Soil Use and Management (2001) **17**, 155–162 DOI: 10.1079/SUM200167

Buffering capacity of cashew soils in South Eastern Tanzania

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Abstract. Cashew soils of South Eastern Tanzania become acidified due to sulphur used for controlling powdery mildew disease (*Oidium anacardii* Noack). The buffering capacity of surface and subsurface horizons of 35 soil profiles of major cashew growing areas — the Makonde plateau, its piedmont and inland plains — was studied. The buffering capacity of surface and subsurface horizons was strongly correlated with clay content and weakly with organic carbon content. In addition, it was only weakly correlated with total exchangeable bases and available P of the surface horizon, but strongly with soil pH, base saturation and cation exchange capacity of the clay fraction of the subsurface horizon. Highly weathered sandy soils, dominant on the Makonde plateau and common on the Piedmont, had the lowest buffering capacity. Soils from the inland plains had better buffering capacities as they are generally more clayey or are less weathered. The risk of severe acidification and of a decline in productivity of cashew and of food crops is highest on the Makonde plateau. Further development and dissemination of methods which can reduce the use of sulphur are required.

Keywords: Mildews, Oidium, cashews, sulfur, buffering capacity, acidification, soil, Tanzania

INTRODUCTION

In 1998, cashew ranked second as the most important foreign exchange earning crop in Tanzania being exceeded only by coffee (Bank of Tanzania 1999). Tanzania's production is about 9% of the world total (FAO 2000). The crop is mostly grown by smallholder farmers and around 70% of the national production comes from South Eastern Tanzania (Topper *et al.* 1998). The first reported export of nuts occurred in 1938 when 210 tonnes of raw nuts were shipped to India (Northwood & Kayumbo 1970). Widespread planting took place after 1945 and a peak production of 145 000 tonnes was reached in the 1973/74 marketing season. A catastrophic decline followed, and a record low production of 17 060 tonnes was reached in 1990 (FAO 2000). The production decline has been attributed to socioeconomic factors linked to the resettlement programme in the 1970s and to the outbreak of powdery mildew disease, caused by *Oidium anarcardii* Noack (Martin *et al.* 1997; Topper *et al.* 1998). Recent market liberalisation and high nut prices have encouraged farmers to increase production and during the 1999/2000 season 106 500 tonnes of nuts were marketed (FAO 2000).

In the early 1980s, research at the Naliendele Agricultural Research Institute in Tanzania led to the identification of sulphur as a suitable chemical for controlling powdery mildew disease (Sijaona 1984; Partel 1988). Sulphur has been widely adopted by farmers and during the last three years (1997–1999) sulphur imports to South Eastern Tanzania (regions of Lindi, Mtwara and Tunduru district) went up from 2500 to 7000 tonnes (CBT 1999). The standard recommendation is to dust 1.25 kg of sulphur per tree per season. For the recommended spacing of 12 × 12 m per tree, this is approximately 90 kg S ha^{-1}. When trees are not dusted, flower buds, flowers, young leaves and young shoots are attacked by the mildew resulting in poor harvest and inferior nut quality. Despite its effectiveness, it was quickly realised that sulphur could have serious environmental consequences. Field surveys indicated that sulphur acidifies soils on which cashew is grown (Majule *et al.* 1997; Ngatunga *et al.* 1998). The sustainable production of cashew and intercropped food crops is of major concern.

Soil acidification

Adverse changes in soil pH can affect plant growth due to a variety of reasons. As acidity increases, exchangeable calcium decreases and calcium deficiencies may ensue. More important may be the indirect effects as the reduction of available phosphate following fixation with soluble iron and aluminium (Shen *et al.* 1998). There are also effects on trace elements, particularly the increased solubility of manganese may prove toxic to plants (Robarge & Johnson 1992). Both fungal and bacterial activity may be curtailed in

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adverse pH environments, leading to poorer nutrient recycling (Hassett & Banwaart 1992).

Under moist aerobic conditions sulphur is oxidized to sulphuric acid by autotrophic bacteria, including five species of the genus *Thiobacillus* (Brady 1990). For every sulphur atom oxidized, two hydrogen ions are formed which may lower soil pH. Nortcliff & Wong (1995) concluded that the rate of sulphur oxidation depends on the size of the microbial population and factors affecting soil microbial activity such as soil water potential, organic matter content, pH and temperature. For example, *Thiobacillus thiooxidans* oxidises elemental sulphur to sulphate and operates optimally between pH 3 and 3.5. *Thiobacillus ferrooxidans* may also be involved in the transformation of S into SO_4^{2-} and operates optimally between pH 2 and 3.5 (Rowell 1981). The size of the sulphur particles is important (Weir *et al.* 1963; Fox *et al.* 1964). Sulphur powder has a large specific surface area facilitating oxidation. The oxidation rate can be expressed in terms of the surface area exposed and, under optimal conditions, rates of 48–76 μg S cm^{-2} day^{-1} have been reported (Watkinson 1989). The powdered sulphur applied in Tanzania, has particle sizes smaller than 50 μm diameter. If the lower rate reported by Watkinson (1989) is applicable to sulphur used in Tanzania, about 3.2 kg S ha^{-1} day^{-1} is oxidized. Hence, it can be assumed that within a year 90 kg ha^{-1} will be completely oxidized.

Buffering capacity

The buffering capacity of a soil is defined as its resistance to changes in pH when an acid or a base is added. It can be expressed as the quantity of protons required for changing the soil pH with one unit (mmol H^+ kg^{-1} soil pH^{-1}) (Rowell 1994). The buffering capacity of a soil depends among other factors on base status (Magdoff & Bartlett 1985; Brady 1990), cation exchange capacity (McFee 1983) and presence of weatherable minerals. Soil components that constitute buffering mechanisms also include clay and humic fractions. Buffering at intermediate pH levels (5.0 to 7.5) is mainly governed by exchange reactions whereby functional groups of organic matter and clay act as sinks for H^+ and OH^- (Nielsen *et al.* 1995; Curtin *et al.* 1996). If active acidity is neutralized, residual acidity releases H^+ ions and no change in soil pH occurs until the reserve of H^+ is exhausted. Residual acidity is often greater than active acidity, but is less in sandy soils than in clayey soils (Brady 1990). Laboratory methods for evaluating buffering capacity involve potentiometric titration with either an acid or a base (Magdoff & Bartlett 1985). Field methods involve application of lime and monitoring changes of soil pH and base saturation.

Predicting the long-term effect of sulphur applications in Tanzania is difficult as the buffering capacity of the cashew soils has never been investigated. In this study, the buffering capacity of soils from 35 cashew groves in six landscape units of South Eastern Tanzania was assessed. The objective was to elucidate the role of physicochemical soil properties in the buffering capacity of the soils and to assess the implications for soil management of current sulphur use in South Eastern Tanzania.

MATERIALS AND METHODS

Soil samples were taken from 35 profiles in farmers' cashew groves spread over six landscape units, known as major cashew growing areas of South Eastern Tanzania (Figure 1). Results of detailed physical and chemical analysis of the soil profiles were reported by Cools (1998) and are summarized in Table 1. Soil profiles were classified according to

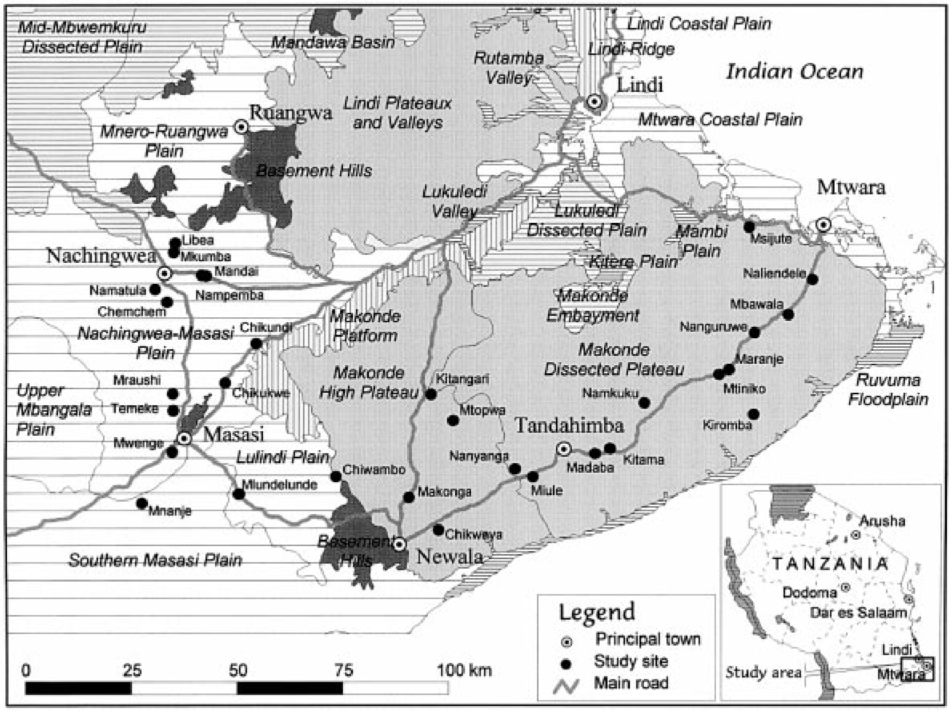


Figure 1. Landscape units of South Eastern Tanzania and location of study sites (adapted from Bennett *et al.* 1979).

Table 1. Summary statistics (mean and standard deviation for $n > 1$) per landscape unit and soil groupings of physicochemical soil properties of 35 soil profiles in cashew groves in South Eastern Tanzania.

Major landscape unit / Soil grouping[b]	Horizon	pH_{H20}	pH_{KCl}	OC (%)	P (g kg^{-1})	Ca ←	Mg	K	Na (cmol$_c$ kg^{-1})	TEB	CEC	CECclay →	BS[a] (%)	Clay (%)	Sand (%)	Silt (%)	Silt:Clay
Makonde plateau																	
Acrisol	top[c]	5.6	4.5	0.4	3.3	0.8	0.9	0.3	0.2	2.3	1.8	22.5	100	8	87	5	0.6
	sub	5.4	4.2	0.2	2.1	0.7	0.3	0.2	0.2	1.3	3.2	21.3	42	15	83	2	0.1
Alisols (*n*=3)	top	5.4 ± 0.1	4.1 ± 0.2	0.7 ± 0.4	10.1 ± 6.0	0.8 ± 0.2	0.3 ± <0.1	0.1 ± 0.1	0.04 ± 0.03	1.2 ± 0.2	2.6 ± 0.3	26.6 ± 1.9	48 ± 1	10 ± 2	88 ± 2	2 ± 1	0.2 ± 0.1
	sub	5.1 ± 0.2	4.1 ± 0.2	0.3 ± 0.2	6.0 ± 1.9	0.9 ± 0.4	0.4 ± 0.3	0.1 ± 0.1	0.02 ± 0.01	1.4 ± 0.6	3.8 ± 0.8	34.5 ± 20.1	37 ± 8	12 ± 4	83 ± 2	5 ± 5	0.6 ± 0.7
Ferralsols (*n*=13)	top	5.2 ± 0.7	4.4 ± 0.7	0.7 ± 0.4	9.6 ± 10.2	1.0 ± 1.2	0.4 ± 0.6	0.2 ± 0.2	0.25 ± 0.72	2.0 ± 1.9	3.7 ± 2.0	30.8 ± 27.2	47 ± 26	14 ± 4	83 ± 5	3 ± 2	0.3 ± 0.2
	sub	5.0 ± 0.5	4.1 ± 0.3	0.3 ± 0.2	1.9 ± 2.1	0.7 ± 1.3	0.3 ± 0.6	0.2 ± 0.1	0.09 ± 0.20	1.2 ± 1.9	3.0 ± 2.7	11.6 ± 7.9	34 ± 16	23 ± 7	74 ± 7	2 ± 2	0.1 ± 0.1
Piedmont																	
Acrisol	top	5.9	4.9	0.8	7.2	2.7	1.3	0.3	0.02	4.3	6.5	58.9	66	11	80	9	0.8
	sub	4.9	3.8	0.4	0.6	2.0	1.2	0.1	0.02	3.3	9.3	16.3	35	57	41	2	< 0.1
Arenosol	top	5.8	5.1	0.9	2.3	2.1	0.4	0.3	0.57	3.4	10.0	125.0	34	8	89	3	0.1
	sub	6.2	5.0	0.2	0.7	1.0	0.2	0.3	0.14	1.5	4.0	40.0	39	10	87	3	0.3
Ferralsol	top	5.9	5.2	0.3	2.5	0.7	0.3	0.1	0.08	1.1	1.8	43.8	65	4	93	3	0.8
	sub	6.3	4.8	0.1	1.4	0.4	0.2	0.1	0.02	0.7	0.9	11.5	76	8	90	2	0.3
Luvisol	top	5.8	4.8	1.0	0.7	4.9	1.5	0.9	0.13	7.4	10.6	32.1	70	33	59	8	0.6
	sub	6	4.8	0.6	0.4	4.0	1.6	0.8	0.12	6.6	10.4	27.4	63	38	53	9	0.2
Inland plain																	
Acrisol	top	5.8	5.1	0.7	2.3	0.8	0.6	0.2	0.03	1.6	2.5	36	62	7	84	9	1.3
	sub	6.2	4.8	0.3	3.5	1.2	0.8	0.3	0.02	2.4	3.1	13.4	76	23	72	5	0.2
Alisols (*n*=3)	top	5.8 ± 0.8	4.9 ± 1.1	0.5 ± 0.2	7.8 ± 7.6	2.1 ± 1.2	0.8 ± 0.2	0.2 ± 0.1	0.04 ± 0.03	3.1 ± 1.3	5.2 ± 1.2	67.0 ± 47.6	61 ± 28	11 ± 8	85 ± 8	4 ± <1	0.5 ± 0.5
	sub	5.5 ± 0.5	3.8 ± 0.6	1.1 ± 0.4	2.0 ± 5.4	5.0 ± 1.7	1.6 ± 0.4	0.02 ± 0.1	0.03 ± 0.02	6.7 ± 2.1	13.6 ± 3.6	31.7 ± 3.2	49 ± 20	43 ± 11	53 ± 10	4 ± 2	0.1 ± 0.1
Cambisols (*n*=2)	top	6.4 ± 0.1	5.4 ± <0.1	0.6 ± 0.2	4.4 ± 0.4	1.3 ± 0.9	0.4 ± 0.1	0.2 ± 0.1	0.05 ± 0.04	1.9 ± 0.9	2.7 ± 1.5	49.9 ± 36.1	79 ± 4	6 ± 1	87 ± 8	8 ± 6	1.2 ± 0.8
	sub	6.5 ± 0.1	4.7 ± 0.5	0.2 ± 0.1	1.6 ± 0.9	1.4 ± 0.9	0.5 ± 0.1	0.2 ± 0.1	0.04 ± 0.01	2.0 ± 1.0	2.4 ± 1.2	23.8 ± 2.1	85 ± 1	10 ± 4	82 ± 9	8 ± 4	0.8 ± 0.1
Ferralsols (*n*=5)	top	5.6 ± 0.6	4.6 ± 0.4	0.6 ± 0.4	2.4 ± 1.6	2.1 ± 1.0	1.0 ± 0.3	0.3 ± 0.1	0.07 ± 0.04	3.4 ± 1.3	6.4 ± 2.5	36.7 ± 14.9	56 ± 18	20 ± 9	75 ± 10	5 ± 2	0.2 ± 0.2
	sub	5.4 ± 0.5	4.3 ± 0.4	0.3 ± 0.2	0.6 ± 0.6	2.2 ± 1.4	1.0 ± 0.6	0.2 ± 0.2	0.08 ± 0.09	3.5 ± 1.6	7.8 ± 1.8	16.5 ± 7.1	43 ± 13	51 ± 14	45 ± 15	4 ± 2	0.1 ± <0.1
Luvisol	top	6.9	6.0	0.3	1.5	1.7	0.5	0.2	0.02	2.4	2.5	24.6	98	10	82	8	0.8
	sub	7.4	5.8	0.3	2.6	4.4	2.4	0.3	0.02	7.1	6.3	25.1	100	25	69	6	0.2
Phaeozem	top	6.2	5.2	1.1	2.9	0.8	0.5	0.3	0.02	1.6	2.2	24.3	74	9	83	8	0.9
	sub	6.7	5.2	0.2	2.6	1.2	1.0	0.2	0.02	2.4	2.7	24.6	90	11	83	6	0.6
Plinthosol	top	5.6	4.6	0.4	4.7	0.7	0.4	0.1	0.02	1.3	2.3	25.7	54	9	85	6	0.7
	sub	5.5	3.7	0.4	1.9	3.6	1.7	0.1	0.07	5.4	10.4	24.8	52	42	53	5	0.1

[a] BS, base saturation = Σ(Ca,Mg,K,Na)x100/CEC, [b] classification following the FAO Legend (FAO 1988), [c] top = surface horizon (0–20 cm); sub = subsurface horizon (around 50 cm).

the 'Revised Legend of the Soil Map of the World' (FAO 1988). The statistical analyses were done following the soil groupings defined according to the FAO Legend. Correlations were made with the World Reference Base for Soil Resources — further referred to as WRB — (FAO-ISRIC-ISSS 1998).

Soils and landscapes

Soils and landscapes of South Eastern Tanzania were mapped at a reconnaissance scale (1:250 000) by Bennett *et al.* (1979) (Figure 1). Separated from the Indian Ocean by a narrow coastal plain, plateaux dominate the eastern part of the study area. Of these, the Makonde plateau is the most populated and it produces about 50% of the cashew nuts from South Eastern Tanzania. The plateau consists of sandy sedimentary deposits of Neogene age on which deep soils are formed, with sandy topsoils and sandy loam or sandy clay loam subsoils. Following the FAO Legend, the dominant soils of the Makonde plateau are Xanthic Ferralsols — or Veti-Acric Ferralsols in World Reference Base (WRB). Most commonly associated soils are Haplic Ferralsols (Lixic and Haplic Ferralsols in WRB) and Haplic Alisols (Profondic Alisols and Arenic Luvisols in WRB). Based on relief characteristics, the plateau has been subdivided into the Makonde High Plateau and the Makonde Dissected Plateau.

Westwards of the plateaux are inland plains which, within the study area, Bennett *et al.* (1979) mapped as the Lulindi plain, the Nachingwea-Masasi plain and the Southern Masasi plain. These are gently undulating plains with broad flat topped interfluves, wide shallow valleys, formed on PreCambrian Basement rocks, mostly gneiss. Soil changes reflect variations in lithology, drainage and erosional history. On the interfluvial crest, least affected by erosion, typically highly weathered, deep, red, sandy clay loam or sandy clay soils occur. They are Rhodic Ferralsols and Haplic Acrisols according to the FAO Legend or Veti-Acric Ferralsols and Profondic Acrisols according to WRB. On the slopes, a variety of less weathered, often shallow soils occur. Most common soil units are Rhodic Luvisols and Chromic Cambisols (Rhodic and Chromic Luvisols, Mollic and Rhodi-Bathileptic Cambisols in WRB). Gleyic Alisols and Albic Plinthosols (Gleyic Luvisols and Endoeutric Plinthosols in WRB) occur in the valleys, while Ferralic and Luvic Arenosols (FAO Legend as well as WRB) are common on the Piedmont of the Makonde plateau.

Buffering capacity

Buffering capacity was examined for the surface horizon (0–20 cm) and the subsurface horizon at around 50 cm. Twenty grams of fine earth (less than 2 mm) of each sample was placed in 100 ml glass bottles to which 50 ml of distilled water was added as for standard soil pH measurements. Sulphuric acid was added to these bottles as 0 (reference), 0.5, 1 and 2 ml of 0.015M H_2SO_4. These additions represented 0, 0.75, 1.5 and 3 mmol H^+ kg^{-1} soil. The bottles were shaken for 30 minutes after which a first pH measurement was made; a second measurement was made after 24 hours.

The concentrations of added acid were based on the rationale that for every sulphur atom, two hydrogen ions are formed. If sulphur is applied according to the recommendation of 90 kg ha^{-1}, it can be calculated that an amount of 5.6 kmol H^+ ha^{-1} is added annually. For the upper 20 cm of soil, this is 2 mmol H^+ kg^{-1} soil, if a bulk density of 1.4 g cm^{-3} is assumed.

Statistical analysis

Pearson correlation coefficients, with two tailed levels of significance, were calculated to identify relationships between buffering capacity and physicochemical soil properties. The buffering capacity is calculated as the quantity of protons added (3 mmol H^+ kg^{-1} soil) divided by ΔpH, with ΔpH = pH (0 mmol H^+ kg^{-1} soil) - pH (3 mmol H^+ kg^{-1} soil).

The effect on the ΔpH of the quantity 'H^+ added' (random factor with four levels), sampling depth (fixed factor with two levels 0–20 and 50 cm), time (random factor with two levels 0.5 h and 24 h), landscape unit (fixed factor with six levels) and soil groupings (fixed factor with nine levels) was analysed with a variance analysis of repeated measures. The procedure adopted was the PROC MIXED of the statistical package SAS (Littell *et al.* 1996). The PROC MIXED model takes into account both fixed and random effects as listed above. Multiple pairwise comparisons of the least square means derived from the PROC MIXED model, were made for the 'Landscape units' and 'Soil groupings' with the Tukey-Kramer procedure. This way, groups of 'Landscape units' and 'Soil groupings' whose least square means of pH do not differ from the single degree of freedom test at 95% level of probability, were identified.

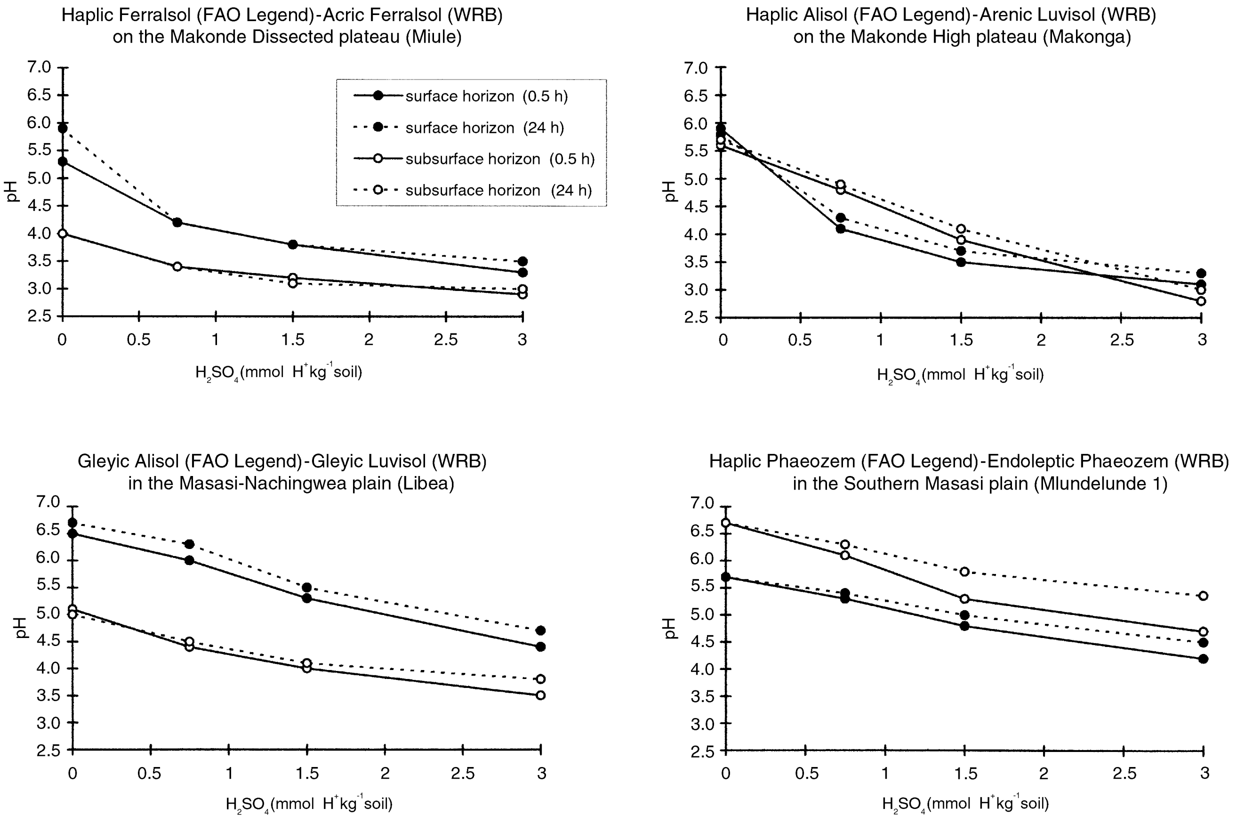
RESULTS AND DISCUSSION

Titration curves

The titration curves in Figure 2 illustrate two examples from the Makonde plateau and two from the inland plains. The examples from the plateau had a more acidic initial soil pH than those of the inland plains. They also had markedly larger ΔpH. The pH measured after 24 h was higher than after 30 minutes, but the increase was more pronounced for the soils of the plains. The buffering capacities derived from the titrations are presented in Table 2. The buffering capacity of these tropical soils is about 10 times lower than those of a range of British soils reported by Rowell (1994).

Buffering capacity in relation to soil properties

The correlation coefficients (with $P<0.1$) are presented in Table 3. The buffering capacity of the surface horizon measured after 30 minutes showed a significant positive linear relationship with the clay content and, reciprocally, a negative relationship with the sand content. In the subsurface horizon the silt content and especially the silt:clay ratio is negatively related to the buffering capacity, but this is difficult to interpret as absolute silt contents were very low (Table 1). Higher organic carbon contents are positively correlated with higher buffering capacity. These observations support earlier findings by Rowell (1981) and Van Breemen *et al.* (1984), who showed that the buffering


Haplic Ferralsol (FAO Legend)-Acric Ferralsol (WRB) on the Makonde Dissected plateau (Miule)

Haplic Alisol (FAO Legend)-Arenic Luvisol (WRB) on the Makonde High plateau (Makonga)

Gleyic Alisol (FAO Legend)-Gleyic Luvisol (WRB) in the Masasi-Nachingwea plain (Libea)

Haplic Phaeozem (FAO Legend)-Endoleptic Phaeozem (WRB) in the Southern Masasi plain (Mlundelunde 1)

Figure 2. Titration curves of two profiles from the Makonde plateau and two from the inland plains.

capacity lies in the exchange capacity of the clay and the organic matter content of the soil. Although the relationship is weaker, this also explains the correlation found with the CEC (cation exchange capacity) of the soil.

For the divalent exchangeable bases (Ca^{2+} and Mg^{2+}) and the available P only a weak correlation was found for the surface horizon. As the pH of the soil profiles were in the acidic range, exchangeable bases are bound to the exchange complex provided by the organic matter, the clay fraction or sesquioxides. As the buffering capacity seems only to relate with these elements in the surface horizon, this could indicate an exchange reaction of H^+ with these elements bound to humic substance of the Ah horizon.

The high correlation between the buffering capacity and the initial pH of the subsurface horizon means that more acidic soils are better buffered than the less acidic ones. Magdoff & Bartlett (1985) and Godefroy & Dormoy (1990) have reported similar findings, namely that soils are poorly buffered between pH 4.5 and 6.5 and well buffered below pH 4. They further stated that soils are well buffered above pH 7. Since there are no profiles in this study with pH values exceeding this range, this could not be verified. Base saturation and the CEC of the clay fraction (CECclay) seem to be linked to this phenomenon. Low pH, base saturation and CECclay are typical of some highly weathered soils. At first sight this could paradoxically lead to the conclusion that highly weathered soils have a better buffering capacity than poorly weathered soils. However, the correlation coefficient between the buffering capacity and initial pH(H_2O), pH(KCl) and BS (base saturation) was less strong with the measurement done after 24 h, while the coefficient with the clay content and the CEC increased. Dissolution of primary soil minerals can be assumed after which protons are absorbed on the exchange complex. This may explain the increase in pH after 24 h, as illustrated by the soils from the inland plains in Figure 2, and results in a better buffering capacity.

Buffering capacity in relation to landscape units and soil groupings

Results of the variance analysis of factors contributing to the pH are presented (Table 4). The factors 'Landscape unit', horizon 'Depth', quantity 'H^+ added', 'Time' and 'Soil groupings' contributed significantly to the model. However, as significant interactions were found between the factors 'Landscape unit', 'Depth' and 'H^+ added' on the one hand and 'Soil groupings' on the other, the model was split into two new models containing four non-interacting factors each. Model 1 contained the factors 'Landscape unit', 'Depth', 'H^+ added' and 'Time' and Model 2 contained the factors 'Soil groupings', 'Depth', 'H^+ added' and 'Time'. In these models the factor 'Time' is less significant.

The results of the family of pairwise tests of the landscape units (Model 1) and of the soil groupings (Model 2) are presented in a line plot in Figure 3. On the left hand side, landscape units with least square means that do not differ ($P<0.05$) are grouped together. Similarly, on the

Table 2. Buffering capacities (BC in mmol H^+ kg^{-1} pH^{-1}) of 35 soil profiles in cashew groves in South Eastern Tanzania measured 30 minutes and 24 h after addition of sulphuric acid.

Landscape unit		Surface horizon (0–20 cm)		Subsurface horizon (around 50 cm)	
Soil unit[a]	Profile	$BC_{30\ min}$	$BC_{24\ h}$	$BC_{30\ min}$	$BC_{24\ h}$
Makonde Dissected plateau					
Haplic Acrisol	Nanguruwe	1.3	1.3	1.8	1.7
Haplic Alisol	Madaba	1.2	1.3	1.4	1.3
Haplic Ferralsol	Miule	1.5	1.3	2.7	3.0
”	Mtiniko	1.9	1.9	1.3	1.4
”	Msijute	2.7	2.7	1.3	1.4
Rhodic Ferralsol	Naliendele	1.6	1.5	2.0	2.3
Xanthic Ferralsol	Kiromba	1.6	1.7	2.1	2.3
”	Maranje	2.0	2.0	2.1	2.0
”	Mbawala	2.0	2.1	1.5	2.5
”	Namkuku	2.0	2.0	3.0	2.7
”	Kitama	2.3	3.0	1.6	2.0
”	Nanyanga	2.3	2.5	2.5	2.5
Makonde High plateau					
Haplic Alisol	Makonga	1.1	1.2	1.1	1.1
”	Kitangari	1.6	1.8	2.0	2.5
Haplic Ferralsol	Mtopwa	2.5	2.3	2.5	3.3
Rhodic Ferralsol	Chikwaya	3.8	10.0	0.9	1.3
Xanthic Ferralsol	Chiwambo5	2.0	2.0	2.3	2.7
Piedmont					
Haplic Acrisol	Chikundi	2.5	3.3	4.3	5.0
Ferralic Arenosol	Chiwambo3	1.4	1.6	1.1	1.1
Plinthic Ferralsol	Chikukwe	0.9	1.0	1.0	1.3
Chromic Luvisol	Chiwambo2	2.0	2.3	2.0	2.1
Nachingwea Masasi plain					
Albic Plinthosol	Temeke	1.4	2.0	2.5	2.7
Eutric Cambisol	Chemchem	1.3	1.4	1.2	1.3
Gleyic Alisol	Libea	1.4	1.5	1.9	2.5
Haplic Alisol	Nampemba	1.6	1.9	2.7	3.8
Humic Cambisol	Mwenge	1.8	1.9	1.0	1.3
Rhodic Ferralsol	Mkumba	1.3	1.8	3.8	5.0
”	Namatula	1.9	2.3	1.4	2.1
”	Mandai	2.7	4.3	2.7	4.3
”	Mraushi	2.7	2.7	3.3	3.8
Southern Masasi plain					
Haplic Acrisol	Mnanje	1.4	1.9	1.3	1.8
Lulindi plain					
Chromic Luvisol	Mlundelunde2	1.4	1.8	1.1	1.8
Gleyic Alisol	Chiwambo1	1.3	1.4	1.4	1.4
Haplic Phaeozem	Mlundelunde1	2.0	2.5	1.5	2.2
Rhodic Ferralsol	Chiwambo4	1.4	1.8	2.0	2.1

[a] classification following FAO Legend (FAO 1988).

right hand side groups of ‘Soil groupings’ are presented. This analysis results in a ranking of landscape units (Model 1) and soil groupings (Model 2) in terms of their buffering capacity.

The Makonde Dissected Plateau (Group L_1, Figure 3), followed by the Makonde High Plateau and the Piedmont (Group L_2) have the lowest buffering capacity. Soils of the inland plains have on average higher buffering capacities (groups L_4 and L_5). The Piedmont is placed in both Group L_2 and L_3, which reflects the heterogeneity of the soils of this unit; soils are partly derived from sandy colluvium from the Makonde Plateau, partly from Pre-Cambrian Basement material.

A similar analysis applied to the soil groupings (Model 2) resulted in three groups (Figure 3), and reveals the complexity of the inland plains. Soils with the lowest buffering capacity are Ferralsols, Arenosols (Group S_1) and Alisols and Plinthosols (Group S_1/S_2 in Figure 3). Light textured Ferralsols and Arenosols are typical for the Makonde plateau and its piedmont. But Ferralsols, Alisols and Plinthosols are also common in the plains. The soils with largest buffering capacities, Cambisols, Luvisols and Phaeozems (Group S_3), are typically found in the plains. These soils have moderate contents of organic carbon, of exchangeable bases and moderate cation exchange capacity which provide better buffering capacity.

In both models there was a significant contribution of the factor ‘Depth’. Buffering capacity of the subsurface horizon is usually better than that of the surface horizon, which has to be attributed to the greater clay content. In the surface horizon organic matter plays a relatively greater role as a sink for H^+.

Table 3. Pearson correlation coefficients between buffering capacity (BC) and physicochemical properties of 35 soil profiles in cashew groves. The BC was measured 30 minutes and 24 h after addition of sulphuric acid

Soil property	Surface horizon (0–20 cm)		Subsurface horizon (around 50 cm)	
	BC_{30min}	BC_{24h}	BC_{30min}	BC_{24h}
Sand	–0.47***	–0.36**	–0.56****	–0.65****
Clay	0.47***	0.34**	0.63****	0.71****
Silt	–	–	–0.36**	–
Silt/Clay	–	–	–0.47***	–0.46***
OC[a]	0.36**	–	0.31*	0.30*
P	0.47***	0.49***	–	–
Ca	0.31*	–	–	–
Mg	0.39**	0.30*	–	–
K	–	–	–	–
Na	–	–	–	–
TEB[b]	0.31*	–	–	–
CEC	0.36**	–	–	0.32*
CECclay	–	–	–0.33*	–0.33*
BS[c]	–	–	–0.54***	–0.47***
pH-H_20	–	–	–0.62****	–0.51***
pH-KCl	–	–	–0.55***	–0.43**

two tailed levels of significance: - $P \geqslant 0.1$; *$P < 0.1$; ** $P < 0.05$; *** $P < 0.01$; **** $P < 0.001$

[a]OC = organic carbon [b] TEB = total enchangeable bases [c] BS = Base saturation

Table 4. Variance analysis of factors contributing to changes in pH upon addition of H_2SO_4 to samples from 35 soil profiles under cashew.

Factor	F-value	Probability
Overall model		
Landscape unit	16.11	< 0.001
Depth	50.09	< 0.001
H^+ added	721.44	< 0.001
Time	8.61	< 0.01
Soil grouping	12.66	< 0.001
Landscape unit × Soil grouping	18.02	< 0.001
Depth × Soil grouping	8.85	< 0.001
H^+ added × Soil grouping	2.08	< 0.05
Time × Soil grouping	0.35	0.944
Model 1		
Landscape unit	35.14	< 0.001
Depth	44.09	< 0.001
H^+ added	250.00	< 0.001
Time	5.67	< 0.05
Model 2		
Soil grouping	48.42	< 0.001
Depth	64.76	< 0.001
H^+ added	822.03	< 0.001
Time	8.30	< 0.01

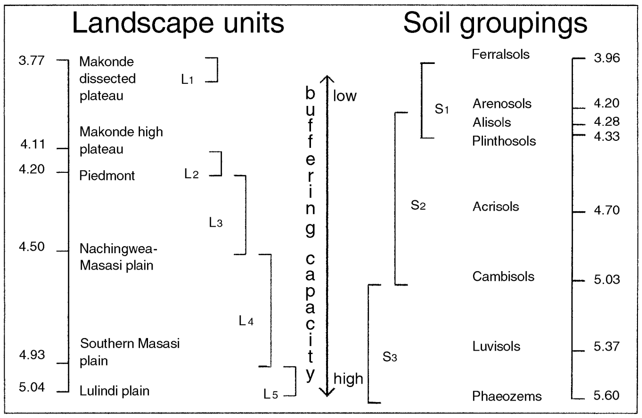


Figure 3. Line plot of least square means (pH) indicating non-significant difference ($P \leqslant 0.05$) between landscape units and soil groupings in relation to buffering capacity.

Implications for soil management

Assuming that all sulphur dusted enters the soil, four years of dusting is likely to cause a pH decline between 0.3 and 3.1 pH units in the surface horizon and between 0.6 and 2.7 pH units in the subsurface horizon. These pH changes are similar to the field observations made by Majule *et al.* (1997) and Ngatunga *et al.* (1998). Although cashew trees develop deep rooting systems and tolerate low pH levels, concerns for their long-term productivity seem justified. Moreover, Smith *et al.* (1995) demonstrated that about 80% of the sulphur drifts away, which may have important consequences for intercrops such as maize, sorghum, cowpea and finger millet.

As soils of the Makonde plateau have the lowest buffering capacity, alternative approaches for controlling the powdery mildew disease are most pressing here. Liming, cultural practices which reduce the incidence of the disease, or organic fungicides are the basic options as long as resistant varieties are not widely available. To neutralize 90 kg S ha^{-1}, about 200 kg $Ca(OH)_2$ ha^{-1} is required. Although this is locally available as burnt coral lime, such quantities would be financially prohibitive for smallholder farmers and its widespread use would be detrimental to the marine environment. Fossil coral lime, available in the coastal plain and not yet exploited, would be a better alternative. Much less sulphur would be needed, and much less lime would be required, if the incidence of the powdery mildew disease could be suppressed by cultural practices as demonstrated by Kasuga *et al.* (1998) and by Nathaniels (1998). To achieve this would require a large involvement of extension staff as these techniques require farmers to understand aspects of the epidemiology of the disease. The water based organic fungicides hexaconazole, triadimenol and penconazole, have proven effective for controlling powdery mildew disease (Smith *et al.* 1998). They have the disadvantage of costing more than sulphur and of being more toxic to humans and animals (Tomlin 1994). Moreover, they are applied in water which is scarce on the Makonde plateau.

CONCLUSIONS

The buffering capacity of cashew soils is determined by the clay content, organic carbon content and the weathering status. Soils of the Makonde plateau, where about 50% of the cashew nuts from South Eastern Tanzania are produced, are the most susceptible to soil acidification. Overall, soils of the plains have a higher buffering capacity but the situation is more complex as soils are more diverse. In the long run, acidification due to sulphur is likely to reduce the productivity of both cashew trees and food crops. Further development and dissemination of techniques which can reduce the use of sulphur are therefore urgently needed.

ACKNOWLEDGEMENTS

This study was made possible thanks to the Tanzanian Agricultural Research Fund and the Cashew Research Fund with additional support from the Belgian Administration for Development Co-operation. We would like to thank Musa Mapua, Musa Dalis and Musa Mumina for their assistance during the fieldwork and in the laboratory. Special thanks are due to the numerous farmers for their kind cooperation.

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Received September 2000, accepted after revision January 2001.