Mineralogical Considerations in Soil Fertility Management on Selected Farmlands in Limpopo and Northwest Provinces, South Africa

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Abstract

Achieving high crop productivity in temperate to sub-tropical soils is a major challenge due to the inherent soil characteristics. The situation is further exacerbated by the erratic climatic conditions and poor farmers' management practices particularly on smallholder farmlands. Hence, a reconnaissance survey was undertaken to bridge the current information gap on chemical and mineralogical characteristics on smallholder farmlands necessary to educate farmers on appropriate management strategy for high and sustainable crop yield. Surface soil samples were collected on 38 farmlands from three municipalities in Northwest and Limpopo provinces of South Africa for physical and mineralogical characterization. Particle size distribution (PSD) was obtained by hydrometer technique whereas random powder analysis (RPA) was employed for mineral identification. This was complemented with an evaluation of soil nutrient status. Texturally, the soils were broadly classified as light textured (≥ 70 % sand) and heavy textured (≥ 30 % clay). The former was characterized by the following mineral assemblage; quartz ± feldspar ± kaolinite ± goethite ± calcite with quartz as the major constituent and kaolinite as minor to trace phases. On average, the heavy texture soils were richer in kaolinite (54 %), mica + smectite (32.1 %) and quartz (26.7 %); and were comparatively richer in nutrients than the light texture soils. The predominance of 1:1 and 2:1 clays in the heavy texture soils confers medium to high cation exchange capacity and infers provenance ascribed to deposition and formation in low energy environments under moderate to high temperature conditions. Furthermore, the characteristic low relief and rainfall in the study areas coupled with moderate to high permeability, favoured the leaching of silica and enrichment of soluble cations readily available for plant uptake. Education of farmers on the appropriate use of fertilizers to enhance plant nutrient uptake and crop yield is highly recommended for increase and sustainable crop production on these farmlands.

Keywords: *Clay minerals, ECEC, crop yield, food security, management practices, soil fertility*

1. Introduction

The desire to eradicate poverty and hunger among millions of the world's human population through increase and sustainable food production is hindered by low agricultural productivity particularly in many Sub-saharan Africa (SSA) countries. This is attributed to numerous factors including the inherent soil characteristics (texture and mineralogy) and farmers' poor management practices such as cropping systems and low to non-use of both inorganic and organic fertilizers (Bado et al. 2004; Dugje et al. 2008; Kutu and Asiwe, 2010) or other soil amendments. Most agricultural farmlands including arid and non-arid soils are dominated by highly weathered low activity clays (LACs), low cation exchange capacity and poor nutrients and water retention. Soil fertility and plant nutrient availability in these soils are largely controlled by soil organic matter (SOM) content (Agboola and Omueti, 1982; Fernandez and Sanchez, 1990; Feller, 1993). Degradation of these soils is exacerbated through loss of SOM following the clearing of natural vegetation and simple land perturbations (Srivastava and Singh, 1989). Excessive human activities such as continuous cultivation and none to low organic inputs into the soil coupled with unfavourable environmental factors often trigger changes in soil physical and chemical characteristics, which affect soil temperature, water content and nutrient cycling processes and consequently exert negative impact on soil productivity. Thus, increased organic matter mineralization after the disruption of the internal recycling system particularly under natural ecosystem leads to increase potentials for rapid nutrient depletion and loss.

The mineralogical composition of soil as dictated by the physical, geochemical and pedochemical weathering, the quality and quantity of organic matter input and the activities of soil biota exert variable effects on soil productivity (Brady and Weil, 1999; Ngole and Ekosse, 2008; Eugène et al., 2010). Hence, the relevance of mineralogical composition study relates to its effects on most soil chemical processes (Faure, 1991) and numerous microbial activities indirectly through their effect on the physico-chemical and chemical properties (Stotzky, 1997; Wattel-Koekkoek et al. 2001). Though small-scale farmers have appreciable knowledge of a productive soil based on experience, the low crop yields often recorded on such supposedly productive soils by this group of farmers possibly suggests a poor link between such indigenous knowledge and their production practices. Regrettably, many of the new generation smallholder farmers may have limited access to such indigenous knowledge due to the declining interest in agriculture and hence possibly results in knowledge gap on its scientific implications for improved land husbandry for increase crop yield. Yet, there are sufficient proofs of the significant implications of inherent soil characteristics such as soil mineralogy on land use (Bühmann et al. 2006a). In South Africa like many other African countries where over 65% of the farming population is dominated by small-scale resource-poor farmers, the provision of such information will constitute an essential step in the right direction to capacitating this important group of farmers. This study therefore aimed at the characterization of selected smallholder farmlands within Limpopo and North West Provinces so as to provide the necessary data for educating them towards adoption of appropriate land management practices for increase and sustainable food crop production.

2. Materials and Methods

2.1 Description of the study sites

The study was carried out in six different villages namely Boons-Magaliesburg area, which is around 35 km north of Vendersdorp municipality (North West Province); Baloon, Nghezemani and Saselomane around Thohoyandou in Thulamela municipality and at Jele and Sofaya in Maruleng municipality (Limpopo Province). Limpopo Province lies within 23^{o} 26’ 22” south of the equator; and has geographical features such as the presence of small and large rivers (e.g. the Sand, Nzhelele, Nwanedi, Luvuvhu, Crocodile and Letaba rivers). The two municipalities are also characterized by summer rainfall and lowveld vegetation with subtropical climate at the eastern and northern parts. Agriculture constitutes the key economic activity in these areas though most small-scale farmers still practice subsistence agriculture. Vendersdorp on the other hand is located within the North West Province and falls within the Vaal River Valley that consist mostly of bushveld vegetation. The area benefits from the Vaal River that flows to other neighbouring provinces and surrounded by the Magaliesburg Mountains with extensive field crop and animal production. The average annual rainfall at Boons-Magaliesburg is 650mm while at Thulamela and Maruleng it is around 600mm. Rainfall in both provinces is often not evenly distributed throughout the year but often occurs between October and April/May during the summer growing season.

2.2 Soil sampling and analyses

Thirty eighty farmers’ fields were visited in three municipalities within North West and Limpopo provinces and information regarding farmers’ management practices gathered through oral interview using a well-structured questionnaire. The fields consisted of individual and community as well as restitution farmlands managed by over 120 small-scale and emerging farmers. Information gathered included that on cropping systems, land husbandry (tillage systems and seedbed forms), plant nutrients management practices (type, sources and quantity of fertilizer material used; methods and time of fertilizer application) and farmers’ knowledge and extent of practice of soil testing as a soil management tool. The interview was accompanied by soil sample collection from topsoil (0-20 cm) from the fields of farmers interviewed. The collected soil samples were analysed for physical, chemical and mineralogical properties. Soil analyses were carried out at Agricultural Research Council, Institute for Soil, Climate and Water (ARC-ISCW) Analytical laboratory using standard laboratory procedures. The determinations included pH (H_2O), exchangeable acidity (1M KCl), organic carbon (Walkley-Black), total N (Kjehldal method) according to Okalebo et al. (2002), Bray1-P and ammonium acetate extractable K, Ca, Mg, and Na. The effective cation exchange capacity (ECEC) for each soil was thereafter calculated as the sum of exchangeable bases and exchangeable acidity. Particle size analysis of the soil samples was carried out using the hydrometer method as cited by Brady & Weil (1999). The mineralogical study on clay fraction of the soil samples ($< 2\ \mu m$) was carried out based on random powder analysis (Whittig and Allardice, 1986) using a Philips X-ray diffractometer for the purpose to quantifying the content of the various clay mineral associations present in the soil.

3. Results

3.1 Distribution of clay minerals and soil primary particles

Table 1 shows a marked variation in the composition of clay mineral assemblage found on the different farmlands at the three localities. Kaolinite and quartz jointly constituted more than 65 % of the clay minerals assemblage in soil at the different localities. The mean contents of quartz and mica in soils from Boons (North West Province) were more than 72 % and 43 % higher, respectively than those from Thulamela and Maruleng (Limpopo Province). There was also a considerable presence of interstratified clay mineral such as smectite in virtually all the soil samples from Thulamela and Maruleng which occurred in 20 % of the soils sampled at Boons. The mean content of the smectite mineral in soils from Maruleng was more than quadruple the average content in soils from Boons and doubled the average content in soils from Thulamela.

Table 1: Percent distribution of clay mineral types in the collected soil samples

Farmers' fields	Quartz	Kaolinite	Mica	Chlorite	Goethite	Smectite	Hematite	Talc	Feldspar
Magaliesburg (North West Province)									
Boons 1_2	43	24	23	-	10	-	-	-	-
Boons 1	44	34	15	-	7	-	-	-	-
Boons 2	53	24	16	-	7	-	-	-	-
Boons 3	49	22	25	-	-	4	-	-	-
Boons 4	49	30	13	-	9	0	-	-	-
Boons 5	15	57	8	-	-	15	5	-	-
Boons 6	30	39	-	-	3	28	-	-	-
Boons 7	25	34	20	-	7	14	-	-	-
Boons 8	44	23	5	-	13	15	-	-	-
Boons 9	20	56	15	-	-	-	9	-	-
Boons 10	20	61	12	-	-	-	7	-	-
Boons 11	21	60	10	-	9	-	-	-	-
Boons 12	34	30	11	-	8	17	-	-	-
Boons 13	42	32	23	-	3	-	-	-	-
Boons 14	31	44	22	-	3	-	-	-	-
Boons 15	23	43	30	-	4	-	-	-	-
Boons 16	35	40	21	-	4	-	-	-	-
Boons 17	21	59	14	-	-	-	6	-	-
Boons 18	15	68	10	-	-	-	7	-	-
Boons 19	12	61	18	-	-	-	9	-	-
Thohoyandou-Thulamela (Limpopo Province)									
Baloon 1-1Ud	21	51	12	16	-	-	-	-	-
Baloon 1-2Ld	2	75	5	18	-	-	-	-	-
Nghezemane	0	58	10	26	6	-	-	-	-
Saselomane1	39	33	12	-	-	14	-	2	-
Saselomane2	39	30	9	-	-	18	-	4	-
Saselomane3	22	42	16	-	-	8	-	-	12
Saselomane4	7	70	4	13	6	-	-	-	-
Saselomane5	15	51	-	-	9	25	-	-	-
Maruleng (Limpopo Province)									
Jele1-2Ld	-	85	5	-	-	1	9	-	-
Jele1-1Ud	17	43	-	-	6	34	-	-	-
Jele2	32	10	9	-	4	45	-	-	-
Sofaya1	22	44	0	-	7	27	-	-	-
Sofaya2	29	31	16	-	10	14	-	-	-
Sofaya3	6	83	7	-	-	4	-	-	-
Sofaya4	3	94	-	-	1	2	-	-	-
Sofaya5	40	12	14	-	6	28	-	-	-
Sofaya6	16	32	14	-	4	34	-	-	-

Chlorite and feldspars as well as talc constituted additional clay minerals found exclusively in soils at Thulamela municipality. The presence of variable amount of goethite and/or hematite, a resistant clay mineral group, on approximately 87 % of the fields visited suggests that the soils were at the intermediate to advanced stages of weathering (Ajiboye et al. 2008).

The maximum, minimum and mean values as well as the standard deviation of sand, silt and clay as well as the range of textural classification for the soils from the different localities are contained in Table 2. The different textural classification of these soils is influenced by the high degree of variation in the proportion of sand, silt and clay contents. The sand fraction was more relevant to soil textural classification than the clay and silt contents while the low percent silt content in these soils agrees perfectly with the fairly low quartz clay content, which suggests the low possibility for predisposing these fields to hardsetting behaviour (Gusli et al. 1994; Bühmann et al. 2006a).

Table 2: Summary of particle size distribution and textural classification of the soils

Primary particles	Maximum	Minimum	Mean	Std. dev.	Textural class
Boons-Magaliesburg (n=20)					
Sand (%)	73.5	27.4	50.9	15.6	
Silt (%)	37.1	12.5	24.2	7.84	SaLm, ClLm,
Clay (%)	42.0	12.0	24.9	8.7	SaClLm, Lm.
Thohoyandou-Thulamela (n=8)					
Sand (%)	81.1	32.8	52.2	17.1	
Silt (%)	33.1	4.9	20.1	9.8	LmSa, Lm,
Clay (%)	50.1	12.0	26.8	10.9	SaClLm, ClLm.
Jele/Sofaya-Maruleng (n=9)					
Sand (%)	80.3	41.5	64.7	12.4	
Silt (%)	14.5	4.0	9.8	3.3	SaLm, LmSa,
Clay (%)	44.0	6.0	24.9	12.4	SaClLm, SiCl.

Lm: Loam, SaLm: Sandy loam, LmSa: loamy sand, SaClLm: Sandy clay loam, ClLm: Clay loam, SiCl: Silty clay, Std. dev.: Standard deviation.

3.2 Soil nutrient composition in relation to farmers' management practices

A critical requirement in soil fertility management includes ensuring nutrients sufficiency level for optimum plant growth and high crop yields. Nutrient availability is optimum at pH value around 6.5 in mineral soils (Nelson, 1968). The mean pH values recorded in these soil samples ranged from 5.68 at Boons in North West to 6.94 at Nghezemane in Thulamela municipality indicating fairly acidic to neutral conditions (Table 3). Though the high pH values obtained in some of the soil samples was attributed to the presence of soluble bases particularly calcium, the correlation between pH and the sum of exchangeable bases was poor (r^2=0.056). On the other hand, calcium content gave a strong and positive correlation with the effective cation exchange capacity of the soils (r^2=0.990). Furthermore, the content of exchangeable acidity of the soils that ranged from 0.024 to 0.106 cmol(+)/kg may probably be related to the presence of moderate level of crystalline minerals such as hematite present. The organic carbon content in the soils was fairly high, ranging from 0.42 to 2.48 %; but being generally much lower in the soils around Maruleng municipality. Nevertheless, majority of these values were relatively high in view of the low rainfall amount in those parts of the country and the higher summer temperatures that favour high organic matter mineralization. The total N level in the soils ranged from 0.017 to 0.160 % and was generally described as low except in ten soils from farmers' fields at Boons-Magaliesburg where the values were within the threshold level of 0.08 to 1.0 %.

Available P level in the soils ranged from 0.98 to 40.71 mg kg^{-1} and are described as generally low. Only six of the farmers' fields showed adequate plant available P level in terms of sufficiency range of 15 to 35 mg kg^{-1} for grain crops (Buys, 1986) suggesting a possible fairly good inorganic fertilizer use practice by these farmers to increase crop yield. As expected, the K level in virtually all the soil samples was above the 40 mg kg^{-1} optimum level (Buys, 1986) due to the moderate level of K-bearing mineral (mica) in the soils except in few cases. The Ca content of the soils was generally within the optimum level of 300 to 2000 mg kg^{-1} (Buys, 1986) while the Mg level was similarly above the minimum threshold limit of 35 mg kg^{-1} suggested by Mengel and Kirkby (1982). Although Ca:Mg ratio of 4:1 in soil was considered optimum (Buys, 1986), lower values that ranged from 2:1 to 3:1 were recorded in more than 68 % of the soil samples studied (data not shown). This was possibly attributed to the presence of highly weathered K-bearing minerals and the ease of removal of Mg from the soil through leaching (Bühmann et al. 2006b).

Table 3: Summary of selected chemical properties of the soil samples

Farmer's field per locality	pH (H_2O)	% Total N	% Org. C	Bray1-P mg/kg	Ex. Acid [cmol(+)/kg]	Ca mg/kg	K mg/kg	Mg mg/kg	ECEC [cmol(+)/kg]
Boons 1-2	6.20	0.060	1.1	2.07	0.067	419	89	143	3.70
Boons 1	6.50	0.043	0.85	1.08	0.062	304	30	126	2.77
Boons 2	6.02	0.067	1.18	1.92	0.068	399	89	122	3.40
Boons 3	6.04	0.048	0.84	2.02	0.069	394	105	96	3.19
Boons 4	5.81	0.035	0.7	1.57	0.106	320	68	100	2.79
Boons 5	5.88	0.078	1.32	1.59	0.053	919	251	256	7.59
Boons 6	5.68	0.080	1.38	2.02	0.071	712	242	283	6.76
Boons 7	6.28	0.160	2.48	1.42	0.053	1820	104	695	15.41
Boons 8	6.04	0.077	1.31	1.18	0.035	943	246	337	8.32
Boons 9	5.84	0.087	1.34	1.77	0.049	1048	181	437	9.56
Boons 10	5.83	0.104	1.75	2.41	0.054	763	304	321	7.37
Boons 11	5.84	0.129	2.14	1.57	0.049	932	262	374	8.63
Boons 12	6.35	0.130	2.22	0.98	0.046	1281	241	644	12.52
Boons 13	6.04	0.109	1.86	1.77	0.046	834	313	260	7.31
Boons 14	5.88	0.093	1.34	1.76	0.049	757	257	249	6.67
Boons 15	5.83	0.101	1.65	1.97	0.041	876	295	277	7.75
Boons 16	5.97	0.088	1.45	2.31	0.046	789	308	242	6.90
Boons 17	6.77	0.047	0.69	40.71	0.036	468	174	124	3.93
Boons 18	6.10	0.046	0.67	10.89	0.076	273	75	90	2.46
Boons 19	6.20	0.025	0.42	18.19	0.056	287	56	92	2.48
Baloon 1-1Ud	6.14	0.037	1.06	4.31	0.048	599	166	173	5.03
Baloon 1-2Ld	6.29	0.020	0.67	1.44	0.055	526	150	174	4.69
Nghezemane	6.94	0.058	1.34	3.92	0.061	1479	140	526	12.58
Saselomane1	6.63	0.067	1.52	1.63	0.061	2421	143	803	19.73
Saselomane2	6.36	0.055	1.48	1.71	0.064	1674	91	489	13.22
Saselomane3	6.37	0.063	1.45	2.91	0.057	2585	149	735	19.46
Saselomane4	6.24	0.071	1.59	1.71	0.039	1236	118	443	10.40
Saselomane5	6.37	0.078	1.72	2.83	0.057	2419	126	791	19.39
Jele1-2Ld	5.98	0.021	0.43	2.95	0.057	326	37	75	2.51
Jele1-1Ud	5.74	0.022	0.45	14.95	0.053	450	86	117	3.59
Jele2	6.16	0.022	0.47	2.25	0.054	278	25	79	2.34
Sofaya1	6.54	0.042	1.17	3.30	0.024	649	91	201	5.33
Sofaya2	6.16	0.052	1.38	5.86	0.040	645	175	308	6.43
Sofaya3	6.48	0.035	1.10	2.29	0.038	600	50	171	4.61
Sofaya4	6.36	0.017	0.66	11.88	0.069	429	61	79	3.03
Sofaya5	6.98	0.026	0.80	20.13	0.043	1046	112	114	6.62
Sofaya6	6.19	0.029	1.07	5.00	0.050	724	129	168	5.53

The values of ECEC found in these soils were moderate to high and ranged from 2.51 to 19.73 cmol(+)/kg with an average of 7.41 cmol(+)/kg. The high values in soils from Thohoyandou might be associated with the presence of Ca and Mg-rich minerals such as feldspars, talc and chlorites. A strong correlation (r^2=0.654) exists between percent organic carbon and ECEC signifying the importance of SOM as a cation exchange site and source of nutrient storage.

4. Discussion

The heterogeneity of clay mineral assemblage on the fields at the three localities has implications on the scale and scope of management advisory policies and/or farmers' decisions. It also reflects the intensity of weathering at the different localities. The more than 65 % mineral composition in these soils jointly represented by chemically inert and low activity clays such as quartz and kaolinite with poor nutrients retention capacity suggest that the soils may be fragile and must be carefully managed. Such careful management is crucial for the success of agricultural production mostly by resource-poor and emerging farmers whose livelihood revolve solely around farming on these lands. However, the presence of considerable amount of mica and/or smectite in these soils, which were more in soils from Maruleng municipality (average value of 28 % compared to 21 % and 17 % in soils at Boons and Thulamela, respectively) has positive implications due to the charge characteristics of these minerals. It constitutes an enormous advantage in view of its potential influence on cation exchange capacity (CEC) via higher organic matter accumulation (Wattel-Koekkoek et al. 2001; Ngole and Ekosse, 2008). Nutrient retention from inorganic fertilizer application and the potential fertility status on the fields could be enhanced in such mica and/or smectite-rich soils.

The presence of fairly high proportion of mica, a K-bearing clay mineral, suggests that the K pool on these fields can be naturally replenished. This agrees with the high exchangeable K level obtained in these soils. The reduction in the percent quartz clay and increase in the percent kaolinite increases the nutrient retention, the organic matter stabilizing effects and possibly the aggregate stability of the soils (Bühmann et al. 2006a). This has a potential positive impact on soil fertility status and improved soil structure. Furthermore, the reduction in the quartz clay content, a chemically inert soil component (Zelazny et al., 1996), in virtually all the samples suggests a highly reduced tendency for hardsetting or soil compaction of the fields. Soils with a marked hardsetting tendency tend to have a high content of clay-size quartz (Cass and Johnston, 1985). The low level of available P in these soils could possibly be attributed to limited use of inorganic fertilizers while the manures that were reportedly utilized by majority of the smallholder farmers were possibly applied at suboptimal level. The more than 30 % clay content in over thirty seven percent of the soil samples collected (eight from Boons, two from Thulamela and four from Maruleng) exerted heavy textural characteristic on the soils and has great influence on soil tilth.

5. Conclusions

The results of this study showed a marked variation in soil fertility status across the various fields, which was influenced by the differences in mineralogical composition. The dominance of 2:1 expanding clay minerals such as mica and/or smectite in these soils impacted improved soil fertility conditions that could favour increase agricultural productivity. The presence of kaolinite also serves as source of binding agent in the soil for organic matter accumulation. Thus, management strategy that promotes high plant residue return with the aim of increasing the soil organic matter level on these fields will ensure increase and sustainable crop production. Application of P fertilizers and basal level of calcite lime to raise the Ca:Mg ratio on these fields will also be beneficial. Cautious improved fertilizer programme such as the complementarily use of inorganic fertilizer with animal manures should also be vigorously promoted among rural smallholder farmers so as to increase the exchange sites for nutrients retention and also conserve moisture. Where access to inorganic fertilizers is limited due to financial resource constraints on the part of the resource-poor farmers, integration of grain legumes into the farmers' cropping systems should be promoted. Education of rural small-scale and emerging farmers on the relevance of clay mineralogy for better land husbandry and improve soil fertility management is crucial for increase and sustainable crop production.

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