

THE EFFECT OF LIMING ON SOIL BUFFER CAPACITY, ACIDIFICATION RATES AND MAINTENANCE LIMING

3.1 INTRODUCTION

Although soil acidification is a natural process, modern agricultural practices have accelerated acidification of soils relative to natural ecosystem processes in many parts of the world (Singh *et al.*, 2003). Soil acidification is the result of proton production that occurs because of various natural biological and chemical processes in the soil. Most of these natural processes are buffered around pH 5.5 (H₂O) except under more severe leaching conditions, especially in more sandy soils. Apart from the natural processes, soil acidification is enhanced by losses of bases either by crop removal or leaching in the absence of an active root system, and the application of ammonical fertilizers (Singh *et al.*, 2003; Doerge & Gardner, 1985; Hart, 2002; Gasser, 1973). Regular liming is therefore required to balance the acidifying effect of these processes, and to ensure the efficient utilization of fertilizers by crops (Bolton, 1977). The effect of lime in raising soil pH extends beyond the first year after application, but predicted rates at which limed soils reacidify are often not known. The rate of these acidifying processes is slow under natural conditions, but generally accelerates under agricultural practices (Helyar & Porter, 1989). The rate at which any given production system acidifies is a function of the soil's buffer capacity, climate, and farming practice (Sumner & Noble, 2003). Magdoff *et al.* (1987) showed that the dominant soil properties contributing to a soil's pH buffering include the amount of organic matter and the quantity and type of clay minerals present. The buffer capacity of a soil may change over time due to a reduction in organic matter. This can lead to under or over predictions of proton production, especially in situations where the levels of organic matter changed dramatically over the study period.

The Australian Agriculture Assessment (2001) has shown that the soil acidification rates in Australia vary from an alkalizing farming system under tobacco production (-260 kg lime ha⁻¹ year⁻¹) to strongly acidifying farming systems such as banana production (+2000 kg lime ha⁻¹ year⁻¹), with an annual mean requirement of between 50 to 250 kg lime ha⁻¹ year⁻¹. In the former case, net alkalinization is associated with approximately 70% of the nitrogen fertilizer being in the nitrate form. In contrast, the extremely high acidification rates recorded in banana production systems are a consequence of fertigation with high rates of ammonium-based fertilizers (average application rate of 508 kg N ha⁻¹ year⁻¹), coupled with the removal of significant amounts of bases

in both harvested product and pruning following bunch removal (Sumner & Noble, 2003). Annual soil acidification in South Africa may vary from less than 500 kg lime ha⁻¹ year⁻¹ to 1500 kg lime ha⁻¹ year⁻¹ and more (FSSA, 2003). This shows that soil acidification rates can vary quite dramatically between both soils and systems. It is therefore important that both the soil acidity status and estimates of the rate of acid production of soils are known, to facilitate corrective action by farmers.

Against this background the present study was undertaken in order to determine (i) the changes in soil buffer capacity, (ii) acid production loads, (iii) acidification rates, and (iv) maintenance lime requirements of two lime-amended soils in a resource-poor farming area.

3.2 MATERIALS AND METHODS

3.2.1 Experimental soils

The study was conducted on two acid soils in the Mlondozi district of Mpumalanga, South Africa. Two trials that were recorded for six and five years were laid out on Hutton (Humic Ferralsols) and Oakleaf (Rhodic Cambisols: FAO-ISS-ISRIC, 1998) soil forms, respectively (see Table 2.1 for chemical and physical analysis). A detail description of the experimental design was discussed in section 2.2.1.

3.2.2 Soil sampling and analysis

Topsoil samples (0 - 250 mm) were taken annually in March. Eight soil samples were taken within each plot between the rows and a composite sample was made up. The composite samples were air-dried and ground to pass through a 2 mm sieve.

Soil pH (H₂O) was determined in a 1:2.5 (soil:water) suspension using a combined calomel reference glass electrode and pH meter (Reeuwijk, 2002). Extractable acidity, (Al + H), and Al were determined in a 1 mol dm⁻³ KCl extractant. The ammonium acetate (1 mol dm⁻³, pH 7) method was used to extract the cations Ca and Mg (Thomas, 1982). These cations were determined on an atomic absorption flame spectrophotometer (The Non-Affiliated Soil Analysis Work Committee, 1990). Acid saturation was determined as the ratio between extractable acidity and the sum of extractable Ca, Mg, K, Na and extractable acidity, expressed as a percentage.

3.2.3 Soil buffer capacity (soil BC)

Potentiometric titrations (Ponizovskiy & Pampura, 1993) were performed on samples that were

equilibrated overnight with 1 M KCl. A 50 g 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 min⁻¹. For each soil a linear regression function was fitted to the relationship between 0.05 M NaOH added and the soil. Equation 3.1, adapted from Bache (1988), was used to calculate soil buffer capacity (soil BC).

$$\text{Soil BC (cmol}_c \text{ kg}^{-1} \text{ soil pH unit}^{-1}) = \Delta(\text{OH}^-) / \Delta \text{pH} \quad [3.1]$$

where ΔpH is the change in pH (pH unit) due to the addition of OH^- (cmol_c kg soil⁻¹) as NaOH.

The soil BC calculated in Equation 3.1 was converted to (kmol H⁺ (ha_{250 mm})⁻¹ (pH unit)⁻¹) using an average soil bulk density of 1300 kg m⁻³ using Equation 3.2 as suggested by Singh *et al.*(2003):

$$\text{Soil BC [(kmol H}^+ \text{ (ha}_{250 \text{ mm}})^{-1} \text{ (pH unit)}^{-1})] = (\text{BC} \times \text{V} \times \text{BD}) / 100 \ 000 \quad [3.2]$$

where V is volume of soil layer (m³ ha⁻¹) to a depth of 250 mm; BD is bulk density (kg m⁻³) and 100 000 to convert cmol (H⁺) to kmol (H⁺).

3.2.4 Acid production loads (APL) and acidification rates

Predicted acidification rates: The acid production load (kmol H⁺ (ha_{250mm})⁻¹ (year)⁻¹) was calculated with Equation 3.3 as described by Helyar and Porter (1989):

$$\text{APL} = (\Delta\text{pH}/\Delta\text{t}) \times \text{soil BC} \quad [3.3]$$

where $\Delta\text{pH}/\Delta\text{t}$ is the rate of pH decline (pH unit year⁻¹).

The decrease in soil pH in one year (pH year⁻¹) was calculated with Equation 3.4 as reported by Singh *et al.* (2003), using the APL and soil BC:

$$\Delta\text{pH units year}^{-1} = \text{APL}/\text{soil BC} \quad [3.4]$$

The number of years required for a soil to reach a critical pH value where production losses are likely to occur was calculated as expressed by Hill (2003) in Equation 3.5:

$$\text{Time (years)} = [(\text{pH}_{(\text{current})} - \text{pH}_{(\text{critical})}) \times (\text{soil BC})] / \text{APL} \quad [3.5]$$

where $\text{pH}_{(\text{current})}$ is the current pH, $\text{pH}_{(\text{critical})}$ is the critical pH.

Measured acidification rates: Equation 3.6 as described by Doerge and Gardner (1985), was used to determine the measured annual change in soil pH. The use of pH (H₂O) as an indicator to predict acidification rates has been debated by many researchers (Walker, 1953; Bolton, 1977; Doerge & Gardner, 1985) because of the annual fluctuations in soil pH (Hart, 2002). According to Doerge and Gardner (1985) the sources and sinks of Ca²⁺ and Mg²⁺ are less complicated than those of H⁺ and a high degree of correlation exists between soil hydrogen activity and basic cation saturation. Therefore the pH acidification rate ($\Delta\text{pH unit year}^{-1}$) of a soil can be calculated if the relationship between pH and levels of extractable basic cations, and the measured annual change in basic cations are available (Doerge & Gardner, 1985). The annual change in soil pH was indirectly measured as the ratio between soil pH and levels of extractable basic cations, multiplied by the annual change in basic cations.

$$(\Delta \text{pH}/\Delta [\text{Ca} + \text{Mg}]) \times (\Delta \text{Ca} + \text{Mg year}^{-1}) = \Delta \text{pH year}^{-1} \quad [3.6]$$

where $\Delta(\text{Ca} + \text{Mg})$ is the change in soil (Ca + Mg) in mol_c kg⁻¹ soil

3.2.5 Maintenance liming

Maintenance liming requirement was determined from the annual change in Ca²⁺ + Mg²⁺ ($\Delta \text{Ca} + \text{Mg year}^{-1}$) for the top 250 mm soil (Equation 3.7). This was achieved using the assumption that 1 mol of CaCO₃ neutralizes 2 mol of H⁺ in the soil.

$$([\Delta(\text{Ca} + \text{Mg}) \text{ year}^{-1}] \times \text{BD} \times V \text{ ha}^{-1} \times \text{CaCO}_3)/100\ 000 = \text{tonnes CaCO}_3 \text{ ha}^{-1} \text{ year}^{-1} \quad [3.7]$$

where $\Delta(\text{Ca} + \text{Mg})$ is the change in soil (Ca + Mg) in mol_c kg⁻¹ soil; BD is the soil bulk density (kg m⁻³); V the soil volume (m³) in the top 250 mm and CaCO₃ is 1 mol pure CaCO₃ (100.09 g CaCO₃ mol⁻¹).

3.2.6 Statistical analysis

The effect of liming on soil BC, APLs and acidification rates was evaluated statistically by analysis of variance (ANOVA) (Genstat, 2003). The Bonferroni multiple comparison test for means separation was used to test all main effects at the 5% probability level.

Pearson's correlations were calculated between measured pH changes and calculated acidification risk according to Equation 3.5 using Genstat (2003). Measured pH change is the rate of pH decline measured over 6 and 5 years (pH unit year⁻¹) in the Hutton and Oakleaf soil

forms, respectively. The broken-stick analysis, a non-linear regression analysis, was used to evaluate critical pH ranges where a change in soil BC could be expected.

3.3 RESULTS AND DISCUSSION

The values that will be discussed are replicate means per lime application level in order to evaluate the main effect of lime application.

3.3.1 Effect of lime application on soil BC

Hutton soil form: Liming had a highly significantly ($P < 0.001$) decreasing effect on soil BC (Table 3.1 and 3.2).

Table 3.1 ANOVA table of probabilities of treatment effects on soil BC, acid production load, acidification rate and extractable Ca and Mg for the Hutton and Oakleaf soil forms

Variable	Hutton		Oakleaf	
	F-ratio			
	Lime	Year x Lime	Lime	Year x Lime
Soil BC ($\text{cmol}_c \text{ kg soil}^{-1}$)	44.74 ^{***}	3.33 ^{**}	2.82 ^{***}	1.10ns
Acid production load ($\text{kmol} (\text{H}^+) \text{ ha}^{-1} \text{ year}^{-1}$)	4.65ns	-	4.33 [*]	-
Acidification rate (pH unit year^{-1})	5.90 [*]	-	9.66 ^{**}	-
Extractable Ca ($\text{cmol}_c \text{ kg soil}^{-1}$)	129.41 ^{***}	0.191ns	60.81 ^{***}	0.099ns
Extractable Mg ($\text{cmol}_c \text{ kg soil}^{-1}$)	130.63 ^{***}	0.113ns	48.63 ^{***}	3.74 ^{***}

*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$ and ns = not significant

A reduction in mean soil BC values of 0.232 and 0.263 $\text{cmol}_c \text{ kg soil}^{-1} \text{ pH unit}^{-1}$ in the 5 and 10 tonnes lime ha^{-1} treatments, respectively, compared to the unlimed plots was recorded over the 6-year period (Table 3.2). Furthermore, a highly significant ($P < 0.001$) interaction between lime application and time on soil BC was found in the Hutton soil (Table 3.1). Table 3.2 shows that soil BC was significantly ($P < 0.001$) reduced within the first year of lime application, although no significant difference was found in soil BC between the 5 and 10 tonnes lime ha^{-1} treatments. A significant reduction ($P < 0.001$) of 0.045, 0.343 and 0.435 $\text{cmol}_c \text{ kg soil}^{-1} \text{ pH unit}^{-1}$ in the 0, 5 and 10 tonnes lime ha^{-1} treatments, respectively, over the 6 years of the trial period was recorded in the Hutton soil.

Table 3.2 Soil BC values ($\text{cmol}_c \text{ kg soil}^{-1} \text{ pH unit}^{-1}$) as influenced by time and lime application for the Hutton and Oakleaf soil forms

Year	Lime application (tonnes ha^{-1})					
	Hutton			Oakleaf		
	0	5	10	0	5	10
1998	1.144a ¹	1.037c	1.091bc	-	-	-
1999	1.130ab	0.936e	0.917e	3.269a ¹	3.055a	3.234a
2000	-	-	-	-	-	-
2001	1.006d	0.863f	0.821f	3.027ab	2.428c	2.792bc
2002	1.082bc	0.768g	0.660h	3.124ab	2.841abc	2.881abc
2003	1.099b	0.694h	0.656h	3.250a	2.473c	2.557c
Mean	1.092a ²	0.860b	0.829b	3.168a ²	2.699b	2.866ab

1 LSD 0.05 (level x time) = 0.087, column and row values having the same symbols are not statistically different at the 5% level ($P < 0.05$)

2 LSD 0.05 (level) = 0.061, row values having the same symbols are not statistically different at the 5% level ($P < 0.05$)

1 LSD 0.05 (level x time) = 0.462, column and row values having the same symbols are not statistically different at the 5% level ($P < 0.05$)

2 LSD 0.05 (level) = 0.326, row values having the same symbols are not statistically different at the 5% level ($P < 0.05$)

Oakleaf soil form: Similar to the Hutton soil form, liming resulted in a highly significant ($P < 0.001$) reduction in mean soil BC over the 5-year period as shown in Table 3.1. The application of 5 tonnes lime ha^{-1} decreased mean soil BC values by $0.469 \text{ cmol}_c \text{ kg soil}^{-1} \text{ pH unit}^{-1}$. Although no significant difference in soil BC between 0 and 10 tonnes lime ha^{-1} was recorded, the mean soil BC in the highest lime treatment was $0.302 \text{ cmol}_c \text{ kg soil}^{-1} \text{ pH unit}^{-1}$ lower than the control (Table 3.2).

Although no statistically significant interaction between lime and years on soil BC was found, there was a tendency for a decline in soil BC over time (Table 3.2). The 5 and 10 tonnes lime ha^{-1} treatments showed a reduction in soil BC of 0.582 and $0.677 \text{ cmol}_c \text{ kg soil}^{-1} \text{ pH unit}^{-1}$, respectively, from 1999 to 2003.

Comparison of the experimental soils: It is clear from the results that the two experimental soils reacted differently to lime application in terms of the soil BC values. The soil BC determines to a great extent soil acidification as measured by a decrease in soil pH. Various soil constituents such as organic matter, Fe and Al oxides, and CaCO_3 (in calcareous soil) contribute to the soil BC at different pH values (Bolan & Hedley, 2003). Although this aspect will be dealt with in detail in another article, it is important to note that significant positive relationships between soil BC and organic C were established in both the Hutton ($P < 0.05$) and Oakleaf ($P < 0.01$) soils (Table 3.3).

Table 3.3 Pearson's coefficient of correlation (r) between soil BC, organic C and extractable acidity for the Hutton and Oakleaf soil forms

Variables	Hutton			Oakleaf		
	r	P	Number of observations	r	P	Number of observations
Soil BC vs organic C	+0.464	<0.05	28	+0.666	<0.01	22
Soil BC vs extractable acidity	+0.564	<0.01	28	-0.209	ns	22
Soil BC vs extractable Al	+0.571	<0.01	28	-0.214	ns	22
Soil BC vs APL	-0.520	ns	6	-0.825	<0.01	6

ns = not significant

Table 3.3 furthermore, shows that a strong positive relationship exists between soil BC and extractable acidity ($P < 0.01$) and Al ($P < 0.01$) in the Hutton soil, while no relationships between these parameters could be established for the Oakleaf soil. It is postulated that the significant reduction in soil BC in the Hutton soil over time and with liming (Tables 3.2 and 3.3) is mostly the result of a reduction in extractable acidity and Al due to lime application.

3.3.2 Acid production loads

Hutton soil form: In calculating APLs using Equation 3.3, no statistically significant effect of lime on APL was recorded (Tables 3.1 and 3.4). However, the net APL for the 5 and 10 tonnes lime ha^{-1} treatments was respectively 0.83 and 0.76 $\text{kmol}(\text{H}^+) \text{ha}^{-1} \text{year}^{-1}$ higher than the 0 tonnes lime ha^{-1} application.

Table 3.4 Acid production loads and acidification rates for the topsoil (0-250 mm) over a six and five year period, respectively in the Hutton and Oakleaf soil forms as a function of liming

Lime rate (tonnes ha^{-1})	Initial pH (H_2O)		Acid production load ($\text{kmol}(\text{H}^+) \text{ha}^{-1} \text{year}^{-1}$)		Acidification rate (pH (H_2O) units year^{-1})	
	Hutton	Oakleaf	Hutton	Oakleaf	Hutton	Oakleaf
0	5.33	4.54	1.61 ^{a1}	4.59 ^a	-0.046 ^{a1}	-0.044 ^a
5	6.31	4.86	2.44 ^a	8.04 ^{ab}	-0.116 ^b	-0.078 ^a
10	6.47	5.15	2.37 ^a	8.82 ^b	-0.140 ^c	-0.110 ^b
LSD _(0.05)	-	-	0.87 ^{ns}	3.48 [*]	0.020 [*]	0.035 [*]

1 Column values having the same symbols are not statistically different at $P < 0.05^*$

2 ns = not significant

Oakleaf soil form: A statistically significant ($P < 0.05$) increase in APL with lime application

was recorded (Table 3.1), with increased acid production values of 3.45 and 4.23 kmol (H⁺) ha⁻¹ year⁻¹ between the unlimed and the 5 and 10 tonnes lime ha⁻¹ treatments, respectively (Table 3.4).

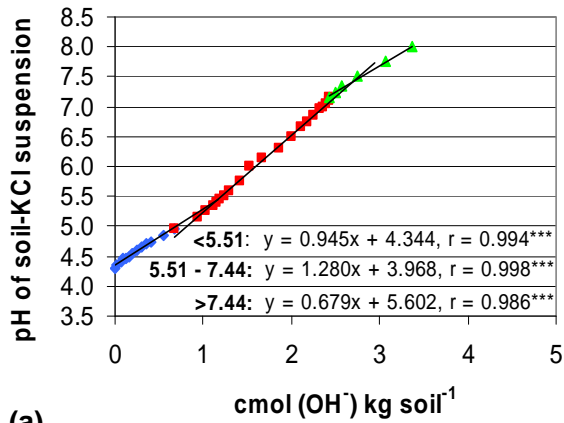
Comparison between experimental soils: The APLs for all treatments in the Hutton and the Oakleaf soils control were lower than the net rates of 3 to 5 kmol (H⁺) ha⁻¹ year⁻¹ reported by Helyar *et al.* (1990). However, the APLs recorded in the 5 and 10 tonnes lime ha⁻¹ treatments in the Oakleaf soil, were much higher although the crop production system was similar to that of the Hutton soil.

3.3.3 Soil BC vs soil acidification rate

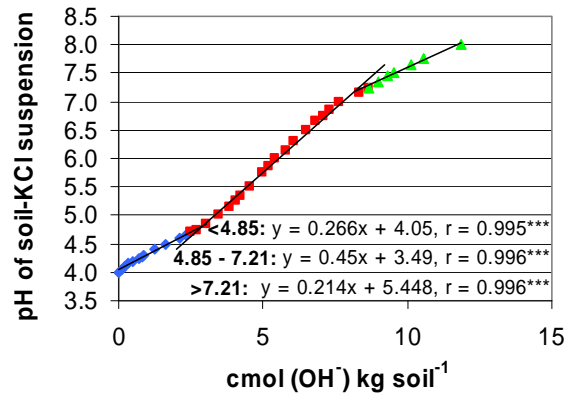
Hutton soil form: The soil BC is needed as a measure of soil acidification rates as calculated from Equation 3.4. Although the soil BC for a given soil is not constant over the whole pH range (Bache, 1988), numerous studies used a constant value for soil BC in estimating acidification rates (Singh *et al.*, 2003; Noble *et al.*, 2002; Hill, 2003; Helyar *et al.*, 1990). Non-linear regression analysis was used to identify critical pH values where a change in soil BC could be expected. Figure 3.1 (a, c & e) shows that minimum buffering (maximum slope of pH versus added OH⁻) occurs between 5.51 to 7.44, 5.54 to 7.47 and 5.51 to 7.54 in the 0, 5 and 10 tonnes lime ha⁻¹ treatments, respectively.

In order to evaluate the potential of soil BC in estimating soil acidification rates, the rate of predicted soil acidification (Equation 3.4), using soil BC at different pH ranges (<5.55, 5.55-7.50, >7.50 and 4.20-8.50), was correlated with measured soil acidification rate as indicated in Figure 3.2 (a). The measured acidification rate (pH units year⁻¹) was calculated from the measured annual change in basic cations, and the relationship between pH and extractable basic cations as described in Equation 3.6.

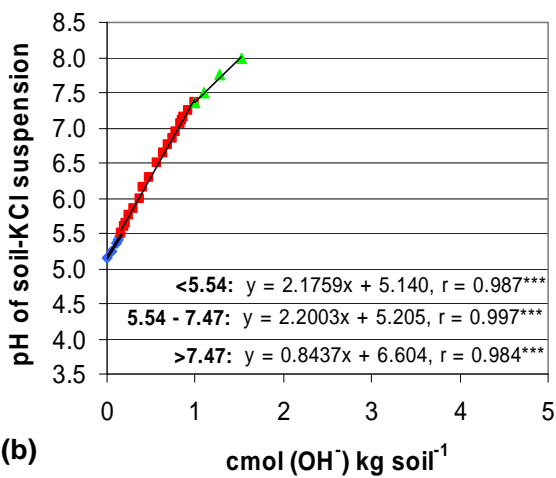
All four calculated acidification rates correlated highly significantly ($P < 0.001$) with measured soil acidification rates (Figure 3.2 (a)). The ability of the four soil BCs to predict soil acidification rates is arranged as follows according to correlation with measured acidification rates: $BC_{(<5.55)} > BC_{(4.2-8.5)} = BC_{(>7.50)} > BC_{(5.55-7.50)}$. The soil acidification rate determined with the soil $BC_{(4.2-8.5)}$ crossed the 1:1 line at 0.03 pH units year⁻¹. Below this value the soil $BC_{(4.2-8.5)}$ slightly overestimated acidification rates and above 0.03 acidification rates were slightly underestimated. The soil $BC_{(4.2-8.5)}$ gave a regression line nearly parallel to the 1:1 line, and is therefore the most appropriate of all the soil BCs for direct prediction of soil acidification rates.



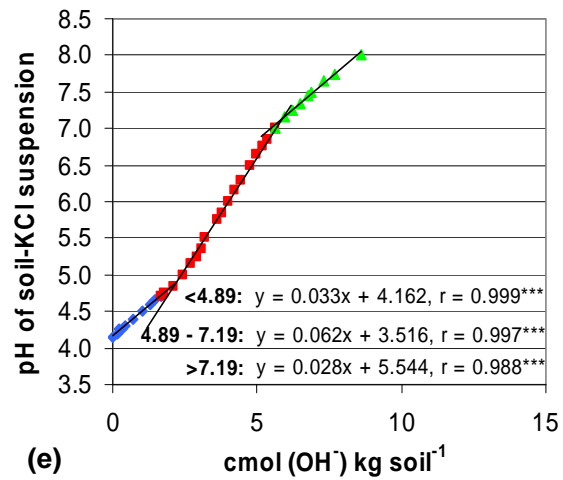
(a)



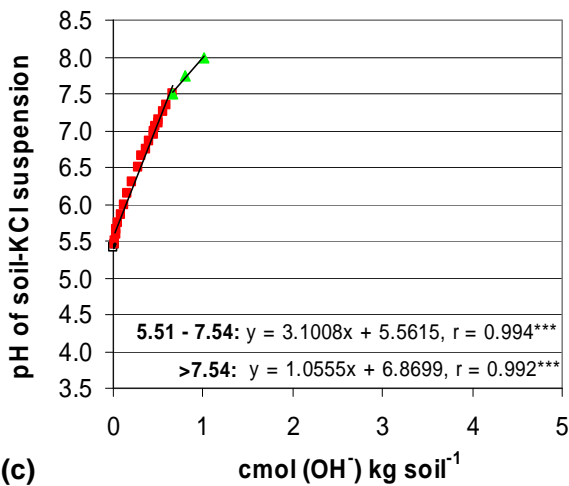
(d)



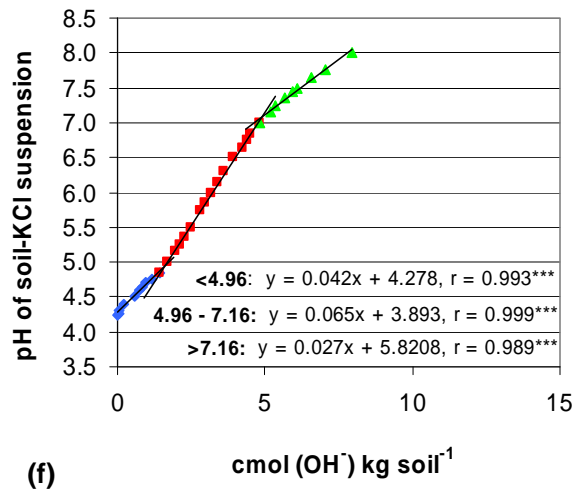
(b)



(e)



(c)



(f)

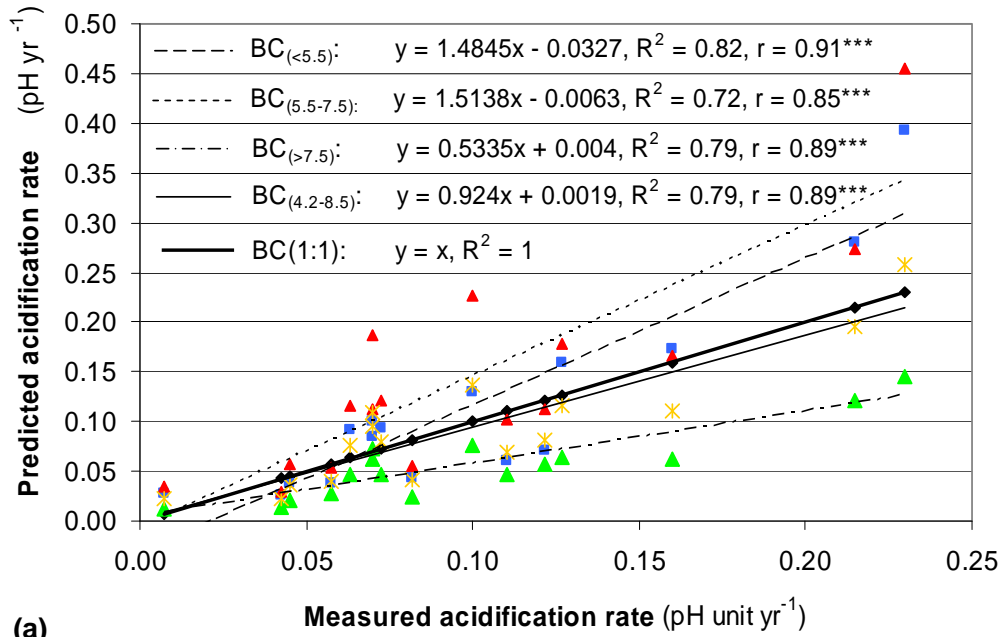
Figure 3.1 Titration curves for the critical pH ranges for (a) 0 (b) 5 and (c) 10 tonnes lime ha⁻¹ treatments in the Hutton and for (d) 0 (e) 5 and (f) 10 tonnes lime ha⁻¹ treatments in the Oakleaf soil forms, respectively (***) P < 0.001, (**) P < 0.01 and (*) P < 0.05).

The $BC_{(<5.55)}$ crossed the 1:1 line at an acidification rate of $0.07 \text{ pH unit year}^{-1}$. Above this value, soil acidification rates were overestimated. The $BC_{(>7.5)}$ consistently underestimated soil acidification rate and $BC_{(5.55-7.50)}$ overestimated soil acidification rate (Figure 3.2 (a)).

Oakleaf soil form: The Oakleaf soil revealed good buffering to base (OH^-) addition (Figure 3.1 (d, e & f)). The Oakleaf soil was moderately buffered in the mid-range (≈ 4.90 to 7.19) with increased buffering below 4.85 to 4.96 , and above 7.21 to 7.16 . The ability of the different soil BCs to predict soil acidification rates is as follows: $BC_{(4.2-8.5)} > BC_{(5.55-7.5)} = BC_{(>7.5)} > BC_{(<5.55)}$. The soil acidification rates determined with soil $BC_{(4.2-8.5)}$ crossed the 1:1 line at a measured soil acidification rate of $0.12 \text{ pH unit year}^{-1}$. Above this rate soil acidification rates were overestimated and below this value an under-prediction of soil acidification occurred. The $BC_{(4.2-8.5)}$ set of values gave a regression line in closest agreement to the 1:1 line. The other soil BC ranges gave either a consistent over- or under-prediction of measured soil acidification rates (Figure 3.2 (b)).

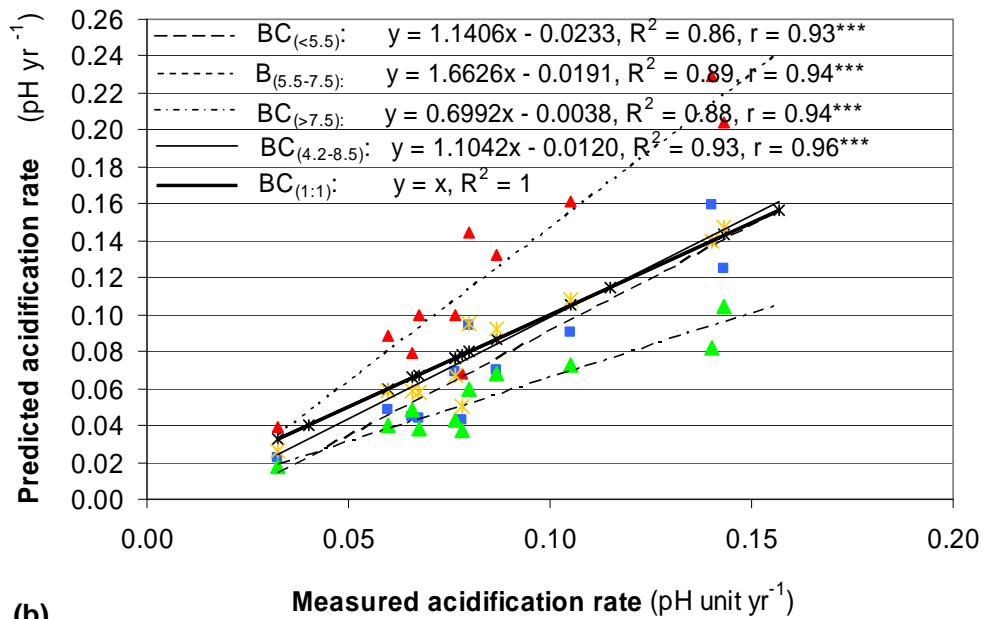
Comparison between soil forms: Figure 3.3 (a, b) shows that linear regression analysis of the titration curves over pH range 4.2 to 8.5 shows a strong relationship ($P < 0.001$) between the amount of OH^- added and pH in all lime treatments, while r values ranged from 0.983 to 0.996 for the Hutton and 0.993 to 0.996 for the Oakleaf soil form (Figure 3.3 (a, b)).

Even the 0 lime ha^{-1} treatment in the Oakleaf soil with the lowest pH of 4 gave a strong fit to the linear equation with an r^2 of 0.991 . Furthermore, it has been shown that the soil $BC_{(4.2-8.5)}$ appropriately predicts measured soil acidification rates in both soils. Therefore, the soil BC over the pH range 4.2 to 8.5 was used to estimate soil acidification rates in this study.



(a)

■ <5.5 ▲ 5.5-7.5 ▲ >7.5 ✖ 4.2-8.5



(b)

■ <5.5 ▲ 5.5-7.5 ▲ >7.5 ✖ 4.2-8.5

Figure 3.2 Relationship between measured and predicted acidification rates for the (a) Hutton and (b) Oakleaf soil forms (***) P < 0.001, (**) P < 0.01).

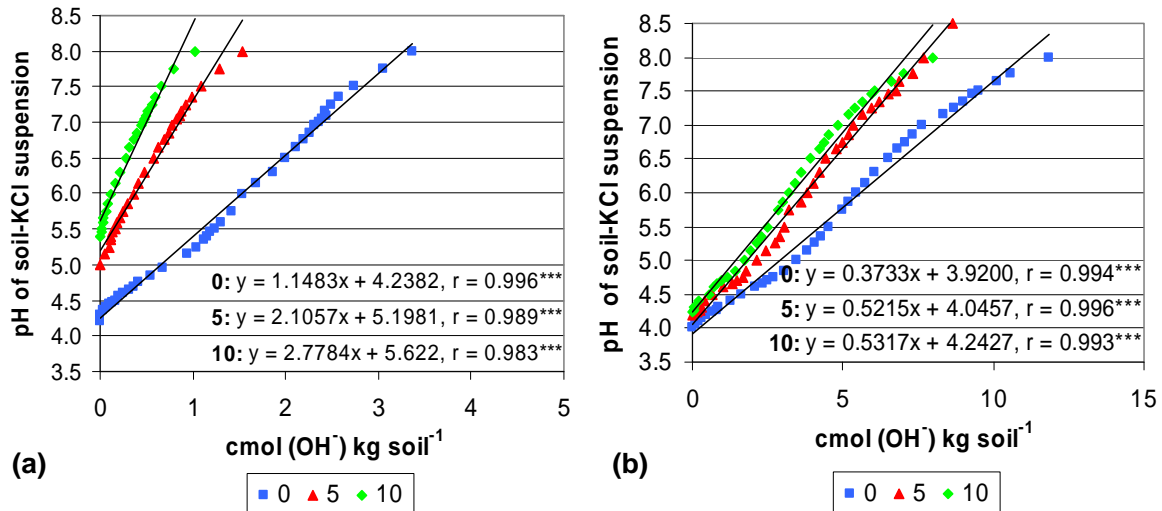


Figure 3.3 Combined titration curves for the 0, 5 and 10 tonnes lime ha^{-1} treatments in the (a) Hutton and (b) Oakleaf soils.

3.3.4 Effect of lime application on soil acidification rate

Hutton soil form: Soil acidification rates showed significant acceleration with lime application (Table 3.1). Lime addition significantly ($P < 0.01$) increased the acidification rate from -0.046 to -0.116 and -0.140 $\text{pH units year}^{-1}$ starting at initial $\text{pH (H}_2\text{O)}$ values of 5.33, 6.31 and 6.47, respectively. Table 3.4 shows that liming resulted in a significant decrease in soil BC, consequently leading to accelerated acidification rates. Statistically significant differences in acidification rates were furthermore observed between the 5 and 10 tonnes lime ha^{-1} treatments. A significant ($P < 0.05$) correlation existed between acidification rate and initial soil $\text{pH (H}_2\text{O)}$ (Figure 3.4 (a)).

Figure 3.4 (a) shows that at an initial $\text{pH (H}_2\text{O)}$ of 4.40, an acidification rate of 0 is predicted, and at a $\text{pH (H}_2\text{O)}$ of between 5.5 and 6.0 an acidification rate of between -0.10 and -0.13 pH unit year^{-1} is predicted.

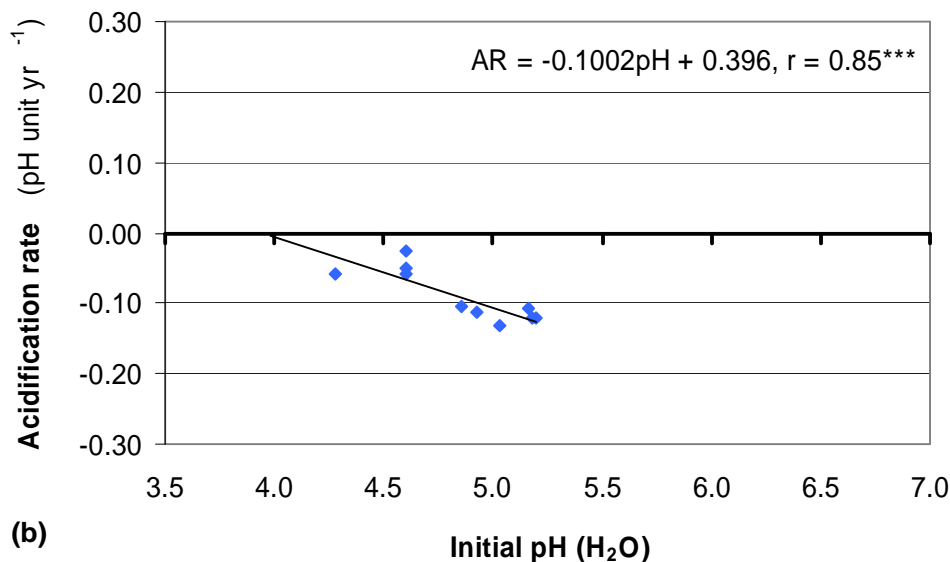
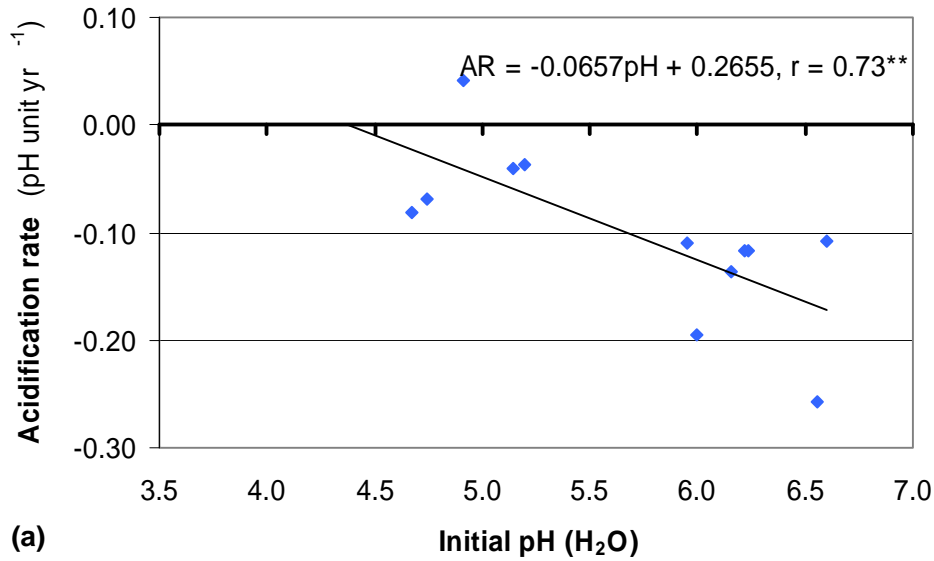


Figure 3.4 Relationship between initial pH (H₂O) and acidification rate (pH unit year⁻¹) in the (a) Hutton and (b) Oakleaf soil forms (*** P < 0.001, ** P < 0.01 and * P < 0.05).

Oakleaf soil form: Liming had a highly statistically significant (P<0.01) effect on acidification rate (Tables 3.1 and 3.4), with accelerated acidification rates with lime application recorded. Table 3.4 shows that acidification rate indicated a 0.044, 0.078 and 0.110 reduction in pH annually starting at an initial pH (H₂O) of 4.54, 4.86 and 5.15 in the 0, 5 and 10 lime ha⁻¹ treatments, respectively.

Figure 3.4 (b) shows the acidification rate plotted against initial soil pH (H₂O). A significant (P<0.001) regression relationship exists between acidification rate and initial soil pH (H₂O), with an acceleration in acidification with higher initial soil pH (H₂O) values. From this relationship it is shown that at a pH (H₂O) of 3.95 an acidification rate of zero could be expected and at pH (H₂O)

of 5, $-0.11 \text{ pH unit year}^{-1}$. The increased rate of acidification with increase in soil pH, as brought about by lime application, corresponds with the findings of Scott *et al.* (1999), Gasser (1973) and Hoyt and Henning (1982) who found an increased rate of pH decline with lime application. Scott *et al.* (1999) demonstrated acidification rates that varied from $-0.02 \text{ pH unit year}^{-1}$, following the application of $0.5 \text{ tonnes lime ha}^{-1}$, to $-0.10 \text{ pH unit year}^{-1}$ after a $5 \text{ tonnes lime ha}^{-1}$ application.

3.3.5 Lime loss and maintenance lime rate

Hutton soil form: Liming highly significantly ($P < 0.001$) increased the mean amount of extractable Ca and Mg (Tables 3.1 and 3.5). Mean extractable Ca increased from 0.71, to 1.56 and $2.10 \text{ cmol}_c \text{ kg}^{-1}$, in the 0, 5 and 10 tonnes lime ha^{-1} treatments, respectively. Table 3.5 shows an increase in extractable Mg of 0.61 and $1.01 \text{ cmol}_c \text{ kg}^{-1}$ compared to the unlimed treatment.

Table 3.1 shows that no significant interaction was found between lime level and time. After lime application in 1997, maximum extractable Ca and Mg levels were obtained two to three years after lime application (Table 3.5). However, no significant decrease or increase in extractable Ca and Mg was recorded over 6 years, and significantly higher extractable Ca and Mg values were observed in the limed compared to the unlimed plots at the end of 2003. In 2003, no statistically significant differences in Mg values were found between the recommended 5 tonnes ha^{-1} application rate and $10 \text{ tonnes lime ha}^{-1}$. A statistically significant ($P < 0.05$) linear decrease in the sum of extractable Ca + Mg with time (Figure 3.5 (a)) was shown after maximum extractable Ca + Mg was reached.



Table 3.5 Extractable Ca and Mg values (cmol_c kg soil⁻¹) as influenced by time and lime application for the Hutton and Oakleaf soil forms

Year	Lime application (tonnes ha ⁻¹)											
	Hutton						Oakleaf					
	Ca			Mg			Ca			Mg		
	0	5	10	0	5	10	0	5	10	0	5	10
1998	0.70a	1.40b	1.67bc	0.56a	1.03b	1.32cd						
1999	0.76a	1.76bc	2.07de	0.59a	1.38cd	1.60d	0.23a	0.98de	1.83f	0.10a	0.58b	1.13c
2000	0.87a	1.49b	2.54f	0.62a	1.10bc	1.90e	0.34a	0.89cde	1.23de	0.14a	0.74b	0.60b
2001	0.66a	1.57b	2.35ef	0.53a	1.25b	1.80de	0.38a	0.84b	1.29e	0.26a	0.58b	0.84b
2002	0.63a	1.56bc	1.98cde	0.44a	1.05b	1.38cd	0.20a	0.45ab	1.22de	0.22a	0.22a	0.64b
2003	0.66a	1.60b	1.97cde	0.44a	1.05b	1.26b	0.46a	0.50ab	1.18de	0.20a	0.25a	0.59b
Mean ²	0.71a	1.56b	2.10c	0.53a	1.14b	1.54c	0.32a	0.73b	1.35c	0.18a	0.47b	0.77c

1 LSD 0.05 (level x time) = 0.42 (Ca) and 0.28 (Mg); column and row values having the same symbols are not statistically different (P<0.05).

2 LSD 0.05 (level) = 0.17 (Ca) and 0.13 (Mg); row values having the same symbols are not statistically different (P<0.05)

1 LSD 0.05 (level x time) = 0.42 (Ca) and 0.26 (Mg); column and row values having the same symbols are not statistically different (P<0.05)

2 LSD 0.05 (level) = 0.19 (Ca) and 0.12 (Mg); row values having the same symbols are not statistically different (P<0.05)

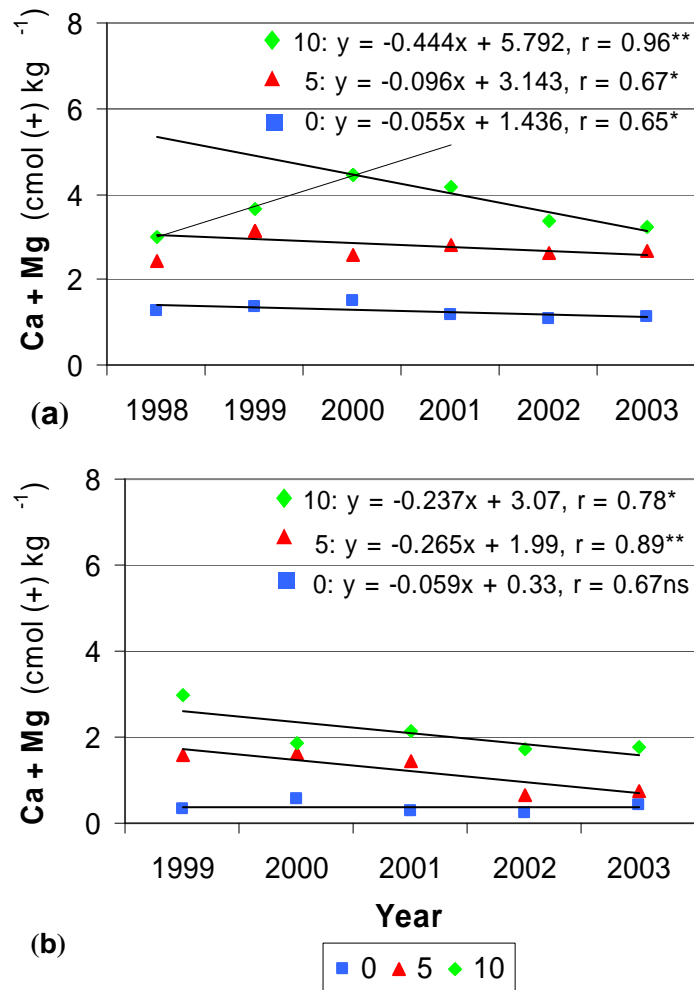


Figure 3.5 The relationships between extractable (Ca + Mg), and time in the (a) Hutton and (b) Oakleaf soil forms.

This can be attributed to natural acidification processes, leaching losses, as well as crop uptake and consequent removal of Ca and Mg through the harvesting of the seed. After obtaining maximum concentrations in 1999 and 2000 in the 5 and 10 tonnes ha⁻¹ lime rates, respectively, the amount of extractable Ca + Mg varied linearly with time (Figure 3.5). The slopes of the regression lines increased with the rate of lime application, with values of -0.055, -0.096 and -0.444 cmol_c kg⁻¹ for the 0, 5 and 10 tonnes lime ha⁻¹ application, respectively (Figure 3.5 (a)). This indicates that the annual loss (leaching and removal by crop) in basic cations increased with lime application.

The annual maintenance lime requirement, calculated from Equation 3.7, amounted to 0.2, 0.3 and 1.4 tonnes CaCO₃ ha⁻¹ year⁻¹ for the 0, 5 and 10 tonnes lime rates in the Hutton soil form, respectively (Table 3.6).

Table 3.6 Maintenance lime requirement rates in the topsoil (0-250 mm) of the Hutton and Oakleaf experimental soils as a function of liming

Lime rate (tonnes lime ha ⁻¹)	Maintenance lime requirement (tonnes CaCO ₃ ha ⁻¹ year ⁻¹)	
	Hutton	Oakleaf
0	0.2	0
5	0.3	0.8
10	1.4	0.8

The fairly rapid loss of lime from the 10 tonnes lime ha⁻¹ treatment was probably not only caused by cultivation and increased mineralization rates of organic matter, but also by the high lime application level. It can be postulated that free lime was present in the soil for the 10 tonnes ha⁻¹ lime treatment and was leached, although this phenomenon was not determined. Gasser (1973) postulated that the loss of lime doubles for each increase of one pH unit. Hoyt and Henning (1982) speculated that if the soils they were studying would have been limed to pH 5.7 instead of 6.7, the loss of lime might have been one-half of that found in the experiment (0.49 tonnes CaCO₃ ha⁻¹ year⁻¹).

Oakleaf soil form: Liming significantly ($P < 0.05$) increased the mean extractable Ca by 0.41 and 1.03 cmol_c kg⁻¹, and the Mg by 0.29 and 0.59 cmol_c kg⁻¹ in the 5 and 10 tonnes lime ha⁻¹ treatments, respectively (Table 3.5). Although no significant interaction between lime level and time was recorded for extractable Ca, a highly significant interaction was found for extractable Mg (Table 3.1). The extractable Ca and Mg in the unlimed plot remained relatively unchanged over 5 years, while a decreasing trend in extractable Ca was recorded in the limed treatments. A highly significant ($P < 0.001$) decrease in extractable Mg was found within 4 and 2 seasons in the 5 and 10 tonnes lime ha⁻¹ plots, respectively (Table 3.5). Factors (e.g. leaching due to rainfall, yield removal) responsible for reacidification caused a decrease in the extractable Ca and Mg in the 5 tonnes lime ha⁻¹ rate to such an extent that no significant difference could be found compared to the control after four years.

Figure 3.5 (b) shows that extractable Ca and Mg varied linearly with time with statistically significant ($P < 0.05$ and $P < 0.01$) decreases in extractable Ca and Mg over the trial period in the 5 and 10 tonnes lime ha⁻¹ treatments, respectively. Although a slight decrease in the amount of Ca²⁺ and Mg²⁺ was observed in the control, the relationship was not statistically significant as shown in Figure 3.5 (b).

The maintenance lime requirement for the Oakleaf soil ranged from 0 tonnes in the control, to 0.8 tonnes CaCO₃⁻¹ ha⁻¹ year⁻¹ in the 5 and 10 tonnes lime ha⁻¹ treatments (Table 3.6). Although

liming increased the rate of lime loss between unlimed and limed plots, no apparent difference in maintenance lime requirement was found between the 5 and 10 tonnes ha⁻¹ lime rates.

Comparison between experimental soils: According to the FSSA (2003), maintenance applications of agricultural lime of 0.3 to as much as 1.5 tonnes CaCO₃ ha⁻¹ year⁻¹ are necessary under normal maize cultivation practices in South Africa. Although the average maintenance lime requirement for the 10 tonnes ha⁻¹ lime treatment of the Hutton soil and the lime treatments of the Oakleaf soil are in accordance with lime losses generally expected, the acidification rates were in general moderate for the two experimental soils. This can be ascribed to the conservative (low risk) fertilizer application strategies that were evaluated for resource-poor farmers. Another reason for the low acidification rates is the use of limestone ammonium nitrate (LAN (28% N)) as nitrogen (N)-source. LAN is ranked as an N-source with a low acidifying effect due to its nitrate and lime content. Nitrogen-containing fertilizers which contain large quantities of ammonium and amine nitrogen have a greater acidifying effect on soil than nitrate-containing fertilizers (FSSA, 1998).

3.4 CONCLUSIONS

Results from the study showed that acidification rates increased with lime application, but due to stronger soil BC in the Oakleaf soil reacidification was found to be lower. Continuous maize cultivation and inappropriate nitrogenous fertilization have the potential to generate sufficient acidity that crop production (e.g. maize, legumes etc.) could be abandoned due to Al and manganese toxicity in many agricultural lands in Mlondozi. It is furthermore important that soils should be regularly tested and should be limed to a point where phytotoxic levels of extractable Al are eliminated. Management strategies (e.g. split application of N) to reduce the acidifying effect of fertilizer should also be implemented. However, the assessment of acidification rates could be a valuable tool in determining soil acidification and serve as an indicator to adapt management practices to reduce soil acidification. This stresses the importance of implementing sound management strategies in conjunction with government interventions, especially for resource-poor farmers.

LIMING EFFECTS OF SOIL PROPERTIES, NUTRIENT AVAILABILITY AND GROWTH OF MAIZE

4.1 INTRODUCTION

A generation ago, prevention of starvation due to food shortage on a global scale was the primary goal in agricultural strategies, a concern successfully addressed by the so-called “green revolution” in various aspects. However, there has been a concomitant rise in incidence of nutrient deficiencies in human populations worldwide (Graham & Welch, 2000). In South Africa, resource-poor rural communities are especially vulnerable because most of the household’s food is produced on the land on which they live. If nutrient deficiencies or toxicities occur in these soils, their quality of life can be influenced dramatically (Steyn & Herselman, 2006). Furthermore, many of the resource-poor rural areas are characterized by acid soils, commonly deficient in P, Ca, Mg, Mo and Si, with Al and Mn at toxicity levels. Aluminium toxicity limits nutrient use efficiency and crop production due to reduced root growth which greatly restricts the ability of the plant to explore the soil volume for nutrients and water.

Liming of acid soils to alleviate soil acidity is a common practice, changing the availability and soil solution concentrations of various nutrients. Increasing pH, HCO_3^- or Ca^{2+} concentration of the soil solution may interact with solubility and uptake of elements, and sometimes change the general vitality or growth rate of plants (Tyler & Olsson, 2001). Several studies have shown that the solubility of P, Ca, Mg, Mo and Si increases with increasing pH while the solubility and availability of Zn, Cu, B, Mn, Fe and Al in soils declines with increasing pH (Mengel & Kirkby, 1987; Reddy *et al.*, 1995; Haynes, 2001; Thibaud & Farina, 2006). Furthermore, economic considerations often require judicious management of applied fertilizer inputs under resource-poor farming conditions. Ohki (1983) showed that soils with pH (H_2O) of less than 5.0 often contain toxic levels of Mn that may be detrimental to growth of maize.

The present study was undertaken to investigate the relationships between nutrient availability and maize grain yield in a resource-poor farming area in the Mpumalanga Province of South Africa. This area is characterized by acid soils deficient in Ca, Mg, P and K (Booyens *et al.*, 2000). Steyn and Herselman (2006) further reported that trace elements such as B, Co, Cu, Fe, I, Mn, Mo, Se and Zn have a high risk of being deficient in this area. The objectives of the study were to determine (i) the effect of lime application on soil and leaf nutrient concentrations, and (ii)

critical nutrient levels in soil and maize leaves as affected by soil acidity and lime application.

4.2 MATERIAL AND METHODS

4.2.1 Experimental layout and procedure

The experimental layout and procedure described in Chapter 2 are applicable in this discussion as the data derived from the two field trials were used to evaluate the objectives as stated. Some additional chemical topsoil (0-250 mm) characteristics of the experimental soils that were not mentioned in Table 2.1 are summarized in Table 4.1.

Table 4.1 Selected soil chemical topsoil (0-250 mm) properties¹ of the experimental sites

Soil form ²	Experimental soil	
	Hutton	Oakleaf
P (mg kg ⁻¹)	5.59	9.32
K (mg kg ⁻¹)	81	38
Ca (mg kg ⁻¹)	150	90
Mg (mg kg ⁻¹)	57	43
Cu (mg kg ⁻¹)	2.78	1.61
Zn (mg kg ⁻¹)	0.53	0.89
B (mg kg ⁻¹)	0.81	3.81
Mo (mg kg ⁻¹)	0.01	0.01

¹ According to the The Non-Affiliated Soil Analysis Work Committee (1990)

² Soil classification working group, 1991

4.2.2 Soil and leaf sampling and analysis

Topsoil samples (0-250 mm) were taken annually in February/March at flowering. Eight soil samples were taken within each plot between the rows and a composite sample was made up. The composite samples were air-dried and ground to pass through a 2 mm sieve. Soil pH (H₂O) was determined in a 1:2.5 (soil:water) suspension (Reeuwijk, 200). Extractable acidity was determined with a 1 mol dm⁻³ KCl extraction. Extractable P was determined according to the Bray-1 extraction method. The P concentrations of the extracts were determined on a continuous flow analyzer (Bray & Kurtz, 1945). The NH₄OAc (1 mol dm⁻³, pH 7) method was used to determine the extractable cations Ca, Mg and K. The cations in solution were determined on an atomic absorption spectrophotometer (Thomas, 1982). The di-ammonium EDTA method was used to determine Cu, Zn, Co and Mo. Water-soluble B was determined by

the hot water extraction method. Copper, Zn, Mo, Co and B were determined by ICP-MS (The Non-Affiliated Soil Analysis Work Committee, 1990).

Maize leaf samples were taken annually at flowering (end of February or beginning of March), 8 to 10 weeks after planting. The maize leaf immediately opposite and below the first ear was sampled. The leaf samples were washed in deionized water, dried at 70 °C to constant mass and milled. Nitrogen was determined by dry oxidation (Bellomonte *et al.*, 1987) using a Carlo-Erba CNS instrument. For the determination of P, K, Ca, Mg, K, Fe, Mn, Al, Cu, Zn and B, 1 g samples were wet-digested on a digestive block with 1:3 (nitric acid (HNO₃ (c)) : perchloric acid (HClO₄ (c))) and determined by ICP-OES (Zasoski & Burau, 1977). For the determination of Mo, 0.5 g leaf samples were wet-digested with HNO₃ (c) and determined by ICP-MS (Chao-Yong & Schulte, 1985).

4.2.3 Statistical analysis and data interpretation

The effects of liming on soil fertility properties, leaf nutrient concentrations and maize grain yield were evaluated statistically by analysis of variance (ANOVA) (GenStat, 2003). The values that will be discussed are annual replicate means per lime application level and replicated means per lime application level over years. The Bonferroni multiple comparison test for means separation was used to test all the main effects at a 5% probability level.

The evaluation of critical threshold values for soil and leaf nutrients was based on relative grain yield values. The advantages and shortcomings of the relative yield concept were discussed by Bray (1944) and Van Biljon *et al.* (2004, 2008), but the conclusion was that applying relative yield to field data enables one to include results from different climatic zones, soil types, maize cultivars, plant spacing and seasons. Relative yields were determined as percentages of the highest yield annually in each of the three randomized blocks and the average of these replicates presented the relative yield for each treatment. Critical threshold nutrient levels, where a significant decrease in relative yield could be expected, were determined by three methods namely: (i) Non-linear regression analysis using the “broken stick model” (GenStat, 2003) to obtain the upper threshold value and biological optimum. (ii) The probability approach of Cate and Nelson (1971) to obtain the lower threshold value (Van Biljon *et al.*, 2008). The “between groups” sum of squares is calculated directly by procedures commonly used in analysis of variance of one-way classification data (Cate & Nelson, 1971; Möhr, 1976; GenStat, 2003). (iii) At a 90% relative yield, where a 10% reduction in growth was recorded. The relationships between relative yield and nutrient concentrations were based on pooled data for both experimental sites.

4.3 RESULTS AND DISCUSSION

4.3.1 Effect of liming on soil and leaf nutrient values

Variance analyses of the soil and leaf nutrient content as affected by lime application are given in Tables 4.2 to 4.4.

Table 4.2 ANOVA table of probabilities of lime treatment effects on soil and leaf nutrients in the Hutton and Oakleaf soil forms

Variable	Hutton		Oakleaf	
	F-ratio			
	Soil	Leaf	Soil	Leaf
N	-	6.26**	-	1.06ns
P	3.42**	7.00**	0.48 ns	0.19 ns
K	0.64ns	0.19ns	1.54 ns	0.42 ns
Ca	155.38***	57.33***	22.09***	12.40***
Mg	160.63***	79.21***	35.47***	57.91***
Cu	15.25***	0.49ns	1.68 ns	0.96 ns
Zn	5.41**	4.03*	0.62 ns	7.09**
B	14.92***	1.25ns	15.90***	1.62 ns
Mo	2.99*	-	3.80*	-
Mn	-	9.07***	-	6.99**
Fe	-	7.20**	-	1.76 ns
Al	351.28***	1.13ns	37.47***	1.21 ns
Yield	5.22**		33.09***	

*** P < 0.001, ** P < 0.01, * P < 0.05 and ns = not significant

Hutton soil form: A secondary effect of soil acidity is low soil Ca and Mg values, resulting in low leaf Ca and Mg concentrations. Liming is the most common and effective practice to replenish the soil cation pool (Fageria & Baligar, 2003). Table 4.3 shows that liming significantly increased extractable soil Ca, Mg, Cu, Zn and Mo, and decreased soil P and B levels.

A significant increase in leaf N, P, Ca and Mg, and a decrease in leaf Mn and Fe concentrations were recorded (Table 4.4).

Table 4.3 The effect of lime application on selected soil chemical properties in the Hutton and Oakleaf soil forms

Nutrient	Lime application (tonnes ha ⁻¹)					
	Hutton			Oakleaf		
	0	5	10	0	5	10
P (mg kg ⁻¹)	6.62a	4.90b	4.71b	7.54a	6.68a	7.25a
K (mg kg ⁻¹)	77.2a	78.9a	71.4a	35.5 a	30.9 a	34.4a
Ca (mg kg ⁻¹)	142.7a	312.4b	419.1c	96a	161b	281c
Mg (mg kg ⁻¹)	64.6a	139.5b	188.3c	30.6a	54.1b	99.2c
Cu (mg kg ⁻¹)	2.52a	2.84b	3.16b	1.33a	1.42a	1.38a
Zn (mg kg ⁻¹)	0.74a	0.88b	0.96b	0.810a	0.71a	0.67a
B (mg kg ⁻¹)	0.39b	0.42b	0.33a	1.81a	1.53b	1.60b
Mo (mg kg ⁻¹)	0.59a	0.69ab	0.71b	0.24a	0.24ab	0.26b

Row values having the same symbols are not statistically different at P = 0.05

Oakleaf soil form: The application of lime had a highly significantly effect on increased soil Ca, Mg and Mo and decreased soil B levels. No effects on available soil P, K, Cu and Zn values was recorded (Tables 4.2 and 4.3). A highly significant increase in leaf Ca, Mg and Zn, and a decrease in leaf Mn, were found (Tables 4.2 and 4.4).

Table 4.4 The effect of lime application on leaf nutrient uptake as reflected by the first ear leaf at tasselling to initial silking in the Hutton and Oakleaf soil forms

Nutrient	Lime application (tonnes ha ⁻¹)					
	Hutton			Oakleaf		
	0	5	10	0	5	10
N (%)	1.65a	1.64a	1.81b	1.73a	1.76a	1.81a
P (%)	0.14a	0.16ab	0.17b	0.21a	0.21a	0.21a
K (%)	1.62a	1.60a	1.63a	1.23a	1.25a	1.20a
Ca (%)	0.29a	0.41b	0.45b	0.25a	0.30b	0.32b
Mg (%)	0.23a	0.32b	0.37c	0.17a	0.27b	0.35c
Cu (mg kg ⁻¹)	8.09a	7.9a	8.2a	8.3a	8.1a	8.7a
Zn (mg kg ⁻¹)	32.0b	28.9a	34.3c	24.0a	28.7b	30.4b
B (mg kg ⁻¹)	16.1a	16.9a	19.3a	15.3a	16.2a	13.7a
Mn (mg kg ⁻¹)	43.2b	36.9a	35.8a	64.6b	51.4a	55.9a
Fe (mg kg ⁻¹)	304b	228b	225b	322a	267a	256a
Al (mg kg ⁻¹)	526a	430a	396a	642a	476a	425a
Yield (tonnes ha ⁻¹)	2.25a	2.73b	2.78b	0.34a	0.79b	1.32c

Row values having the same symbols are not statistically different at P = 0.05

Comparison between soils: In general, liming increased the mean extractable Ca and Mg values over 6 years to above the optimum Ca range of 300 - 2000 mg kg⁻¹ and Mg >50 mg kg⁻¹, respectively, in the Hutton soil, as suggested by Buys (1986). However, liming did not increase extractable Ca values to within the optimum range in the Oakleaf soil form, but 5 and 10 tonnes lime ha⁻¹ increased extractable Mg to above the critical level of 50 mg kg⁻¹. Soil P and K values were deficient in both soils (Tables 4.3 and 4.5).

Table 4.5 Critical thresholds for selected soil nutrient indices

Nutrient indices	Soil nutrient content		
	Deficiency threshold (mg kg ⁻¹)	Critical threshold (mg kg ⁻¹)	90% relative yield (mg kg ⁻¹)
K	<80 ¹	50 ⁴	78-95
Ca	<200 ¹	228 ⁴ , 345 ⁵	348
Mg	<50 ¹	78 ⁴ , 105 ⁵	140
Cu	<1 ²	1.68 ⁴ , 2.83 ⁵	2.85
Zn	<3 ²	-	-
B	<1 ³	-	-

¹ Buys (1986)

² Steyn & Herselman (2006)

³ Mengel & Kirkby (1987)

⁴ Cate & Nelson (1971) procedure

⁵ Broken-stick analysis

Leaf N and P concentrations below critical concentrations were recorded in the Hutton soil, and the Oakleaf soil was deficient in leaf N and K nutrients according to values reported in Table 4.6. Because of the relatively large amounts of N used by crop plants, N is usually the nutrient element applied to agricultural land in the largest amounts. Once Al toxicity and P deficiency have been managed by a combination of soil amendments, yield potential is likely to be limited by N supply (Haynes, 2001). Due to the low leaf N concentrations recorded in the present study, increased application of N fertilizer and/or the use of legumes in rotation, as intercrops, or green manures, needs to be implemented.

Steyn and Herselman (2006) raised a concern that the trace elements B, Co, Cr, Cu, Fe, I, Mn, Mo, Se and Zn have a high risk of being deficient in Mpumalanga, especially in resource-poor farmlands. Over-liming may further cause deficiency of micronutrients such as Zn, Cu and B, if soils are relatively poor in these elements. A decrease in soil B levels with liming was observed (Tables 4.2 and 4.3) in both experimental soils. Although liming did not suppress B levels to below deficient levels in the Oakleaf soil, the hot water-soluble B in the Hutton soil was far below the deficiency (<1 mg kg) threshold suggested by Mengel and Kirkby (1987) and Steyn and

Herselman (2006). However, liming had no effect on leaf B uptake and both soils had leaf B concentrations within the adequate range of 5 to 25 mg kg⁻¹.

Table 4.6 Critical threshold values for selected plant nutrient indices in maize crops

Nutrient indices	Plant nutrient concentration	
	Adequate Range	Toxicity/Excessive Threshold
N (%)	2.60-4.00 ¹	>4.0 ³
P (%)	0.17-0.32 ¹	>0.8 ³
K (%)	1.50-3.50 ²	>4.0 ³
Ca (%)	0.20-0.50 ³	>0.9 ³
Mg (%)	0.20-1.00 ¹	>0.85 ³
Cu (mg kg ⁻¹)	6-20 ³	>50 ³
Zn (mg kg ⁻¹)	18-60 ³	>150 ³
B (mg kg ⁻¹)	5-25 ¹	>25 ¹
Mo (mg kg ⁻¹)	0.1-0.5 ¹	-
Fe (mg kg ⁻¹)	30-200 ³	>350 ¹
Mn (mg kg ⁻¹)	20-200 ³	>300 ¹
Al (mg kg ⁻¹)	<200 ¹	>400 ¹

¹ Reuter and Robinson (1997)

² Hanway (1962)

³ Weir and Cresswell (1994)

On the basis of 3 mg kg⁻¹ as the threshold value for Zn deficiency, all the treatments in both soils had very low soil Zn values. Lime application did not affect Zn level in the Oakleaf soil form, but a non-significant trend of increase in Zn by 0.14 and 0.22 mg kg⁻¹, was observed with 5 and 10 tonnes lime ha⁻¹, respectively, in the Hutton soil form. Parker *et al.* (1991) reported that Zn deficiency of crops, especially maize, is very common. It was, however, found that liming did not influence the uptake of leaf Zn content in the two sites studied. Although soil Zn levels were low, both soils had leaf Zn concentrations within the adequate range of 18 to 60 mg kg⁻¹.

Soil and leaf Cu values were in the optimum range (>1 mg kg⁻¹ and >6 mg kg⁻¹, respectively) in both experimental soils. The extractable soil Mo values in the Oakleaf soil were in the deficiency range with an observed increase in Mo with lime application. In some areas, however, particularly on acid soils (pH (H₂O) <5.5), Mo deficiency can arise because of Mo fixation in the soil. Mo deficiency symptoms are commonly observed on soils derived from quartzic material, as is the case in the study area (Mengel & Kirkby, 1987).

4.3.2 Critical soil nutrient concentrations and yield

Critical concentrations are not single values but a narrow range of nutrient concentrations, above which the plant is over supplied with nutrients, and below which the plant is deficient and a growth stress may be expected to occur (Melsted *et al.*, 1969). According to Ulrich and Hills (1973), the critical concentration lies within the transition zone and is associated with (i) the breaking point of the curve; (ii) the midpoint of the transition zone; or (iii) a reduction in growth, usually 10%.

The values discussed are pooled data per lime application level for both experimental soils. The regression equations presented in Figures 4.1 (a-d) describe relationships between soil concentrations of the nutrients tested and relative grain yield. Critical threshold values for soil K, Ca, Mg and Cu concentration indices, according to the Cate-Nelson method, non-linear (broken-stick) analysis and at a 90% relative yield, are given in Tables 4.5 and 4.7. No relationship could be established between yield and soil P, B, Zn or Mo, and between yield and leaf nutrient concentrations. Furthermore, critical threshold levels according to the broken-stick method could only be determined for soil Ca, Mg and Cu as indicated in Table 4.6. Figure 4.1 shows the typical relationship of increasing yields with increasing soil K, Ca, Mg, and Cu contents.

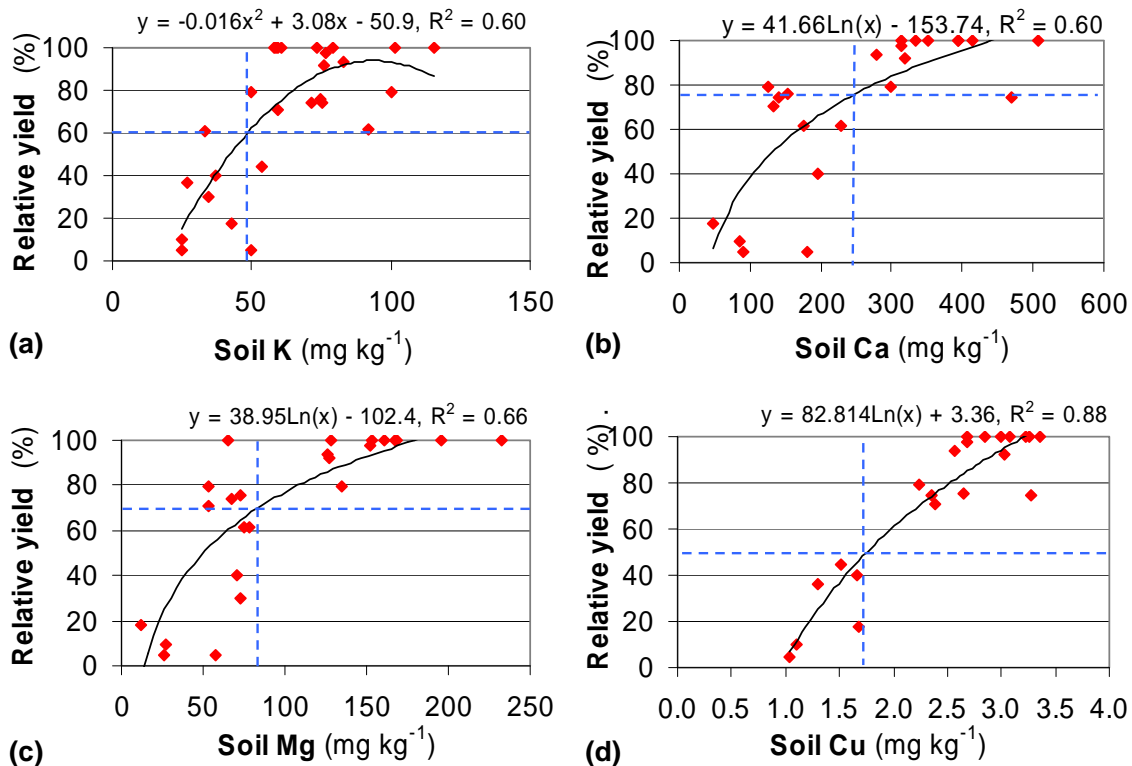


Figure 4.1 The relationship between relative yield and soil (a) K, (b) Ca, (c) Mg, and (d) Cu.

Table 4.5 and 4.6 shows that the measured critical threshold values for soil Ca, Mg and Cu were 228-345, 78-105 and 68-2.83 mg kg soil⁻¹, respectively, which are in the range of adequate values reported by Buys (1986) and Steyn and Herselman (2006). However, critical K levels (Table 4.5) were lower than the adequate range reported by Buys (1986) and Mengel and Kirkby (1987).

Table 4.7 Non-linear regression analysis between relative yield and selected soil nutrients for pooled data in the Hutton and Oakleaf soil forms

Variables	R ² (%)	F	Critical value (mg kg ⁻¹)
Relative yield vs soil Ca	57.6	70.73*	345
Relative yield vs soil Mg	63.4	80.94*	105
Relative yield vs soil Cu	89.4	282.42*	2.83

*** P < 0.001, ** P < 0.01, and * P < 0.05

4.4 CONCLUSIONS

The present study indicates that a risk exists for soil P, K, B and Zn to be deficient in the study area. However, the deficiencies of Cu, Zn and B were not reflected in plant uptake with leaf concentrations well above adequate ranges. Critical values, as reported in this study, are not infallible but can serve as a guide in the interpretation of the problems associated with soil acidity. If used properly they can help identify nutrition deficiencies and imbalances responsible for yield depression which could assist in the implementation of useful and sound cultivation practices.