate in the past, and geomorphological features of the area have influenced the development of the soils and caused a substantial variation in their mineralogy. That is certainly a strong impact on their physico-chemical characteristics and resilience.

The Mkulula, Ikuwala and Rujewa soils may be considered to be younger soils pedologically speaking than the Ilambilola soil and particularly the Kiponzelo soil. The reason for this, is that the three first mentioned soils are formed on sedimentary plains on which new deposits of sediments occur from time to time and where there is an influx of base-rich groundwater. On the other hand, the Ilambilola and Kiponzelo soils are formed on hillocks where no fluvial deposits have taken place and from where bases are leached down and removed through the groundwater.

The high clay content in the subsurface horizons, which contain a large amount of kaolinite and a substantial content of gibbsite, discloses that the climate in the past might have been more much more humid than at present, as these characteristics cannot have developed under the present semi-arid conditions. On the other hand, no gibbsite is present in the clay fraction of the Ilambilola soil and the percentage of kaolinite is lower. In that case, its location on a hillock instead of on a lower slope may be the reason for the lower content of weatherable

minerals in this soil compared with that in the Ikuwala soil, which is situated not too far away.

From a plant nutrient point of view, the larger content of weatherable minerals both in the sand, silt, and clay fractions of the Rujewa and Ikuwala soils, leads to greater release of Ca, Mg, K, and of certain micro nutrients by weathering. This means, that a land use system involving low intensity subsistence farming will be much more sustainable on these two soils than on the Kiponzelo soils and to a certain extent on the Ilambilola soil. The Mkulula soil falls somewhat outside this grouping due to its salinity problems.

Physically, the problem of compaction and crusting causes the Ikuwala and Rujewa soils to be much more erodible than the Kiponzelo soil. This makes land use on these soils less sustainable than the Kiponzelo soils, if proper soil conservation measures are not applied.

Inclusion of deep rooting perennial crops in the land use system, especially those which are able to absorb the strongly retained P at depth, and which are able to fix N, will prolong sustainable agriculture, as they will both assure more recycling of leached down plant nutrients and those released by weathering, besides greater availability of P and N.

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