

## LONG-TERM EFFECTS OF LIME ADDITIONS ON SUGARCANE YIELD AND SOIL CHEMICAL PROPERTIES IN NORTH QUEENSLAND

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### SUMMARY

In many highly weathered soils of the humid tropics, crop exploitation of the subsoil environment is limited through acid soil infertility. Since the use of mechanical profile modification is often prohibitive, surface incorporation of soil amendments is often the only means available to rectify this problem. A field trial was established with sugarcane on a strongly Acidic Dystrophic Brown Dermosol (Oxic Humitropept) in 1978 to evaluate the effects of surface incorporated lime additions on yield and performance of sugarcane. Eighteen years after the establishment of this trial, significant responses in cane yield were still evident following a single application of 5 t lime ha<sup>-1</sup> made in 1978, as well as repeated applications of 5 t ha<sup>-1</sup> on three occasions over the past 18 years. Progressive reductions in exchangeable acidity were accompanied by increases in subsoil Ca<sup>2+</sup> and Mg<sup>2+</sup>. Soil pH increased significantly to a depth of 100 cm, this being attributed to the formation of ion pairs with NO<sub>3</sub><sup>-</sup> in the surface soil, the subsequent leaching of these complexes and the differential uptake of NO<sub>3</sub><sup>-</sup> at depth by roots. The results from this long-term study indicate that surface incorporation of lime is an economically viable approach to the remediation of subsoil acidity on soils such as those studied, namely, those with a low inherent cation exchange capacity and anion exchange capacity.

### INTRODUCTION

Soils of the Tully/Innisfail region of the north Queensland sugarcane belt are characteristically highly weathered, have low cation exchange capacities, low base saturation and relatively high concentrations of exchangeable aluminium (Al) throughout the profile (Isbell and Edwards, 1988). However, organic enriched surface layers often exhibit a modest capacity to retain nutrient cations, but extremely low cation exchange capacities (CECs) at depth result in subsoil infertility and in many cases acidity (Gillman *et al.*, 1989). Under intensive agricultural production, continual acidification of these soils is likely to occur through the use of high inputs of ammoniacal nitrogen fertilizer inputs, the high level of base removal as a result of crop export and the general high rainfall

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environment of the region which facilitates the losses of basic cations through leaching (Moody and Aitken, 1995).

Whilst the alleviation of acid soil infertility of surface horizons by regular additions of lime effectively neutralizes a high proportion of acidity generated through anthropogenic activities, the remediation of subsoil acidity is more problematic. Considerable work has been conducted in which lime has been mechanically mixed into the soil to a depth of 0.5–1 m in order to neutralize acidity (McKenzie and Nyborg, 1984; Hammel *et al.*, 1985). Such treatments have included the following: chisel ploughing in combination with rotary tillage (Doss *et al.*, 1979); subsoil lime injectors both mechanical (Anderson and Hendrick, 1983) and pneumatic (Saayman and van Huyssteen, 1981); mould-board ploughing (Lutz and Jones, 1971); and various mechanical procedures in combination with lime and gypsum (Farina and Channon, 1988). These methods have all shown that the neutralization of subsoil acidity has been effective in establishing a more hospitable rooting environment which has usually translated into increased yields particularly in years of below average rainfall. The economic efficacy of such treatments is determined by current commodity price structures, soil type and tillage costs, and therefore they are not feasible options for all situations (Sumner, 1995). However, in view of the residual value of lime, the economics of lime application whether for top or subsoil amelioration should be considered over more than one crop year (Mallawaarachchi *et al.*, 1998).

Several conflicting reports exist on the efficacy of surface applications of lime in ameliorating subsoil acidity. In some cases there has been no significant movement of lime to depth even after a considerable time lapse, whilst in others there has been rapid movement to depth. In many cases, the downward movement of  $\text{Ca}^{2+}$  has been used as a liming index even though there has been no movement of alkalinity (Sumner, 1995). In the current study the long-term effects of surface incorporated lime are evaluated with reference to changes in subsoil chemical characteristics and yield 18 years after the initiation of the study.

#### MATERIALS AND METHODS

##### *Site*

The trial was established in November 1978 at the Bureau of Sugar Experiment Stations (BSES) experimental farm, Tully, north Queensland (lat 17°59'S, long 145°56'E). The long-term mean annual rainfall is approximately 4300 mm, being concentrated between October and March. Prior to the establishment of sugarcane the alluvial plain was dominated by climax rainforest, remnants of which can be found in close proximity to the trial along natural water courses that have not been cleared for cultivation. The soil is classified as an Acidic Dystrophic Yellow Dermosol (Isbell, 1996) or an Oxic Humitropept (Soil Survey Staff, 1992). The clay mineralogy of this soil is dominated by kaolin (65–80%) with sub-dominant illite (10–20%) and vermiculite (1–5%).

Table 1. Treatment codes and combinations as applied from 1978 to 1990 in a sugarcane trial at Tully, north Queensland.

Treatment code	Year of treatment		
	1978	1983	1990
T1	nil	nil	nil
T2	5 t lime ha <sup>-1</sup>	nil	nil
T3	5 t lime ha <sup>-1</sup>	5 t lime ha <sup>-1</sup>	5 t lime ha <sup>-1</sup>

### Experimental design and analysis

The experiment consisted of five replications of a randomized complete block design with six treatments investigating the influence of additions of lime on the growth of sugarcane. For brevity only the effects of lime (calitic) additions are considered in this study (Table 1). The lime treatments were surface broadcast in November 1978 prior to planting the plant cane crop in 1979 and they were incorporated using a plough and disc to a depth of 20 cm. The lime source used had a neutralizing capacity of 97.5%, a Ca content of 37%, a Mg content of 0.7% and was 98% <0.25 mm. Dimensions of harvested plots were 4.3 by 11.0 m. Blocks were separated by a 5 m discard. Yields were measured from 1980 on an annual basis, except in 1989 and 1990 when the crop was severely damaged by cane grubs and in 1984 and 1991 which were fallow periods. Maintenance fertilizer additions of nitrogen, phosphorus and potassium were standard rates recommended for the sugar industry and were as follows:

Nitrogen: 140 and 165 kg ha<sup>-1</sup> N for plant and ratoon (the 2nd and subsequent crops after the plant cane crop) cane respectively;

Phosphorus: 45 and 30 kg ha<sup>-1</sup> P for plant and ratoon crops respectively;

Potassium: 100 and 120 kg ha<sup>-1</sup> K for plant and ratoon cane respectively.

### Soil analysis

Soil samples were collected to depth from each of the plots after harvest in November 1995, 17 years after the establishment of treatments. Samples were obtained using a 50-mm diam. truck-mounted hydraulic core sampler and composite samples for each depth interval formed from three cores per plot. Each core was taken from midway up the planting mound. Cores were sectioned into the following depth intervals: 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50, 50–70, 70–90 and 90–110 cm. Prior to chemical analysis, soils were air-dried and ground to pass a 2-mm sieve. Exchangeable Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> were extracted using 0.1M BaCl<sub>2</sub>/0.1M NH<sub>4</sub>Cl (Gillman and Sumpter, 1986) and determined by atomic absorption spectroscopy (Ca<sup>2+</sup> and Mg<sup>2+</sup>) and flame emission spectroscopy (K<sup>+</sup> and Na<sup>+</sup>). Exchangeable acidity (Al<sup>3+</sup> + H<sup>+</sup>) was determined after extraction with 1M KCl and extracts titrated against 1M NaOH (Rayment and Higginson, 1992). Soil pH was determined in both water (pH<sub>w</sub>)

and 0.01M CaCl<sub>2</sub> (pH<sub>Ca</sub>) in a 1:5 soil-to-solution ratio. Mineral nitrogen (N) in the soil profile was determined by extracting 10 g air dried soil in 2M KCl for 1 h. The extract was filtered and analysed for nitrate-N and ammonium-N using autoanalyser techniques (Rayment and Higginson, 1992).

Routine soil sampling of the trial was undertaken over the entire period of this study. However, due to logistical problems, only composite treatment samples were analysed thereby preventing any rigorous statistical analysis of this data. Consequently the discussion is confined to the soil chemical properties as determined in 1995.

### Statistical analysis

Statistical analysis of the data was undertaken using Genstat 5. Preliminary analysis of the soil chemical data was undertaken to determine whether transformation was required to standardize the variances. A simple ANOVA was used to analyse the data on a treatment by individual depth interval basis.

## RESULTS

### Yield responses

The difference in mean cane yield between treatment T1 (no lime) and the two lime treatments (T2 and T3) are presented in Fig. 1. There was a consistent and

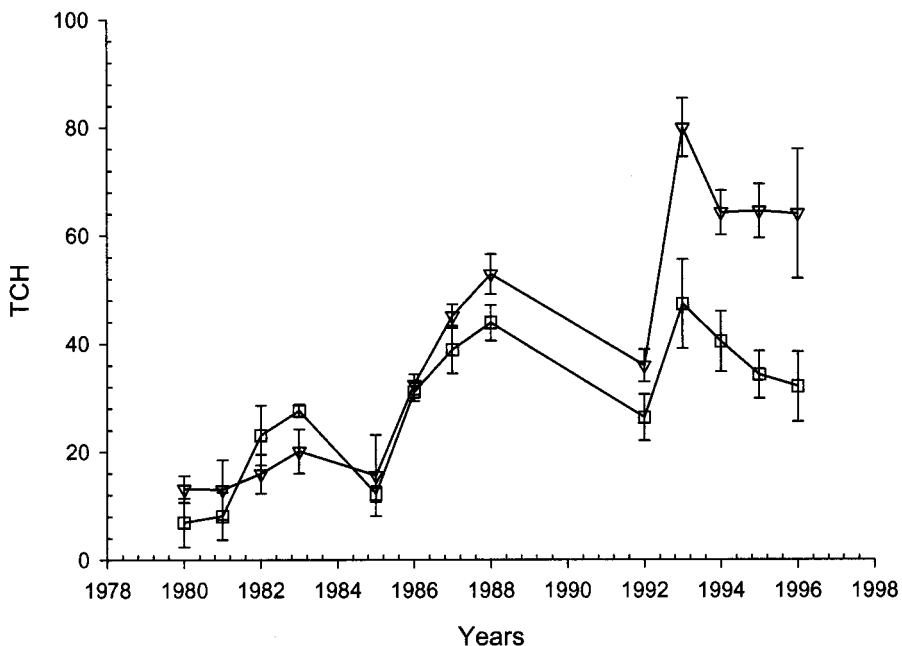


Fig. 1. Yield differences (tonnes cane harvested – TCH) compared with the control (T1 = no lime applications, represented by the x axis) associated with 5 t lime ha<sup>-1</sup> applied in 1978 (□) and 5 t lime ha<sup>-1</sup> applied in 1978, 1983 and 1990 (▽). Vertical bars represent s.e.m.

significant increase in yields in those treatments receiving lime. While yield differences were lower in 1985 and 1992, the years which coincided with plant cane crops, there was in general an increase in the differences in yield from T1 with successive ratoons. The influence on yield of a single application of lime made in 1978 (T2) was still evident 18 years after application clearly indicating the long-term residual effects. However, from 1993 to 1996, treatment T2 showed significant ( $p < 0.05$ ) decreases in yield from T3 (Fig. 1). As discussed previously, the magnitude of the response increased with time (Mallawaarachchi *et al.*, 1998). This increase in yield almost certainly reflects the progressive improvement in subsoil properties as greater quantities of alkalinity moved down the profile. This effect is substantiated by soil analytical data discussed below. It is plausible that, depending on the longevity of the response to repeated applications of lime on soil chemical properties, the cumulative benefits of lime additions may increase further with time. The magnitude of these responses to lime are considered to be particularly meaningful in that even at a single application ( $5 \text{ t lime ha}^{-1}$ ) made in 1978, significant increases in yield were still being observed 18 years after application. Consequently, due to the persistence of the observed response, the economics of applying lime on these soils are extremely attractive (Mallawaarachchi *et al.*, 1998).

#### *Exchangeable $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$ , $\text{K}^+$ and $\text{Na}^+$*

The effects of lime additions are reflected clearly in terms of soil analytical data 17 years after the initiation of the study (Fig. 2). Significant increases in exchangeable  $\text{Ca}^{2+}$  at a depth of 60 to 100 cm were observed in all treatments receiving additions of lime (Fig. 2a). The greatest increase in  $\text{Ca}^{2+}$  was evident in those treatments receiving repeated applications of lime and was most marked in the plough-layer. In contrast, those treatments receiving a single application of lime showed no significant increase in  $\text{Ca}^{2+}$  at a depth of 0 to 50 cm suggesting that any previous effects of increased  $\text{Ca}^{2+}$  in the upper portion of the profile were no longer evident 17 years after application. This may be indicative of the higher level of root activity and hence exploitation in this portion of the profile. In studies on root dynamics at a site in close proximity, over 60% of the active root systems of a sugarcane crop is confined to the top 50 cm soil (R. O. Nable, personal communication). The extremely low level of exchangeable  $\text{Ca}^{2+}$  in the control treatment after 17 years of continuous production (profile mean concentration  $0.07 \text{ cmol}_c \text{ kg}^{-1}$ ) would suggest that this treatment is predisposed to severe  $\text{Ca}^{2+}$  deficiency since it falls well below the published critical value of  $0.55 \text{ cmol}_c \text{ kg}^{-1}$  (Calcino, 1994). Similarly, those treatments receiving single and repeated applications of lime exhibited a mean profile  $\text{Ca}^{2+}$  concentration of 0.19 and  $2.0 \text{ cmol}_c \text{ kg}^{-1}$ , suggesting that a total application of  $5 \text{ t lime ha}^{-1}$  was insufficient to alleviate possible  $\text{Ca}^{2+}$  insufficiency over a prolonged period without further applications. Consequently, observed responses in yield in the presence of lime may in part be attributed to increased  $\text{Ca}^{2+}$  availability down the profile. Indeed plots of yield against mean exchangeable  $\text{Ca}^{2+}$  levels at depths of 0–25

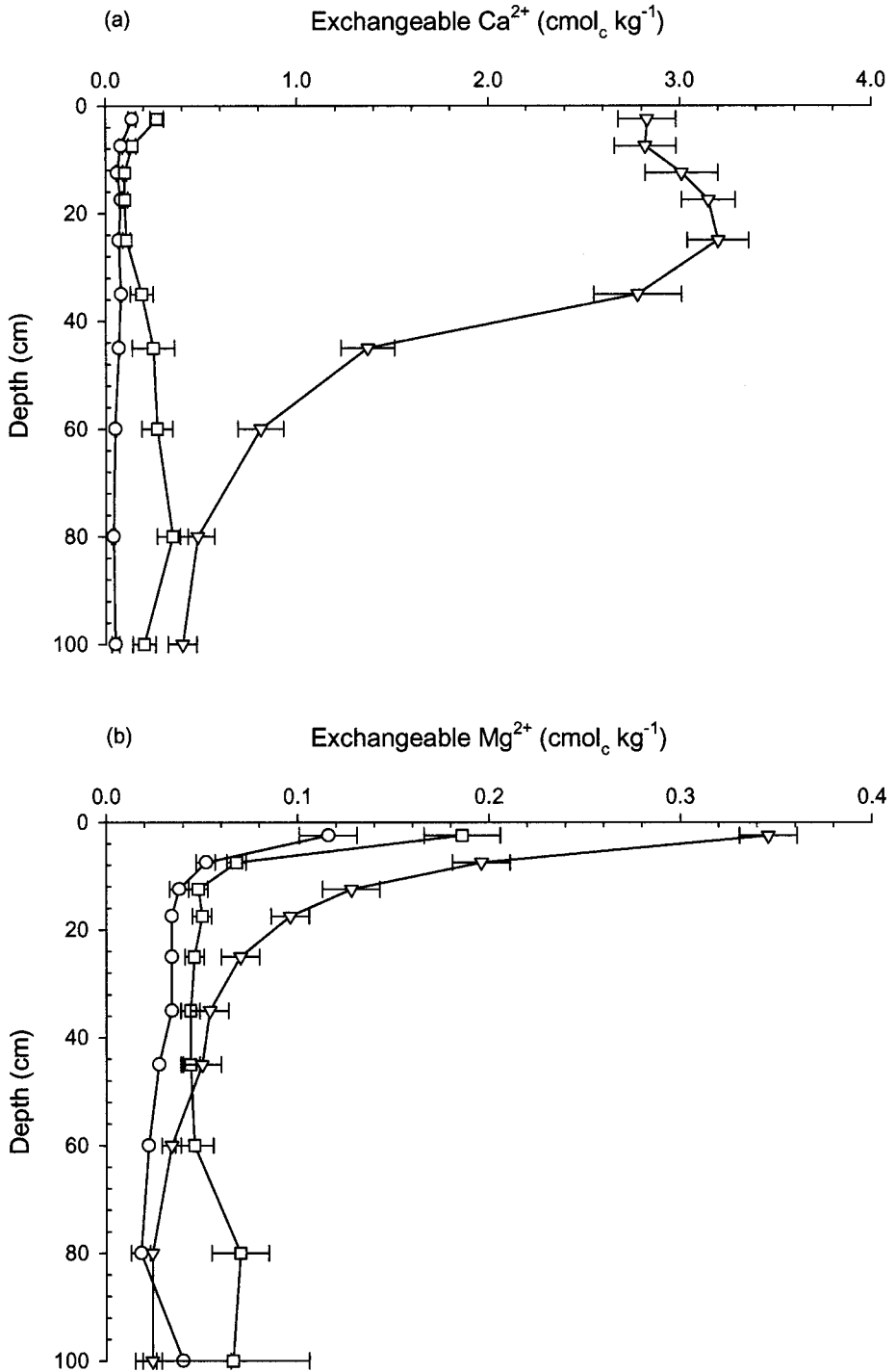


Fig. 2. Long-term effects of lime additions on (a) exchangeable  $\text{Ca}^{2+}$ , (b)  $\text{Mg}^{2+}$ , (c)  $\text{K}^+$  and (d)  $\text{Na}^+$ ; (O) denotes the control (no lime) treatment, (□) a single application of lime and (▽) multiple applications of lime. Horizontal bars represent s.e.m.

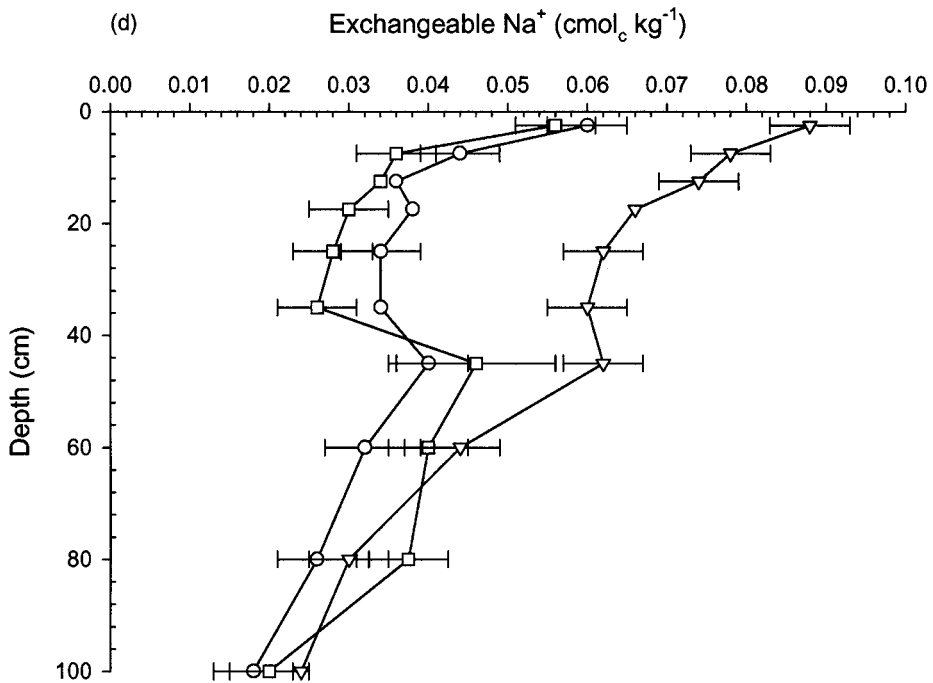
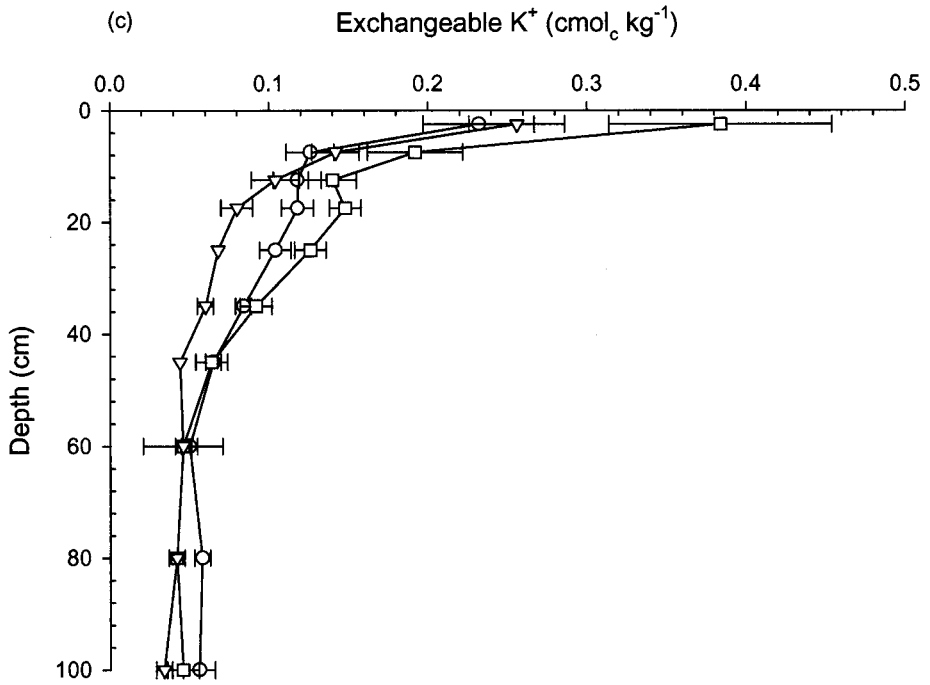


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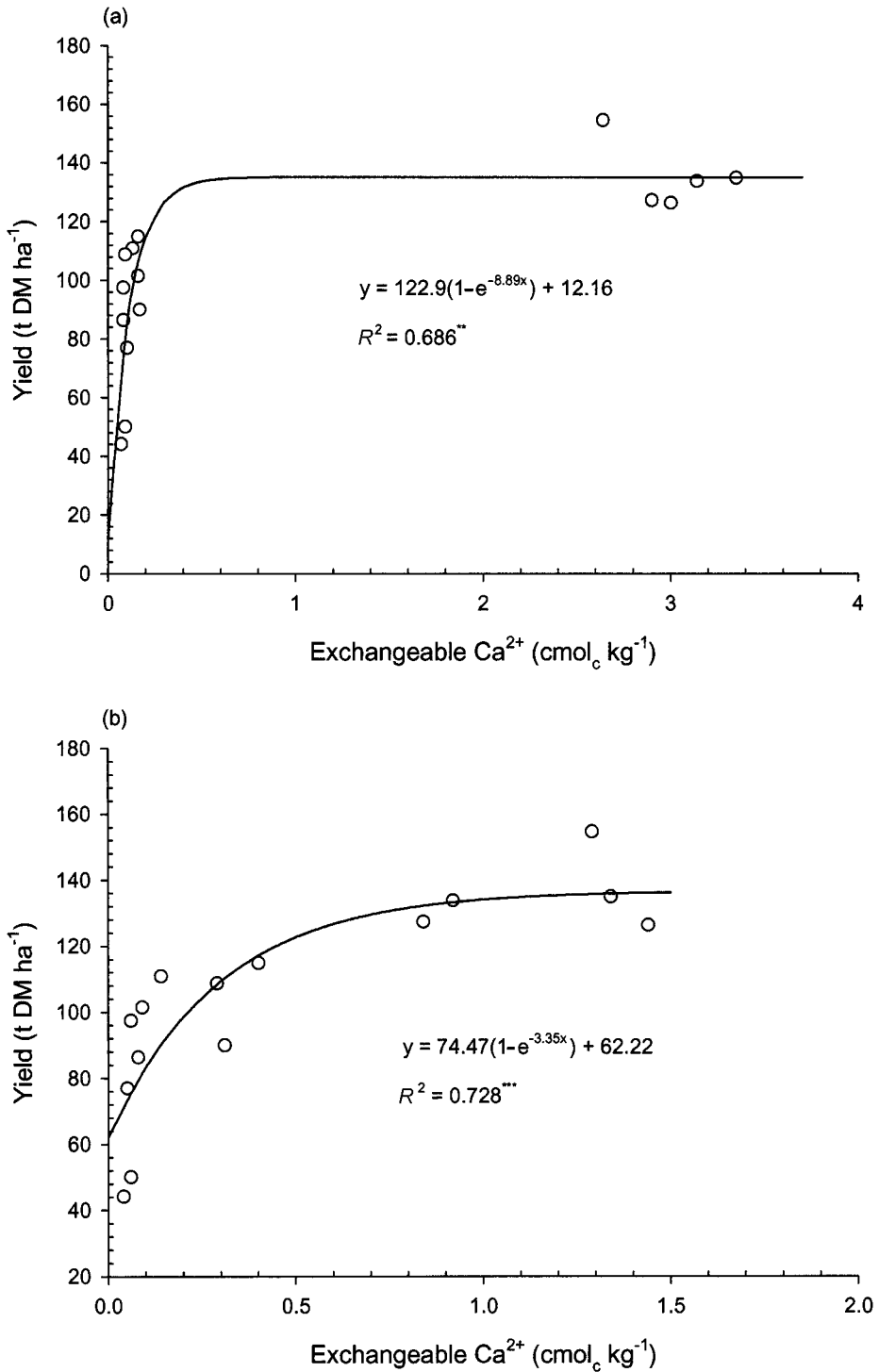


Fig. 3. Relationship between yield of sugarcane and exchangeable Ca<sup>2+</sup> at soil depths of (a) 0–25 cm and (b) 25–100 cm.



and 25–100 cm respectively showed significant correlations between this soil parameter and yield (Fig. 3a; b).

Similarly,  $Mg^{2+}$  concentrations on the exchange complex increased in the presence of repeated lime additions in the top 25 cm. Thereafter there was no significant difference (Fig. 2b). In contrast, significant increases in  $Mg^{2+}$  were observed at depth in treatments receiving a single application of lime. The mean concentration of  $Mg^{2+}$  down the profile in all treatments were below the critical value quoted by Calcino (1994) suggesting that responses to  $Mg^{2+}$  would be forthcoming on this site. In the current study a significant relationship between exchangeable  $Mg^{2+}$  in the top 25 cm and yield was observed (Fig. 4). No significant relationship between subsoil exchangeable  $Mg^{2+}$  and yield was observed. The increase in  $Mg^{2+}$  in treatment T3 is rather surprising considering that no additions of  $Mg^{2+}$  were made to these treatments and that the source of lime was classified as calcitic. However, it is clear that there were significant amounts of Mg in the lime used and in a recent survey of calcitic lime products marketed in north Queensland (G. Ham, personal communication), MgO concentrations ranged from 0.89% to 7.48% suggesting that the observed increase in  $Mg^{2+}$  could be due to contamination in the liming source.

Significant displacement of  $K^+$  occurred with repeated applications of lime compared with the control at a depth of 20–50 cm (Fig. 2c). This may in part be attributed to the increased  $Ca^{2+}$  and  $Mg^{2+}$  concentrations on the exchange

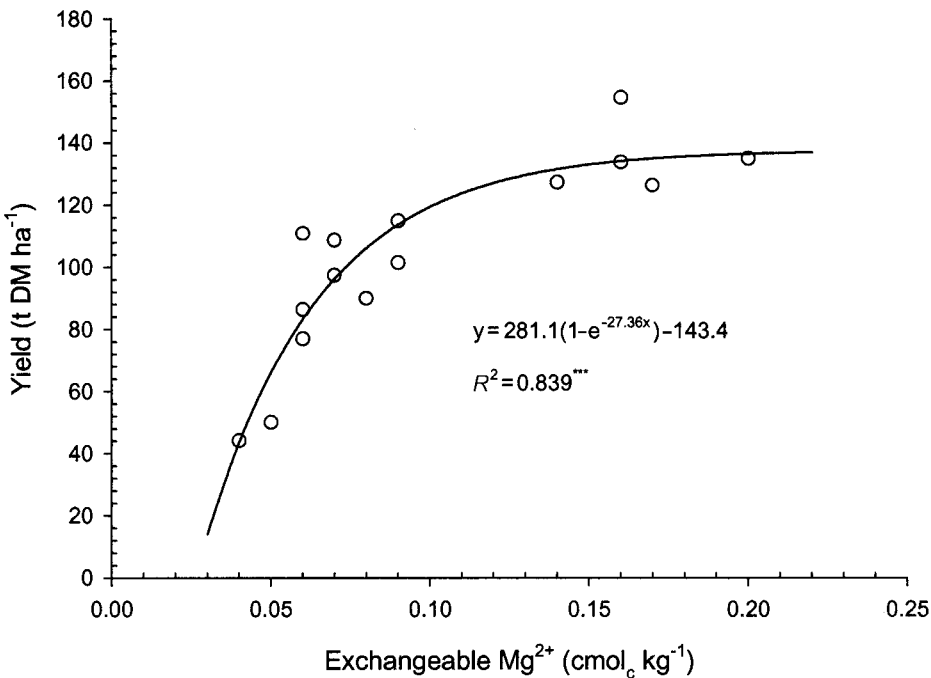


Fig. 4. Relationship between exchangeable  $Mg^{2+}$  at a soil depth of 0–25 cm and sugarcane yield.

complex in this treatment. The concentration of  $\text{Na}^+$  on the exchange complex increased significantly at a depth of 0–40 cm in those treatments receiving repeated lime additions, this being ascribed to possible impurities in the lime source (Fig. 2d).

#### *Soil pH and exchangeable acidity*

In the treatment receiving no amendments (T1) the  $\text{pH}_w$  profile ranged from 4.6 in the upper horizons to 4.3 at a depth of 100 cm (Fig. 5a). This relatively uniform  $\text{pH}_w$  distribution in the nil treatment clearly indicates the problem of subsoil acidity and hence its possible impact on productivity. Additions of lime resulted in a significant increase in soil  $\text{pH}_w$  to a depth of 100 cm when compared with treatment T1 (Fig. 5a). This difference in  $\text{pH}_w$  at 100 cm was approximately 0.5 of a pH unit between the T1 and limed treatments (T2 and T3). In contrast, the aforementioned differences between treatments were not as striking when  $\text{pH}_{\text{Ca}}$  values were compared (Fig. 5b). In this case at 100 cm significant differences were observed only in the treatment receiving repeated applications of lime. The differences observed in the  $\text{pH}_w$  measurements at depth in the profile can in part be ascribed to changes in the ionic strength of the soil solution. In this respect, there was a significant increase in electrical conductivity values in those treatments receiving lime additions (data not presented). With respect to T1 there was very little difference between  $\text{pH}_w$  and  $\text{pH}_{\text{Ca}}$  at depth which would suggest that this soil was close to its point of zero charge.

Significant decreases in exchangeable acidity were observed to a depth of 60 cm in treatment T3 (Fig. 6). This decrease is due to a combination of increased  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  with depth resulting in increased base saturation (Table 2). In contrast, significant differences between T1 and T2 were only evident in the horizon at 40–60 cm. This is consistent with further re-acidification occurring in the upper horizons over time thereby reducing the initial beneficial effects that may have accrued through the addition of lime. It is of note that with increasing pH there were no significant increases in effective cation exchange capacity (ECEC:  $\Sigma \text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+ + \text{Na}^+ + \text{Al}^{3+} + \text{H}^+$ ) (Table 2). This is consistent with a soil that is dominated by permanent charge and confirms previous determinations of charge characteristics for a similar soil by Gillman and Abel (1987).

#### DISCUSSION

The data presented here provide clear evidence that surface incorporated lime is capable, under suitable soil and climatic conditions, of markedly reducing the potential negative effects of subsoil acidity. The progressive downward movement of  $\text{Ca}^{2+}$  to depth in the profile is difficult to explain on the basis of previously reported results where lime has had relatively little influence on amending subsoil acidity (Pavan *et al.*, 1984; Farina and Channon, 1988). In order for lime applied or incorporated into surface soils to have an influence on subsoil acidity, alkalinity

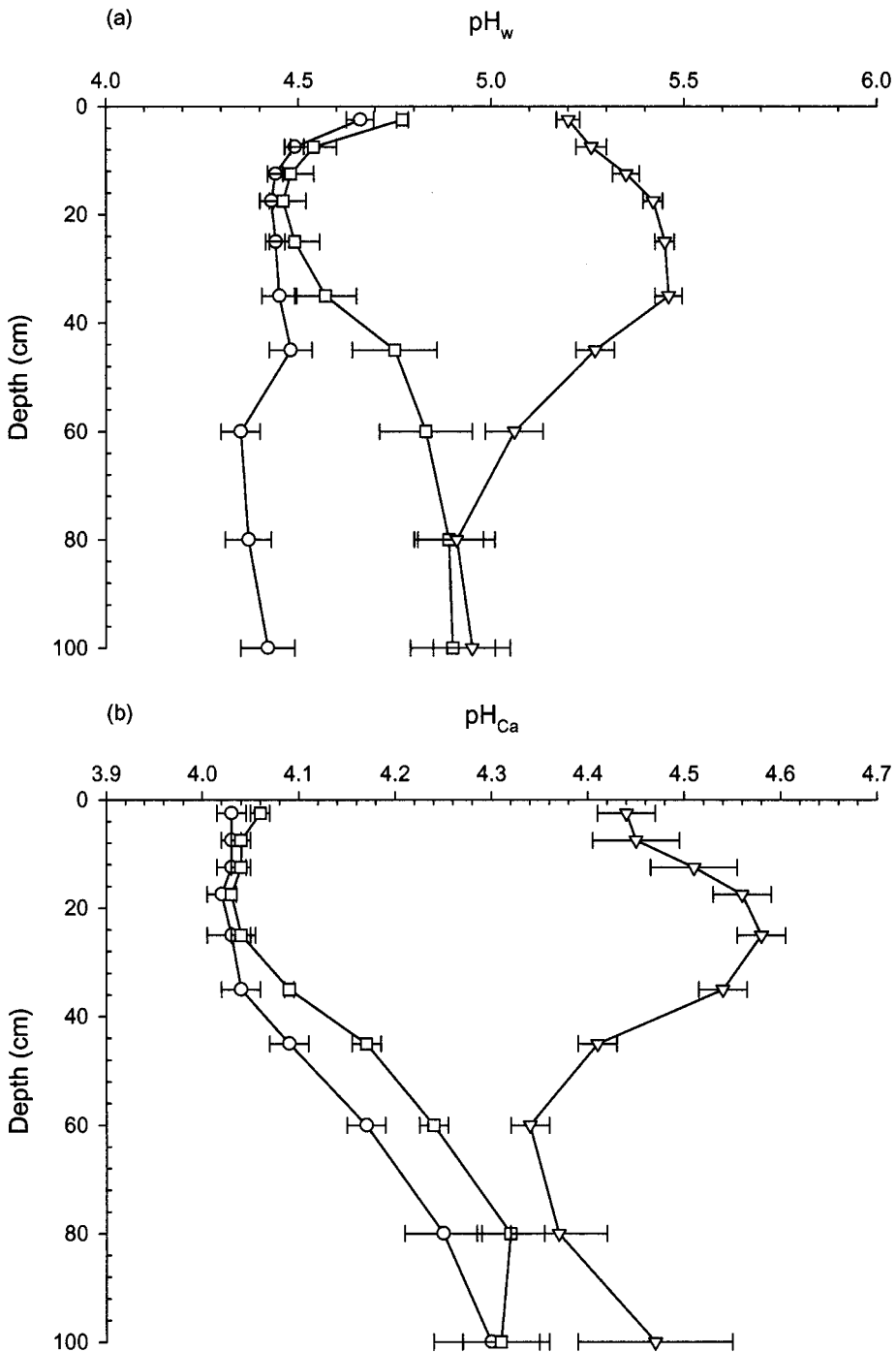


Fig. 5. Long-term effects of lime additions on (a)  $pH_w$  in water and (b)  $pH_{Ca}$  in 0.01M  $CaCl_2$ . (○) denotes the control (no lime) treatment, (□) a single application of lime and (▽) multiple applications of lime. Horizontal bars represent s.e.m.

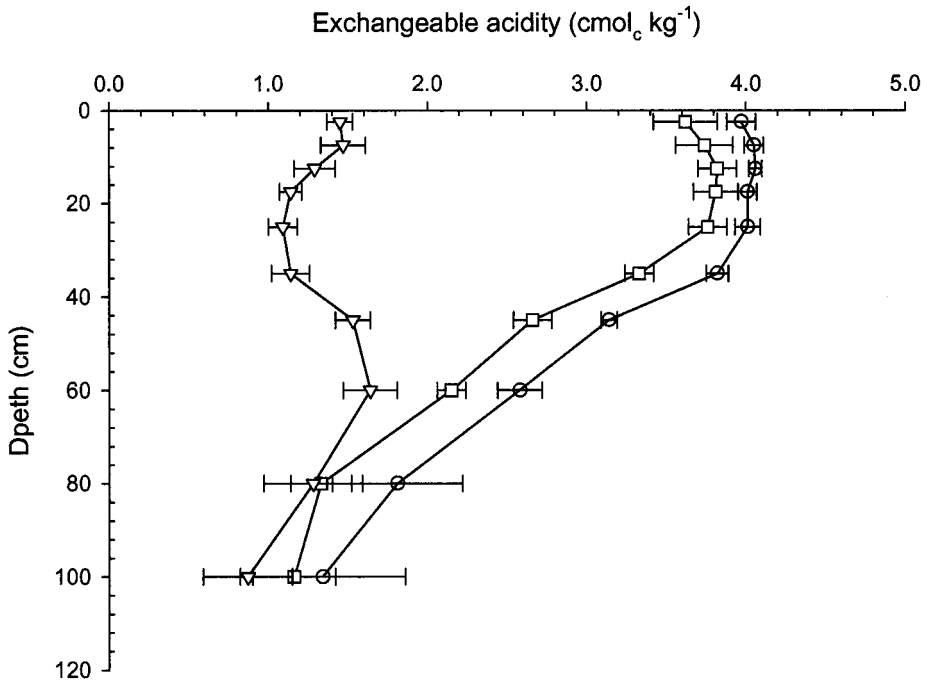


Fig. 6. Long-term effects of lime additions on exchangeable acidity. (○) denotes the control (no lime) treatment, (□) a single application of lime and (▽) multiple applications of lime. Horizontal bars represent s.e.m.

in the form of  $\text{HCO}_3^-$  or  $\text{OH}^-$  must be transported by mass flow from surface horizons to the subsoil (Sumner, 1995). Notwithstanding the fact that the  $\text{HCO}_3^-$  ion is relatively unstable and decomposes to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  (Pavan *et al.*, 1984), the concentration of the aforementioned anions increases logarithmically at  $\text{pH}_w > 5.6$ . Consequently, for significant downward movement of alkalinity to occur, topsoil  $\text{pH}_w$  must be increased to a value well above 5.6 (Sumner, 1995). In addition, on soils exhibiting variable charge characteristics the movement of this alkaline front would be further retarded by the additional requirement that a portion of the available alkalinity must be used to develop pH-dependent negative charge. Since there was no significant change in the ECEC with treatments, it can be concluded that the soil in question has very little if any pH-dependent charge (Table 2). In addition, in the current study  $\text{pH}_w$  did not rise above 5.5 thereby suggesting that an alternative mechanism was operative that facilitated the significant downward movement of alkalinity and the observed increase in pH with depth.

The transfer of alkalinity to depth from surface applications or incorporations of lime has been reported previously by several authors (Abruna *et al.*, 1964; Adams and Pearson, 1969). This is effected through the formation of  $\text{Ca}(\text{NO}_3)_2$  in the limed topsoil in the presence of ammonium-based fertilizers and its subsequent leaching to the subsoil where the more rapid rate of assimilation of  $\text{NO}_3^-$  over

Table 2. Effective cation exchange capacity (ECEC) and base saturation values for each of the treatments with and without lime (see Table 1) in a sugarcane trial at Tully, north Queensland.

Soil depth (cm)	Treatments		
	T1	T2	T3
	<i>ECEC (cmol<sub>c</sub> kg<sup>-1</sup>)</i>		
0–5	4.51 (0.12)†	4.52 (0.47)	4.97 (0.33)
5–10	4.36 (0.10)	4.18 (0.26)	4.71 (0.34)
10–15	4.32 (0.05)	4.13 (0.27)	4.60 (0.39)
15–20	4.28 (0.11)	4.14 (0.29)	4.53 (0.38)
20–30	4.25 (0.15)	4.08 (0.28)	4.49 (0.39)
30–40	4.05 (0.15)	3.68 (0.28)	4.10 (0.46)
40–50	3.34 (0.27)	3.06 (0.27)	3.05 (0.15)
50–70	2.73 (0.29)	2.54 (0.30)	2.57 (0.36)
70–90	1.95 (0.85)	1.83 (0.52)	1.86 (0.68)
90–110	1.51 (1.09)	1.49 (0.70)	1.35 (0.65)
	<i>Base saturation (%)</i>		
0–5	12.1 (3.1)	19.8 (3.0)	70.8 (3.7)
5–10	7.1 (1.2)	10.6 (2.1)	68.7 (5.8)
10–15	5.9 (0.8)	7.7 (0.4)	71.9 (5.4)
15–20	6.3 (0.5)	7.9 (1.0)	74.8 (2.7)
20–30	5.7 (0.5)	7.6 (0.9)	75.6 (3.3)
30–40	5.7 (0.4)	9.3 (3.2)	71.7 (6.6)
40–50	6.1 (0.5)	12.8 (6.5)	61.0 (8.0)
50–70	5.7 (1.0)	14.9 (5.7)	36.3 (9.4)
70–90	9.4 (5.9)	26.9 (8.37)	35.2 (15.8)
90–110	16.5 (5.1)	22.0 (8.2)	41.7 (16.3)

†Values in parentheses are s.e.m.

Ca<sup>2+</sup> by roots causes the subsoil pH to increase through the efflux of bases from the root (Sumner, 1995). Adams and Pearson (1969) demonstrated that significant increases in subsoil pH were obtained with high rates of either Ca(NO<sub>3</sub>)<sub>2</sub> or NaNO<sub>3</sub>. However, it has been demonstrated that in the absence of actively growing plants the application of Ca(NO<sub>3</sub>)<sub>2</sub> as a means of remediation of subsoil acidity is largely ineffective (Kotze and Deist, 1975). Clearly in order for this mechanism to be operative there must be significant root proliferation at depth in the profile and therefore a high degree of tolerance in the species to acid soil infertility. It is suggested that significant movement of Ca<sup>2+</sup>, and to a lesser degree Mg<sup>2+</sup>, was facilitated through the possible formation of ion pairs with NO<sub>3</sub><sup>-</sup>. Indirect evidence of this mechanism can be inferred from the mineral nitrate profiles of the individual treatments. Significant accumulations of NO<sub>3</sub>-N at depths greater than 60 cm in the profile of the T1 treatment were observed thereby inferring limited root activity (Fig. 7).

Sugarcane is generally considered to be tolerant to high levels of soluble aluminium (Hetherington *et al.*, 1986). However, it has been shown to have a relatively high requirement for Ca<sup>2+</sup> (Ridge *et al.*, 1980). With the enhanced

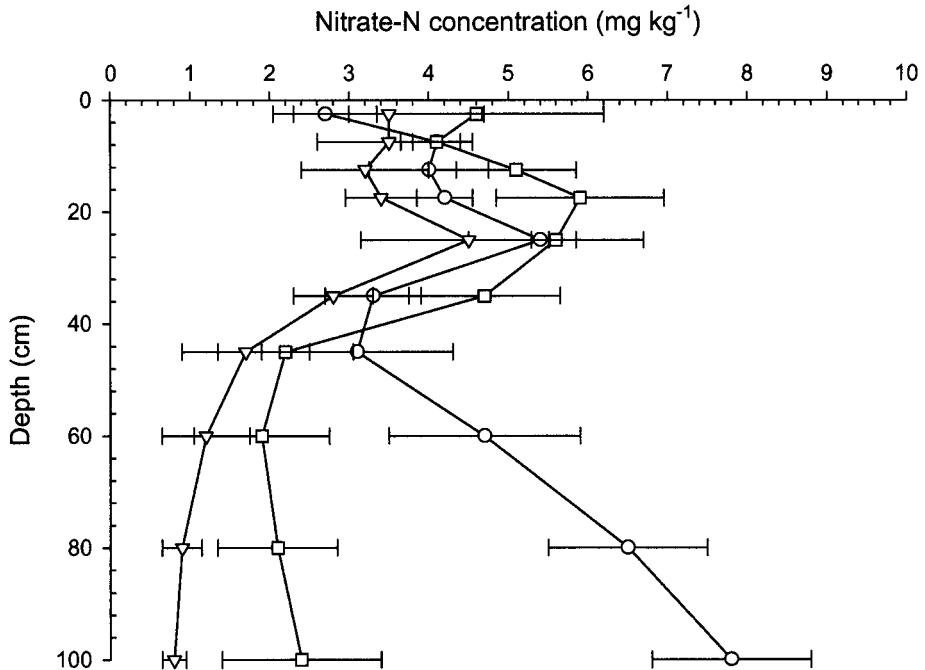


Fig. 7. Effects of lime treatments on soil mineral nitrate profiles. (○) denotes the control (no lime) treatment, (□) a single application of lime and (▽) multiple applications of lime. Horizontal bars represent s.e.m.

Ca<sup>2+</sup> and Mg<sup>2+</sup> status with depth a more hospitable environment for root growth may have been created, thereby facilitating the uptake of leached NO<sub>3</sub><sup>-</sup> from depth with an associated increase in pH.

As further supportive evidence that significant leaching had occurred, a Ca<sup>2+</sup> mass balance was attempted for the three treatments. The following assumptions were used:

1. The concentration of Ca<sup>2+</sup> in the lime source was assumed to be 36.9% based on recent survey data of calcitic lime (G. Ham, personal communication).
2. The total amount of Ca<sup>2+</sup> in the profile was calculated using measured exchangeable values and bulk densities measured previously on this site. These were 1.17, 1.22 and 1.24 g cm<sup>-3</sup> at depths of 0–5, 15–20 and 45–50 cm respectively (Ford and Bristow, 1995).
3. Total export of Ca<sup>2+</sup> from the site as harvested product was calculated from yield data over the study period and a mean Ca<sup>2+</sup> concentration in the stalks on a fresh weight basis was 0.017% (Kingston and Aitken, 1996).

Of the 1846 and 5538 kg Ca<sup>2+</sup> added in the form of lime to treatments T2 and T3 respectively, 879 and 1104 kg Ca<sup>2+</sup> was not accounted for and is assumed to have been leached below a depth of 110 cm (Table 3). This estimation of a Ca<sup>2+</sup> mass balance clearly indicates that significant leaching has occurred in this environ-

Table 3. Estimated Ca budget for two lime treatments applied in a sugarcane trial at Tully, north Queensland.

	T2	T3
Total amount of Ca <sup>2+</sup> applied (kg ha <sup>-1</sup> )	1846	5538
Total Ca <sup>2+</sup> in the soil profile (kg ha <sup>-1</sup> )	608	4035
Total Ca <sup>2+</sup> exported in the crop (kg ha <sup>-1</sup> )	359	399
Total Ca <sup>2+</sup> leached (kg ha <sup>-1</sup> )	879	1104

ment and, if NO<sub>3</sub><sup>-</sup> was the counter ion associated with Ca<sup>2+</sup>, one would expect significant losses to have taken place.

The results also demonstrate that considerable economic benefit can be derived from repeated lime additions under field conditions and emphasizes the need for managers to routinely consider lime applications as part of their management inputs on these particular soils. After 17 years, repeated applications of lime (T3) resulted in a yield increase of more than 65 t DM ha<sup>-1</sup> compared with the control. In many parts of the world the lime cost:sugar price ratio is such that the initial cost of lime would have been redeemable within a few seasons. Mallawaarachchi *et al.* (1998) undertook a comprehensive economic evaluation of long-term yield responses observed in this study and concluded that frequent prophylactic applications of lime are an extremely reasonable insurance premium to maintain sustained yields. In addition, the soil analytical data presented would suggest that the benefits of lime are likely to persist for several more seasons to come. The possibility also exists that smaller application rates than those used here might have been equally beneficial, at least in the short term, and further research in this area would be desirable.

These results confirm previously reported optimal soil Ca<sup>2+</sup> and Mg<sup>2+</sup> for sugarcane that are currently in use in the Australian sugar industry (Calcino, 1994). These recommendations specifically address the issue of Ca<sup>2+</sup> nutrition and should not be confused with the issues of remediation or prevention of soil acidification. In the case of remediation of a Ca<sup>2+</sup> insufficiency the use of materials such as gypsum or phosphogypsum could be considered since these are far more effective sources of Ca<sup>2+</sup> that specifically address the issue. In contrast, if the objective is to reduce soil acidity, then the goal should be to increase the soil pH to some predetermined level. In this case the use of liming materials such as calcitic or dolomitic lime is warranted. In the current study the use of liming materials was probably the most effective means of remediation of a Ca<sup>2+</sup> deficiency and acidity problem. The results presented show clearly that in the case of a single application of 5 t lime 17 years ago, there has been significant re-acidification of the surface soil horizons and a progressive downward movement of protons with time. It has been suggested that in order to avoid the progressive downward movement of protons due to topsoil re-acidification, the soil pH<sub>w</sub> in these surface layers should be maintained above 5.6 (Noble *et al.*, 1997).

Finally, the soils data discussed sheds some light on a possible mechanism involved in the remediation of subsoil acidity. The results clearly demonstrate that under this high-leaching environment there has been a progressive downward movement of alkalinity which has been time-dependent. In this respect, the soil under discussion would fall into the Type 2 group as outlined by Gillman and Sinclair (1987). These soils are characterized as having a low cation exchange capacity (CEC) and anion exchange capacity (AEC). Consequently, from a management perspective, surface applications of liming materials will be effective in changing subsoil chemical characteristics on these soil types. Without major profile modification, subsoil acidity has been corrected with minimal energy inputs which can only be of benefit from both an economic and environmental perspective.

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