

Relationships between soil buffer capacity and selected soil properties in a resource-poor farming area in the Mpumalanga Province of South Africa

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In this study, the soil buffer capacity (soil BC) was measured for 80 topsoil samples of the most dominant soil forms in a small-scale farming area. Soils used in the study ranged from weakly to strongly buffered, with soil BC values ranging from 0.12 to 2.23 cmol (+) kg⁻¹ pH unit⁻¹. Relationships of soil BC over limited pH ranges showed that at soil BC_(pH<4.5) the main buffering mechanism was extractable Al > organic C > clay. At soil BC_(pH4.5-6.5) the buffering mechanism was extractable Al > clay > CBD-Al > organic C > CBD-Fe. The main buffering mechanism between pH 6.5-8.5 was clay > CBD-Fe, organic C > CBD-Al. At the general pH range of buffering (4.5-8.5), clay > organic C > extractable Al > CBD-Al > CBD-Fe were the main buffering mechanisms. The main soil forms, viz., Clovelly and Hutton, tended towards lower soil BC, extractable Al (or acidity) and acid saturation, and higher pH, extractable Ca and Mg values, compared to the Magwa and Inanda soil forms which had higher soil BC but lower extractable Al (or acidity), pH and extractable Ca and Mg levels. Clovelly soils tended to have lower clay, CBD-Fe and CBD-Mn contents than the Hutton soils in the study area.

Keywords: Potentiometric titration curves, principal component analysis, soil buffering capacity

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Introduction

One of the main problems with soil acidity is the relationship between the total acidity of the system (*i.e.* the nature and amounts of proton donors in the solid phase) and the intensity of acidity (*i.e.* the activity of hydrogen ions in the soil solution). This relationship is defined as the soil buffer capacity (Bache, 1988). The determination of soil buffer capacity (soil BC) has long been of interest to soil chemists and crop scientists. The reason is that many crops respond positively to the addition of lime to acid soils, but because of the differences in soil BC, soils of similar pH may require vastly different quantities of lime to yield the same increase in pH. A soil's BC is furthermore also needed to understand the rate of natural soil weathering as well as the rate of soil acidification from acid-forming nitrogen fertilizers, acid rain, and acid mine waste (Bloom, 2000).

Laboratory measurement of soil BC by titration techniques is used to directly determine lime requirement (McLean *et al.*, 1966; Follett & Follett, 1983), to calibrate rapid lime requirement tests and to ascertain soil BC in acidification studies enabling calculation of acidification rates (Helyar & Porter, 1989; van Breemen, 1991; Aitken & Moody, 1994).

The general factors responsible for soil BC and pH buffering in soils, include the amount of organic matter (OM) and the type of clay minerals present (Magdoff *et al.*, 1987). Soil buffering caused by the protonation and deprotonation of minerals and organic materials reduces the change in soil pH when acids or bases are added to the soil. In most soils, the general pH range of buffering by soil components is from 4.0 to 8.0. Acid buffering mechanisms include aluminosilicate dissolution at low pH and CaCO₃ dissolution in the upper pH range. Buffering at intermediate pH (5.0 to 7.5), which is of more interest in agriculture, is mainly by cation exchange reactions in which functional groups associated primarily with variable-charge minerals and soil organic matter act as

sinks for H⁺ and OH⁻ ions. The buffering that occurs because of organic matter is from the weakly acidic carboxylic and phenolic functional groups (Nielsen *et al.*, 1995; Curtin *et al.*, 1996; Curtin & Ukrainetz, 1997; Weaver *et al.*, 2004).

Currently limited information is available on the soil properties that govern the soil BC of South African soils. In this study the relationships between soil properties and buffer capacities for 80 acidic soils from the Mlondozi district of Mpumalanga were investigated. The objectives of the study were to (i) determine soil buffer capacity, and (ii) examine the relationships between soil buffer capacity and selected soil properties.

Material and methods

Soils

The data used in this study were collected from a total of 80 topsoil (0-250 mm) samples in the Mlondozi district. The soils represented the most dominant soil forms, namely Clovelly and Magwa, with the Hutton and Inanda soil forms sub-dominant (Booyens *et al.*, 2000).

The area of study lies between 26°05'S - 26°30'S and 30°44'E - 31°00'E. The long-term annual rainfall of the area ranges between 893 - 992 mm from north to south in the district, with monthly average daily temperature ranging from 10.2°C for June to 18.9°C for December. The soils developed on quartz monzonite of the Mpuluzi Granite formation.

Soil analysis

Topsoil samples were air-dried and ground to pass through a 2 mm sieve. A particle size analysis was performed on the <2 mm soil fraction using the pipette method. The cation exchange capacity (CEC) was determined with 1 mol dm⁻³ ammonium acetate (NH₄OAc) extraction at pH 7. The Walkley-Black method was used for the determination of organic carbon. Extractable acidity (H + Al) and Al were determined

in a 1 mol dm⁻³ potassium chloride (KCl) extraction and titration with 0.1 M NaOH. Extractable Al was determined in the same extract by complexing it by adding 10 cm³ NaF to the titrate, and titrating again to an end point. Soil pH (H₂O) and pH (KCl) were determined in 2:5 (soil:water) and (KCl) suspension, respectively, using a combined calomel reference glass electrode and pH meter. Free oxides of iron, aluminium and manganese in soils were determined by heating 4 g of soil in a water-bath at 77°C in a Na-citrate/Na-bicarbonate/Na-dithionite solution (CBD-method) and the amount of Fe, Al and Mn recorded by atomic absorption (The Non-Affiliated Soil Analysis Work Committee, 1990).

Potentiometric titration curves

Potentiometric titrations (Ponizovskiy & Pampura, 1993) were performed on samples that were equilibrated overnight with 1 M KCl. Each soil sample was suspended in 100 ml 1 M KCl, stirred and left overnight. The suspension was titrated with 0.05 M NaOH whilst being stirred on a Metrohm potentiograph to a pH of 8.5. The titration rate was 0.667 ml minute⁻¹. For each soil a linear regression function was fitted to the relationship between 0.05 M NaOH added and soil pH. Equation 1, revised from Bache (1988), was used to determine soil buffer capacity (soil BC).

$$\text{Soil buffer capacity (cmol (+) kg}^{-1} \text{ soil pH unit}^{-1}) = d(\text{OH}^-)/dpH \quad [1]$$

where dpH is the change in pH (pH unit) due to the addition of $d(\text{OH}^-)$ (cmol (+) kg soil⁻¹) of base (NaOH).

Bache (1988) showed that the soil BC of any given soil is not constant over the whole pH range. Therefore in order to evaluate the effect, the soil BC was determined over limited pH ranges, namely <4.5, 4.5-6.5, 6.5-8.5 and 4.5-8.5.

X-ray diffraction analysis

X-ray diffraction analyses were performed on soil samples

according to the method described by Jackson (1956). X-ray diffraction (XRD) analyses were carried out on a PANalytical X'pert Pro system unit with a MPPC generator (PW 3050/609theta/theta) goniometer. Standard experimental conditions were 40 kV, 35 mA, a scanning speed of 10 min/45° 2θ and a sample spinning speed of 8 sec revolution⁻¹. Relative intensities or peak heights and the width at half height of X-ray diffraction peaks were used to produce estimates of the approximate amounts of minerals present in the sample and are expressed as percentages of the total composition of the sample.

Statistical analysis

Soil BC was determined over limited pH ranges, namely <4.5, 4.5-6.5, 6.5-8.5 and 4.5-8.5, and correlated with selected soil properties using Pearson's coefficient of correlation. The latter also known as the product moment correlation coefficient, is a measure of the linear relationship between two random variates (-1<r<1) (Draper & Smith, 1981). Forward Selection Stepwise Regression was used to find those soil properties most responsible for describing the variation found in soil BC.

Principal Component Analysis (PCA) was applied to the soil data in order to identify the interrelationship between the main variates that explained the soil BC, and therefore to simplify the interpretation of the soil characteristic data. The first axis, score [1] (SC [1]), explained 50.35% of the variation in the entire dataset, and the second axis, score [2] (SC [2]), explained 29.54% of the remaining variation. Axis 3, score [3] (SC [3]), only explained a trivial amount of 9.68%. Table 1 shows which soil properties contribute to which axis. Soil BC, pH (H₂O), pH (KCl), extractable acidity and Al, acid saturation, log Ca and Mg were the strongest correlated with SC [1] and to a lesser extent correlated to SC [2] and SC [3], and will therefore contribute to SC [1]. Similarly clay, CEC, log CBD-Fe and CBD-Mn were the strongest correlated with SC [2] and therefore will contribute to SC [2].

Table 1 Correlation matrix obtained from principal component analyses between the variables and some scores

Variable	Score 1 SC [1]	Score 2 SC [2]	Score 3 SC [3]
Soil buffer capacity	0.918	0.232	0.093
pH (H ₂ O)	-0.833	0.243	0.142
pH (KCl)	-0.786	0.269	0.044
Extractable acidity	0.948	-0.076	0.186
Extractable Al	0.940	-0.065	0.167
Acid saturation	0.914	-0.299	0.108
Log Ca	-0.733	0.527	-0.048
Log Mg	-0.735	0.533	-0.071
Log C	0.398	0.608	0.199
Clay	0.416	0.758	-0.056
CEC	0.271	0.758	0.113
Log CBD-Al	0.511	0.636	-0.145
Log CBD-Fe	0.344	0.815	-0.255
Log CBD-Mn	0.076	0.699	-0.191
Quartz	-0.407	0.003	0.772
Kaolinite	0.064	-0.359	-0.823

All statistical analyses were done using Genstat (2003).

Table 2 The range of selected soil physical and chemical topsoil (0-250 mm) properties for the experimental soils

Soil property	Range	Four classes per soil property			
pH (H ₂ O)	4.60-7.54	<5.0 (13 ¹)	5.0-5.5 (34)	5.5-6.0 (23)	>6.0 (10)
pH (KCl)	3.72-6.42	<4.0 (31)	4.0-4.5 (32)	4.5-5.0 (9)	>5.0 (8)
Extractable Al (cmol(+) kg ⁻¹)	0-1.87	<0.5 (48)	0.5-1.0 (23)	1.0-1.5 (7)	>1.5 (2)
Extractable acidity (cmol(+) kg ⁻¹)	0-2.61	<0.5 (39)	0.5-1.5 (35)	1.5-2.5 (5)	>2.5 (1)
Acid saturation (%)	0-93.50	<20 (38)	20-40 (11)	40-60 (22)	>60 (9)
Organic C (%)	1.13-9.14	<1.5 (9)	1.5-2.0 (24)	2.0-3.0 (35)	>3.0 (12)
Clay (%)	8.30-53.10	<20 (6)	20-30 (21)	30-40 (37)	>35 (16)
BC _{4.5-8.5} (cmol(+) kg ⁻¹ pH unit ⁻¹)	0.12-2.23	<0.25 (9)	0.25-0.5 (16)	0.5-1.0 (35)	>1.00 (20)
CEC (cmol (+) kg ⁻¹)	3.34-15.5	<5.0 (14)	5.0-7.5 (39)	7.5-10.0 (13)	>10.0 (14)
CBD-Al (%)	0.06-2.43	<0.5 (26)	0.5-1.0 (38)	1.0-1.5 (11)	>1.5 (5)
CBD-Fe (%)	0.38-7.11	<1.5 (25)	1.5-3.0 (35)	3.0-4.5 (12)	>4.5 (8)
Kaolinite (%)	32-91	<40 (2)	40-60 (39)	60-80 (36)	>80 (5)
Quartz (%)	0-52	<15 (35)	15-30 (36)	30-45 (7)	>45 (2)
Gibbsite (%)	0-44	<5 (51)	5-15 (16)	15-25 (8)	>25 (5)
Goethite (%)	0-30	<5 (26)	5-10 (18)	10-15 (23)	>15 (13)
Mica (%)	0-9	<3 (49)	3-6 (22)	6-9 (9)	>9 (0)

¹ Number of soils per class

Results and discussion

Soil characteristics

Some of the physical and chemical properties of the experimental soils are reported in Table 2.

The soils used in this study represent a wide range of properties. The mean soil pH (H₂O) and mean pH (KCl) ranged from highly acidic to alkaline and were 4.60 to 7.54 (mean 5.35), and 3.72 to 6.42 (mean 4.13), respectively. The mean pH (KCl) was 1.20 times lower than the mean soil pH (H₂O), indicating that the soils used in the study contained a considerable amount of reserve acidity.

The organic C content ranged between 1.13 and 9.14% (mean 2.12%) and clay content 8.3 to 53.1% (mean 32.2%). The relatively high level of organic C is the result of moderate annual temperature and high rainfall which reduces the decomposition and mineralization rates. The CEC of the soils varied from low to medium (3.59 to 15.5 cmol (+) kg⁻¹) with a mean of 6.5 cmol (+) kg⁻¹. The dominant clay mineral was kaolinite. Kaolinite is a low activity clay which has little or no permanent charge and therefore little capacity to buffer soil pH (Bloom, 2000). Soil BC data shown in Table 2 are comparable with the normal range found in the literature (0.38-1.34; De Sá Mendonça *et al.*, 2005).

Potentiometric titration curves

Figure 1 illustrates combined data titration curves for the main soil forms found in the study area.

Titration curves followed the same general pattern as reported for surface soil horizons (Magdoff *et al.*, 1987). The Hutton, Magwa and Inanda soils tended to be relatively moderately buffered in the midrange (pH 5.25-7.5) with no clear lower asymptotes and an upper asymptote up to pH 8.5. The Clovelly soil forms were very poorly buffered by comparison. The Inanda soils showed a tendency to be well buffered (Figure 1). The differences in the titration curves and resultant soil BC can probably be ascribed to a combination of differ-

ent factors, of which the differences in extractable acidity (0.34 vs 1.07 cmol (+) kg⁻¹) and Al (0.25 vs 0.77 cmol (+) kg⁻¹) that were observed between the soil forms, could make substantial contributions.

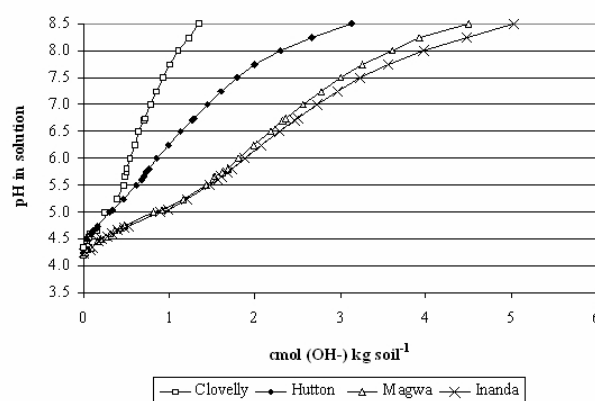


Figure 1 Combined titration curves for the dominant soil types.

Maximum buffering, defined as the minimal slope of pH versus added acid or alkali (Magdoff & Bartlett, 1985), seems to occur at both pH 5.0 and 7.5. Figure 1 also shows that the buffer curves were fairly linear in the pH range 5.0 to 7.5, especially for the Magwa and Inanda soil forms.

Table 3 Correlation matrix for the relationship between soil buffer capacity and selected soil properties

	BC	BC	BC	BC	pH	pH KCl	Extr acid	Extr Al	L Ca	L org. C	Clay	CEC	L CBD- Al	L CBD- Fe	L CBD- Mn	Qt	Kt	Go	
	4.5-8.5	<4.5	4.5-6.5	6.5-8.5	(H ₂ O)														
BC <4.5	0.65 ^{***}																		
BC 4.5-6.5	0.86 ^{***}	0.77 ^{***}																	
BC 6.5-8.5	0.94 ^{***}	0.48 ^{***}	0.64 ^{***}																
pH (H ₂ O)	-0.55 ^{***}	-0.55 ^{***}	-0.74 ^{***}	-0.42 ^{***}															
pH KCl	-0.47 ^{***}	-0.58 ^{***}	-0.65 ^{***}	-0.35 ^{***}	0.92 ^{***}														
Extr acid	0.65 ^{***}	0.82 ^{***}	0.86 ^{***}	0.48 ^{***}	-0.75 ^{***}	-0.66 ^{***}													
Extr Al	0.68 ^{***}	0.83 ^{***}	0.87 ^{***}	0.51 ^{***}	-0.76 ^{***}	-0.65 ^{***}	0.98 ^{***}												
Log Ca	-0.21	-0.33*	-0.47 ^{***}	-0.04	-0.70 ^{***}	0.64 ^{***}	-0.72 ^{***}	-0.69 ^{***}											
Log org. C	0.69 ^{***}	0.65 ^{***}	0.58 ^{***}	0.69 ^{***}	0.15	-0.12	0.38 ^{***}	0.38 ^{***}	0.03										
Clay	0.74 ^{***}	0.63 ^{***}	0.62 ^{***}	0.77 ^{***}	-0.17	-0.10	0.32**	0.32**	0.05	0.55 ^{***}									
CEC	0.60 ^{***}	0.49 ^{***}	0.44 ^{***}	0.61 ^{***}	-0.08	-0.09	0.26*	0.23**	0.15	0.48 ^{***}	0.73 ^{***}								
Log CBD ^a -Al	0.68 ^{***}	0.62 ^{***}	0.60 ^{***}	0.68 ^{***}	-0.25 [*]	-0.15	0.36**	0.38 ^{***}	-0.11	0.66 ^{***}	0.64 ^{***}	0.39 ^{***}							
Log CBD ^a -Fe	0.66 ^{***}	0.52 ^{***}	0.50 ^{***}	0.71 ^{***}	-0.17	-0.09	0.18	0.19	0.13	0.53 ^{***}	0.70 ^{***}	0.56 ^{***}	0.85 ^{***}						
Log CBD ^a -Mn	0.38 ^{***}	0.23	0.25*	0.45 ^{***}	-0.01	0.03	0.02	0.035	0.26*	0.15	0.46 ^{***}	-0.58 ^{***}	0.38 ^{***}	0.68 ^{***}					
Quartz	-0.23*	-0.26	-0.28*	-0.18	0.31**	0.17	-0.23*	-0.21	0.18	-0.08	-0.21	-0.03	-0.29*	-0.24*	-0.01				
Kaolinite	-0.20	-0.11	-0.09	-0.23*	-0.13	-0.04	-0.07	-0.04	-0.10	-0.28	-0.17	-0.31**	-0.13	-0.16	-0.09	-0.55***			
Goethite	0.22	0.11	0.04	0.30**	0.11	0.17	-0.19	-0.16	0.30**	0.13	0.30**	0.08	0.33**	0.41 ^{***}	0.21	-0.10	-0.14		
Gibbsite	0.38 ^{***}	0.35 [*]	0.40 ^{***}	0.32 ^{**}	-0.23 [*]	-0.20	0.43 ^{***}	0.38 ^{***}	-0.24	0.38 ^{***}	0.26 [*]	0.29 ^{**}	0.35 ^{**}	0.25 [*]	-0.01	-0.19	-0.56 ^{***}	-0.18	

^a Sodium-citrate-bicarbonate-dithionite

* P<0.05, **P<0.01 & ***P<0.001

Soil BC over limited pH ranges vs soil properties

The relationships between soil BC for different soil pH ranges and selected soil properties are presented in Table 3.

It was found that all soil BCs were highly significantly ($P < 0.001$) correlated with clay content, log organic C content, extractable Al and acidity, log CBD-Al and Fe, and CEC, and to a lesser extent with pH (H_2O & KCl), CBD-Mn and gibbsite. However, the buffer capacity of any given soil is not constant over the whole pH range (Bache, 1988). The buffer capacity reactions in soils include proton desorption and adsorption reactions by mineral and organic minerals, as well as ion exchange, dissolution and precipitation reactions. Some of the soil components are effective in buffering over a wide range of pH values, while others are effective over a limited pH range (Bloom, 2000). Therefore, the relationship of soil BC, over limited pH ranges, with selected soil properties was further evaluated.

Soil BC (pH<4.5): The correlation matrix (Table 3) reveals that extractable acidity and Al was the best correlated with soil $BC_{(pH<4.5)}$, followed by organic C and clay content

(all $P < 0.001$). Previous studies showed that the soil BC increases as pH drops below 4.5. This is mainly due to Al buffering, proton adsorption by clays and hydrous oxides (Kauppi *et al.*, 1986; Bache, 1988; Bloom, 2000). The significant correlation of organic C and clay content with soil $BC_{(pH<4.5)}$ is consistent with previous studies which showed that both of these parameters buffer pH over a wide range of pH values (Magdoff *et al.*, 1987; Bloom, 2000; Weaver *et al.*, 2004). In acid mineral soils, many of the $-COOH$ sites in soil organic matter are taken up by Al^{3+} and this strongly bound Al has a large effect on buffering.

Soil BC (pH4.5-6.5): Soil properties found to correlate highly significantly ($P < 0.001$) with soil $BC_{(pH4.5-6.5)}$, were extractable acidity and Al, which can be regarded as the primary buffering mechanism, followed by clay, CBD-Al, organic C and CBD-Fe. This is somewhat contradictory to the statement of Bache (1988) who reported that for most surface soils, pH-dependent charge associated with organic matter is the main buffering mechanism over the pH range 4.5-6.5.

Table 4 Summary of the forward stepwise regression analysis for buffer capacity at different pH ranges

Soil buffer capacity pH range	Variables in model	Variance accounted for (%)	F
Soil $BC_{pH<4.5}$	Extractable Al	69.00	114.64***
	+ Clay	74.00	10.65**
Soil $BC_{pH4.5-6.5}$	Extractable Al	75.2	225.73***
	+ Clay	88.0	78.59***
	+ pH (KCl)	89.9	14.67***
	+ log Organic C	91.4	13.41***
	+ log CBD-Fe	92.2	8.29**
Soil $BC_{pH6.5-8.5}$	Clay	59.1	110.65***
	+ log Organic C	68.5	3.61***
	+ pH (H_2O)	75.4	21.64***
	+ log CBD-Mn	78.2	10.19**
	+ log Ca	79.4	5.47*
Soil $BC_{pH4.5-8.5}$	Extractable Al	80.1	299.43***
	+ log Fe-CBD	88.4	53.07***
	+ Clay	89.4	8.55**

* $P < 0.05$, ** $P < 0.01$ & *** $P < 0.001$

Forward stepwise regression analysis shows (Table 4) that extractable Al, clay, pH (KCl), organic C and CBD-Fe are significantly related with soil BC, with extractable Al being the most important variable, accounting for 75.2% of the variation in soil $BC_{(pH4.5-6.5)}$. Progressive addition of the variables clay, pH (KCl), organic C content and CBD-Fe increased the explained variation to 91.4%.

Soil BC (pH6.5-8.5): Clay content was found to have the highest correlation with soil $BC_{(pH6.5-8.5)}$, followed by CBD-Fe, organic C and CBD-Al (Table 3). Forward stepwise regression analysis showed that clay, organic C, pH (H_2O), CBD-Mn, and Ca were significantly related with soil $BC_{(pH6.5-8.5)}$. Clay content and organic C accounted for 68.5% of the variation in soil $BC_{(pH6.5-8.5)}$ (Table 4).

Soil BC (pH4.5-8.5): In most soils, the general pH range of buffering by soil components is from 4.0 to 8.0 (Weaver *et al.*, 2004). Clay content was the best correlated with soil $BC_{(pH4.5-8.5)}$, followed by organic C, extractable Al, CBD-Al

and CBD-Fe (Table 3). Bloom (2000) showed that some soil components, such as soil organic matter, oxides and hydroxides of Fe and Al, allophone, imogolite and silicate clay edges are effective in buffering over a wide range of pH values. Organic matter is a very important component of pH buffering in surface soils, even in typical upland soils that contain very little soil organic matter (Bloom, 2000). Carboxylic acids found in soils appear to have a range of pKa values, and so contribute to buffering over the pH range from 2.0 to 7.0. The similar relationship between soil $BC_{(pH4.5-8.5)}$ and clay content ($r=0.74$) and between soil $BC_{(4.5-8.5)}$ and organic C ($r=0.69$) was surprising. Previous studies showed that organic matter may have a buffer capacity >300 times that of kaolinite clays (Bache, 1988; Aitken *et al.*, 1990).

Gibbsite, although not one of the primary soil properties related to soil $BC_{(pH4.5-8.5)}$, correlated significantly with soil $BC_{(pH4.5-8.5)}$ (Table 3). Oxides and hydroxides that accumulate in soils upon weathering are important mechanisms in the

pH buffering of soils, particularly in highly weathered soils (Uehara & Gillman, 1982). The most common Al hydroxide mineral in highly weathered soils is gibbsite, $[\text{Al}(\text{OH})_3]$ (Bloom, 2000).

Multiple regression shows (Table 4) that extractable Al accounted for 80.1% of the variation in soil $\text{BC}_{(\text{pH}4.5-8.5)}$. Progressive addition of the variables Fe-CBD and clay content increased the explained variation to 89.4%.

Relationships between dominant soil forms and selected soil properties

Figure 2 shows the interrelationships of dominant soil forms in the study area and selected soil properties.

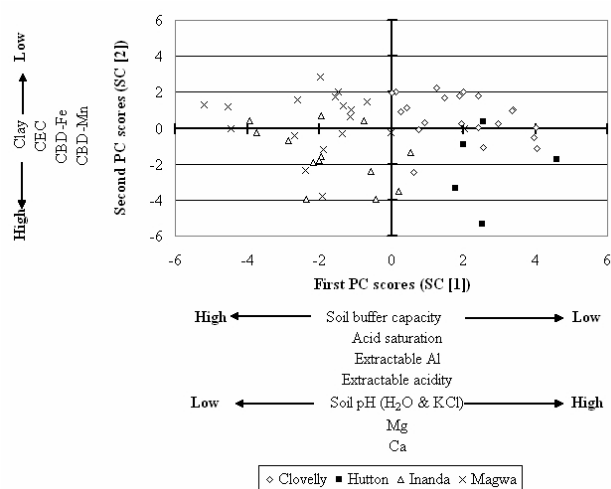


Figure 2 Principal component analysis evaluating the interrelationships between dominant soil forms, soil buffering capacity and other selected soil properties

Although no clear clusters were observed, trends with soil type and soil properties were observed. It was found that Clovelly and Hutton soils tended to have lower soil BC, extractable Al (or acidity) and acid saturation values, and higher pH (H_2O & KCl), Ca and Mg values. Magwa and Inanda soil forms had higher soil BC, higher extractable Al (or acidity) and acid saturation values, and lower pH (H_2O & KCl), Ca and Mg values.

Figure 2 further shows that Clovelly soils tended to have lower clay, CBD-Fe and CBD-Mn contents, while Hutton soils tended to be higher in clay, CBD-Fe and CBD-Mn. No clear clusters were evident from the SC [2] components in Figure 2 for Magwa and Inanda soils, with clay, CBD-Fe and CBD-Mn contents extending from low to high values in the Magwa and Inanda soils.

The PCA results indicate that, although the Hutton and Clovelly soil forms will have the initial benefit of lower soil acidity levels and therefore a lower risk for agricultural crop production, the long-term acidification risk will be higher than that of the Magwa and Inanda soils. This is due to the lower soil BC associated with the Hutton and Clovelly soils, which means that smaller amounts of lime amelioration will be needed in these soils than in the Magwa and Inanda soils to maintain or reach a recommended soil acidity level.

Conclusions

Typical soil BCs over the general pH range 4.5 to 8.5 varied from 0.12 to 2.23 $\text{cmol} (+) \text{kg}^{-1} \text{pH unit}^{-1}$. Composite titration curves for dominant soil forms showed that Inanda soils tended to be well buffered, while Clovelly soils revealed poor buffering. Maximum buffering for the experimental soils occurred at both $\text{pH} < 5.5$ and > 7.5 , with general poor buffering between $\text{pH} 5.5$ to 7.5 .

Linear regression analysis showed that clay content, organic C and extractable Al (acidity) were highly significantly correlated with the general $\text{BC}_{(4.5-8.5)}$. The results showed that the study area's soil BC values are determined primarily by three soil properties, viz. organic C content, content of clay minerals, and the type of clay minerals. Since the primary clay mineral in the Mlondozi district is kaolinite with low soil BC, the clay content rather than the type of clay is the primary determinant of soil BC in the region.

Multiple regression showed that extractable Al contributed significantly to soil BC in the pH ranges < 4.5 and $4.5-6.5$, accounting for 69 and 75%, respectively, of the variation in soil $\text{BC}_{<4.5}$ and soil $\text{BC}_{(4.5-6.5)}$. Similarly, regression analysis indicates that clay content, organic C, pH (H_2O), CBD-Mn, and Ca contributed most to the prediction of the soil $\text{BC}_{(6.5-8.5)}$.

Principal component analysis showed that Clovelly and Hutton soils tended to have lower soil BC, extractable acidity, Al and acid saturation values, and higher pH, Ca and Mg contents. Magwa and Inanda soils had higher soil BCs, extractable Al (acidity) and acid saturation, and lower pH, Ca and Mg values.

It can be concluded that the more strongly buffered Magwa and Inanda soils would require more lime to neutralize soil acidity as compared to the Clovelly and Hutton soils with lower soil BC. The current knowledge of the soils in the study area indicates that there is considerable diversity in the dominant soils. Poor crop growth on Magwa and Inanda soils could be expected due to low pH and Al toxicity. It is a well-known fact that liming and adequate rates of fertilizer application are the most effective management strategies to overcome acidity and soil fertility constraints to crop production. Due to the high soil BC values of these soils, large amounts of lime would be necessary to alleviate soil acidity. However, the Hutton and Clovelly soils will be more prone to soil acidification than the Magwa and Inanda soils due to the lower soil BCs of the former.

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