ALUMINIUM TOXICITY—A GROWTH LIMITING FACTOR IN SOME NATAL SANDS

By M. E. SUMNER

Department of Soil Science, University of Natal, Pietermaritzburg

Abstract

The inability of crop roots to penetrate subsoil layers in some Natal sandy soils and the associated low yields are the result of toxic quantities of aluminium. The phenomenon which is common in acid sandy soils in Natal may be easily remedied by deep liming or leaching with gypsum.

Introduction

The first irrigated field experiments with maize and cotton conducted at the Makatini Research Station on the Maputa sand showed clearly that root penetration below about 30 cm was exceedingly poor (Cairns[2]). The Maputa Series is the fine sand member of the Fernwood Form (van der Eyk, Macvicar and de Villiers[8]) having a uniform clay content down the profile of about 6% and a total available moisture capacity of 5 cm/m. This structureless sand appears to have no physical limitation to the penetration of roots. However, Cairns[2] found that the tap root of cotton would penetrate only to approximately 30 cm after which it grew horizontally with no root development below this level. Neutron moisture meter studies indicated that little moisture utilization by the maize and cotton below 30 cm took place. Yields of maize and cotton obtained were poor despite liberal irrigations and fertilizer applications. Irrigations were based on class A pan evaporation using a factor of 1 for E_t/E_o assuming a rooting depth of 120 cm. As the roots did not exploit this volume of soil, the plants experienced frequent periods of moisture stress resulting in low yields.

The aim of the present investigation is to establish the reason for the failure of roots to enter the Maputa subsoil.

Materials

Bulk samples of the Maputa topsoil (0-15 cm) and subsoil (45-60 cm) were taken from a virgin area of the experimental site at the Makatini Research Station. Some selected properties of the Maputa Series are presented in Table I.

In addition bulk samples of the Fernwood and Clansthal Series at 0-30, 30-60 and 60-90 cm were taken on the Tongaat Sugar Co. estate.

Methods

Pot Technique

Unless stated otherwise, all experiments were carried out in plastic pots of 2½ kg capacity. Nutrients in solution were added and thoroughly mixed with the soil at the following rates: 125 ppm N, 140 ppm P, 70 ppm K, 100 ppm Ca, 10 ppm Mg, 50 ppm S, 0.1 ppm Mo, 1 ppm B and 3 ppm each of Mn, Fe, Cu and Zn. Analytical reagent grade $CaCO_3$ was used as a liming material and where necessary soils were equilibrated in the field moist state with lime for 45 days before planting. Trudan (*Sorghum sudanense*) (30 seedlings per pot) was grown for 30 days as the indicator plant in all experiments. All pots (undrained) were watered daily with deionized water to field capacity by weighing.

Analytical Methods

Exchangeable aluminium index (EAI) was determined by extracting 5 g soil with 50 ml 0.2N NH_4Cl for two minutes on a reciprocating shaker (Reeve and Sumner[6]). Aluminium was determined by the aluminon method of Frink and Peech[3]. Exchangeable manganese was extracted by the method of Adams[1] and determined by atomic absorption. Where

TABLE I

Some selected properties of Maputa topsoil and subsoil (after Hensley [4,5])

Particle size distribution* (%)			pH			Exchange characteristics† (me%)		
Fraction‡	Topsoil 0–15 cm	Subsoil 45–60 cm		Topsoil 0–15 cm	Subsoil 45–60 cm		Topsoil 0–15 cm	Subsoil 45–60 cm
Coarse sand	6.6	7.0	Water	5.0	4.4	Na	0.02	0.00
Medium sand	29.9	32.8	0.01M $CaCl_2$	4.1	3.9	K	0.22	0.28
Fine sand	55.9	52.3				Ca	0.13	0.06
Silt	1.0	0.7				Mg	0.28	0.12
Clay	5.0	6.0				S value	0.65	0.46
						CEC	1.28	1.40

* Pipette method

‡ As defined by van der Eyk *et al.*[8]

† N NH_4OAc method

plant material was analysed dry ashing at 600° C followed by solution in 6 N HCl was used.

Experimental Procedure and Results

As a preliminary step, it was necessary to establish whether any nutrient element deficiencies occurred in the Maputa soil which could account for the observed rooting pattern. To this end three completely randomized replications of treatments arranged according to the substractive technique in which each nutrient element is omitted in turn from a complete treatment were used. A number of additional treatments were incorporated to evaluate the effects of organic matter, soil sterilization and lime. The results are presented in Table II.

In addition to being deficient in N, P, K, Ca, Zn and B this soil responds very markedly to lime. Soil sterilization with ethylene oxide has no significant effect indicating that nematodes are not responsible for the poor growth. Large organic matter additions to the pot receiving all nutrients has a small significant effect. However, in the presence of lime, this effect disappears. Analysis of soil and plants from selected treatments is most revealing (Table III).

TABLE II
Effect of various nutrient treatments on yield of Trudan on Maputa subsoil

Treatment	Yield* %
Complete nutrients	100.0
-N	20.7
-P	10.9
-K	15.1
-Ca	22.6
-Mg	90.3
-B	80.8
-Zn	49.4
-S	90.5
No nutrients	11.1
Complete nutrients : Sterilized §	107.0
Complete nutrients + 40 t Ca humus/ha †	126.0
Complete nutrients + 2 t AR $CaCO_3$/ha‡	244.0
Complete nutrients + 40 t Ca humus/ha + 2 t AR $CaCO_3$/ha	236.0
Lsd (0.05)	16.2
(0.01)	22.1
(0.001)	29.6

* Mean of three replications
§ With ethylene oxide
† Well decomposed compost converted to Ca form by leaching with N $CaCl_2$ and washing with water
‡ Allowed to incubate after addition of $CaCO_3$ in field moist state for 45 days

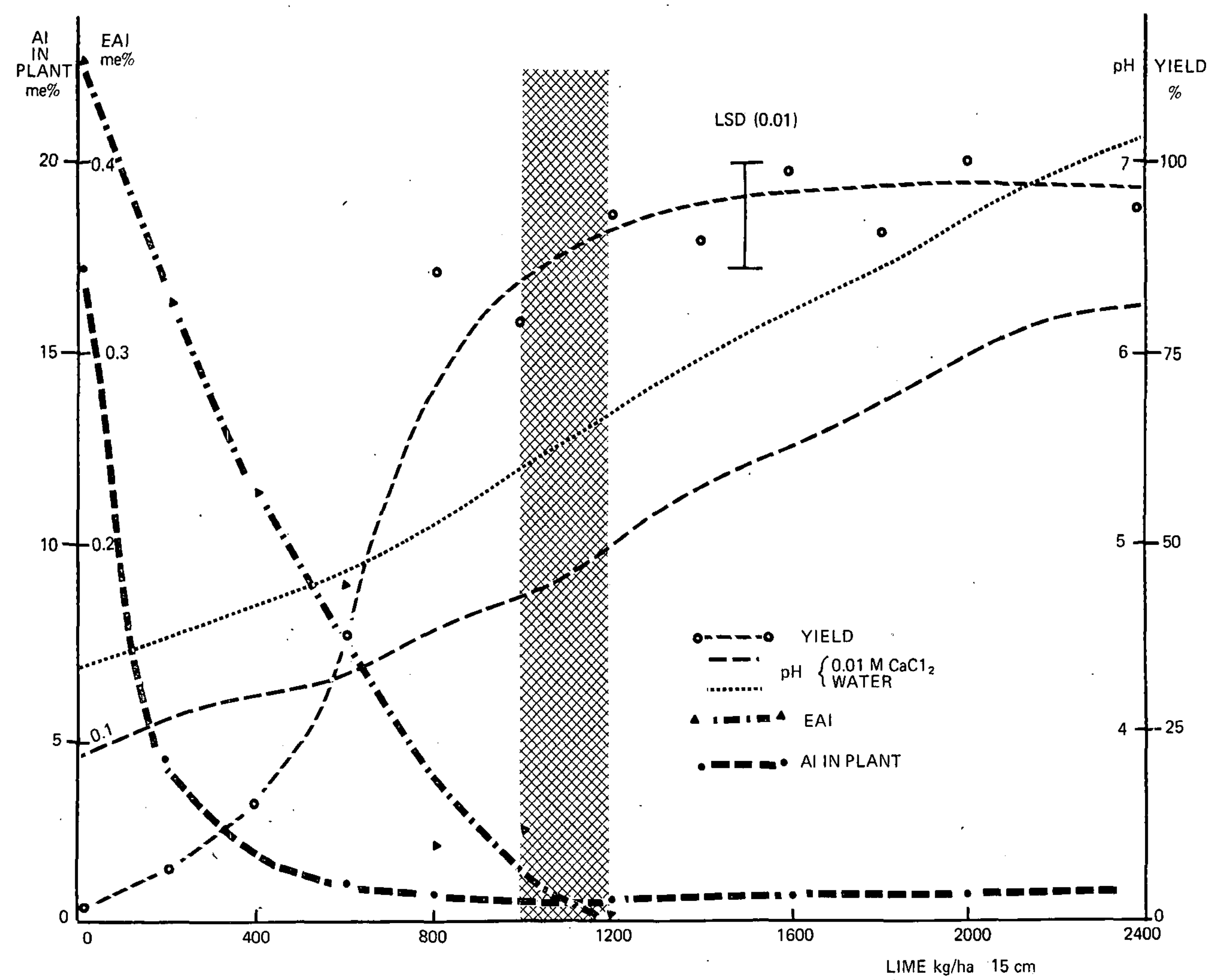


FIGURE 1: Effect of lime on yield and aluminium content of Trudan in relation to exchangeable aluminium index (EAI) and pH of Maputa subsoil.

TABLE III
Effect of lime and organic matter on yield and Mn content of Trudan and on labile Mn and Al in Maputa subsoil

Treatment	Yield %	pH Water	EAI* me%	Exch Mn ppm	Soln Mn ppm	Plant Mn ppm
Complete nutrients	100	4.2	0.46	3.76	2.35	236
Complete nutrients + 2 t AR $CaCO_3$/ha	244	6.1	0.01	1.40	0.00	151
Complete nutrients + 40 t Ca humus/ha	126	4.3	0.24	5.17	3.53	250
Complete nutrients + 2 t AR $CaCO_2$/ha + 40 t Ca humus/ha	236	6.0	0.02	1.17	0.00	53

* Exchangeable aluminium index

Increase in yield closely follows increase in pH and decreases in EAI, exchangeable Mn and Mn in solution brought about by the addition of lime. The yield increase due to the addition of organic matter is accompanied by a decrease in EAI and increases in exchangeable and solution Mn. This evidence points to the possibility of Al or Mn toxicity as the cause of the poor root development.

The effect of lime was studied in a subsequent experiment of three completely randomized replications with 12 levels of lime, 0 through 2 400 kg $CaCO_3$/ha as the only treatment variable. Pots of 1 kg capacity containing 20 seedlings were used. After harvesting, pH, EAI and exchangeable Mn were determined in bulked samples from the three replications. The plants were analysed for Al, Ca, Mg, K and Na. The results are presented in Table IV and Figure 1.

TABLE IV
Effect of lime on yield and cation composition of Trudan tops grown on Maputa subsoil

Lime level kg/ha	Yield* %	Al me%	Ca me%	Mg me%	K me%	Na me%	Total cations me%	Mn ppm
0	2.8	17.1	6.7	36.6	47.3	100.1	267.8	208
200	7.1	4.2	9.6	35.8	46.5	26.1	122.2	125
400	16.6	2.7	9.0	36.3	53.0	5.2	106.2	125
600	41.5	2.0	9.3	37.8	67.4	3.0	116.5	97
800	85.5	1.6	10.5	44.2	64.5	4.3	125.1	156
1000	78.0	1.0	11.0	49.5	65.5	4.3	131.3	135
1200	93.0	1.3	10.5	40.9	64.6	2.2	119.5	156
1600	99.0	1.5	8.0	48.2	66.4	2.2	126.3	156
2000	100.0	1.4	13.0	45.9	65.8	2.9	129.0	146
2400	93.5	1.5	11.6	44.6	68.4	2.5	128.6	160

* Percentage of the maximum yield

Yield and EAI are inversely proportional as previously reported by Reeve and Sumner[6] who found 0.2 me% to be the threshold value for EAI in heavier soils above which yield was seriously affected. In the present case, the threshold value is much closer to zero as one would expect from the lower buffering capacity of this soil. This threshold value is reached after the addition of between 1 000 and 1 200 kg $CaCO_3$/ha 15 cm corresponding to pH values in water and 0.01M $CaCl_2$ of 5.5 and 4.8 respectively. Yield is also inversely proportional to Al in the plant in agreement with the findings of Soileau, Engelstad and Martin[7] for cotton where the threshold value for leaf Al above which yields decreased was 2.3 me%. There appears to be no relationship between yield and Mn in the plant which tends to discount the likelihood of Mn toxicity. Plants having high Al contents have somewhat depressed Mg and K contents and increased Na content.

The results of similar experiments on Fernwood and Clansthal profiles and on Maputa topsoil are summarized in Table V. Response to lime is obtained in all cases except those where EAI is zero and the pH values in water and $CaCl_2$ are above 5.5 and 4.8 respectively which is in agreement with the data in Figure I. Yield increase is highly correlated with EAI (= 0.998***). The foregoing results show that Al toxicity can be easily remedied by applying lime in fairly small quantities.

TABLE V
Yield increase of Trudan on liming in relation to pH and exchangeable aluminium index (EAI) of three Natal sands

Soil	Depth cm	Yield* increase %	Lime required for maximum yield kg/ha	EAI me%	pH Water	pH 0.01M $CaCl_2$
Maputa	0–15	25	1000	0.15	5.0	4.1
Maputa	45–60	97	1200	0.46	4.4	3.9
Fernwood	0–30	10	600	0.04	4.5	4.0
Fernwood	30–60	0	0	0.00	5.8	5.0
Fernwood	60–90	0	0	0.00	6.3	5.2
Clansthal	0–30	14	1000	0.08	4.8	4.0
Clansthal	30–60	69	1600	0.34	4.7	3.7
Clansthal	60–90	80	1600	0.40	4.6	3.7

* Expressed as a percentage of the maximum yield

In order to establish whether Al toxicity is widespread in sandy soils in Natal a number of Maputa profiles from the Makatini Flats and an Avalon profile from the Natal Midlands were analysed for EAI and pH (Table VI). Considering the data in Tables V and VI together, it is clear that Al toxicity is likely to be encountered in sandy soils when the pH values in water and 0.01 M $CaCl_2$ fall below 5.5 and 4.8 respectively.

TABLE VI

Variation in pH and exchangeable aluminium index (EAI) with depth in profiles of some sandy soils from Natal

Soil Series	Depth cm	Clay %	pH Water	pH 0.01M $CaCl_2$	EAI me%
Maputa	0–15	5.0	5.0	4.1	0.15
TP 24943*	45–60	6.0	4.4	3.9	0.46
Maputa	15	4.7	5.6	4.1	0.12
TP 51801	45	4.8	5.2	3.8	0.31
	75	3.3	3.9	3.5	1.32
Maputa	15	4.9	5.5	4.0	0.06
TP 21904	45	4.2	5.5	4.0	0.09
	75	4.6	5.4	3.8	0.15
Maputa	15	4.5	4.7	3.7	0.38
TP 60121	45	4.7	5.4	3.9	0.20
	75	4.8	5.5	4.1	0.19
Avalon	0–15	14.0	4.9	3.9	0.19
	15–30	15.0	4.7	3.9	0.32
	30–45	24.0	4.6	3.9	0.64
	45–60	34.0	5.0	4.0	0.66
	60–75	42.0	6.1	4.8	0.03
	75–90	46.0	6.4	4.9	0.00

* Soils Research Institute Test Pit Number (Hensley[4,5])

To study the effect of lime incorporation to various depths on the growth and rooting pattern of Trudan, an experiment in large drums (200 litre capacity) in which the treatment variables were depth of lime incorporation and moisture, was undertaken. The drums were filled by placing 20 cm of Maputa topsoil (0-15 cm) receiving the complete nutrient treatment over 60 cm of Maputa subsoil (45-60 cm) receiving no nutrients. Lime was added at a uniform rate of 1 t $CaCO_3$/ha 15 cm to different depths. Water was applied periodically to bring the soil back to field capacity when the soil moisture tension at 35 cm depth reached seven bars. Trudan was harvested after 60 days and roots were removed in successisve 10 cm layers by sieving. The roots were washed, dried and weighed (Table VII).

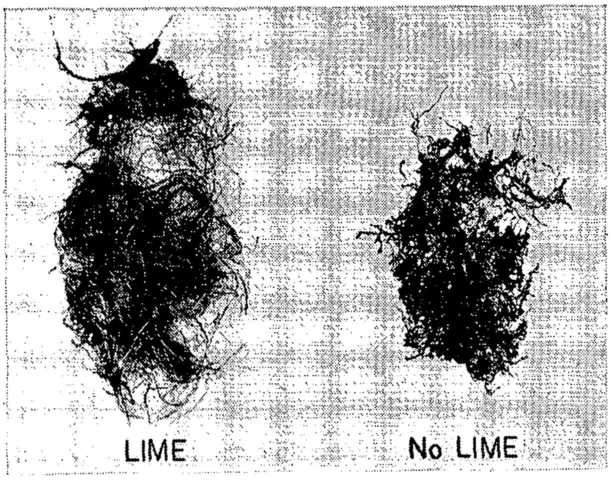
Root penetration into unlimed subsoil is very limited despite the fact that the plants in Treatment 1 suffered severe moisture stress for long periods although the soil below 40 cm had a moisture content only slightly below that at field capacity. Roots growing in unameliorated subsoil are severely stunted, discoloured and thickened by comparison with the thin, fibrous and light-coloured appearance of healthy roots (Plate 1). It is doubtful whether the former roots functioned effectively. Total root and top weights and the quantity of roots in the topsoil increase with depth of liming. Under optimum conditions, roots appear to proliferate in the fertilized topsoil and relatively few roots are required to remove moisture from the deeper layers.

The cost of incorporating lime to depth in order to eliminate Al toxicity is likely to be considerable. An alternative might be to treat the soil with gypsum in the hope that the labile Al might be leached out. With this in mind, Maputa subsoil was leached with a saturated gypsum solution in the ratio of 1 kg soil to 1 litre of gypsum solution followed by 1 litre of distilled water. Trudan was grown in this material in 1 kg pots and compared with limed and untreated subsoil leached with 2 litres of distilled water (Table VIII). All pots received a complete nutrient treatment after leaching. Leaching with saturated gypsum solution is reasonably effective in removing exchangeable Al and results in a considerable increase in yield over the control treatment.

TABLE VII

Effect of depth of lime incorporation in the Maputa Series on exchangeable aluminium index (EAI) and yield of Trudan roots and tops

Depth		Treatment 1 Limed 0–20 cm Unlimed 20–80 cm		Treatment 2 Limed 0–50 cm Unlimed 50–80 cm		Treatment 3 Limed 0–80 cm	
cm		Wt roots g	EAI me%	Wt roots g	EAI me%	Wt roots g	EAI me%
0–10	Topsoil	23.7	0.01	43.4	0.00	66.6	0.00
10–20	Topsoil	17.8	0.02	23.6	0.01	12.1	0.01
20–30	Subsoil	8.5	0.22	5.8	0.00	6.1	0.00
30–40	Subsoil	2.4	0.46	2.0	0.00	2.9	0.02
40–50	Subsoil	0.0	0.46	1.3	0.02	2.8	0.00
50–60	Subsoil	0.0	0.46	0.7	0.30	1.5	0.00
60–70	Subsoil	0.0	0.46	0.0	0.42	1.0	0.01
70–80	Subsoil	0.0	0.46	0.0	0.46	1.0	0.01
Total		52.4		76.8		94.0	
Weight of tops (g)		30		220		240	



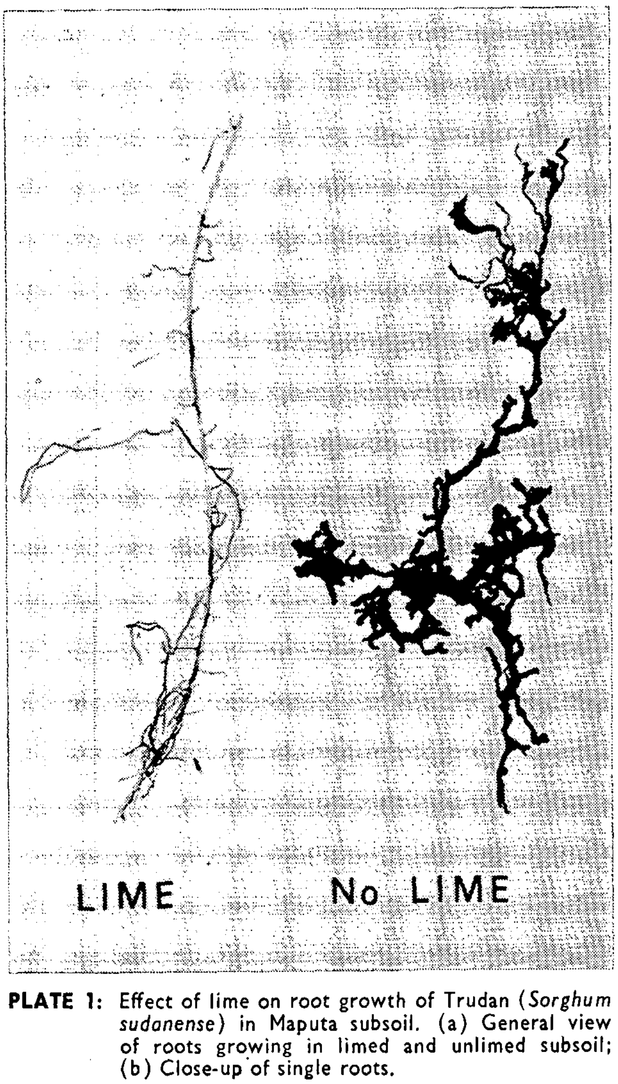


PLATE 1: Effect of lime on root growth of Trudan (*Sorghum sudanense*) in Maputa subsoil. (a) General view of roots growing in limed and unlimed subsoil; (b) Close-up of single roots.

TABLE VIII
Effect of lime and leaching with gypsum on pH and exchangeable aluminium index (EAI) of Maputa subsoil and on yield of Trudan

Treatment†	Yield* %	pH Water	pH 0.01M $CaCl_2$	EAI me%
Control	40	4.4	3.9	0.46
Leached with saturated gypsum	72	4.7	4.3	0.10
2t $CaCO_3$/ha	100	6.4	5.7	0.00

* Percentage of the maximum yield
† All pots received the complete nutrient treatment

To establish whether gypsum would be effective under field conditions, plots receiving gypsum in the original experiments at Makatini Research Station in November 1966 (Cairns[2]) were sampled in February 1970 at 15 cm intervals down the profile. All plots received the same total amount of water after gypsum application. Gypsum decreased EAI and increased pH and exchangeable Ca in the upper layers of the soil (Figure 2). Labile Al and Ca move down to the lower layers indicating that gypsum additions, given time and sufficient water for leaching, are a feasible means of ameliorating this soil.

Conclusions

The poor growth of crops on acid sandy soils may very often be the result of poor root penetration due to toxic quantities of exchangeable Al in subsoils.

The Al toxicity can be readily remedied by deep liming or by leaching with water containing gypsum.

Acknowledgements

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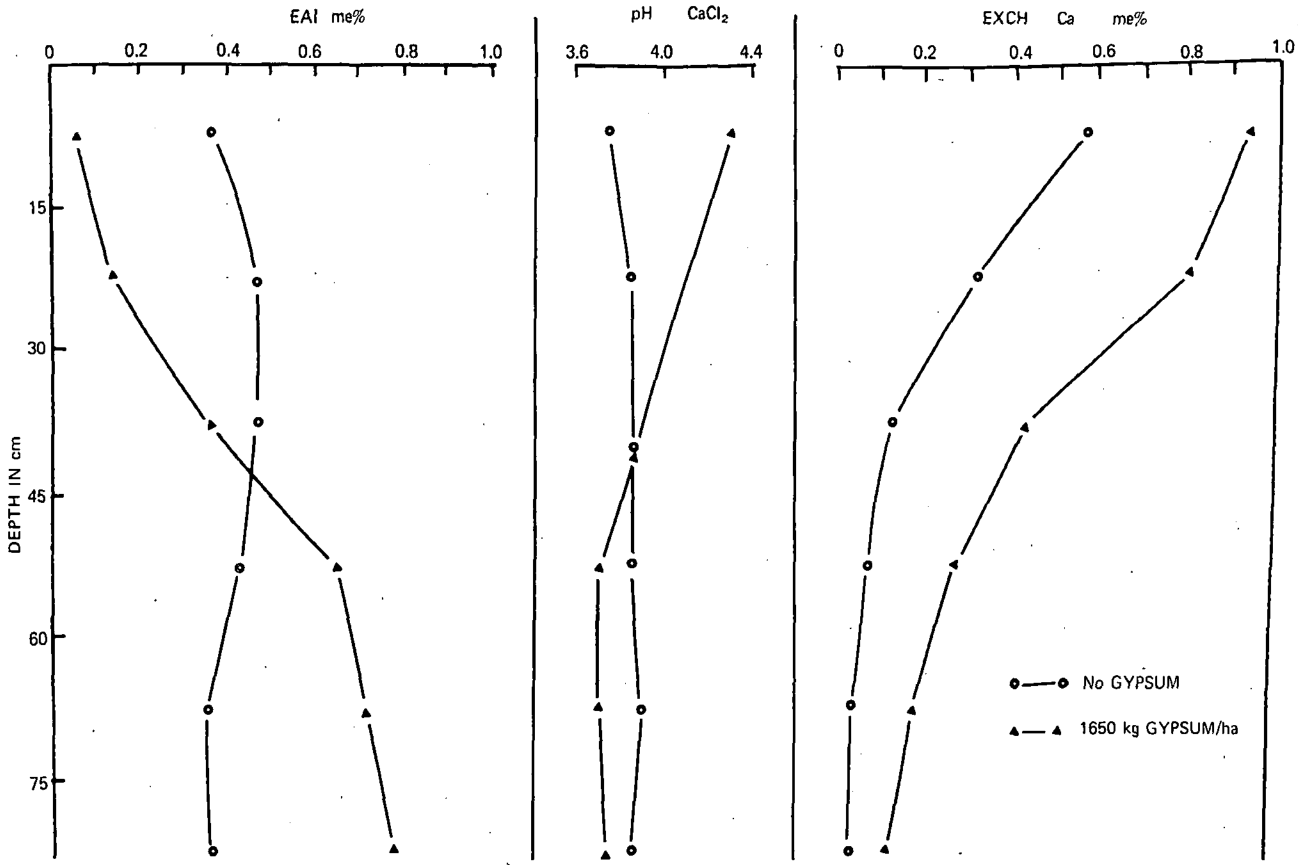

FIGURE 2: Effect of surface application of gypsum on exchangeable aluminium index (EAI), pH and exchangeable calcium down a Maputa Series profile.

Discussion

Mr. du Toit: This work is a possible break-through for both the Makatini Flats and parts of the sugar industry.

I am surprised at the high potash content of the Makatini soil and also at the big response to potash in the pot trials.

The Maputa and Fernwood series are very similar and yet show rather different reactions to aluminium and to lime.

Professor Sumner: I must confess that Table I is not my work — it is from previous work done by Hensley.

Since doing this work I have sampled some Fernwood soils near here and although there are some like the Maputa, others do not conform, as far as aluminium is concerned.

Professor Orchard: There may be 0.2 of a milli-equivalent of potassium there but there is a big density of plant in a small pot and the plants need a lot of potassium. But there is not actually enough in the pot and hence the response.

Mr. du Toit: Was there response to potash in the field?

Professor Sumner: The yields were so low that there was no response.

Professor Orchard: I would not expect a response in the field.

Dr. Mac Vicar: In the Fernwood at Tongaat where there was no aluminium and no response to nitrogen — was it a poor area?

Professor Sumner: It was a poor area but not the worst area of Fernwood at Tongaat.

Mr. du Toit: There may have been eelworm at Tongaat, which was not present at Makatini.

Mr. Meyer: Was there any increase in the P taken up by the plant with increased liming and the aluminium decrease in the soil? I bring this up because there is evidence that when aluminium accumulates in the roots it fixes P.

Professor Sumner: I regret to say that I did not analyse for P, because there was no fixation in the soil.

Mr. Moberly: It should be possible to mix in the lime if deep ploughs are used.

Mr. Alexander: Why is aluminium not present in the top 25 cm layer?

Professor Sumner: If you look at the profiles in Table VI you will see that aluminium is present from the surface downward.

Mr. Gilfillan: We have tried mixing in lime on a field scale on Clansthal series where pH's ranged from 4.0 to 5.0.

We dug pits 1.2 m long and 0.9 m deep and have sampled to see how the pH varied. In the control pits the variation was 4.0 to 4.5.

Applying a ton of lime per hectare 15 cm, we

Nardi ploughed to about 75 cm. After six weeks the pH's appear to have gone up slightly but indications are that mixing has not been uniform. Lime seems to have been effective in a line straight up and down the pit where the pH's went from 3.9 to 6.4.

We are carrying on the experiment but it appears so far that Nardi ploughing is not the complete answer.

Professor Sumner: The Clansthal, Fernwood and Maputa soils are unbuffered sands. If lime is applied indiscriminately on these soils the growth failure may worsen as a result of overliming.

The lower level of lime for good growth is about 1,000 kg/ha 15 cm and the upper boundary about 3,000 kg/ha 15 cm.

Dr. Hill: In unbuffered soils, would the addition of lime be reflected immediately in a pH reading without bringing about immediate removal of aluminium?

Professor Sumner: I doubt whether this would be the case.

Mr. Harris: Was it established that nematodes were not a problem?

Professor Sumner: In the initial experiment we sterilized one sample of the Maputa sub-soil. There could have been nematodes in the Maputa top soils and the Fernwood and Clansthal.

Mr. Wood: Have you any idea of threshold values in relation to soil texture?

Professor Sumner: The threshold value for sand is about 0.04 me % Aluminium. In a Balmoral or Clovelly, the heavier textured acid soils of the Midlands it is about 0.2 me % so there is a sliding scale with texture. The heavier the texture the higher the threshold value will be i.e. the more clay there is the higher the aluminium level that can be tolerated. It will of course vary with the crop.