Evaluation of the effect of soil acidity amelioration on maize yield and nutrient interrelationships using stepwise regression and nutrient vector analysis

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The interrelationships between elemental content of selected soil and leaf nutrients and maize grain yield were evaluated in a liming experiment conducted on a Hutton and Oakleaf soil in a resource-poor farming area in the Mpumalanga Province of South Africa. Improved uptake of Mo by maize with increased soil P status was found on the Hutton soil, while N and P uptake improved, due to lime and fertiliser application, on both soils. Boron uptake by maize was depressed with lime application on the Oakleaf soil. Maize yield on the Hutton soil was adversely affected by Al toxicity, while plant Ca deficiency was the dominant factor that limited maize grain yield, followed by Al level and a depressed B uptake on the Oakleaf soil. Nutrient vector analyses showed a toxic build-up of Fe, followed by Al and to a lesser extent Mn. These toxic elements depressed the uptake of Ca, Mg and B by maize on the Hutton soil. On the Oakleaf soil, Al toxicity, followed by high concentrations of Mn and Fe, markedly reduced the uptake of Ca, Mg and K by maize.

Keywords: Al-toxicity, Ca deficiency, Mg deficiency, nutrient interactions, resource-poor farmers, vector analysis

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Introduction

Soil acidity is a major constraint to crop production throughout the world (Sumner & Noble, 2003). Vast areas in South Africa, occupied by resource poor rural communities in the higher rainfall areas, are characterised by acid soils and commonly deficient in Ca, Mg, Mo and P (Beukes, 1995). The productivity of acid soils is limited by two fundamental factors; the presence of phytotoxic substances (e.g. soluble Al and Mn) and nutrient deficiencies (e.g. P, Ca, Mg and Mo). Aluminium toxicity limits nutrient use efficiency and crop production through reducing root growth, which greatly restricts the ability of the plant to explore the soil volume for nutrients and water. This also leads to restricted uptake of P, Ca, and Mg by plant roots and deficiencies of these nutrients are common in plants suffering from Al toxicity (Foy & Flemming, 197□; Foy, 19□4; Haynes, 2001).

Aluminium toxicity interferes with active ion uptake processes functioning across the root-cell plasma membrane (Wright, 19□9; Haynes, 2001). Toxic concentrations of Al have been shown to reduce P and Ca uptake by crops. The mechanism of Al/P interactions is proposed to be an adsorption/precipitation reaction between Al and P at the root surface or in the root free space (McCormick & Borden, 1974; Tan & Keltjens, 1990; Haynes, 2001). Aluminium toxicity also results in inhibition of Ca and Mg uptake by plants. Mengel and Kirkby (19□7) reported that Al (probably $AlOH^{2+}$) specifically depressed Mg^{2+} uptake in oats, whereas the uptake of Ca and K was little affected. Foy (1992), also, reported antagonistic effects between Ca and Al in soil. These effects include decreased susceptibility to Al toxicity at increased Ca^{2+} levels, and reduced uptake and translocation of Ca as solution Al^{3+} is increased (Haynes, 2001).

On acidic soils, excessive levels of soluble Mn can induce Fe, Ca and Mg deficiency in some plants, thereby causing the development of Mn toxicity symptoms on older leaves and Fe deficiency symptoms on younger leaves (Grundon *et al.*, 1997; Thibaud & Farina, 2006). In the case of Mn induced Ca deficiency ("crinkle leaf"), reported in cotton and beans, the transportation of Ca to the growing points is affected (Mengel & Kirkby, 19□7).

The present study was undertaken to investigate the effect of lime application on maize yield, as well as soil and leaf nutrients in a resource poor farming area in the Mpumalanga Province of South Africa. The area is characterised by acidic soils that could lead to toxic levels of Al and Mn that are detrimental to maize growth. Although it is generally accepted that liming effectively reduces elevated concentrations of soil Al and Mn in soil, it could also decrease the availability of B, Zn and Cu (Mengel & Kirkby, 19□7; Alloway, 2004). It is, therefore, also necessary to study nutrient interactions as effected by soil acidity in order to understand the potential soil and leaf nutrient imbalances that may arise from lime application. The objectives of the study were therefore to: (i) determine the interrelationships between maize grain yield, soil and leaf nutrient contents and (ii) evaluate possible lime induced nutrient interactions by means of nutrient vector analyses.

Material and methods

Experimental layout and procedure

Two field trials, that continued for six and five years respectively were conducted on a Hutton soil from the Hayfield family and on Oakleaf soil from the Caledon family (Soil Classification Working Group, 1991), respectively. Some physical and chemical topsoil (0-250 mm) characteristics of the experimental soils are summarised in Table 1.

Table 1 Selected soil physical and chemical topsoil (0-250 mm) properties[1] of the experimental sites

	Experimental soil	
Soil form[2]	Hutton	Oakleaf
Soil family[2]	Hayfield	Caledon
Clay (< 2 µm) (%)	35.4	37.0
Organic C (%)[1]	2.05	5.64
CEC (cmol (+) kg^{-1})	5.34	10.31
pH (H_2O)	5.44	4.57
Extractable Al (cmol (+) kg^{-1})	0.23	1.2□
P (mg kg^{-1})	5.59	9.32
K (cmol (+) kg^{-1})	0.21	0.10
Ca (cmol (+) kg^{-1})	0.75	0.45
Mg (cmol (+) kg^{-1})	0.47	0.35
Cu (mg kg^{-1})	2.7□	1.61
Zn (mg kg^{-1})	0.53	0.□9
B (mg kg^{-1})	0.□1	3.□1
Mo (mg kg^{-1})	0.01	0.01

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

2 Soil classification working group, 1991.

Treatments comprised of two factorial combinations, namely lime (three treatments) and fertiliser (two treatments), which were arranged in a randomised block design with three replicates. Fertiliser treatments included no fertiliser (control) vs. fertilisation of 25 kg P ha^{-1}, 30 kg K ha^{-1} and 30 kg N ha^{-1} at planting, followed by a topdressing of 50 kg N ha^{-1} as limestone ammonium nitrate (LAN), eight weeks after planting. All fertilisers were band-placed. Lime ($CaCO_3$ = 43.65%, $MgCO_3$ = 41.03%, calcium carbonate equivalent neutralising value of □6.90%) treatments consisted of once-off applications of 0, 5 and 10 tons of dolomitic lime ha^{-1} that were broadcast prior to planting and mixed with the soil to a depth of 300 mm. Individual plot size was 9.25 m x 3.6 m (33.30 m^2) and consisted of four maize rows. Only the two middle rows were used for data collection. Maize seed (cultivar CRN 36314) was hand-sown at the end of October using a row spacing of 0.91 m. Plant density was 55 000 plants per hectare, which was thinned out to approximately 35 000 plants per hectare at the three leaf stage. Trials were harvested annually during May/June. Maize grain mass was determined and corrected to a moisture content of 12.5%.

Soil and maize plant sampling and analysis

Topsoil samples (0 - 250 mm) were collected annually in February/March at flowering.

Eight sub samples were collected within each plot between the rows and bulked as a composite sample, air-dried and ground to pass through a 2 mm sieve prior to analysis.

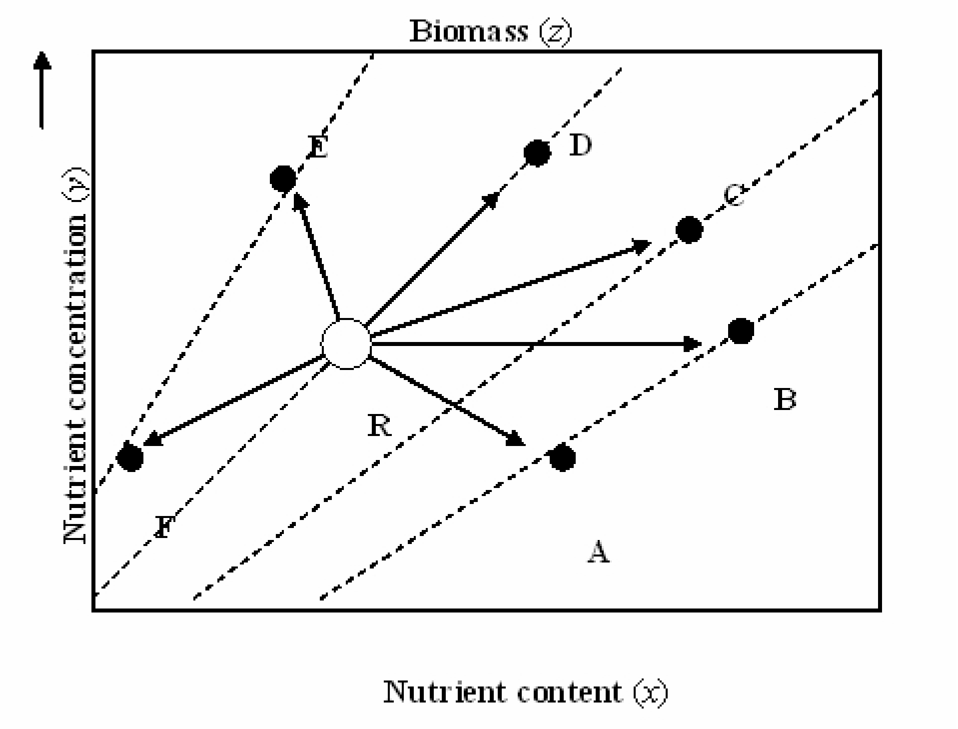
Soil pH (H_2O) was determined in a 1:2.5 (soil:water) suspension. Extractable acidity (H + Al) and Al was determined in a 1 M potassium chloride (KCl) extraction and titration with 0.1 M NaOH. Extractable Al was determined in the same extract after complexation with NaF, and consequent titration. Acid saturation was determined as the ratio of extractable acidity (Al + H) to the sum of exchangeable Ca, Mg, K and extractable acidity (Al + H), expressed as a percentage. Extractable P was determined according to the Bray-1 extraction method. The P concentrations of the extracts were determined on a continuous flow analyser. The neutral, molar method was used to determine the extractable cations Ca, Mg and K. The cations in solution were determined on an atomic absorption spectrophotometer. The 0.02 M di-ammonium EDTA ($(NH_4)_2EDTA$) extract was used to extract Cu, Zn, Co, Mo and B, and were determined by ICP-MS. Water soluble B was determined by the hot water extraction method (The Non-Affiliated Soil Analysis Work Committee, 1990).

Maize leaf samples, immediately opposite and below the first ear, were annually collected at flowering (end of February, beginning of March), □to 10 weeks after planting. The leaf samples were washed in deionised water, dried at 70ºC and milled. Nitrogen was determined by dry oxidation (Bellomonte *et al.*, 19□7) 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 block digester with 1:3 (HNO_3 and $HClO_4$) and analysed using an ICP-OES (Zasoski & Burau, 1977). For the determination of Mo, 0.5 g leaf samples were wet-digested with HNO_3 and analysed using an ICP-MS (Chao-Yong & Schulte, 19□5). Above-ground dry matter biomass was determined at flowering by cutting the above-ground plant parts at the soil surface. The plant parts were dried at 65ºC to constant mass and then weighed.

Statistical analysis and data interpretation

The values that will be discussed are annual replicate means per lime application level and replicated means per lime application level over years. Pearson's correlations were calculated between all variates measured. Forward selection stepwise regression was used to determine those soil properties most responsible for the variation found in maize grain yield (Genstat, 2003).

To facilitate interpretation, yield data and the chemical composition of leaf samples was interpreted using a graphical vector nutrient diagnostic technique (Timmer & Stone, 197□; Timmer & Teng, 1999, Ströhmenger, 2001). Nutrient vector analysis involves graphical representation of the relative changes in biomass, leaf nutrient concentrations and contents in leaves in response to nutrient treatments (Grundon *et al.*, 1997). The relationship (Figure 1) is examined by comparing growth and nutrient status of crops in a nomogram that plots biomass (*z*) on the upper axis, leaf nutrient content (*x*) on the lower axis, and corresponding nutrient concentration *(y)* on the vertical axis.



Vector shift	Change in relative			Nutritional effect	Nutrient status	Possible diagnosis
	x	y	z			
A	+	+	-	Dilution	Non-limiting	Growth dilution
B	+	+	0	Accumulation	Non-limiting	Sufficiency, steady state
C	+	+	+	Accumulation	Limiting	Deficiency response
D	0	+	+	Accumulation	Non-limiting	Luxury consumption
E	-	-,+	+	Concentration	Excess	Toxic accumulation
F	-	-	-	Antagonism	Limiting	Induced deficiency by E

Figure 1 Nutrient vector analysis (Timmer & Teng, 1999).

When relative yield is normalised to 100% at a specified reference sample (*i.e.* the 5 ton lime ha^{-1} application in this study), differences are depicted as vectors because of shifts in both direction and magnitude (Timmer & Teng, 1999). The dashed diagonals are isopleths representing change of *y* on *x*, where *z* remains unchanged (Ströhmenger, 2001). Diagnosis is based on vector direction of individual nutrients, indicating occurrence of dilution (A), sufficiency (B), deficiency (C), luxury consumption (D), toxicity (E) and antagonism (F), as depicted in Figure 1. Vector magnitude reflects the extent or severity of specific diagnoses, and facilitates relative ranking and prioritising (Temmer & Teng, 1999).

Results and discussion

Interrelationship between maize grain yield, soil and leaf nutrients

Linear interrelationships between maize grain yield and selected soil and leaf nutrients are presented in Tables 2 and 3.

Hutton soil form: Table 2 shows a strong relationship (P<0.001) between soil P and soil Mo (r=0.62).

Table 2 Correlation matrix for the relationship between maize grain yield, soil and leaf nutrients for the Hutton experimental soil

	Soil									**Leaf**										
	Al	**P**	**Ca**	**Mg**	**K**	**Zn**	**Mo**	**Cu**	**B**	**N**	**Ca**	**Mg**	**P**	**K**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**	**B**
Soil P	0.11																			
Soil Ca	-0.4□**	0.0□																		
Soil Mg	-0.42*	-0.13	**0.95*****																	
Soil K	-0.16	-0.190	-0.0□	-0.02																
Soil Zn	-0.1□	0.2□	**0.60*****	**0.60*****	0.17															
Soil Mo	-0.09	**0.62*****	0.13	-0.06	-0.1□	0.05														
Soil Cu	-0.24	0.03	0.36	0.46*	0.23	**0.64*****	0.12													
Soil B	0.17	**-0.65*****	0.06	0.27	0.17	0.10	**-0.76*****	0.10												
Leaf N	-0.1□	0.10	-0.03	-0.0□	-0.04	0.02	-0.35	-0.02	-0.10											
Leaf Ca	-0.24	0.19	0.19	0.02	-0.01	-0.04	0.04	-0.4□**	-0.29	0.32										
Leaf Mg	-0.41*	-0.14	**0.70*****	**0.74*****	-0.04	0.50**	0.15	0.43*	0.13	-0.21	0.06									
Leaf P	-0.15	0.32	0.14	0.06	-0.07	0.26	-0.11	0.15	-0.04	**0.85*****	0.26	0.01								
Leaf K	0.04	0.17	-0.06	-0.10	-0.39	-0.31	0.23	-0.19	-0.3□*	-0.14	-0.07	-0.23	-0.07							
Leaf Fe	-0.14	-0.27	-0.25	-0.11	-0.06	-0.131	-0.22	0.20	0.05	-0.03	-0.32	-0.09	-0.32	0.31						
Leaf Al	0.05	-0.35	-0.09	0.12	-0.04	-0.12	-0.42*	0.12	0.44*	-0.04	-0.44*	0.11	0.06	0.10	**0.63*****					
Leaf Mn	0.26	-0.32	0.31	0.41*	-0.12	0.34	-0.4□**	0.07	**0.63*****	0.21	0.0□	0.22	0.21	-0.30	-0.14	0.07				
Leaf Zn	-0.19	-0.24	0.12	0.29	-0.05	0.16	-0.3□*	0.42*	0.35	0.13	-0.14	0.24	0.10	-0.13	0.56**	0.51**	0.27			
Leaf Cu	-0.06	-0.0□	0.34	0.34	-0.12	0.31	-0.37*	0.10	0.36	0.44*	0.26	0.22	0.34	-0.37*	-0.16	-0.05	**0.62*****	0.44*		
Leaf B	-0.22	-0.21	0.20	0.34	0.05	0.31	-0.34	0.36	0.34	0.35	0.01	0.27	0.40*	-0.07	0.23	0.37*	0.2□	0.47*	0.14	
Yield	-0.2□	-0.01	0.14	0.03	0.22	0.22	-0.1□	-0.01	0.05	0.46*	0.46*	-0.06	0.30	-0.24	0.3□*	-0.54**	0.20	-0.10	0.35	0.17

$^{*}P<0.05$, $^{**}P<0.01$ & $^{***}P<0.001$

Table 3 Correlation matrix for relationship between maize grain yield, soil and leaf nutrients for the Oakleaf experimental soil

	Soil									Leaf									
	Al	**P**	**Ca**	**Mg**	**K**	**Zn**	**Mo**	**Cu**	**B**	**N**	**Ca**	**Mg**	**P**	**K**	**Fe**	**Mn**	**Zn**	**Cu**	**B**
Soil P	0.14																		
Soil Ca	**-0.95*****	-0.09																	
Soil Mg	**-0.94*****	-0.04	**0.99*****																
Soil K	-0.24	-0.01	0.45*	0.46*															
Soil Zn	0.07	0.24	0.05	0.09	0.45*														
Soil Mo	0.35	0.04	-0.24	-0.26	0.15	0.43*													
Soil Cu	0.57**	0.12	-0.57**	**-0.59*****	0.09	0.31	0.19												
Soil B	0.53**	0.10	-0.41*	-0.42*	0.07	**0.62*****	**0.70*****	0.19											
Leaf N	0.16	0.34	-0.22	-0.20	-0.09	-0.32	-0.09	0.15	-0.34										
Leaf Ca	-0.36	0.23	0.34	0.39*	0.09	-0.27	-0.37*	-0.01	**-0.69*****	**0.66*****									
Leaf Mg	**-0.76*****	0.15	**0.79*****	**0.81*****	0.20	-0.06	-0.34	-0.4□**	**-0.62*****	0.04	0.54**								
Leaf P	0.19	0.09	-0.29	-0.30	-0.34	**-0.58*****	0.14	-0.26	-0.25	**0.70*****	0.1□	-0.05							
Leaf K	0.15	0.12	-0.14	-0.07	-0.06	0.37	-0.12	0.16	0.17	-0.19	-0.02	-0.22	-0.27						
Leaf Fe	0.21	-0.02	-0.19	-0.14	-0.02	0.2□	0.23	-0.1□	0.43*	0.15	0.01	-0.19	0.15	0.10					
Leaf Mn	0.51**	0.25	-0.36	-0.35	0.12	0.03	0.23	-0.0□	0.3□*	0.36	-0.01	-0.40*	0.46**	0.16	0.49**				
Leaf Zn	-0.40	0.3□*	0.40*	0.43*	0.01	-0.17	0.1□	-0.16	-0.56**	**0.62*****	**0.83*****	**0.69*****	0.2□	-0.16	-0.12	-0.05			
Leaf Cu	0.31	0.23	-0.34	-0.32	-0.09	-0.23	0.11	0.0□	-0.10	**0.88*****	0.4□**	-0.15	**0.66*****	-0.22	0.47**	0.56**	0.40*		
Leaf B	0.01	0.21	-0.10	-0.10	-0.25	-0.11	0.13	0.27	-0.26	0.0□	0.23	0.22	-0.13	-0.42*	-0.02	-0.44*	0.15	0.10	
Yield	-0.54**	0.24	0.49**	0.53**	0.15	-0.06	0.37*	-0.01	**0.66*****	0.51**	**0.92*****	**0.67*****	0.04	-0.10	0.02	-0.20	**0.79*****	0.34	0.36

* $P<0.05$, $^{**}P<0.01$ & $^{***}P<0.001$

Increased P status of the soil has been found to greatly increase the absorption of Mo by plants (Podzolkin, 1967; Gupta & Munro, 1969; Blamey & Nathanson, 1975; Barnard, 197□; Thibaud & Farina, 2006). Although P and Mo are chemically similar, the size of the $H_2PO_4^-$ anion fits better than $H_2MO_4^-$ in the fixation sites and therefore the preferred $H_2PO_4^-$ fixation results in the release of Mo. Leaf P concentrations tended to increase with increasing leaf N.

A negative correlation ($P<0.01$) was obtained between maize grain yield and leaf Al (r=-0.54), but significant ($P<0.05$) positive correlations were observed between maize grain yield and leaf N (r=0.46), leaf Ca, and leaf Fe (r=0.3□), respectively. Further analysis using stepwise regression (Table 4) revealed that, of these factors, leaf Fe was the most important, accounting for 33.7% of the variation in maize grain yield. Progressive addition of the variables leaf Ca, Zn, and Mg increased the explained variation to 56.2%.

Oakleaf soil form: Strong negative correlations ($P<0.001$) were observed between soil Al and soil Ca (r=-0.95), soil Mg (r=-0.94) and leaf Mg (r=-0.76), respectively (Table 3). These results indicated that the high levels of Al observed in this soil were accompanied by low concentrations of Ca and Mg in soil and leaf tissues.

Table 4 Summary of the forward stepwise regression analysis for yield for the two experimental soils

Variables in model	Hutton	
	Variance accounted for (%)	F
Leaf Fe	33.70	13.04***
+ leaf Ca	47.7	12.63***
+ leaf Zn	52.3	12.19*
+ soil Mg	56.2	11.90*
Yield = -0.19 – 0.00719 leaf Fe + □22 leaf Ca – 0.0176 leaf Zn – 0.03402 soil Mg		
	Oakleaf	
Leaf Ca	□3.10	□4.37***
+ soil Al	□7.60	6.□7*
+ leaf B	93.00	3.50ns
Yield = -1.062 + 10.3□□leaf Ca – 0.461 soil Al + 0.1735 leaf B		

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

Improved plant growth due to an increase in leaf N resulted in increased uptake of leaf P (r=0.70), leaf Ca (r=0.66), leaf Zn (r=0.62), and leaf Cu (r=0.□□), respectively. In many soils, N is the main limiting factor of growth and yield. Therefore, crops often respond to the applied nutrients, e.g. Zn and N together, but not to Zn alone (Alloway, 2004). Strong positive correlations (Table 3) were found between leaf Zn and leaf Ca (r=0.□3), as well as with leaf Mg (r=0.69). These somewhat contradictory results are difficult to explain because it is well-known that Ca and Mg inhibit the absorption of Zn by plant roots through their influence on soil pH when applied as calcitic or dolomitic lime (Mengel & Kirkby, 19□7; Alloway, 2004).

Acidic conditions in soil often enhance the solubility of heavy metals such as Cu. Table 3 shows that an increase in soil Mg, accompanied with an increase in soil pH, resulted in a significant decrease in soil Cu (r=-0.59). Strong ($P<0.001$) negative relationships between soil B and leaf Ca (r=-0.62), and leaf Mg (r=-0.69), were found (Table 3). Previous studies showed that the sharp decrease in available B with liming (Gupta & MacLeod, 19□1; Dwivedi *et al.*, 1992) could be ascribed to increased soil pH rather than to the amount of Ca added through lime. Significant positive correlations ($P<0.001$) were obtained between maize grain yield vs. leaf Ca (r=0.92), as well as with leaf Zn (r=0.79), leaf Mg (r=0.69), and soil B (r=0.66), respectively. Stepwise regression (Table 4) revealed that, of these factors, leaf Ca was the most important accounting for □3% of the variation in maize grain yield. Progressive addition of the variables soil Al and leaf B increased the explained variation to □□9%.

Nutrient uptake interactions

Evidence exists to the effect that the plant's internal requirement for some nutrients, and hence its critical concentration for deficiency diagnosis, varies with the supply of other nutrients (Grundon *et al.*, 1997). Figure 2a & b shows the vector analysis for 0 and 10 ton lime ha^{-1} treatments on the Hutton and Oakleaf soils relative to the 5 ton lime ha^{-1} treatment for the Hutton soil form, whose status was normalised to 100% to allow comparison on a common base.

Hutton soil form: The nomogram shows downward, left-pointing vectors associated with Ca and Mg, and the largest, upward right-pointing vectors associated with Fe, Al and Mn respectively, in the 0 ton lime ha^{-1} treatment (Figure 2a). As indicated by Timmer & Teng (1999), the vector length increases with reduced plant biomass or the severity of decline. The results from Figure 2a indicate that toxic build-up of Fe, followed by Al, and to a lesser extent by Mn, inhibited the uptake of Ca and Mg in the 0 lime ha^{-1} treatment. Aluminium toxicity is frequently accompanied by high levels of Fe and Mn and low concentrations of Ca and Mg in plant tissue. This is to be expected, since Al toxicity is associated with acid soil conditions where the availability of both Fe and Mn is high and where the levels of Ca and Mg are often low because of leaching. The nomogram in Figure 2a indicates an increased uptake of Ca and Mg, and decreased uptake of Al, Mn and Fe. Calcium and Mg deficiency was corrected by the application of dolomitic lime, which antagonistically reduced Al, Mn and Fe uptake and availability.

The uptake of B was also markedly reduced in the 0 lime ha^{-1} treatment (Figure 2a) presumably due to elevated Fe, Al and Mn leaf concentrations associated with acid soils. One of the consequences of soil acidity may be the leaching of soil B. Boron in soil occurs mainly as H_2BO_3, a weak acid of which the dissociation is reduced under low pH conditions, resulting in the leaching of H_2BO_3 (Fölscher, 197□). Liming, as seen in the 10 ton lime ha^{-1} treatment, effectively alleviated B deficiency, and reduced Al and Mn uptake.

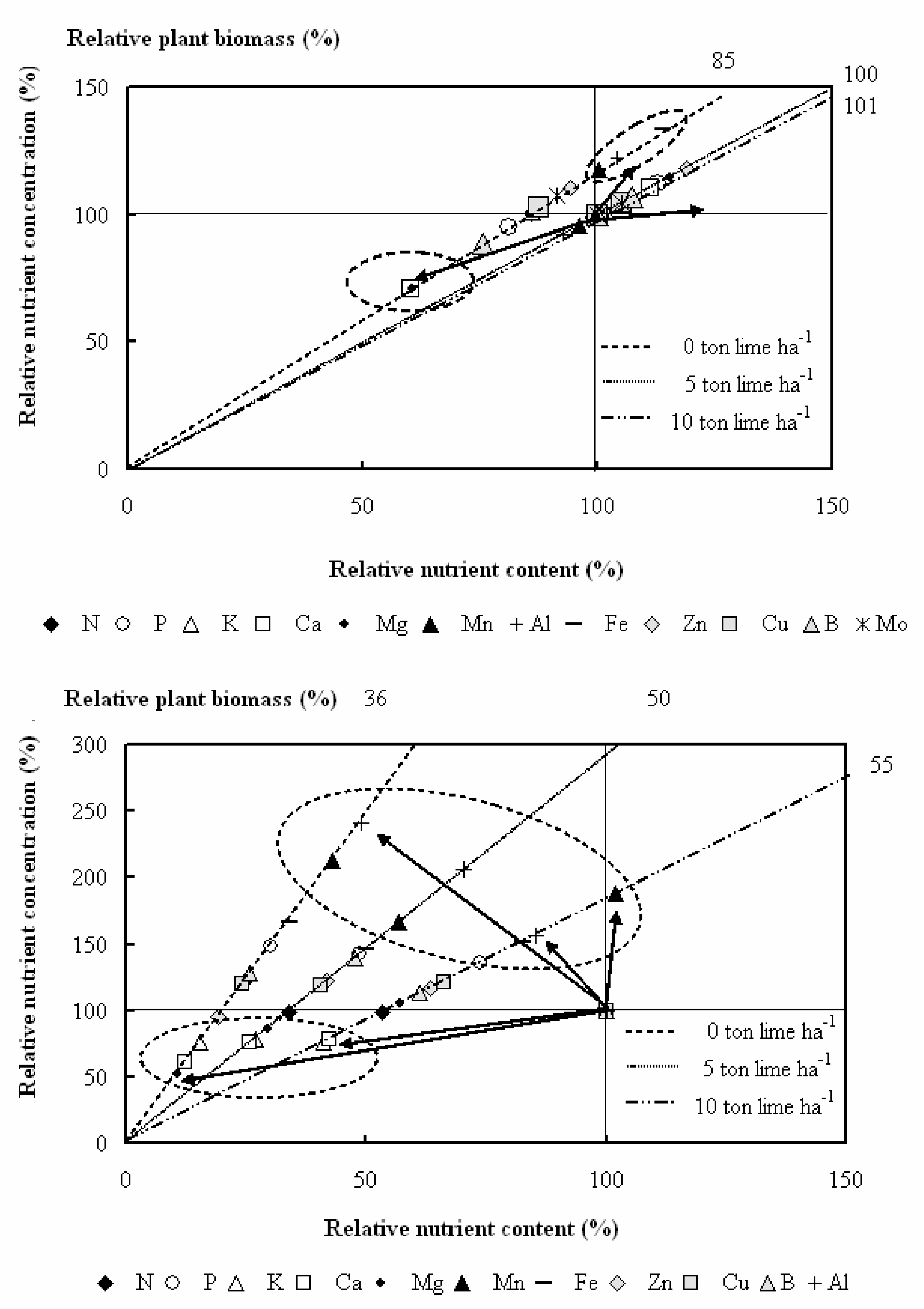


Figure 2 Relative response in nutrient concentration, content and dry mass of maize plants grown at differential lime rates (0, 5 and 10 ton lime ha^{-1}).

An increased accumulation of leaf Zn, Mg, P, Ca, N, and to a lesser extent B, Mo, Cu and K, without any gain in maize biomass, was observed in the 10 ton lime ha^{-1} treatment (Figure 2a). This indicates a non-limiting luxury consumption of Zn, Mg, P, Ca, N, B, Mo, Cu and K by the maize plants treated with 10 ton lime ha^{-1}.

Oakleaf soil form: The nomogram shows downward, left-pointing vectors associated with Ca and Mg, and the largest, upward left-pointing vectors associated with Fe, Al and Mn, respectively, in the 0 and 10 ton lime ha^{-1} treatments (Figure 2b). Results in Figure 1 show that soil Al, followed by Mn and Fe, markedly reduced the uptake of Ca and Mg. Effective liming, *i.e.* 10 ton lime ha^{-1} treatment, alleviated the problem of Fe, Al and Mn toxicity as shown in Figure 2b. According to Haynes (2001) several mechanisms explain the antagonistic effect of Al on Ca and Mg uptake. Firstly, Ca^{2+} and Mg^{2+} in the root apoplasm are thought to be replaced by Al^{3+} and this reduces the amount of Ca^{2+} and Mg^{2+} in the vicinity of the plasma membrane, reducing their rate of uptake. It has also been reported that Al^{3+} blocks Ca^{2+} channels in the plasma membrane and that Al^{3+} blocks binding sites for Mg^{2+} on transport proteins at the plasma membrane (Rengel & Robinson, 19□9; Haynes, 2001). Antagonistic reduction of B uptake due to Al, Mn, and to a lesser extent Fe, toxicity was not observed in the Oakleaf soil.

Figure 2b shows a right-pointing vector that was associated with high Al, and to a lesser extent Mn and a downward, left-pointing vector associated with K in all treatments (0, 5 and 10 ton lime ha^{-1}). This indicates that the problems associated with soil acidity were not alleviated with 5 and 10 ton lime applications. The predominant constraint resulting from increasing soil acidity is a severe chemical imbalance caused by toxic levels of Al, and Mn ions linked with a parallel critical deficiency in available N, P, K, Ca, Mg, Mo, and sometimes, Zn (Fageria & Baligar, 2003).

Furthermore, at low pH levels cell membranes are impaired and become more permeable. This results in a leakage of plant nutrients and particularly of K, which diffuses out of the root cells into the soil solution. This detrimental effect of high H^{+} concentrations on biological membranes can be counterbalanced by Ca^{2+} applied as lime (Mengel & Kirkby, 19□7).

Conclusions

Nutrient vector analyses showed a toxic build-up of Fe, followed by Al, and to a lesser extent by Mn. The toxic elements depressed the uptake of Ca and Mg in the Hutton soil. In the Oakleaf soil, Al-toxicity, followed by high levels of Mn and Fe markedly reduced the uptake of Ca and Mg. Antagonistically reduced B uptake due to Fe, Mn, and Al toxicity was observed in the Hutton soil. Toxic levels of Al, Mn and Fe antagonistically depressed the uptake of K in the Oakleaf soil.

Generally the results indicate that soil acidity had a confounding influence on soil fertility, leaf nutrient uptake and maize growth. Aluminium-, Mn- and Fe-toxicity, respectively, and deficient levels of Ca and Mg were the factors that most adversely affected nutrient uptake and maize grain yields in the study area. The highest yields were associated with low leaf Al, Fe and Mn levels. It was also found that the uptake of leaf K and leaf B levels was decreased extensively under severe leaf Al, Mn and Fe toxicity.

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