

FINAL REPORT

SRDC PROJECT CSR024

IMPROVING THE ENVIRONMENT FOR SUGARCANE GROWTH THROUGH THE AMELIORATION OF SOIL ACIDITY

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EXECUTIVE SUMMARY

Most soils used for growing sugarcane in wet tropical northern Queensland are highly acidic. Comparisons between new cane land and land that has been growing sugarcane for many years have demonstrated that our soils have become degraded under continuous sugarcane monoculture and that many of the changes in soil chemical properties are associated with soil acidification. Continued acidification, due to heavy applications of nitrogen fertilizer and the removal of base cations in the cane sent to the mill, will not only further acidify surface soils but will also progressively acidify the lower parts of the soil profile, making amelioration difficult and costly. Low soil pH not only reduces the availability of some nutrients to plants but also reduces soil surface charge resulting in a permanent reduction in the capacity of the soil to hold nutrients. Since many soils in the wet tropics already have a low cation exchange capacity, further reductions in cation exchange capacity (CEC) due to accelerated acidification may lead to sub-optimal levels of exchangeable calcium, magnesium and potassium, which will have a direct impact on sugarcane yields.

Current industry recommendations for applying lime are based on perceived economic crop responses to calcium and are based only on the level of soil exchangeable calcium in the surface layer. Whilst this philosophy may be appropriate for soils with very low cation exchange capacities and suboptimal levels of exchangeable calcium, where frequent lime applications would be required to maintain soil calcium levels, it does not offer a sustainable management solution for highly acidic soils with adequate exchangeable calcium levels. Over 85% of cane growing soils in the Herbert River District fall into this category, having exchangeable calcium levels above the critical level and yet having an average soil pH of less than 5.

This project aims to enhance the sustainability of the sugar industry by investigating and developing strategies for ameliorating soil acidity and thus making soils more amenable not only for sugarcane production but also for leguminous fallow crops which are now considered to be an important part of a sustainable sugarcane production system. Replicated experimental trials involving five rates of lime and three rates of gypsum were established on farms in the Herbert River District with contrasting soils that were highly acidic but had exchangeable calcium above the critical level. A fourth trial site was included later in the project with very low exchangeable calcium levels. Cane yields and CCS were monitored and soil samples taken from different depths in selected treatments in each trial were analysed in order to monitor changes in soil chemical properties.

The application of both lime and gypsum had marked effects on some soil properties but their overall effect on cane yields was limited. Increasing additions of lime resulted in significant increases in the pH of surface horizons. However these changes were confined to surface horizons and demonstrated the difficulties of transferring alkalinity to depth in these soils over a relatively short period of time. The increases in soil pH and exchangeable calcium were lower than that expected on the basis of laboratory-based experiments, which included an assessment of soil pH buffer capacity, the neutralising value and solubility of the lime. The lime had a solubility of only 80% that of pure CaCO_3 and thus was much slower in its rate of reaction. The gypsum too contained significant insoluble impurities. It is therefore not surprising that the effects of lime and gypsum application need to be evaluated over several years and that economic responses to lime, even on responsive sites, may not appear for several years after the initial application. The results also suggest that a Quality Assurance program for lime and gypsum would be of value to both sellers and users of these soil ameliorants.

Studies of the charge characteristics of the different soils used for the experiments show that by increasing soil pH, a considerable amount of soil variable charge can be generated and that provided soil pH can be maintained above 5.5, the exchange complex will be dominated by exchangeable base cations. A target soil pH of 5.5 is thus appropriate for liming programs in the sugar industry as this will not only minimise the amount of soluble aluminium and manganese in soil profiles but will also reduce the risk of subsoil acidification. Liming recommendations will need to be adjusted for different soils to achieve this target pH due to differences in soil pH buffering capacity and CEC.

This project has provided a basis for making more precise lime recommendations for the Australian sugar industry based on the specific properties of different soil types. The implementation of these recommendations will help arrest the long-term degradation of sugarcane soils due to accelerated acidification. A reduction in soil acidity will improve the capacity of the soil to store nutrients and the availability of these nutrients. It will also enable leguminous crops to be successfully incorporated into the sugarcane production system thus helping to reduce the pest and disease problems associated with sugarcane monoculture.

1. INTRODUCTION AND PROJECT BACKGROUND

Soils of the wet tropical region of the north Queensland sugarbelt 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). Surface layers enriched with organic matter often exhibit a modest capacity to retain nutrient cations. However, extremely low CEC's at depth results in subsoil infertility and in many cases acidity (Gillman *et al.*, 1989).

Soil acidification (declining soil pH due to net proton (H^+) accumulation) is a natural process that occurs during pedogenesis and is often associated with high rates of leaching. However, the rate of acidification can be accelerated through farming activities with the result that the soil resource may become significantly degraded. Under intensive agricultural production, continual acidification of these soils is likely to occur through the use of high inputs of ammonium-based nitrogen fertilizer inputs, the high level of base removal as a result of crop uptake and subsequent removal and the generally high rainfall environment of the region which facilitates the losses of basic cations through leaching (Moody and Aitken, 1995). The soil orders that predominate in the sugar producing areas of eastern Australia are inherently acid and of a relatively low fertility (Ahern *et al.*, 1995). Degradation of the soil resource through the loss of fertility that accompanies acidification results in declining productivity and therefore places the products of farming systems operating in acidifying environments subject to scrutiny under the recent ISO 14000 treaty.

Processes of acidification

There is an enormous volume of literature that summarises the deleterious effects of soil acidity on plant growth and root development and the amelioration of acidity in both topsoils and subsoils (eg. Adams, 1981; Kamprath and Foy, 1985; Foy, 1992; Shainberg *et al.*, 1989; Sumner, 1993, 1995). Several effects are generally observed to occur due to soil acidification. These include (1) leaching losses of basic cations (Ca^{2+} , Mg^{2+} and K^+), (2) mobilisation of Al^{3+} and Mn^{2+} ions which may be extremely phytotoxic to some plant species, (3) reduction in the availability of P and Mo, (4) a reduction in the negative charge exhibited by variable charge colloids and (5) changes in biological activity. Acidification of the soil does not occur as long as the soil buffering capacity keeps the pH and base saturation constant. Therefore the sensitivity of a soil to acidification is inversely related to the buffering capacity, being greatest on poorly buffered soils.

It is not our intention here to cover the literature to any depth, but to outline briefly the processes contributing to acidification in sugarcane production areas in Australia. These may be summarised as follows:

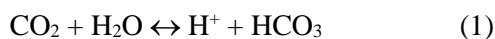
Accumulation of organic matter and a consequent increase in cation exchange capacity (CEC) and exchangeable acidity.

In general, an increase in the cation exchange capacity (CEC) is often observed due to an increase in the soil organic matter (OM) content. Concomitant with this increase in CEC is a corresponding decrease in soil pH. To illustrate this phenomenon, data from Williams and Donald (1957) are presented in Table 1.1 which demonstrate that over time, the CEC increased at a faster rate than the sum of exchangeable basic cations as soil OM built up under a sub-clover pasture system. Consequently a progressive decline in the percentage base saturation and soil pH occurred as insufficient basic cations were present in the soil to satisfy the increased CEC. One could anticipate a similar situation developing as green cane harvesting is adopted on an industry wide basis, although the higher temperatures in the tropics will probably restrict the overall increase in soil organic matter content.

Table 1.1. Some chemical properties of two podzolic surface soils from New South Wales after 26 years under subterranean clover pasture in comparison with undisturbed sites (from Williams and Donald 1957).

Soil Treatment	pH	CEC (pH 7.0) (cmol _c kg ⁻¹)	Exchangeable cations (cmol _c kg ⁻¹)				
			Ca	Mg	K	Na	Total
Undisturbed	5.90	79.3	48.4	10.7	3.2	1.0	63.3
Pasture	5.32	136.0	55.8	15.8	5.8	1.3	78.7
Undisturbed	5.80	62.4	24.6	8.4	2.9	0.8	36.7
Pasture	5.15	114.9	34.7	12.6	3.7	1.2	52.2

Associated with acidification arising from CEC increase through OM addition, is the generation of protons (H⁺) that occurs during the cycling of carbon, nitrogen and sulphur through mineralisation of OM. The latter process will not be addressed here. In the case of the C cycle, dissolution of CO₂ to form carbonic acid and the synthesis and dissolution of carboxylic acids are the two main sources of H⁺ ions leading to pH decrease. The reaction can be summarised as follows:



The continuous production of CO₂ through soil and root respiration drives this reaction to the right thereby producing acidity, whilst the unstable HCO₃⁻ decomposes to CO₂ and H₂O (Pavan *et al.*, 1984).

Plant induced processes

Plants take up nitrogen (N) in three main forms: as the anion (NO₃⁻); as a cation (NH₄⁺); or as a neutral N₂ molecule (N₂ fixation). Depending on the form of N taken up and the mechanism of assimilation in the plant, excesses of cation or anion uptake may occur. To maintain charge balance during the uptake process, H⁺ or OH⁻ ions must pass out of the root into the surrounding soil. It has been shown that the uptake of basic cations, NH₄⁺ and N₂ fixation results in a net release of H⁺ whilst the uptake of NO₃⁻ can result in a net release of OH⁻. The extent to which net proton production occurs due to excess cation uptake can be assessed by measuring the ash alkalinity of plant material. In this respect, estimation of the net proton accumulation due to crop export can be measured using the ash alkalinity of the plant material exported.

The ash alkalinities of millable cane exported from the site of a long-term liming trial established by BSES at Tully are presented in Table 1.2. Based on the yield of millable cane and the measured ash alkalinity of the 1995 crop, the equivalent amount of CaCO₃ required to neutralise the acidity generated by crop export from each of the treatments in the trial ranged from 85 to 181 kg CaCO₃ ha⁻¹ for that year (Table 1.2), or approximately 425 to 905 kg CaCO₃ over a 5 year crop cycle.

Table 1.2. Mean cane yield, ash alkalinity and CaCO₃ equivalent exported from site. Data collected from long-term liming trial of Hurney, BSES Tully.

Treatment	^a Cane yield (t ha ⁻¹)	Ash alkalinity (cmol _c kg ⁻¹ DM)	Total ash alkalinity (kmol _c ha ⁻¹)	^b CaCO ₃ equivalent (kg ha ⁻¹)
Nil	21.27	8.04 ± 0.97	1.71	85.5
5 t lime (1978)	31.54	9.03 ± 1.13	2.84	142.4
300 kg Mg (1978)	20.58	6.49 ± 1.00	1.33	66.8
5 t lime + 300 kg Mg (1978)	33.23	10.92 ± 2.35	3.62	181.4
5 t lime (1978; 1983; 1991)	40.63	7.44 ± 0.85	3.02	151.1
5 t lime + 300 kg Mg (1978; 1983; 1991)	40.26	8.15 ± 1.83	3.28	164.0

^a Dry matter yield assumed to be 30 % of the green harvested.

^b Assuming that 1 kmol_c requires 50 kg CaCO₃ to neutralise

Acid generation during nitrification of nitrogenous fertilizers

The nitrification of ammonium based fertilizers such as urea and organic N in crop residues (OM) is in itself an acidifying reaction. The reaction is carried out through the microbial conversion of NH₄⁺ to NO₃⁻ with the consequent production of protons (H⁺). The extent of acid generation by fertilizers is a function of the fertilizer type and environmental and edaphic factors. Estimates of potential net acidity generated by frequently used fertilizer sources in the sugar industry are presented in Table 1.3, with ammonium sulphate being the most acidifying and urea the least on the basis of N per kg fertilizer applied. In view of the potential acidity generated by nitrogenous fertilizers the equivalent amount of CaCO₃ required to neutralise this acidity is also shown. The theoretical amount of CaCO₃ required to neutralise the acidity generated from an application of 180 kg N ha⁻¹ y⁻¹, typical for the

Table 1.3. Estimated potential acidity produced through nitrogenous fertilisers

Source	Nitrification reaction	Net potential acidity generated	Potential acidity generated from 180 kg N ha ⁻¹	^a Amount of CaCO ₃ required to neutralise acidity generated by an application of 180 kg N ha ⁻¹ . (kg ha ⁻¹)
		(kmoles H ⁺ .kg N)	(kmoles H ⁺ ha ⁻¹)	
1. Urea	(NH ₄) ₂ CO + 4O ₂ = 2H ⁺ + 2NO ₃ ⁻ + CO ₂ + H ₂ O	0.072	13.0	650
2. Diammonium phosphate	(NH ₄) ₂ HPO ₄ + O ₂ = 3H ⁺ + 2NO ₃ ⁻ + H ₂ PO ₄ + H ₂ O	0.107	19.3	965
3. Ammonium sulphate	(NH ₄) ₂ SO ₄ + 4O ₂ = 4H ⁺ + 2NO ₃ ⁻ + SO ₄ ⁻ + 2H ₂ O	0.143	25.7	1285

^a Assuming that 1 kmol_c requires 50 kg CaCO₃ to neutralize it

Herbert River District (Webster *et al.*, 1996), ranged from 530 to 1075 kg CaCO₃ ha⁻¹ (Table 1.3) or approximately 2.6 to 5.4 t CaCO₃ ha⁻¹ over a 5 year crop cycle. Clearly the production of NO₃⁻ from ammonium-based fertilizer is a significant source of acidity generation in these production systems. In contrast, the addition of basic nitrate fertilizers such as Ca(NO₃)₂ causes little change in pH due to the lack of nitrification and may in some cases result in an increase in soil pH. This aspect will be discussed further when reviewing possible strategies to control or remediate accelerated acidification.

Although the production of NO₃⁻ through the nitrification process is a net proton accumulating reaction, the subsequent leaching of nitrate can result in a significant decline in exchangeable bases because Ca²⁺ and Mg²⁺ will move downwards as counter ions for the very mobile NO₃⁻, resulting in an accumulation of protons at the point of nitrification (Haynes, 1983). Consequently, there is spatial disjunction between the production of NO₃⁻ and its subsequent uptake by the plant. The result is an accumulation of H⁺ at point of production and net alkalisation due to the uptake of NO₃⁻ by the plant at some other point in the profile. The uncoupling of these two processes results in net proton accumulation at one point in the profile and net alkalisation at some other point. As long as nitrate is taken up at the point of production the outcome is neutral.

Evidence of accelerated acidification under sugarcane

Soil acidification rates can be measured in terms of absolute changes or relative to some control soil. In the former case, acid addition rates can be estimated from analyses of soils before and after a period of acidification as in long-term studies. However, relative rates of acidification can also be derived from survey data (eg. fence line contrasts of developed and undeveloped sites). This approach has been used in a number of studies in the sugar industry (Wood, 1985; Bramley *et al.*, 1996; Moody and Aitken, 1997). The use of fence line comparisons essentially results in a conservative estimation of the net acidification rate.

As part of a wider study on the possible role of changes in soil properties over time on sugar yield decline (Garside *et al.*, 1997), differences in soil chemical properties between new land and land which had been under sugar cane monoculture for more than 20 years were examined in detail by Bramley *et al.* (1996). They found that there was no consistent effect of time under sugar cane monoculture on soil chemical properties across sites located in the Burdekin, Herbert and Tully districts, either when the distribution of properties through the soil profile, or property values at specific depths were considered. However, marked effects were noted at some sites with respect to some soil properties and these were generally consistent with soil acidification. The changes included reduced topsoil pH in old land (0.5-1.5 pH units); increased exchange acidity and aluminium saturation in soils under old land, especially in the Herbert where percent Al saturation increased from approximately 5 to 20%. However, although little change was noted in the Tully soils where much higher Al % (45%) in both old and new land soils were measured, decreased CEC and increased anion exchange capacities (AEC) were found in old land soils at some sites in each region. Wood (1985) obtained similar results in a paired sites study in the Herbert River District where he found that many of the differences in soil chemical properties between new cane land and land that had been under sugarcane for several years could be associated with soil acidification. Sugarcane soils were found to have a lower pH, lower cation exchange capacity and lower levels of exchangeable base cations (calcium, magnesium and potassium). In addition, the analysis of soil samples from 1064 sites in the Herbert sugarcane area, taken as part of the CSR Herbert River soil survey (Wood and Bramley, 1996), has shown that mean topsoil (0-20cm) pH_w (pH in 1:5 soil:water) is 4.97 and mean subsoil (40-60cm) pH_w is 5.28. Schroeder *et al.* (1996) have also reported marked acidification in a range of sugarcane soils in South Africa.

The effects of soil acidification on sugar cane growth have received little attention from Australian researchers, presumably because Hetherington (1986) concluded that cane was tolerant of low pH-induced aluminium toxicity. However, Schroeder *et al.* (1996) reported marked differences between South African varieties in terms of their response to lime application suggesting that not only was cane affected by the effects of low soil pH, but that these effects may be variety specific. In general, most crops perform best when the soil pH is approximately 5.6 to 6.0 (Tisdale *et al.*, 1985).

Amelioration strategies

From the previous discussion it can clearly be seen that soil acidification is a continuing problem confronting the Australian sugar industry and that the largest potential acidifying component in a sugar production system is the contribution derived from the use of nitrogen fertilizers. The contribution to the total proton pool arising from the export of millable cane is relatively small compared to that derived from the nitrification of ammonium and urea based fertilizer sources, assuming that significant leaching occurs (Tables 1.2 and 1.3).

Surface amelioration

The amelioration of acidity in topsoils has been the focus of a considerable amount of research in the past and continues to create a high degree of debate. Hurney (1971) and Haysom *et al.* (1986) found no response to lime applications of up to 10 t ha⁻¹ on soils where the amount of exchangeable soil Ca²⁺ was adequate for cane nutrition, even though the soils had a low pH. Quinan and Wood (1989, 1993) challenged these findings with the results of long-term trials which demonstrated a marked and continuing response of sugar cane to lime over an eight year period at sites near Cairns on soils that had both a low pH and low exchangeable Ca²⁺ levels. They obtained close relationships between soil pH and yield response to lime. Differences in the magnitude of these responses are most likely due to pH buffering capacities, the variable charge characteristics and initial pH of the soils used in these trials. Quinan and Wood (1993) suggested that the effects of lime applications on sugarcane crops should be evaluated over a much longer time frame than had occurred in previous investigations which had been largely short term (2-5 years) and focussed on the effects of relatively low application rates of lime (2.5-5.0 t ha⁻¹). They noted a need for longer term studies (>5 years) to quantify not only the effects of lime additions on cane growth and yields but also to investigate the changes which occurred in soil chemical properties and nutrient availability.

Wood *et al.* (1997) proposed a reconsideration of industry recommendations for lime which currently consider only the level of exchangeable soil Ca²⁺ without giving due regard to the CEC, initial pH or pH buffering capacity of the soil. The fact that mean topsoil pH in the Herbert is only 4.97 in spite of the use of lime by some growers at rates of about 2.5 t ha⁻¹ every crop cycle, suggests that existing liming practices are having little long-term beneficial effect on soil pH in this area, this possibly being a result of their higher buffering capacity and CEC. In contrast, surface soil pH and exchangeable Ca²⁺ (cmol_c kg⁻¹) have risen consistently from 4.86 and 1.21 to 5.61 and 1.57 respectively from 1991 to 1995 in the Innisfail/Babinda districts (Hurney pers. comm.). The observed increase in pH and exchangeable Ca²⁺ in a relatively short period would suggest that routine lime additions can significantly remediate acidification in surface soils in areas with soils having relatively low CEC and buffering capacity.

The phenomenon of a depression in CCS associated with a response to liming products was first noted in the early BSES calcium/magnesium work in the 1970's (Ridge *et al.*, 1980) but was further explored by Kingston *et al.* (1996) and Kingston and Aitken (1996). They concluded that the strongest predictor of CCS depression was a cane yield response of more than 30% to liming products. They also noted a strong association between depression of CCS and elevated

calcium levels in leaf tissue, as reflected by the ratio of calcium to other nutrients. The ratio of calcium to magnesium in leaf dry matter was found to be the strongest nutrient index of ccs depression. Whilst depressed sucrose percent in cane resulting from liming was also observed in South Africa (Wood, 1993), the mechanism suggested for this, that of increased nitrogen availability resulting from enhanced mineralisation of nitrogen from soil organic matter due to enhanced micro-biological activity, was not supported by limited measurements conducted by Kingston *et al.* (1996). There is clearly a need to investigate the causes of reduced sucrose yield further in responsive sites. However, in spite of concerns with respect to the possibility of reduced ccs following liming, regular surface applications of lime remain the most viable option for addressing topsoil acidity and maintaining the sustainability of sugarcane soils.

Subsoil amelioration

Low surface soil pH is often an indication that there is also likely to be significant subsurface acidity. This suggestion arises from evidence that the surface soil is strongly buffered against pH decline below a pH_w of about 5.2. Organic anion oxidation in, and nitrate uptake from the organic-rich surface layer, as well as net H^+ and Al^{3+} leaching, are often sufficient to neutralise net acid addition to the layer once soil pH_w values fall to between 5.2 to 5.6 (Ritchie, 1989; Helyar *et al.*, 1990). Once the surface pH balance is achieved, continuing net acid addition causes pH decline in subsurface layers. Typically the low pH front moves deeper with time via root H^+ excretion and the mass flow of H^+ and Al^{3+} with water. Therefore, continued acid inputs to surface soil will result in a gradual decline in subsurface soil pH values. This aspect of surface soil acidification can be managed effectively through the regular and judicious application of liming materials. However, on soils that are inherently acid to depth, as are many north Queensland sugar soils, strategies to ameliorate subsoil acidity are more problematic.

Considerable work has been conducted in which lime has been mechanically mixed into the soil to depth (0.5 - 1 m) to neutralise acidity (McKenzie and Nyborg, 1984; Hammel *et al.*, 1985). Such treatments including chisel ploughing in combination with rotary tillage (Doss *et al.*, 1979); subsoil lime injectors (Anderson and Hendrick, 1983); mouldboard ploughing (Lutz and Jones, 1971); development of lime applicators that blow lime into the subsoil behind various tillage implements (Saayman and van Huyssteen, 1981; Aitken *et al.*, 1995); and various mechanical procedures in combination with lime and gypsum (Farina and Channon, 1988). These methods have all shown that the neutralisation 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 are determined by current commodity price structures, soil type and tillage costs, and therefore 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.

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 Ca^{2+} has been used as a liming index even though there has been no movement of alkalinity. It has been demonstrated that there is significant movement of Ca^{2+} and Mg^{2+} to depth after surface applications of lime without any measurable reduction in exchangeable acidity ($Al^{3+} + H^+$) (Sumner, 1995). As discussed previously, in the pH_w range of 5.2 to 5.6 mass flow balance exists between alkalinity and acidity due to the insolubility of Al^{3+} , Fe^{2+} and Mn^{2+} and the equal quantities of HCO_3^- and H^+ concentrations (Ritchie; 1989; Helyar, 1991). This point is illustrated by the relationship between percentage exchangeable acidity as a function of the effective CEC and pH_w which clearly shows that at a pH of 5.6 the acid saturation is reduced to approximately 11% (Figure

1.1). Therefore for significant downward movement of alkalinity the pH of the topsoil must be above pH_w 5.6 where the concentrations of HCO_3^- , OH^- and CO_3^{2-} increase logarithmically.

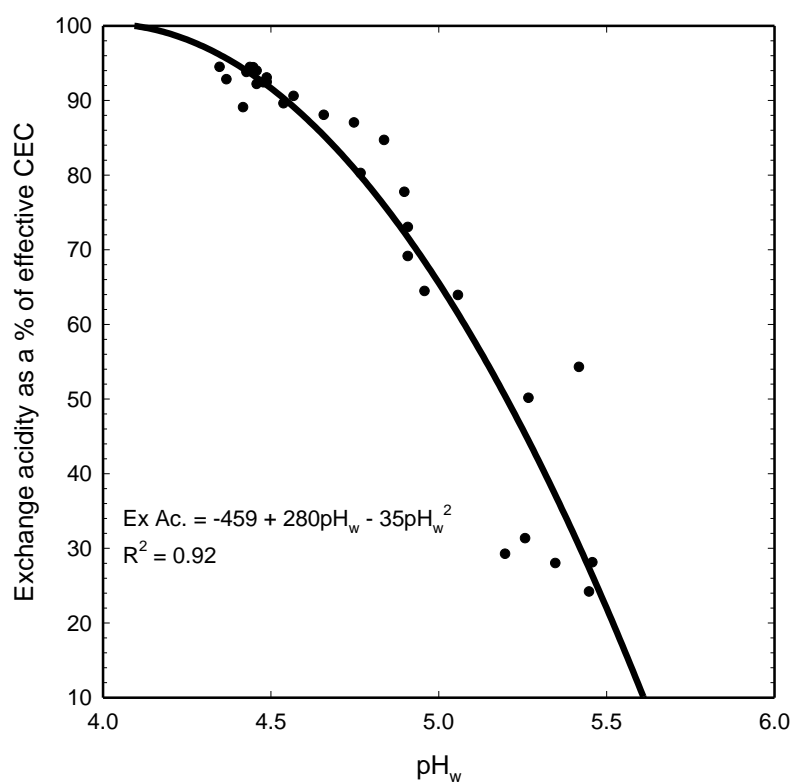


Figure 1.1. Relationship between soil pH and exchange acidity in soils sampled from the long-term lime trial in Tully.

There is now sufficient knowledge about the chemistry of permanent and variable charged soils to predict their behaviour to additions of lime (Uehara and Gillman, 1981; Sposito, 1989; Ulrich and Sumner, 1991). In brief, on acid subsoils which are dominated by permanent charge, (soils of the humid temperate and semiarid tropical and subtropical regions), the only constraint to the movement of alkalinity is the requirement that the acidity present in the subsoil be neutralised as the alkaline front moves downwards (Sumner, 1995). In contrast, in variable charged subsoils (soils of the wet tropics), the advancing alkaline front is retarded by the additional requirement that a portion of the alkalinity is used to generate pH dependent charge. Therefore on variable charged soils at a given acid content, slower movement of alkalinity down the profile than that observed in permanent charge subsoils would be expected (Sumner, 1995).

There are several examples in the literature to demonstrate that alkalinity can be transferred to subsoils by the addition of lime and acidifying fertilizers applied to topsoils (Abruna *et al.*, 1964; Adams, 1981). This can be brought about by acid inputs of ammonium based fertilizers to well limed topsoils where leaching of the resulting $Ca(NO_3)_2$ and other salts formed to the subsoil where the more rapid assimilation of NO_3^- than Ca^{2+} by the roots causes the subsoil pH to increase. This mechanism of amelioration may have a role to play in decreasing subsoil acidification in the sugar industry. Since the industry is a large consumer of acidifying nitrogenous fertilizers, it would be to the advantage of the grower to maintain surface soil pH values at a desirable level to facilitate the downward movement of alkalinity.

The surface application and incorporation of gypsum has been shown to ameliorate soil acidity to depth (Shainberg *et al.*, 1989; Sumner, 1993). When gypsum is applied to topsoils it is relatively soluble and therefore leaches down the profile under excess moisture. When the gypsum front reaches the acid subsoil, it reduces the toxicity of Al^{3+} in one of a number of ways (Sumner, 1993). The formation of AlSO_4^+ and Al-fluoride complexes with the use of phosphogypsum, have been shown to be less phytotoxic to a number of plant species (Alva *et al.*, 1988; Noble *et al.*, 1988). In addition, there is often an increase in soil pH with the addition of gypsum that involves ligand exchange of SO_4^{2-} for OH^- on sesquioxides surfaces that produces alkalinity that neutralises soluble Al^{3+} (Reeve and Sumner, 1972).

The continual decline in soil pH and associated acid infertility can and will have a significant impact on the long-term sustainability of sugar production systems. Although sugar cane can tolerate a wide soil pH range (Blackburn, 1984), some studies have shown that optimum production is achieved when the pH is approximately 6 (Coale and Scheuneman, 1993). In addition, Abruna-Rodriguez and Vicente-Chandler (1967) found that highest cane yields were achieved when the exchangeable acidity was reduced to less than $2 \text{ cmol}_c \text{ kg}^{-1}$. The continual acidification of soils through injudicious nitrogen management brings into question the long-term sustainability of the sugar production system and limits the ability of a producer to diversify their production system as and when market forces dictate; for example by growing another crop such as peanuts. To date, liming strategies have focused on the sugarcane monoculture with scant attention being paid to the requirements of other crops that could be incorporated into these farming systems. Results to date have clearly shown that in certain cases, there has been a significant decline in the soil resource base through exploitive production practices. In particular, production systems which promote soil acidification can be viewed as unsustainable in terms of maintaining productivity.

Current recommendations within the Australian sugar industry are based on the use of exchangeable Ca^{2+} as a means of assessing whether lime additions are warranted (Calcino, 1994). They do not take into account soil pH, soil pH buffering capacity, exchangeable aluminium or cation exchange capacity. The assumption is that sugarcane is tolerant of low soil pH and of relatively high levels of exchangeable aluminium and that soil acidity is not a problem. Lime is recommended solely as a source of calcium for the crop. Whilst these recommendations have proved to be economically sound on certain soils, with yield increases persisting for more than 15 years, many sugar soils remain highly acidic. The recommendations fail to address the problem of continuing soil acidification which occurs largely as a consequence of the application of nitrogen fertilizer and through the removal of nutrients in the part of the crop sent to the mill. Also because they are based on the amount of exchangeable calcium in the soil and not on calcium saturation, they are imprecise as they fail to differentiate between soil types with different CEC's and buffering capacities.

With respect to soils with acidified topsoils that do not have acid subsoils, it is suggested that liming rates should be based on reducing the risk of proton movement to depth. In this respect liming to a pH of 5.6 would minimise the potential for proton movement and substantially reduce the risk of subsoil acidification. With respect to the amelioration of subsoil acidity, the strategy adopted will depend on the economics of implementation. However, the production of $\text{Ca}(\text{NO}_3)_2$ through the addition of lime and ammonium based fertilisers, its subsequent leaching into the subsoil, and the preferential uptake of NO_3^- may offer a feasible and practical method for remediating subsoil acidity and enhancing sustainable production. In addition, the maintenance of desirable exchangeable Ca^{2+} content in both surface and subsurface horizons may warrant the use of gypsum or phosphogypsum.

2. PROJECT OBJECTIVES

This project sought to enhance the sustainability of the Sugar Industry by providing strategies for the amelioration of soil acidity and for improving crop productivity on soils which are inherently acidic. This will not only make soils more amenable to sugarcane production but will also improve the environment for other crops to be grown in association with sugarcane.

The objectives of the project, set at the outset of the project, were as follows:

1. To re-evaluate the basis on which the Industry recommendation for applying lime is made.
2. To investigate the long-term effects and potential benefits on cane growth and crop productivity resulting from the amelioration of soil acidity.
3. To investigate the effects of raising soil pH to 6.0 - 6.5 on chemical properties in sugarcane soils such as soil charge characteristics and the balance of exchangeable cations.
4. To investigate possible reasons for a depression in CCS commonly associated with lime application.
5. To conduct an economic analysis of the responses to lime addition for different soils based on a range of cane prices.

Additional objectives, outlined in the SRDC Subprogram Review Report on Acid and Sodic Soil R&D in August 2000, included:

1. To determine whether there had been any treatment effects on soil physical properties by analysing soil samples taken from selected treatments in one or more of the experiments for wet aggregate stability.
2. To calculate net acidification rates for the sites based on changes in profile pH over the period of the project.

3. PARTIES INVOLVED AND LINKS WITH OTHER INITIATIVES

The project was set up as a partnership between CSR Technical Field Department, the Sugar Yield Decline Joint Venture and the CSIRO Soil Acidification Group at Davies Laboratory in Townsville in an attempt to build up a critical mass of soil acidity researchers working within the northern sugar industry.

- CSR TFD had accumulated a considerable amount of knowledge and data on the soils of the Herbert River District through the CSR Herbert Soil Survey. This dataset clearly indicated that the majority of sugarcane soils in the district had low pH's with a substantial amount of their cation exchange capacity occupied by acidic cations.
- The Sugar Yield Decline Joint Venture was involved with research experiments which suggested that soil acidification was an important component of the yield decline phenomenon and that whilst crop rotations helped to reduce the causes of yield decline, the choice of break crops was severely restricted because of soil acidity.
- CSIRO had recently established a Tropical Agri-Exports Multi Divisional Program with a component specifically focussed on soil acidification in northern Australia.

Other related initiatives included the soil acidification work being conducted as part of subprogram 2.3 of the CRC for Sustainable Sugar Production, some long-term experimentation investigating the effects of lime on soil acidity and soil calcium/magnesium levels being carried out by BSES in the wet tropics involving Alan Hurney, and the soil acidity work being undertaken in southern Queensland and northern New South Wales by BSES and QDPI (now QDNR&M) involving Drs Kingston, Moody and Aitken. Some of the southern work was also funded by SRDC (projects BS98S and BSS155).

4. METHODOLOGY

The lime trials were established with the aim of providing information on the yield response to prophylactic applications of lime as a function of a range of soil chemical properties; and identifying the most appropriate means of predicting lime response. In particular, and in view of the results of the paired sites work (Bramley *et al.*, 1996), it was of interest to know whether a yield response to an increase in soil pH could be elucidated following lime application, separate to any response to the supply of calcium.

Selection of sites and preliminary site characterisation

Initially, three sites were selected in the Herbert River District for conducting the experimental work. They were located in late 1995 on acidic soils with contrasting clay content, cation exchange capacity (CEC) and pH buffer capacity. Selected topsoil properties from the initial 3 sites at Accornero, Reinaudo and Mizzi are presented in Table 4.1.

Table 4.1. Selected properties of the lime trial soils (0-10 cm)

	pH _w	Org C %	Exchange properties (cmol(+) kg ⁻¹)							P mg kg ⁻¹	S	C.S %	F.S %	Silt %	Clay %
			Ca	Mg	K	Na	H+Al	CEC	AEC						
Accornero	4.62	1.47	1.58	1.28	0.32	0.11	4.35	6.55	0.38	55.4	33.2	14.7	19.2	31.3	34.8
Reinaudo	4.77	1.22	2.02	0.89	0.15	0.11	2.39	5.51	0.11	41.0	14.7	2.5	59.2	16.7	21.6
Mizzi	4.69	1.07	0.94	0.27	0.19	0.05	1.42	1.86	0.31	207	21.5	65.8	12.2	10.5	11.6
DiBella	4.84	1.42	0.43	0.32	0.24	0.05	1.62	2.30	0.08	107	16.0	42.2	25.5	14.9	17.4
Feluga	5.38		0.99	0.32	0.39	0.21	0.58	2.21	0.17			46.3	23.0	12.0	18.7

All three sites had extremely acidic topsoils (pH_w <4.8) and covered the range of clay contents and cation exchange capacities occurring in the Herbert. With current industry lime recommendations based on exchangeable calcium levels, none of the sites would have been regarded as deficient in calcium although the Mizzi site would have been considered as marginal in calcium and a lime application of 2.5 t ha⁻¹ lime would have been recommended.

In view of the lack of yield response to lime seen in the original three trials (see section 9), two additional sites were selected later in the project which were considered more likely to be responsive to lime application. An additional site was selected in April 1998 at John DiBella's property near Arnot Creek in the northernmost part of the Herbert River District. This site had sandy soils derived from the acid volcanic rocks of the Cardwell range and, in contrast to most other Herbert River soils, had very low levels of Ca and Mg in the subsoil as well as in the topsoil. The topsoil properties in Table 4.1 for DiBella's show that this site is extremely acidic and has a much lower level of exchangeable calcium than the original three sites and would have been regarded as deficient in calcium using current industry recommendations (Calcino, 1994).

The other site selected was adjacent to the Feluga Yield Decline Joint Venture rotation trial north of Tully. The Feluga trial was part of an experiment set up by Alan Garside and Andrew Noble which aimed to look at the fate of nitrogen (N) following incorporation of a fallow crop under a variety of lime/gypsum regimes. In particular, the hypothesis being tested was that in order for amelioration of subsoil acidity to be effective on certain soils some nitrate leaching is required. The site is characterised by subsoils having a very low Ca and Mg status and a high exchange acidity in the profile below about 30 cm.

Apart from detailed soil chemical characterisation of the profile down to a depth of 90cm, soil particle size was determined on samples taken at similar depth increments to those used for chemical analysis (Table 4.2). The profiles at Accornero's and Mizzi's showed a decrease in % clay and an increase in % sand down the profile. This indicates the heterogeneous nature of the soil parent material which is alluvial in origin and illustrates the layered nature of many soil profiles in the Herbert. The Reinaudo and Feluga sites have a fairly constant soil texture down the profile, whilst at DiBella's there is a decrease in % silt and an increase in % clay with depth.

Table 4.2. Soil particle size analysis for the lime trial sites

Sample depth	Coarse sand %	Fine sand %	Silt %	Clay %
Accornero				
0-10 cm	14.7	19.2	31.3	34.8
10-20 cm	15.4	19.2	34.6	30.8
20-30 cm	16.6	20.0	32.6	30.8
30-50 cm	12.4	23.6	29.3	34.8
50-70 cm	31.4	24.6	17.3	26.7
70-90 cm	28.3	35.1	13.9	22.7
Mizzi				
0-10 cm	65.8	12.2	10.5	11.5
10-20 cm	28.9	52.4	5.1	13.6
20-30 cm	66.3	15.8	6.4	11.5
30-50 cm	69.6	13.0	3.8	13.6
50-70 cm	39.2	48.8	2.5	9.5
70-90 cm	36.0	54.8	1.7	7.5
Reinaudo				
0-10 cm	2.5	59.2	16.7	21.6
10-20 cm	3.6	62.8	12.0	21.6
20-30 cm	1.0	58.1	17.4	23.5
30-50 cm	2.1	61.7	17.3	18.9
50-70 cm	7.8	55.3	14.0	22.9
70-90 cm	8.9	54.2	19.4	17.5
DiBella				
0-10 cm	42.2	25.5	14.9	17.4
10-20 cm	42.6	25.1	14.6	17.7
20-30 cm	44.3	23.5	13.2	19.0
30-50 cm	43.4	25.4	11.2	20.0
50-70 cm	43.0	21.3	9.8	25.9
70-90 cm	40.4	22.6	7.8	29.2
Feluga				
0-10 cm	46.3	23.0	12.0	18.7
20-30 cm	43.0	21.8	12.8	22.3
50-70 cm	38.7	28.6	10.8	22.0
90-110 cm	38.3	30.9	11.6	19.3

Experimental details

Initial trials

After pegging out the trials, lime at rates of 0, 2.5, 5, 10 and 15 t ha⁻¹ and gypsum at rates intended to provide the same amount of calcium (Ca) as 2.5 and 10 t lime ha⁻¹ (3.81 and 15.24 t gypsum ha⁻¹) were applied in a factorial combination at two of the sites (Accornero and Reinaudo). Each treatment was replicated three times, giving a total of 45 plots. At the third site (Mizzi), there were only 39 plots due to insufficient area being available. The highest rate of lime addition in factorial combination with gypsum at Mizzi's was 10 t ha⁻¹ although the trial did include plots to which 15 t ha⁻¹ lime were applied, but not in combination with gypsum. Plots were 9m wide (allowing for 6 rows of cane to be planted at a row spacing of 1.5m) and 10m long. There was a 2 m gap between plots along the row and a 3 m gap (2 rows of cane) across the row. Treatments were broadcast by hand in December 1995 and January 1996 and incorporated to approximately 10 cm by discing. Green manure crops of cowpeas were established immediately following the application of lime and gypsum. Marked differences were observed in the growth of the cowpeas at all 3 sites, particularly between the limed and unlimed plots. The cowpea crops were sampled in May 1996 at two of the sites (Accornero and Reinaudo). However the cowpea crop at Mizzi's was disced into the soil before it could be sampled.

Following incorporation of the cowpea crops and prior to planting, soil samples were taken from the 0-20 cm layer for commercial analysis so that any nutrient deficiencies and imbalances could be identified. Recommendations were provided to each grower on what fertilizer was most appropriate for planting at each site so that any responses to lime and gypsum would not be affected by deficiencies or imbalances in other nutrients. The growers were all requested to plant the same variety (Q124) as cane varieties are likely to differ in their tolerance to soil acidity and response to lime. The trials were planted to cane between May and August 1996. Details of fertilizer applied to each trial and other farm operations are given in Table 4.3. Towards the end of 1996, each trial was re-peggged with the corners permanently marked with metallic balls inserted at around 50 cm depth in auger holes. They can be located using a special type of metal detector. At the same time, the 2 m breaks between plots were made using a small rotary hoe on a Kubota interrow tractor. These breaks were established to facilitate the weighing of cane from each plot during harvest of the crop.

Additional trials

In the trial at DiBella's, lime at rates of 0, 2.5, 5.0, and 10.0 t ha⁻¹ and gypsum at rates of 0, 3.8 and 15.2 t ha⁻¹ were applied in a similar factorial design to that at Reinaudo's and Accornero's on 2 June, 1998. The site was planted to cane (Q124) on 19 June, 1998 and the breaks between plots were established in December 1998. Details of fertilizer applied and other farm operations are given in Table 4.3.

In the trial at Feluga, lime was applied at rates of 0, 2.5, 5.0 and 10 t ha⁻¹ in a factorial design with phosphogypsum at rates of 0 and 5 t ha⁻¹ on 24-25 November 1997. Two additional treatments were also imposed: lime and gypsum at 0 t ha⁻¹ with soybeans either mulched on the surface or left standing, and lime at 5 t ha⁻¹ with additional N applied as urea at 140 kg N ha⁻¹. The soybeans were planted on 16 December 1997 and cane was planted on 6 August 1998.

Table 4.3. Selected management practices used for each trial

	ACCORNERO	MIZZI	REINAUDO	DIBELLA
Variety	Q124	Q124	Q124	Q124
Planting Date	29 May 1996	19 June 1996	12 August 1996	19 June 1998
Planting Fertilizer	430 kg/ha Tecfeed 887 (11.8N, 7.8P, 14.3K, 6.5S, 2.6Zn, 2.0Cu)	370 kg/ha Tecfeed 827 (11.2N, 9.2P, 16.8K, 4.45S, 2.6Zn, 0.2Cu)	370 kg/ha Tecfeed 870 (11.2N, 9.1P, 16.8K, 4.8S, 0.3Cu, 0.03Mo, 0.4Cu, 0.05B, 0.8Zn)	420 kg/ha Incitec blend 98/CB 29262 (10.7 N, 8.4P, 13.5K, 5.7S, 2.3Zn, 2.3Cu)
Grub Control	None	Suscon 20 kg/ha	None	None
Wireworms	Lorsban 1.5 L/ha	Lorsban 2L/ha	Lorsban 1.5L/ha	Lorsban 1.5L/ha
Sett Treatment	Shirtan 120	Canestrike	Shirtan 120	Shirtan 120
Other Fertilizer	490 kg/ha Ammonium Sulphate on 19 August; 65 kg/ha Magnesium Sulphate on 4 November	340 kg/ha 533 (32.6N, 14K in mid September; 120kg/ha Ammonium Sulphate in early October; 65 kg/ha Magnesium sulphate in early October	370 kg/ha Ammonium Sulphate on 24 October; 65 kg/ha Magnesium Sulphate on 12 November	370 kg/ha Ammonium Sulphate; 65 kg/ha Magnesium Sulphate
Cultivation	Cut away twice, ripped 19 August, filled in 7 October	Cut away end August, weeded and ripped mid September, filled in late October	Cut away 24 October, scarified twice, filled in 5 November	Cut away, scarified, filled in
Herbicides	Treflan CR on 30 May, Treflan CR and Atradex on 4 November	Gramoxone, Atrazine, 24D in early August	Gramoxone & Diuron on 10 September	Treflan CR on 19 June, Atrazine
Irrigation	None	1 inch at end August, 1.5 inch in early Oct, 2 inch in early Nov	None	None

Soil sampling and analysis

Initial soil chemical characterisation for each site was determined using samples collected from 5 random clusters of 3 cores from each of the trial sites prior to the implementation of treatments. Soil cores were collected using a jack-hammer soil sampler and stainless steel tubes to a depth of 90 cm from the following depth intervals; 0-10, 10-20, 20-30, 30-50, 50-70 and 70-90 cm. The cluster of three cores was combined to form a composite sample.

Samples were air dried and sieved to pass a 2-mm mesh before pH was measured in water, 0.01 M CaCl₂ and 1 M KCl using a 1:5 soil:solution ratio. Basic exchangeable cations were determined by atomic absorption spectrometry after replacement with 0.1 M BaCl₂-NH₄Cl as recommended by Gillman and Sumpter (1986). Acidic cations were extracted with 1 M KCl and the extractant titrated to pH 8.0 as described by Rayment and Higginson (1992). The effective cation exchange capacity (ECEC) was calculated as the sum of basic and acidic cations (Ca²⁺+Mg²⁺+K⁺+Na⁺+Al³⁺+H⁺). Soil organic carbon was determined by wet oxidation using the Walkley and Black method as modified by Rayment and Higginson (1992). The cation exchange capacity (CEC) and anion exchange capacity (AEC) were determined using the compulsive exchange method of Gillman and Sumpter (1986). DTPA-extractable Fe, Cu, Mn and Zn were determined using the methodology outlined by Rayment and Higginson (1992) and acid-extractable phosphorus (BSES-P) by the method of Kerr and Von Stieglitz (1938). Measurements of soil particle size were also conducted on the same composite samples using the pipette method (Day, 1965).

Estimates of the pH buffering capacity (pH_{BC}) were made on composite samples for the 0-20 cm depth interval for the Mizzi, Reinaudo and Accornero sites using the methodology of Aitken and Moody (1994). In brief, titration curves were established by adding incremental amounts of either NaOH or HCl to a 1:5 soil:water suspension. For each titration 5 g of soil was weighed into each of six polyethylene tubes and appropriate amounts of deionised water were added such that the final volume of alkali or acid was 25 mL. The alkali and acid solutions were 0.04 M (standardised) and for each soil additions of 0, 0.15, 0.25, 0.5, 1.0 and 2.0 mL were made. Additions of 1.0 mL of 0.05 M CaCl₂ were made to each tube to maintain a constant ionic strength. Chloroform (0.25 mL) was also added and the suspensions were equilibrated for 24 h at 25°C on an end-over-end shaker. The suspensions were then removed from the shaker and left to equilibrate for a further 6 days at 25°C. Re-suspension of the samples was undertaken on a daily basis by shaking for a 2 min period. After equilibration the pH was read. In addition to determining the pH buffer capacity using the above method, a modification of the method using a 60°C equilibration temperature over a much shorter time period (4 hours) as recommended by Barrow and Cox (1990) was evaluated.

Statistical analysis of the data was undertaken using Genstat5. Preliminary analysis of the soil chemical data was undertaken to determine whether transformation was required to standardise the variances. A simple ANOVA was used to analyse the data on a treatment by individual depth interval basis.

Analysis of liming materials

The lime used in the trials was a pulverised limestone sourced from near Woodstock in north Queensland with a stated calcium content of 32% and a neutralising value of 85%. The gypsum used in the three initial trials was from a mined deposit near Hughenden. The gypsum used for the DiBella and Feluga experiments was a phosphogypsum.

The composition of the lime and gypsum materials used in the three initial trials was determined by digesting the samples in a mixture of nitric and perchloric acids and analysing the resulting solution using inductively coupled plasma atomic emission spectroscopy (ICP-AES). This method suggested a calcium content of the lime of about 39% and of the gypsum of only 6%. These figures compared with those provided by the supplier of 32% Ca for the lime and 21% for the gypsum were significantly different with respect to the latter source. In view of the digest results, the samples were re-analysed using x-ray fluorescence (XRF) spectroscopy, a technique which provides the total elemental composition. The results obtained from this method were much closer to those expected. Samples of lime and gypsum used for the DiBella trial were also analysed using this method. In addition a particle size analysis was conducted on samples of the lime used in the 3 initial trials in order to assess its effective neutralising value.

Cane yield and ccs estimation

The trials were mechanically harvested each year. Prior to harvest each year, 10 stalks of cane were taken from the two centre rows of each plot for ccs determination. In 1997, 1998 and 2000, the juice was extracted from the cane using a small crushing mill. The ccs results were corrected for the differences in extraction between the small mill and a commercial milling train by subtracting two units of ccs from that measured. Fibre content was assumed to be 13 %. Plot weights were determined during harvest by weighing the billets from each of the central 4 rows of each plot using a tractor drawn weigh-bin equipped with load cells. In the 1998 harvest season, which was severely disrupted by wet weather, the trials at Mizzi's and Accornero's were both harvested without notification, resulting in no yield data being collected. No ccs data were collected for the Mizzi trial either that year as the trial was harvested before pre-sampling could be carried out.

Due to the difficulties experienced in 1998, a comprehensive hand harvesting exercise was undertaken at three of the trials (Mizzi, Reinaldo and Accornero) during the last week of July 1999. The protocol used to hand harvest the trials was as follows:

1. Two 5 m rows were cut out of the middle of the plot and the number of stalks recorded.
2. The entire harvested cane was weighed and 15 sound stalks were selected.
3. The 15 sound stalks were partitioned into 'cabbage' and stalk and weighed individually.
4. From these two components sub-samples were collected for dry matter determination, and in the case of stalks, samples were collected for ccs measurements.
5. The stalks were fibrated using a Jeffco cutter-grinder and the juice for ccs determination was extracted using a hydraulic press.

Machine harvesting of the DiBella trial was undertaken in August 1999 using a tractor drawn weigh-bin. With the machine harvesting at the DiBella site, the entire centre four rows of each six row plot were weighed using the weigh-bin. Ten stalk samples had previously been taken from each plot for cutter grinding and processing through the hydraulic press. The juice samples were used for ccs analysis and samples of juice were also filtered for HPLC sucrose determination. Sub-samples of fibrated cane were oven dried for stalk dry matter determination and were retained for subsequent nutrient analysis.

Although it was planned to harvest the DiBella trial in the years 2000 (first ratoon) and 2001 (second ratoon), the crop was so badly affected by the combined effects of waterlogging, orange rust, rat damage and pig damage that it was decided to be not worth harvesting. The gaps in the crop would have had an overriding effect on the results and would have masked any impact of lime and gypsum application on crop size and ccs.

A comprehensive assessment of yield and yield components (for the 1999 hand harvest) was conducted using the data gathered from the trials. An analysis of variance was conducted on all of the data using the GENSTAT 2 statistical package.

5. CHANGES IN SOIL CHEMICAL CHARACTERISTICS ASSOCIATED WITH LIME AND GYPSUM APPLICATION

Initial soil chemical properties at initiation of trials

The mean soil chemical values for the Reinaudo, Accornero, Mizzi and DiBella trials prior to the implementation of treatments are presented in Tables 5.1 – 5.4. Statistical analysis of the data indicated that the sites were extremely heterogeneous, which is to be expected on these soil types due to their mixed, alluvial parent material. Consequently analysis of the data was undertaken on an individual depth basis. Other than the DiBella site, soil pH increased with depth down the profile with the lowest pH values being recorded in the top 35 cm. In the case of the DiBella site, the lowest pH values were observed in the 50-70 cm depth interval (Table 5.4). Corresponding with the increase in soil pH there is a concomitant decrease in exchangeable acidity (Al + H) (Tables 5.1-5.4). In evaluating the responsiveness of soils to lime and/or gypsum it is important to consider the amount of Ca^{2+} on the exchange complex. Current lime recommendations are based on alleviating a Ca^{2+} deficiency and in this respect a critical concentration of $0.55 \text{ cmol}_c \text{ kg}^{-1}$ has been suggested (Calcino, 1994). Using the aforementioned Ca^{2+} concentration as a benchmark for delineating between responsive and non-responsive sites, all three initial sites would be classified as non-responsive to Ca additions. Indeed, if a comparison is made of exchangeable Ca^{2+} concentrations between the Herbert sites and a long-term liming trial at BSES Tully Experiment Station, where highly significant increases in TCH (tons cane per hectare) have been observed through the addition of lime (see Section 11), the exchangeable Ca^{2+} concentrations down the entire profile for the three initial trials (Reinaudo, Accornero, Mizzi) are considerably higher (Tables 5.1-5.3) and the only site having similar characteristics to the Tully site is DiBella's experiment (Table 5.4).

Soil pH buffering capacities (inverse of the slope for the relationship between pH and concentration of base added) for the three sites are presented in Table 5.5. The methodology used to estimate buffering capacity only applies over the pH range where the change in pH with increasing acid inputs can be approximated by a straight line (generally between pH 4.5 and 6.0) and the neutralisation of exchangeable Al is of minor importance. As the pH decreases to below 4.5, the soil pH is buffered largely through the dissolution of solid phase minerals such as Al and Fe which are relatively slow reactions (i.e. longer than 168 hr). Consequently the values presented in Table 5.5 should not be viewed as absolute but rather as estimates of the actual pH buffering capacity. No clear trends emerged from the various methods used to determine pH buffering capacity other than the fact that a 168 hr incubation period at 60°C gave extremely poor results. The reasons for this are not evident from the data. However, there appeared to be a relatively close agreement between the 4 hr and 168 hr incubation period at 25°C . The Mizzi site, which has a sandy loam field texture, had the lowest buffering capacity whilst the heavy textured soil of Accornero's had the largest (Table 5.5).

Table 5.1. Chemical properties of control treatments collected prior to initiation of trial at Reinaudo site. Each data point is the mean of 5 replicates, figures associated with \pm represent the S.E. of the mean.

Depth	pH _w	pH _{Ca}	pH _{KCl}	EC (dS m ⁻¹)	OC (%)	Total N (%)	Exchangeable cations (cmol _c kg ⁻¹)				H	Al		CEC	ECEC (cmol _c kg ⁻¹)		AEC	BSES P (mg kg ⁻¹)	DTPA extractable (mg kg ⁻¹)				S (mg kg ⁻¹)
							Ca	Mg	K	Na		Al+H	Al		Al+H	Cu			Fe	Mn	Zn		
0-10	4.77	4.01	4.22	0.04	1.22	0.08	2.02	0.89	0.15	0.11	0.40	1.99	2.39	5.51	5.56	0.11	41.0	1.17	139	44	1.32	14.6	
	± 0.02	± 0.01	\pm	± 0.00	± 0.02	± 0.00	± 0.12	± 0.04	± 0.01	± 0.03	± 0.03	± 0.04	± 0.05	± 0.23	± 0.18	± 0.03	± 7.94	± 0.08	± 15	± 3	± 0.14	± 0.4	
10-20	4.74	4.03	4.24	0.05	1.45	0.09	2.11	0.99	0.23	0.09	0.38	1.90	2.28	5.26	5.70	0.28	49.5	1.14	154	44	1.39	15.3	
	± 0.04	± 0.03	± 0.03	± 0.01	± 0.19	± 0.01	± 0.11	± 0.06	± 0.04	± 0.01	± 0.02	± 0.13	± 0.15	± 0.31	± 0.08	± 0.11	± 7.9	± 0.06	± 14	± 6	± 0.10	± 0.9	
20-30	4.85	4.07	4.27	0.04	1.16	0.07	2.26	0.92	0.17	0.10	0.35	1.85	2.21	5.60	5.66	0.21	38.5	1.20	120	47	1.13	17.2	
	± 0.06	± 0.04	± 0.04	± 0.00	± 0.11	± 0.01	± 0.31	± 0.08	± 0.02	± 0.01	± 0.03	± 0.21	± 0.22	± 0.34	± 0.24	± 0.06	± 12.6	± 0.06	± 31	± 6	± 0.16	± 0.7	
30-50	5.29	4.32	4.51	0.03	0.74	0.05	2.92	1.08	0.08	0.13	0.23	1.09	1.32	6.13	5.52	0.23	16.5	1.11	68	42	1.08	15.3	
	± 0.14	± 0.14	± 0.12	± 0.00	± 0.10	± 0.00	± 0.85	± 0.13	± 0.00	± 0.01	± 0.05	± 0.28	± 0.33	± 0.35	± 0.67	± 0.04	± 7.9	± 0.12	± 27	± 2	± 0.30	± 1.3	
50-70	5.64	4.62	4.80	0.02	0.61	0.04	4.69	1.58	0.08	0.16	0.14	0.32	0.46	7.27	6.96	0.21	4.10	1.07	52	34	1.23	12.3	
	± 0.09	± 0.11	± 0.08	± 0.00	± 0.13	± 0.01	± 0.31	± 0.12	± 0.00	± 0.01	± 0.02	± 0.07	± 0.09	± 0.18	± 0.38	± 0.06	± 1.05	± 0.22	± 23	± 3	± 0.56	± 1.2	
70-90	5.92	4.85	4.97	0.02	0.47	0.03	4.77	1.96	0.09	0.16	0.08	0.14	0.22	7.11	7.22	0.25	2.73	0.93	28	23	0.67	10.5	
	± 0.08	± 0.08	± 0.06	± 0.00	± 0.09	± 0.00	± 0.36	± 0.22	± 0.00	± 0.02	± 0.02	± 0.04	± 0.06	± 0.42	± 0.52	± 0.13	± 0.43	± 0.18	± 9	± 1	± 0.21	± 1.4	

Table 5.2. Chemical properties of control treatments collected prior to initiation of trial at Accornero site. Each data point is the mean of 5 replicates, figures associated with \pm represent the S.E. of the mean.

Depth	pH _w	pH _{Ca}	pH _{KCl}	EC (dS m ⁻¹)	OC (%)	Total N (%)	Exchangeable cations (cmol _c kg ⁻¹)						CEC	ECEC (cmol _c kg ⁻¹)	AEC	BSES P (mg kg ⁻¹)	DTPA extractable (mg kg ⁻¹)				S (mg kg ⁻¹)	
							Ca	Mg	K	Na	H	Al					Al+H	Cu	Fe	Mn		Zn
0-10	4.62	3.87	4.10	0.05	1.47	0.10	1.58	1.28	0.32	0.11	0.57	3.77	4.35	6.55	7.64	0.38	55.4	2.25	95	115	1.62	33.1
	± 0.07	± 0.03	± 0.04	± 0.01	± 0.11	± 0.01	± 0.41	± 0.27	± 0.02	± 0.01	± 0.04	± 0.33	± 0.36	± 0.38	± 0.57	± 0.02	± 2.54	± 0.08	± 11	± 8	± 0.14	± 2.5
10-20	4.54	3.87	4.08	0.05	1.55	0.10	2.11	1.34	0.34	0.12	0.63	3.79	4.42	6.36	8.33	0.46	57.0	1.27	98	103	1.58	33.8
	± 0.06	± 0.04	± 0.05	± 0.00	± 0.09	± 0.01	± 0.35	± 0.25	± 0.01	± 0.01	± 0.08	± 0.39	± 0.46	± 0.39	± 0.50	± 0.09	± 3.6	± 0.08	± 8	± 5	± 0.15	± 2.9
20-30	4.89	3.99	4.25	0.04	1.29	0.09	3.38	2.62	0.20	0.22	0.55	3.02	3.57	7.94	9.99	0.44	35.7	1.40	84	89	1.51	28.6
	± 0.13	± 0.07	± 0.09	± 0.01	± 0.09	± 0.01	± 0.71	± 0.79	± 0.02	± 0.06	± 0.13	± 0.46	± 0.55	± 0.96	± 1.56	± 0.07	± 5.8	± 0.09	± 7	± 7	± 0.11	± 2.2
30-50	5.86	4.81	4.89	0.04	0.63	0.05	4.22	3.92	0.12	0.43	0.15	0.51	0.65	7.77	9.35	0.46	5.03	0.90	27	33	0.69	18.6
	± 0.24	± 0.23	± 0.26	± 0.01	± 0.05	± 0.00	± 0.50	± 0.85	± 0.01	± 0.15	± 0.05	± 0.22	± 0.27	± 0.44	± 1.24	± 0.07	± 0.93	± 0.09	± 6	± 6	± 0.08	± 2.7
50-70	6.75	5.65	5.59	0.04	0.25	0.03	3.09	3.50	0.09	0.56	0.02	0.05	0.08	5.29	7.32	0.37	3.71	0.46	8	7	0.21	7.4
	± 0.30	± 0.28	± 0.37	± 0.01	± 0.04	± 0.00	± 0.66	± 0.11	± 0.02	± 0.25	± 0.01	± 0.02	± 0.03	± 0.80	± 1.99	± 0.09	± 0.78	± 0.05	± 1	± 1	± 0.02	± 0.7
70-90	6.70	5.66	5.80	0.04	0.20	0.02	1.88	1.81	0.10	0.34	0.02	0.04	0.06	3.54	4.18	0.19	4.41	0.43	8	6	0.25	6.6
	± 0.30	± 0.24	± 0.30	± 0.01	± 0.03	± 0.00	± 0.37	± 0.69	± 0.03	± 0.16	± 0.00	± 0.01	± 0.02	± 1.17	± 1.19	± 0.02	± 0.89	± 0.03	± 1	± 1	± 0.05	± 0.5

Table 5.3. Chemical properties of control treatments collected prior to initiation of trial at Mizzi site. Each data point is the mean of 5 replicates, figures associated with \pm represent the S.E. of the mean.

Depth	pH _w	pH _{Ca}	pH _{KCl}	EC (dS m ⁻¹)	OC (%)	Total N (%)	Exchangeable cations				H	Al		CEC	ECEC (cmol _c kg ⁻¹)	AEC	BSES P (mg kg ⁻¹)	DTPA extractable				S (mg kg ⁻¹)
							Ca	Mg	K	Na		(cmol _c kg ⁻¹)						Cu	Fe	Mn	Zn	
0-10	4.69	4.15	4.50	0.08	1.07	0.07	0.94	0.27	0.19	0.05	0.23	1.19	1.42	1.86	2.87	0.31	207	0.21	66	13	1.06	21.4
	± 0.07	± 0.03	± 0.04	± 0.01	± 0.06	± 0.01	± 0.13	± 0.06	± 0.02	± 0.00	± 0.02	± 0.12	± 0.13	± 0.24	± 0.15	± 0.07	± 22	± 0.02	± 14	± 2	± 0.15	± 0.6
10-20	4.54	4.11	4.38	0.10	0.97	0.07	0.89	0.22	0.15	0.06	0.26	1.31	1.57	1.80	2.89	0.27	229	0.22	59	10	0.80	23.7
	± 0.05	± 0.04	± 0.05	± 0.01	± 0.12	± 0.01	± 0.17	± 0.06	± 0.01	± 0.00	± 0.03	± 0.18	± 0.21	± 0.14	± 0.27	± 0.02	± 27	± 0.04	± 16	± 2	± 0.15	± 0.4
20-30	4.49	4.09	4.32	0.10	0.97	0.09	0.77	0.16	0.10	0.05	0.26	1.53	1.79	1.46	2.87	0.25	149	0.20	55	9	0.63	25.8
	± 0.09	± 0.05	± 0.07	± 0.01	± 0.06	± 0.01	± 0.18	± 0.06	± 0.01	± 0.00	± 0.03	± 0.19	± 0.22	± 0.18	± 0.16	± 0.04	± 43	± 0.03	± 15	± 2	± 0.10	± 2.3
30-50	4.65	4.14	4.39	0.06	0.59	0.04	0.50	0.15	0.07	0.05	0.23	1.32	1.55	0.72	2.32	0.47	77	0.19	34	7	0.37	23.3
	± 0.16	± 0.11	± 0.12	± 0.02	± 0.06	± 0.01	± 0.16	± 0.09	± 0.01	± 0.01	± 0.04	± 0.23	± 0.27	± 0.63	± 0.46	± 0.26	± 29	± 0.07	± 10	± 2	± 0.11	± 3.0
50-70	5.07	4.43	4.67	0.03	0.16	0.01	0.47	0.33	0.08	0.06	0.15	0.88	1.03	1.11	1.98	0.27	14	0.14	9	1.9	0.06	20.5
	± 0.15	± 0.18	± 0.16	± 0.01	± 0.04	± 0.00	± 0.16	± 0.24	± 0.03	± 0.02	± 0.06	± 0.45	± 0.51	± 0.72	± 0.85	± 0.04	± 6	± 0.09	± 4	± 0.4	± 0.02	± 4.4
70-90	5.35	4.61	4.90	0.02	0.05	0.00	0.78	0.33	0.19	0.06	0.07	0.28	0.35	2.53	1.68	0.22	5	0.07	3	0.7	0.04	12.5
	± 0.05	± 0.14	± 0.09	± 0.00	± 0.02	± 0.00	± 0.11	± 0.07	± 0.06	± 0.00	± 0.01	± 0.07	± 0.08	± 0.94	± 0.17	± 0.02	± 2	± 0.03	± 1	± 0.0	± 0.01	± 1.1

Table 5.4. Chemical properties of control treatments collected prior to initiation of trial at DiBella site. Each data point is the mean of 5 replicates, figures associated with \pm represent the S.E. of the mean.

Depth	pH _w	pH _{Ca}	pH _{KCl}	OC (%)	Exchangeable cations				H	Al		CEC	ECEC		AEC	BSES P (mg kg ⁻¹)	DTPA extractable			
					Ca	Mg	K	Na		(cmol _c kg ⁻¹)	Al+H		(cmol _c kg ⁻¹)	(cmol _c kg ⁻¹)			Cu	Fe	Mn	Zn
0-10	4.83 ± 0.04	4.11 ± 0.03	4.01 ± 0.01	1.42 ± 0.08	0.43 ± 0.06	0.31 ± 0.03	0.24 ± 0.02	0.05 ±	0.26 ± 0.01	1.36 ± 0.09	1.62 ± 0.08	2.34 ± 0.20	2.65 ± 0.09	0.07 ± 0.01	101.2 ± 10.6	0.28 ± 0.03	147 ± 13	13 ± 3	0.95 ± 0.1	
10-20	4.72 ± 0.04	4.04 ± 0.02	3.99 ± 0.02	1.3 ± 0.03	0.30 ± 0.04	0.21 ± 0.01	0.19 ± 0.01	0.04 ±	0.24 ± 0.01	1.60 ± 0.08	1.84 ± 0.10	2.50 ± 0.10	2.59 ± 0.07	0.09 ± 0.02	76.4 ± 8.7	0.27 ± 0.05	145 ± 9	8.9 ± 1.9	0.86 ± 0.07	
20-30	4.52 ± 0.04	4.04 ± 0.03	4.02 ± 0.03	0.87 ± 0.05	0.16 ± 0.02	0.10 ± 0.01	0.14 ± 0.01	0.04 ±	0.24 ± 0.01	1.60 ± 0.12	1.84 ± 0.13	2.16 ± 0.16	2.28 ± 0.12	0.15 ± 0.02	22.4 ± 9.5	0.17 ± 0.06	81.2 ± 10	4.8 ± 1.5	0.46 ± 0.06	
30-50	4.43 ± 0.03	4.06 ± 0.01	4.07 ± 0.01	0.61 ± 0.05	0.11 ± 0.02	0.06 ± 0.01	0.09 ± 0.01	0.04 ± 0.01	0.20 ± 0.01	1.44 ± 0.07	1.64 ± 0.08	1.68 ± 0.08	1.96 ± 0.05	0.48 ± 0.04	2.6 ± 0.6	0.06 ± 0.01	7.6 ± 2.7	4.7 ± 1.3	0.17 ± 0.02	
50-70	4.43 ± 0.02	4.03 ± 0.01	4.05 ± 0.01	0.20 ± 0.01	0.12 ± 0.02	0.07 ± 0.01	0.10 ± 0.01	0.04 ± 0.01	0.21 ± 0.01	1.90 ± 0.04	2.11 ± 0.04	1.94 ± 0.05	2.45 ± 0.04	0.94 ± 0.15	2.2 ± 0.4	0.05 ± 0.01	6.5 ± 3.1	10.8 ± 5.1	0.18 ± 0.03	
70-90	4.49 ± 0.06	4.07 ± 0.01	4.07 ± 0.01	0.18 ± 0.01	0.22 ± 0.07	0.12 ± 0.04	0.11 ± 0.01	0.04 ± 0.01	0.19 ± 0.01	1.9 ± 0.1	2.09 ± 0.11	2.12 ± 0.09	2.59 ± 0.07	1.01 ± 0.11	1.8 ± 0.5	0.10 ± 0.01	4.8 ± 2.0	15.6 ± 5.5	0.10 ± 0.01	

Table 5.5. pH buffering capacity of surface soils collected from the control treatments of liming trials prior to the initiation of the studies

Site	Temperature (°C)	Time (hr)	Slope (s.e) (pH/mmol)	Intercept (pH)	Correlation coefficient (r)	pH Buffer capacity (cmol kg ⁻¹ pH unit)
Mizzi	25	4	0.086 (± 0.001)	4.647 (± 0.012)	0.999	1.15
Reinaudo	25	4	0.047 (± 0.001)	4.324 (± 0.014)	0.996	2.09
Accornero	25	4	0.034 (± 0.001)	4.036 (± 0.007)	0.998	2.89
Mizzi	60	4	0.080 (± 0.001)	4.342 (± 0.010)	0.999	1.24
Reinaudo	60	4	0.053 (± 0.002)	3.943 (± 0.017)	0.996	1.85
Accornero	60	4	0.033 (± 0.001)	3.702 (± 0.007)	0.998	3.02
Mizzi	25	168	0.066 (± 0.001)	4.640 (± 0.007)	0.999	1.50
Reinaudo	25	168	0.041 (± 0.001)	4.311 (± 0.010)	0.997	2.42
Accornero	25	168	0.028 (± 0.001)	4.058 (± 0.005)	0.998	3.52
Mizzi	60	168	0.003 (± 0.010)	4.594 (± 0.080)	0.142	32.78
Reinaudo	60	168	0.019 (± 0.008)	3.993 (± 0.065)	0.745	5.20
Accornero	60	168	-0.003 (± 0.001)	3.732 (± 0.009)	0.800	29.41

Subsequent to this initial assessment of pH buffer capacity, the method for assessing the charge characteristics of soils using the surface charge fingerprint has the ability also to measure the pH buffer capacity of soils through quantification of the amount of acid or bases added to achieve a predetermined pH. During the charge fingerprinting procedure undertaken on composite surface (0-10 cm) samples collected from control plots in 1999, the buffer capacity for the Mizzi, Reinaudo, Accornero and DiBella sites were determined to be 2.52, 3.29, 5.48 and 3.06 cmol/kg.unit pH respectively. These values are somewhat higher than those determined at 25°C over a 168 hr equilibration as presented in Table 5.5. It is plausible that the differences in buffer capacity between the collection of soil samples in 1976 and 1999 may in part be accounted for by an increase in soil organic carbon associated with green cane trash blanketing. In a long-term green cane trash blanketing trial covering 8 years in the Tully area, buffering capacity under the green cane trash blanketing and burnt treatments were 2.35 and 1.96 cmol/kg.unit pH respectively. This increase in buffer capacity was attributed to an increase in soil organic carbon (Noble unpublished).

Changes in soil chemical properties during the study period.

Mizzi Site:

A second sampling at the site was undertaken in late January 1997, approximately 1 year after the implementation of treatments. Samples were collected from selected lime/gypsum factorial treatments (Lime: 0, 2.5 and 10 t/ha; Gypsum: 0, 2.5 and 10 t/ha) to a depth of 90 cm. Soil chemical analysis was undertaken as previously described. Significant main effects of lime were observed with respect to pH_w, pH_{Ca} (data not presented), exchangeable Ca, K and acidity, and CEC (Table 5.6). A significant main effect of gypsum on exchangeable Ca was also observed (Table 5.7).

Table 5.6. Main effects of lime application on selected soil chemical attributes 1 year after application (January 1997) at the Mizzi site.

Lime rate (t/ha)	Depth (cm)					
	0-10	10-20	20-30	30-50	50-70	70-90
	pH _w					
0	4.56	4.35	4.30	4.45	4.71	4.77
2.5	4.71	4.59	4.51	4.61	4.84	5.08
10.0	5.19	4.90	4.82	4.79	4.79	4.84
LSD _(0.05)	0.32	0.11	0.21	0.18	ns	ns
	Exch. Ca ²⁺ (cmol _c /kg)					
0	1.13	1.41	1.10	1.02	0.71	0.52
2.5	1.59	1.67	1.51	1.25	0.69	0.44
10.0	2.75	2.98	2.50	1.83	0.99	0.72
LSD _(0.05)	0.18	0.35	0.51	0.15	ns	ns
	Exch. K ⁺ (cmol _c /kg)					
0	0.153	0.152	0.118	0.104	0.076	0.074
2.5	0.186	0.173	0.134	0.097	0.081	0.070
10.0	0.260	0.292	0.180	0.144	0.099	0.071
LSD _(0.05)	0.079	0.105	0.046	0.023	ns	ns
	Exch. Al+H (cmol _c /kg)					
0	1.37	1.50	1.46	1.18	0.78	0.65
2.5	0.99	1.12	1.19	0.96	0.62	0.32
10.0	0.41	0.56	0.94	0.92	0.92	0.82
LSD _(0.05)	0.28	0.33	0.29	ns	ns	ns
	CEC (cmol _c /kg)					
0	2.15	2.21	1.94	2.00	1.34	1.24
2.5	2.37	2.35	2.19	1.98	1.58	1.14
10.0	3.01	3.12	2.71	2.45	2.14	1.87
LSD _(0.05)	0.58	0.43	0.59	ns	ns	ns

Table 5.7. Main effects of gypsum additions on selected soil chemical attributes 1 year after application (January 1997) at the Mizzi site.

Lime rate (t/ha)	Depth (cm)					
	0-10	10-20	20-30	30-50	50-70	70-90
	Exch. Ca ²⁺ (cmol _c /kg)					
0	1.24	1.73	1.54	1.28	0.81	0.47
2.5	1.72	1.60	1.63	1.33	0.78	0.60
10.0	2.51	2.74	1.93	1.48	0.81	0.60
LSD _(0.05)	0.18	0.24	ns	ns	ns	ns

One year after the implementation of treatments, lime had a significant influence on soil pH, exchangeable Ca, K, acidity and CEC to a depth of 50 cm. Contrasting this, the addition of gypsum resulted in an increase in exchangeable Ca, however, this effect was confined to the top 0-20 cm depth interval (Table 5.7). No significant lime by gypsum interactions were observed.

A third sampling of the site was undertaken in December 1998 of all treatments. Soil cores were collected from the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-90 cm. Samples were analyzed using the aforementioned methodology.

Surprisingly, the main effects of lime were found to be significant for the same attributes as discussed above and the only attribute influenced by the addition of gypsum was exchangeable Ca (Tables 5.8 and 5.9). The influence of lime applications on soil pH was confined to the top 25 cm, thereafter significant variability in pH values were observed

indicating the inherent heterogeneity of these soils. Associated with the increase in pH there was a corresponding increase in exchangeable Ca and K with depth and a decrease in exchangeable acidity that was confined to the surface horizons (Table 5.8). Associated with an increase in soil pH there was a corresponding increase in CEC (Table 5.8). This is associated with the generation of pH dependent charge on the organic matter component thereby increasing the ability of these soils to retain nutrients, a factor that is often overlooked when discussing the positive effects of routine liming applications.

Table 5.8. Main effects of lime application on selected soil chemical attributes 3 years after application (December 1998) at the Mizzi site.

Lime (t/ha)	Depth (cm)					
	0-10	10-20	20-30	30-50	50-70	70-90
pH _w						
0	4.64	4.46	4.42	4.59	4.72	4.99
2.5	4.82	4.69	4.67	4.87	5.04	5.23
5.0	4.9	4.90	4.79	4.32	4.43	4.58
10.0	5.24	5.08	4.92	4.96	5.01	5.09
LSD _(0.05)	0.34	0.44	0.44	ns	ns	ns
Ca (cmol _e /kg)						
0	0.44	0.51	0.56	0.57	0.46	0.35
2.5	0.82	0.87	0.81	0.65	0.39	0.44
5.0	1.24	1.29	1.17	1.40	1.31	1.05
10.0	1.83	1.81	1.48	1.24	0.80	0.68
LSD _(0.05)	0.38	0.58	0.58	0.56	0.64	0.46
K (cmol _e /kg)						
0	0.22	0.19	0.11	0.07	0.06	0.05
2.5	0.22	0.14	0.10	0.07	0.06	0.06
5.0	0.28	0.23	0.17	0.11	0.08	0.08
10.0	0.25	0.20	0.16	0.11	0.08	0.08
LSD _(0.05)	ns	0.05	0.03	0.02	0.02	ns
Al + H (cmol _e /kg)						
0	1.58	1.64	1.45	0.71	0.54	0.25
2.5	1.30	1.35	1.15	0.83	0.70	0.38
5.0	1.31	1.26	1.33	1.18	0.97	0.40
10.0	0.72	0.88	1.03	0.75	0.58	0.37
LSD _(0.05)	0.41	0.46	ns	ns	ns	ns
CEC (cmol _e /kg)						
0	1.856	1.778	1.7	1.15	0.95	0.78
2.5	2.089	1.933	1.59	1.31	1.25	0.93
5.0	2.689	2.489	2.33	2.49	2.76	2.27
10.0	2.756	2.667	2.38	1.66	1.37	1.42
LSD _(0.05)	0.23	0.25	0.31	0.43	ns	ns

If the basic and acidic cations removed by BaCl₂/NH₄Cl and KCl extractants respectively are all exchangeable cations, then their sum (the ECEC) should be equal to CEC at soil pH, within the limits of the experimental error associated with these estimations. A plot of ECEC versus CEC at soil pH for the lime treatments shows poor agreement between these independently determined soil properties where more cations were extracted than could be accounted for by CEC (Figure 5.1). This would suggest that 'soluble' cations are present which may be due to the dissolution of residual lime and /or gypsum and the mineralisation of organic materials over the dry season.

These results indicate that gypsum has had very little influence on the exchange properties of this soil. Increases in Ca concentration were only observed in the 0-10 cm depth interval

(Table 5.9). One would have expected that exchangeable Ca levels would have increased down the entire depth of the profile and that possible sub-optimal levels of K and Mg may have resulted from increasing applications of gypsum. This has not been the case. As is discussed in section 7, it would appear that the gypsum source used in these trials was of a relatively low solubility thereby restricting the rate of dissolution.

Table 5.9. Main effects of gypsum additions on selected soil chemical attributes 3 years after application (December 1998) at the Mizzi site.

Lime rate (t/ha)	Depth (cm)					
	0-10	10-20	20-30	30-50	50-70	70-90
	Exch. Ca ²⁺ (cmol _c /kg)					
0	0.90	0.96	0.84	0.82	0.61	0.55
2.5	1.01	0.96	0.97	0.92	0.66	0.59
10.0	1.34	1.44	1.21	1.16	0.95	0.75
LSD _(0.05)	0.39	ns	ns	ns	ns	ns

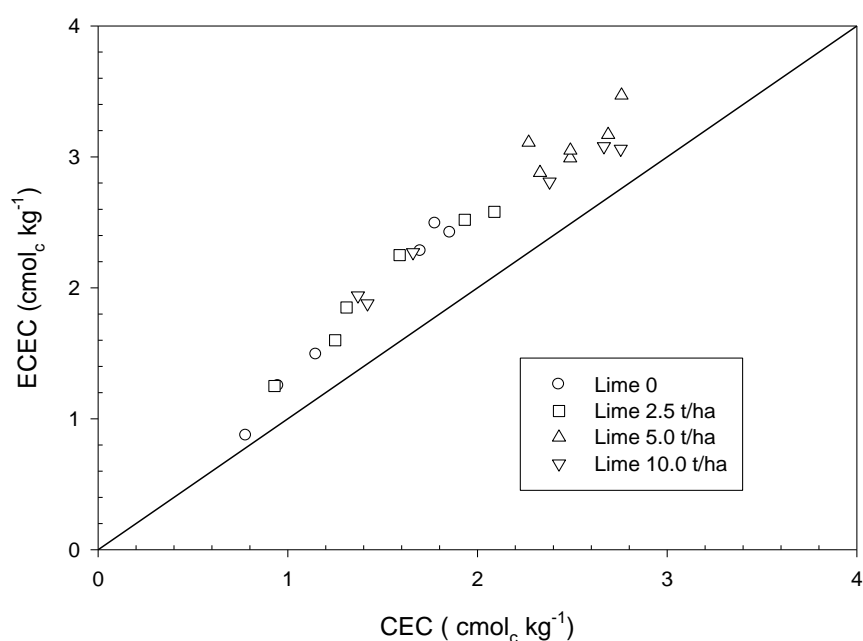


Figure 5.1. Relationship between the effective cation exchange capacity (ECEC) and the total cation exchange capacity (CEC) determined on samples collected from the Mizzi site in December 1998.

In order to assess the influence of time on pH distribution down the profile, plots of pH and selected lime treatments over time were undertaken (Figure 5.2). The heterogeneity of the soil is evident from plots of the control treatments over the three sampling periods (Figure 5.2a). Consequently, a mean value of the control treatment was calculated from the three sampling periods and used to compare the effects of lime additions. It is clearly evident that the downward movement of alkalinity occurred over time, the extent of movement being dependent on the rate of application (Figure 5.2b and c). The decline in pH at 80 cm from the control in the case of the treatment receiving lime at 10 t/ha (Figure 5.2c) is ascribed to the significant increase in electrical conductivity (salt effect) associated with soluble salts. This highlights the potential problems associated with using pH measured in a water matrix.

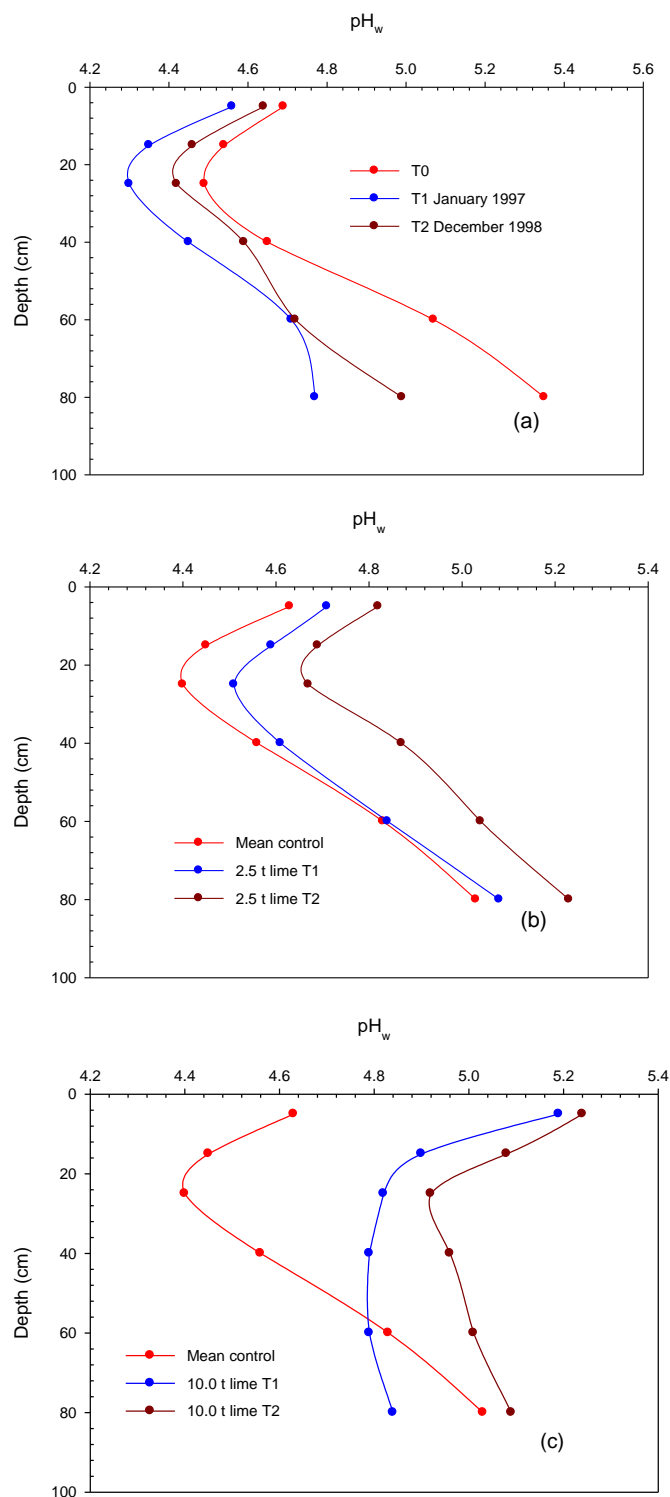


Figure 5.2. Changes in soil pH with time for those treatments receiving 0 (a), 2.5 t/ha (b) and 10 t/ha (c) lime. ‘Mean control’ represents the average pH value for the control treatment over the 3 sampling periods.

Similarly plots of exchangeable Ca over time for the control treatments indicated a high degree of variability over the three sampling dates (Figure 5.3a). However, it is of note that there is an increase in Ca at sampling time T1 but this increase has declined by T2. Similar increases in Ca with the addition of lime at T1 were noted (Figure 5.3b and c) however, by

T2 any increase in the case of 2.5 t/ha lime had all but declined. The decline in exchangeable Ca can in part be attributed to crop export and leaching losses.

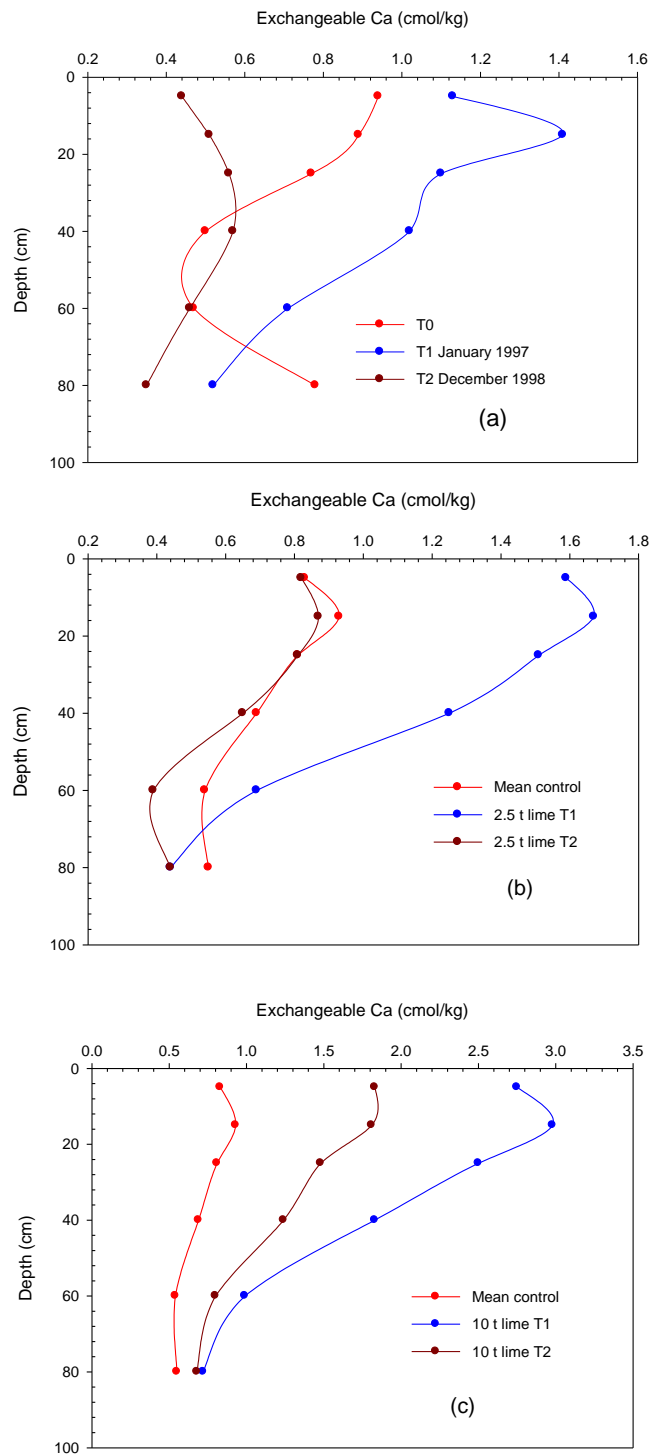


Figure 5.3. Changes in exchangeable Ca with time for those treatments receiving 0 (a), 2.5 t/ha (b) and 10 t/ha lime. ‘Mean control’ represents the average exchangeable Ca value for the control treatment over the 3 sampling periods.

Accornero Trial Site

A second sampling was undertaken in January 1997, approximately 1 year after the imposition of treatments. Soil pH and exchangeable Ca levels were determined and the results are discussed in section 7 and will not be repeated here.

A third sampling was undertaken in July 1999 to a depth of 70 cm. Soil samples were collected from all plots but since previous analysis of samples had indicated that there had been relatively little change in soil chemical properties, it was decided to analyze selectively specific treatment combinations. In the case of the Accornero site, treatments receiving 0, 2.5 and 15 t/ha lime and 0, 3.80 and 15.2 t/ha gypsum and combinations of each were analysed.

Significant increases in soil pH, exchangeable Ca and CEC were observed with increasing additions of lime (Table 5.10). The greatest changes in these properties were observed with an application of 15 t/ha lime. In this respect, significant increases in exchangeable Ca were observed to a depth of 30 cm. However, an application of 2.5 t/ha lime had little influence on these parameters below 10 cm. As expected, exchangeable acidity declined with the addition of 15 t/ha lime to a depth 30 cm. The application of gypsum at 15.2 t/ha had a significant impact on exchangeable Ca, K and acidity (Table 5.11). Exchangeable Ca increased to a depth of 30 cm whilst exchangeable K decreased to a depth of 50 cm. It has been observed in previous studies that high applications of gypsum can have a negative impact on exchangeable K, this being associated with the greater competitive nature of the divalent ion for exchange sites. This has led to sub-optimal K levels on the exchange complex in some cases.

Table 5.10. The main effects of lime addition on soil pH, exchangeable Ca, CEC and exchangeable acidity from selected treatments collected from the Accornero site, Ingham District. Samples collected in 1999.

Depth (cm)	Lime applied (t/ha)			LSD _(0.05)
	Control	2.5	15.0	
		pH _w		
0-10	4.30	4.46	4.68	0.14
10-20	4.33	4.58	4.83	0.10
20-30	4.50	4.61	4.87	0.21
30-50	5.29	5.76	5.20	ns
50-70	6.37	6.54	6.35	ns
	Exchangeable Ca ²⁺ (cmol/kg)			
0-10	3.05	3.92	6.51	0.81
10-20	3.18	4.12	7.04	0.79
20-30	3.15	4.90	6.29	1.44
30-50	4.73	5.22	4.90	ns
50-70	3.52	3.52	3.63	ns
	CEC (cmol/kg)			
0-10	7.71	8.18	8.55	ns
10-20	7.61	8.50	9.84	0.81
20-30	7.66	9.42	9.00	ns
30-50	9.97	9.81	9.99	ns
50-70	8.32	7.80	8.69	ns
	Exchangeable acidity (cmol/kg)			
0-10	4.53	3.85	1.81	0.50
10-20	4.46	3.44	1.59	0.87
20-30	4.00	2.88	1.66	1.03
30-50	1.67	0.92	1.70	ns
50-70	0.46	0.25	0.23	ns

Table 5.11. Main effects of gypsum additions on exchangeable Ca²⁺, K⁺ and acidity from selected treatments collected from the Accornero site, Ingham District. Samples collected in 1999.

Depth (cm)	Gypsum (t/ha)			LSD _(0.05)
	0	3.81	15.20	
	Exchangeable Ca ²⁺ (cmol _c /kg)			
0-10	3.56	4.11	5.81	0.81
10-20	3.77	4.27	6.30	0.79
20-30	3.70	5.05	5.59	1.44
30-50	4.89	4.76	5.20	ns
50-70	3.79	3.67	3.11	ns
	Exchangeable K ⁺ (cmol _c /kg)			
0-10	0.28	0.30	0.30	ns
10-20	0.28	0.28	0.27	ns
20-30	0.24	0.24	0.18	0.05
30-50	0.13	0.14	0.12	0.02
50-70	0.08	0.10	0.07	ns
	Exchangeable acidity (cmol _c /kg)			
0-10	3.81	3.98	2.41	1.07
10-20	3.79	3.65	2.05	0.87
20-30	3.29	3.28	1.97	1.03
30-50	1.29	1.96	1.03	ns
50-70	0.27	0.50	0.17	ns

Reinaudo Site

A second sampling of all plots was undertaken in January 1997 one year after application of lime and gypsum. All the plots were sampled to a depth of 90 cm and analysed for pH and levels of exchangeable Ca. These results are reported in section 7 and will not be repeated here. A second sampling of selected treatments, these being the 0, 5.0 and 10.0 t/ha lime, 0 and 3.8 t/ha gypsum and combinations thereof, was undertaken in 1999. There were no significant differences in soil chemical properties associated with these treatments.

DiBella site

Soil samples were collected in 1999 from all treatments. The main effects of lime and gypsum additions on soil properties are presented in Tables 5.12 and 5.13. The response to increasing additions of lime was confined to the 0-20 cm depth interval. Thereafter there were no significant differences between treatments with depth. Similarly, increases in exchangeable Ca were confined to the surface 20 cm (Table 5.12). Exchangeable acidity decreased with lime additions, whilst CEC increased in the surface 10 cm. The application of gypsum resulted in a significant increase in exchangeable Ca in the 20-70 cm depth interval (Table 5.13), clearly indicating the mobility of the Ca from this source. With the addition of lime and associated increase in soil pH there is an increase in the variable charge component of the soil that is reflected in the increased CEC. In the case of adding 5.0 t/ha of lime on its own, there was an increase in soil pH from 4.38 in the control to 5.75

Table 5.12. The main effects of lime addition on soil pH, exchangeable Ca, CEC and exchangeable acidity from selected treatments collected from the DiBella site, Ingham District. Samples collected in 1999.

Depth (cm)	Lime applied (t/ha)			LSD _(0.05)
	Control	2.5	5.0	
	pH _w			
0-10	4.43	5.49	5.56	0.23
10-20	4.20	4.50	4.53	0.16
20-30	4.13	4.24	4.18	ns
30-50	4.15	4.21	4.14	ns
50-70	4.26	4.18	4.22	ns
	Exchangeable Ca ²⁺ (cmol _c /kg)			
0-10	0.42	3.43	3.65	0.67
10-20	0.31	0.96	1.04	0.44
20-30	0.21	0.39	0.28	ns
30-50	0.22	0.26	0.24	ns
50-70	0.31	0.23	0.31	ns
	CEC (cmol _c /kg)			
0-10	1.88	3.37	3.72	1.19
10-20	1.73	2.03	1.93	ns
20-30	0.98	1.48	1.19	ns
30-50	1.10	1.05	0.88	ns
50-70	0.80	2.07	1.00	ns
	Exchangeable acidity (cmol _c /kg)			
0-10	1.44	0.59	0.30	0.85
10-20	1.61	1.29	1.41	ns
20-30	1.60	1.50	1.48	ns
30-50	1.48	1.31	1.39	ns
50-70	1.66	1.75	1.57	ns

Table 5.13. Main effects of gypsum additions on exchangeable Ca from selected treatments collected from the DiBella site, Ingham District. Samples collected in 1999.

Depth (cm)	Gypsum (t/ha)		LSD _(0.05)
	0	3.81	
	Exchangeable Ca ²⁺ (cmol _c /kg)		
0-10	2.34	2.66	ns
10-20	0.61	0.94	ns
20-30	0.21	0.31	0.14
30-50	0.16	0.31	0.12
50-70	0.21	0.36	0.12

Net acid addition rate estimates for the control treatments

The net acid addition rate (NAAR, kmol H⁺/ha. year) with respect to the control treatments for the duration of the study was calculated for the depth interval 0-30 cm since this is the portion of the profile with the greatest root and biological activity. The estimation of NAAR was based on changes in pH_{Ca} between the start and end of study using the following equation (Helyar and Porter, 1989):

$$NAAR = [((pH_s - pH_e) \times pHBC \times BD \times V)/T] \quad (1)$$

where the subscripts s and e refer to the pH_{Ca} at the start and end of the study respectively; pHBC is the mean pH buffering capacity (kmol H⁺. kg⁻¹. pH unit⁻¹); BD is soil bulk density

which was taken to be 1100 kg m⁻³; V is the soil volume in the depth interval under consideration (m³ ha⁻¹); and T is time (years) between the start and end of the study.

The net acid addition rate was estimated for each of the depth intervals (3 in total) and summed to form the overall NAAR for the trial. Since pHBC capacity was only determined on the 0-10 cm depth interval (Table 5.5) pHBC was estimated using a pedotransfer function developed by Noble et al, (1997) that is independent of soil depth. The function has the following components:

$$\text{pHBC (mmol/kg.pH)} = (6.28 - (0.11 * \text{OC}\%) + (3.71 * \text{Clay}\%) - (0.16 * \text{Silt}\%) + (0.03 * \text{Silt}\% * \text{Clay}\%))$$

where OC, Clay and Silt are the % organic carbon, clay and silt respectively in each depth interval. The NAAR for each of the control treatments are presented in Table 5.14.

Table 5.14. Net acid addition rates (NAAR) determined for the 0-30 cm intervals over the period between sampling.

Trial	Period over which change estimated (years)	NAAR (kmol H ⁺ /ha.yr)
Mizzi	2	0.012
Accornero	3	4.34
Reinaudo	2	2.02
DiBella	1	6.11

The NAAR ranged from 0.012 – 6.11 kmol H⁺/kg.yr for the 4 trials. In the case of the DiBella trial this value should be treated with caution as it may not be representative of the overall acid addition rate, due to the limited time between sampling. This elevated NAAR may in part be accounted for through mineralization of organic matter associated with the ploughout of the previous cane crop. With respect to the other three trial sites, Mizzi had the lowest NAAR which may be attributed to the poorer performance of the cane crop on these plots throughout the trial period. Accornero had the highest rate of acid addition which could be accounted for in the heavier crops harvested from the site. These rates of acidification rates are similar to the values determined previously by Moody *et al.* (1997) who estimated that the NAAR for cane on the wet tropical coast was of the order of 3.4 kmol H⁺/ha.yr.

Surface charge fingerprints of composite samples collected in 1999.

By evaluating the charge characteristics of these soils, a clear understanding can be assessed of the impact of changing the soil pH on surface charge characteristics. This is of importance since one of the positive effects of increasing soil pH is its impact on generating –ve charge on the variable charge component of the soil. The concept of charge fingerprinting, as described by Gillman & Sumpter (1986), provides an assessment of the both the positive and negative charge characteristics of a soil over a pH range that has agronomic significance. When used in conjunction with exchangeable cations extracted from the exchange complex, an assessment of current and potential nutrient-holding capacity and the impact of management can be assessed.

Composite soil samples were produced of the control soils collected in the 1999 sampling for the 0-10 and 10-20 cm depth intervals. Charge fingerprints, which are curves describing the total cation exchange capacity (CEC_T), base cation exchange capacity (CEC_B) and anion exchange capacity (AEC) across a range of pH values were determined on the composite samples from each site using the methodology described by Gillman & Sumpter (1986). The CEC_B is a measure of the maximum amount of exchangeable basic cations that can be

retained in exchangeable form, and is therefore of agricultural significance. In brief, soils were saturated with Ca^{2+} and brought to equilibrium in a 0.002 M CaCl_2 matrix. The pH of the suspension was adjusted to six values ranging from approximately 4.0 to 7.5, and exchangeable Ca^{2+} , Al^{3+} and Cl^- were displaced with NH_4NO_3 . The Al^{3+} and Cl^- content in solution were determined using the pyrocatechol-violet method (Bartlett *et al.*, 1987) and Cl^- using the methodology as described by Rayment & Higginson (1992). Amounts adsorbed were calculated by taking into account the amounts present in the entrained solutes. The CEC_B is operationally defined as the Ca^{2+} adsorbed, CEC_T as the Ca^{2+} and Al^{3+} adsorbed, and the AEC as the Cl^- adsorbed. The amount of Cl^- adsorbed was negligible and has been disregarded. During the equilibration period, $\text{pH}_{0.002}$ was determined in a 1:10 soil:0.002 M CaCl_2 suspension following Ca^{2+} saturation. This value is operationally defined as the soil pH.

In the methodology used to develop the graphical representation, called the charge fingerprint, this estimates the CEC_B , CEC_T and AEC at each pH point. The CEC_B is the total amount of basic cations that can be retained in exchangeable form at any particular solution pH and ionic strength. Contrasting this, the total cation exchange capacity (CEC_T) is the total amount of basic and acidic cations that can be retained in exchangeable form at any particular solution pH and ionic strength. The approach distinguishes that portion of the cation exchange capacity (CEC) that retains the basic cations and predicts changes in CEC and AEC as soil solution pH and ionic strength are varied. It also allows estimation of the amounts of permanent and variable charge, the influence of components such as organic matter on surface charge expression, and the effects on surface charge of natural and man-made degradation.

Since the charge surfaces and buffer capacity curves were similar over both depth intervals, for brevity only the 0-10 cm depth interval is presented. The buffer capacity curve and surface charge fingerprint for the Accornero site is presented in Figure 5.4. The pH buffer capacity of the soil, namely the inverse of the slope of buffer curve is 5.48 cmol/kg.unit pH, and in order to raise the soil pH from its current status of 4.29 to 5.5, an estimated 3.97 t/ha of CaCO_3 would be required, assuming a soil bulk density of 1200 kg/m^3 . Similarly, it is clearly evident from the surface fingerprints that a considerable amount of variable charge can be generated through increasing soil pH. In this respect surface charge was increased from 8.1 to 11.6 cmol/kg over the pH range generated (Figure 5.4). It is important to note that at a pH of approximately 5.5 the two charge curves (CEC_B and CEC_T) converge to form a single curve.

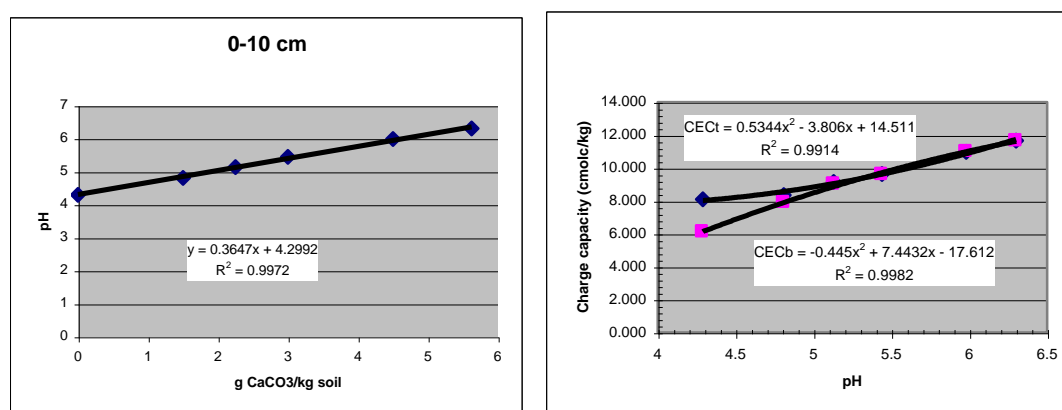


Figure 5.4. pH buffer capacity curve and surface charge fingerprints for the 0-10 cm depth interval for composite control treatment samples collected in 1999 from the Accornero site.

Similar charge fingerprints and buffer capacity curves were produced for the Reinaudo site (Figure 5.5). The buffer capacity was estimated to be 3.30 cmol_c/kg.unit pH and the amount of charge generated when going from soil pH to 6.5 was equivalent to 3.71 cmol_c/kg, almost a doubling of the charge characteristics of the soil. The amount of lime required to raise the soil pH to 5.5 was estimated to be 1.84 t/ha. Surface charge fingerprints and a buffer capacity curve are presented for the Mizzi site in Figure 5.6. Once again there is considerable variable charge generation associated with pH increases. The pH buffer capacity was estimated to be 2.52 cmol_c/kg.unit pH and approximately 1.2 t lime per ha is required to raise current soil pH to 5.5. The pH buffer capacity of the control soil from the DiBella site was estimated to be 3.0 cmol_c/kg.unit pH and would require approximately 1.4 t lime per ha to increase the soil pH to 5.5 (Figure 5.7). Once again there is a significant amount of charge generated through increasing the soil pH (Figure 5.7).

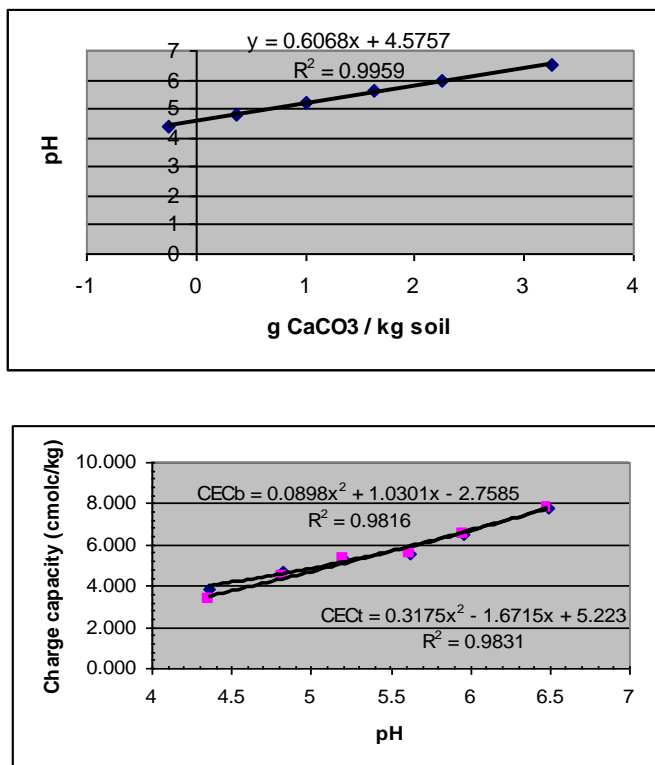


Figure 5.5. pH buffer capacity curve and surface charge fingerprints for the 0-10 cm depth interval for composite control treatment samples collected in 1999 from the Reinaudo site.

It is clearly evident from the charge fingerprints of the 4 respective soils that there is a convergence of the charge curves associated with CEC_b and CEC_T at pH 5.5. This has agronomic significance in that at this pH, exchangeable bases dominate the surface charge. Consequently, from a sustainability and agronomic perspective, this pH would represent the ‘ideal’ situation and should be the benchmark to which growers should be striving to achieve. By solving the buffer curve equations, the quantities of lime (CaCO₃) required to achieve this pH can be determined. In this respect 1.2, 1.4, 1.8 and 3.9 t/ha would be required to achieve the agronomically significant pH of 5.5 for the Mizzi, DiBella, Reinaudo and Accornero sites respectively. These are relatively modest amounts to be applied in a crop cycle in order to avoid degradation of the soil resource base. It is also of note that the surface charge curves differ significantly between sites. In the case of the Mizzi site, the nutrient holding capacity of the soil is limited by the ability of the soil to generate charge. This can be overcome by applying significant amounts of soil organic matter that would result in an increase in the

variable charge component of these soils. However, this effect is transient in that the soil organic matter is rapidly broken down under the climatic conditions that prevail in the tropics. Consequently, continual annual applications are required to maintain any increase in charge. An alternative approach that is currently being assessed in pot trials using soil from the Mizzi site is to increase the surface charge permanently through the addition of permanently charged clays. Highly significant increases in the productivity of forage sorghum have been observed using this strategy and it is suggested that field assessment of this technology should be undertaken.

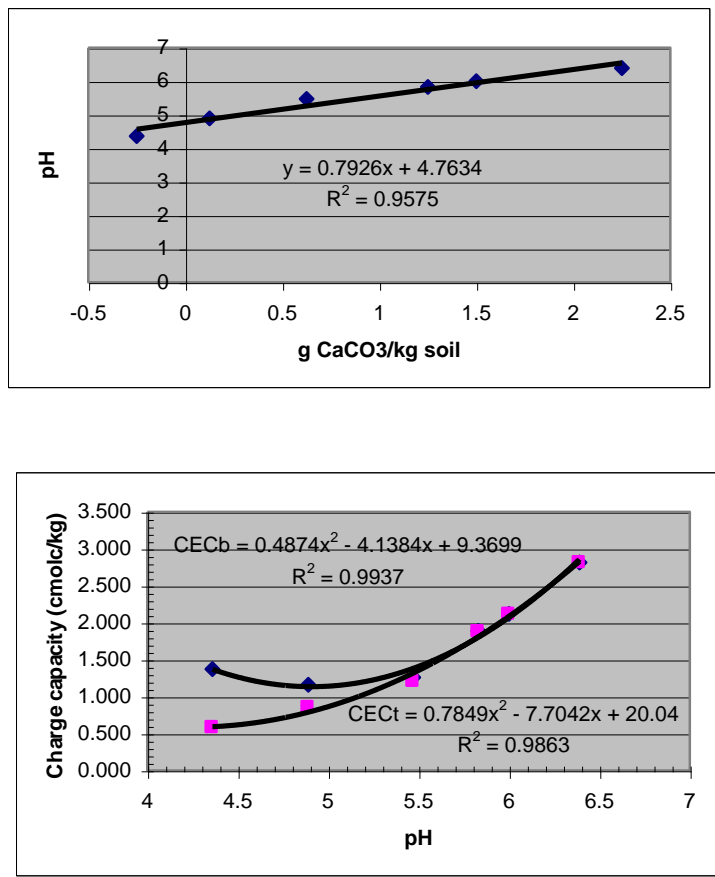


Figure 5.6. pH buffer capacity curve and surface charge fingerprints for the 0-10 cm depth interval for composite control treatment samples collected in 1999 from the Mizzi site.

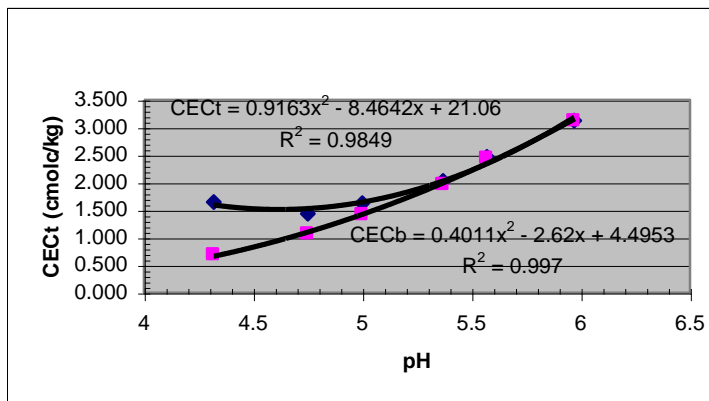
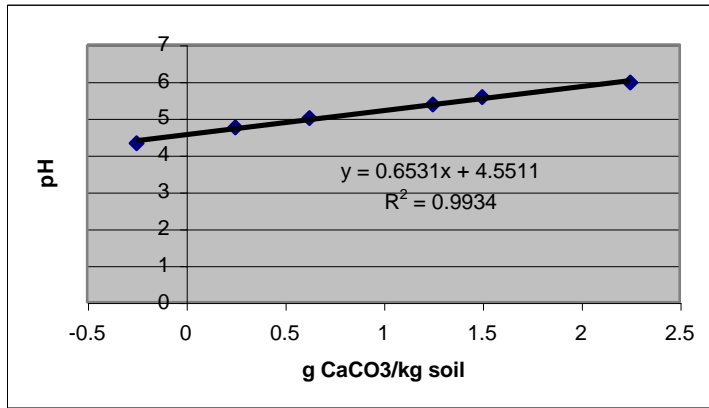


Figure 5.7. pH buffer capacity curve and surface charge fingerprints for the 0-10 cm depth interval for composite control treatment samples collected in 1999 from the DiBella site.

6. CHANGES IN SOIL PHYSICAL CHARACTERISTICS ASSOCIATED WITH LIME AND GYPSUM APPLICATION

The SRDC Subprogram Review Report on acid and sodic soil R&D, circulated in August 2000, included a suggestion that soil samples should be taken from selected treatments in one or more of the experiments for wet aggregate stability analysis, in order to determine whether there have been any treatment effects on soil physical properties.

It was decided to take samples from the DiBella trial and to delay sampling until just before the 2001 harvest season. The reasons for this were firstly that the DiBella trial was still growing sugarcane whereas it was our understanding that both the Accornero and Mizzi trials were ploughed out at the end of 2000. Secondly, the plots were more easily recognised in the DiBella trial than in the Reinaudo trial. Sampling was delayed for as long as possible after the passage of heavy traffic over the soil during the harvesting operation to allow the maximum amount of time for the development of any soil structural differences.

The DiBella trial was sampled in May 2001 with samples removed carefully from the 0-10 cm depth increment in field moist condition using a spade. Samples were taken in triplicate from each of the plots with high lime and high gypsum, with high lime and zero gypsum, and with high gypsum and zero lime applied. This sampling strategy would allow the effects of lime and gypsum application on wet aggregate stability to be separated and also for the combined effects to be assessed.

Whilst there was variability between plots having the same lime/gypsum treatments in both soil exchangeable calcium and the percentage of water-stable aggregates retained on different sized sieves, the mean results do show a treatment effect (Table 6.1). The treatments that received the highest lime and gypsum treatments in combination had the highest mean percentage of water stable soil aggregates for all of the aggregate size fractions above 0.125 mm. The application of 15 t ha⁻¹ lime was more effective than the same amount of gypsum in increasing the percentage of water-stable aggregates. The greatest impact appeared to be on the larger sized soil aggregates, particularly those >0.5 mm diameter.

Table 6.1. Wet aggregate stability of soil samples taken from selected treatments in the DiBella trial

Treatment	Mean % of water-stable soil aggregates retained on each sieve							
	Exch Ca ²⁺	>4.0mm diameter	>2.0mm diameter	>1.0mm diameter	>0.5mm diameter	>0.25mm diameter	>0.125mm diameter	<0.125mm diameter
0 lime; 0 gypsum	0.45	3.0	11.5	17.3	27.7	52.6	74.7	25.3
0 lime; 15 t ha ⁻¹ gypsum	1.21	3.9	13.3	20.3	29.7	54.0	75.5	24.5
15 t ha ⁻¹ lime; 0 gypsum	1.54	6.6	17.5	24.7	35.6	59.0	77.4	22.6
15 t ha ⁻¹ lime; 15 t ha ⁻¹ gypsum	3.36	11.3	23.3	31.4	42.0	63.7	80.5	19.5

For the larger sized aggregates, there appeared to be a relationship between exchangeable calcium in the soil and the percentage of water-stable aggregates. The relationship between exchangeable calcium and aggregates >1 mm diameter is shown in Figure 6.1.

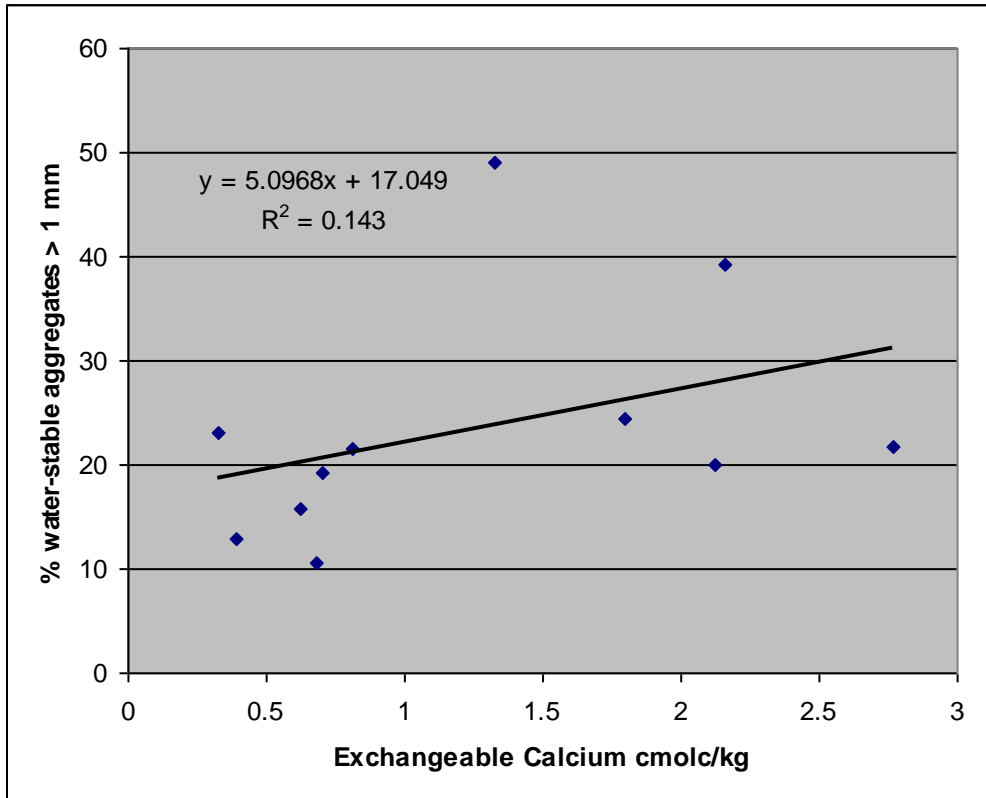


Figure 6.1. Relationship between % water-stable aggregates and soil exchangeable calcium in the 0-10 cm depth increment at the DiBella trial.

These results suggest that applications of calcium based soil amendments, and lime in particular, may be effective in the long term in improving soil structural stability. Thus apart from the beneficial effects of lime on soil chemical properties, such as increasing soil pH and soil exchangeable calcium levels, lime appears to have an important role in improving soil structural stability which will impact on infiltration of water into the soil surface and soil erodibility. Further, more detailed investigations are warranted to follow up these results and find out whether the results are related to increased earthworm populations or a purely the result of higher calcium levels.

7. QUALITY AND EFFECTIVENESS OF LIME AND GYPSUM APPLIED

Methodology

One year after application of the lime and gypsum in the trials at Accornero's, Mizzi's and Reinaudo's, all the plots in each trial were sampled to a depth of 90 cm using coring tubes of 5 cm diameter. Triplicate samples were taken from each plot, bulked on a depth basis, and subsequently analysed for pH and levels of exchangeable Ca. Unless otherwise stated, all analytical methods used were as described by Rayment and Higginson (1992). Statistical analysis of the experimental results was carried out using Genstat and functions available in Microsoft Excel.

Results

Changes in soil pH one year after application of lime and gypsum were surprisingly small even at the high rates applied to some treatments (Figure 7.1). Even when lime was applied at the rate of 15 t/ha, the pH increase in the top 10 cm was only of the order of one pH unit at the Reinaudo trial, and approximately ½ a unit at the Accornero trial. The relative differences between sites in terms of pH response to lime addition were consistent with those for pH buffer capacity as determined in the laboratory by the method of Aitken and Moody (1994), but the magnitude of the shift was markedly less than that predicted on the basis of buffer curve determinations (Figure 7.2) even allowing for the fact that some difference is expected between field and laboratory measurements of the effects of liming materials on soil (eg. Dunn, 1943). The buffer curves suggested that lime applied at 2.5 t/ha, the normal rate of application for most Herbert growers, could be expected to raise the pH to approximately 7.1, 6.2 and 5.9 at the Mizzi, Accornero and Reinaudo sites (Figure 7.2).

These contrasting results suggested that the lime used in this work was of low solubility. Whilst lime is generally regarded as being of low solubility compared, for example, to the fertilizers commonly used in the sugar industry, a series of further tests on both the lime and gypsum was considered warranted.

X-ray fluorescence (XRF) analysis (Table 7.1) indicated that, whilst the lime appeared to be of reasonable quality in terms of its chemical composition (the Ca content was 36 % compared to 40 % in pure CaCO₃), the composition of the gypsum was such that it was considered to be of much poorer quality. In particular, the XRF analysis indicated that this particular sample of gypsum contained insufficient sulphur (S) for all the Ca to be present as CaSO₄. The fact that the gypsum was found to contain 5.5 % silica (Si) suggests that some of the Ca was present as insoluble CaSiO₃.

Table 7.1. Major element XRF results (%) for the lime and gypsum.

	Ca	S	Si	Mg	K	Al	Fe	Mn	Na	Ti	P
Gypsum	23.6	15.7	5.55	1.14	0.22	1.80	1.07	0.02	<0.01	0.12	0.035
Lime	36.0	0.012	1.80	0.48	0.10	0.41	0.31	0.02	<0.01	<0.001	0.015

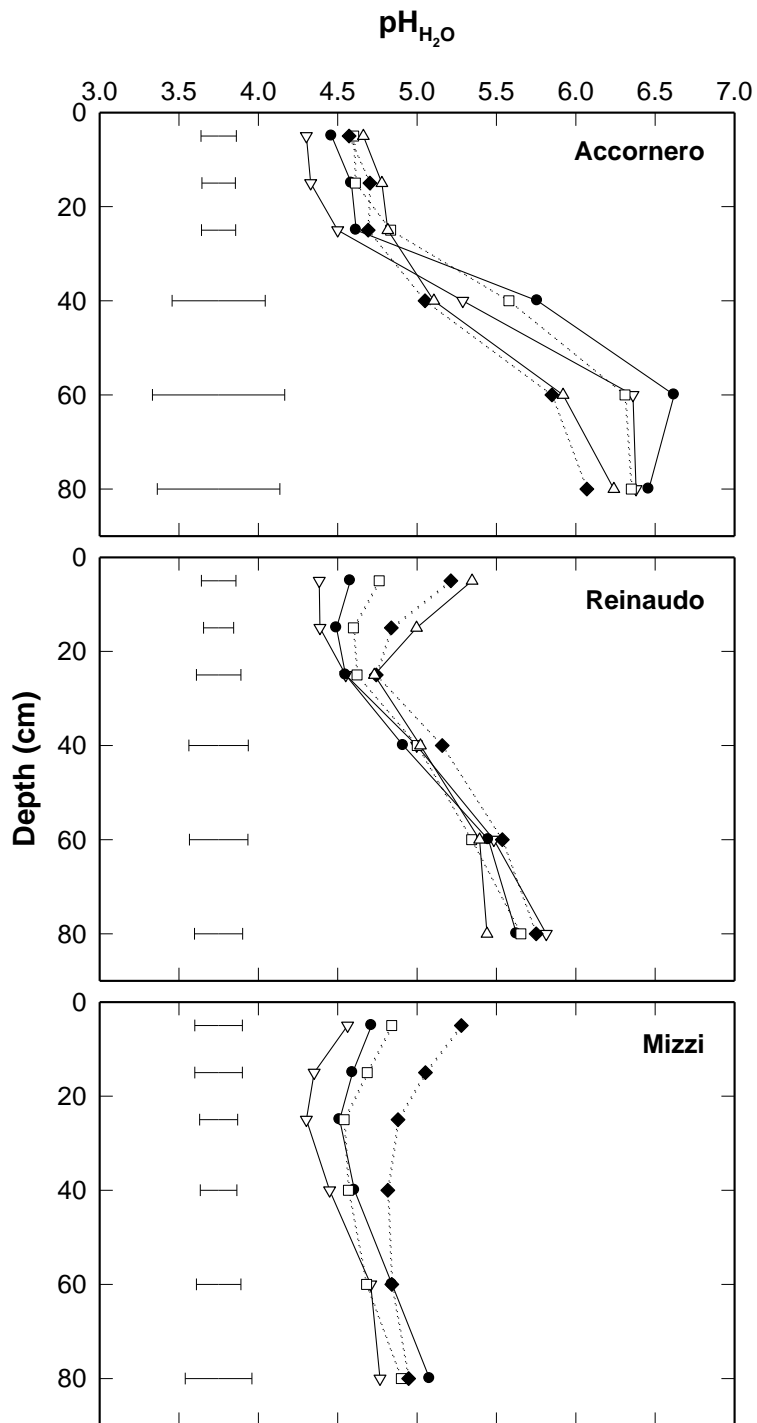


Figure 7.1. Soil pH at the three lime trial sites one year following application of lime at rates of 0 (▽), 2.5 (●), 5 (□), 10 (◆) and 15 (△) t/ha. The horizontal bars denote least significant differences at the 5% level.

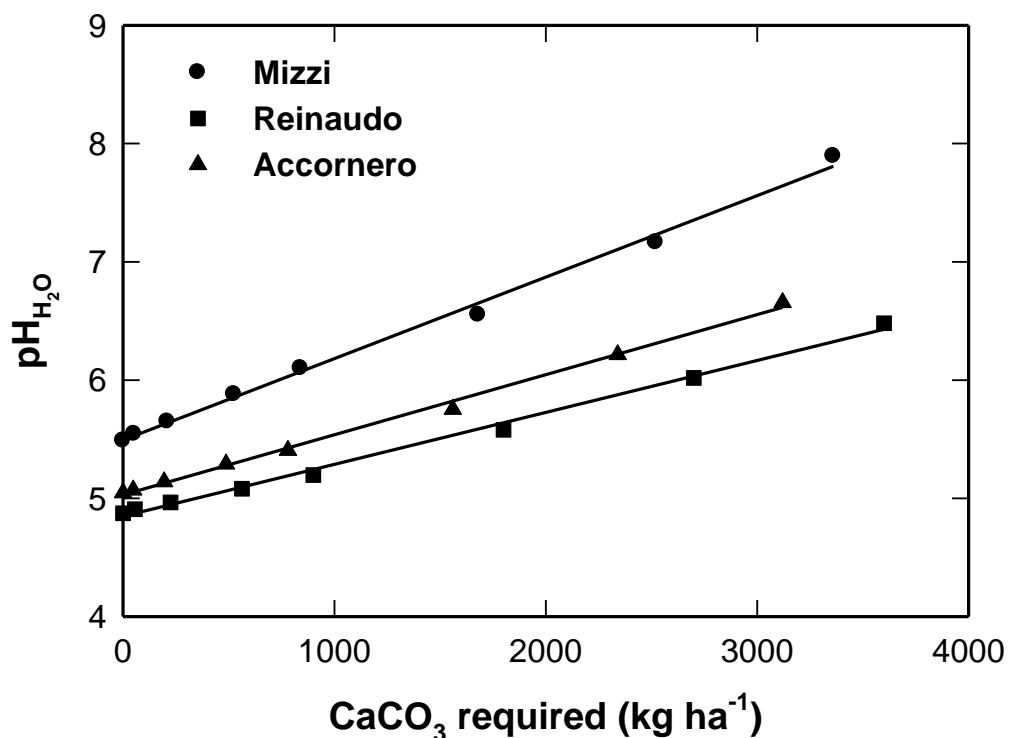


Figure 7.2. pH buffer curves for the top 15 cm of the soil profile at the three trial sites. The curves were derived using the laboratory method of Aitken and Moody (1994).

A laboratory experiment in which powdered samples of lime and pure CaCO₃ were dissolved overnight in distilled water demonstrated that the commercial lime product used in the trials was only 80% as soluble as pure CaCO₃. This result highlights the fact that measures of neutralizing value - 94.25 % for the lime used here - are of questionable utility, especially from a marketing point of view, in the absence of additional information on product solubility. Nevertheless, even if the neutralising capacity had been 80%, as opposed to the measured value of 94.25%, a larger pH shift than is shown in Figure 7.1 would still have been expected had all the lime dissolved, notwithstanding that Figure 7.1 also indicates that based on soil pH, the effects of lime application were integrated over approximately 25 cm of the profile at the Reinaudo and Accornero sites, and over about 50 cm at Mizzi. Thus, it would not necessarily have raised the pH of the surface layer as high as was predicted by pH buffer capacity determinations (Figure 7.2). In light of these observations, and knowing the bulk density profile at each site, the amount of lime that must have dissolved in order to cause the increases in exchangeable calcium status (Figure 7.3), in plots which received the highest additions of lime and gypsum, was estimated. It was assumed on the basis of the data presented in Figures 7.1 and 7.3 that the effect of lime and gypsum application was confined to the top 30 cm of the soil profile at the Accornero and Reinaudo sites, but extended to 60 cm at the freely-drained Mizzi site which is characterised by a greater coarse sand content (Table 4.2). These estimates (Figure 7.4) indicate that one year after lime application, at least 40 % of the lime added should have remained undissolved.

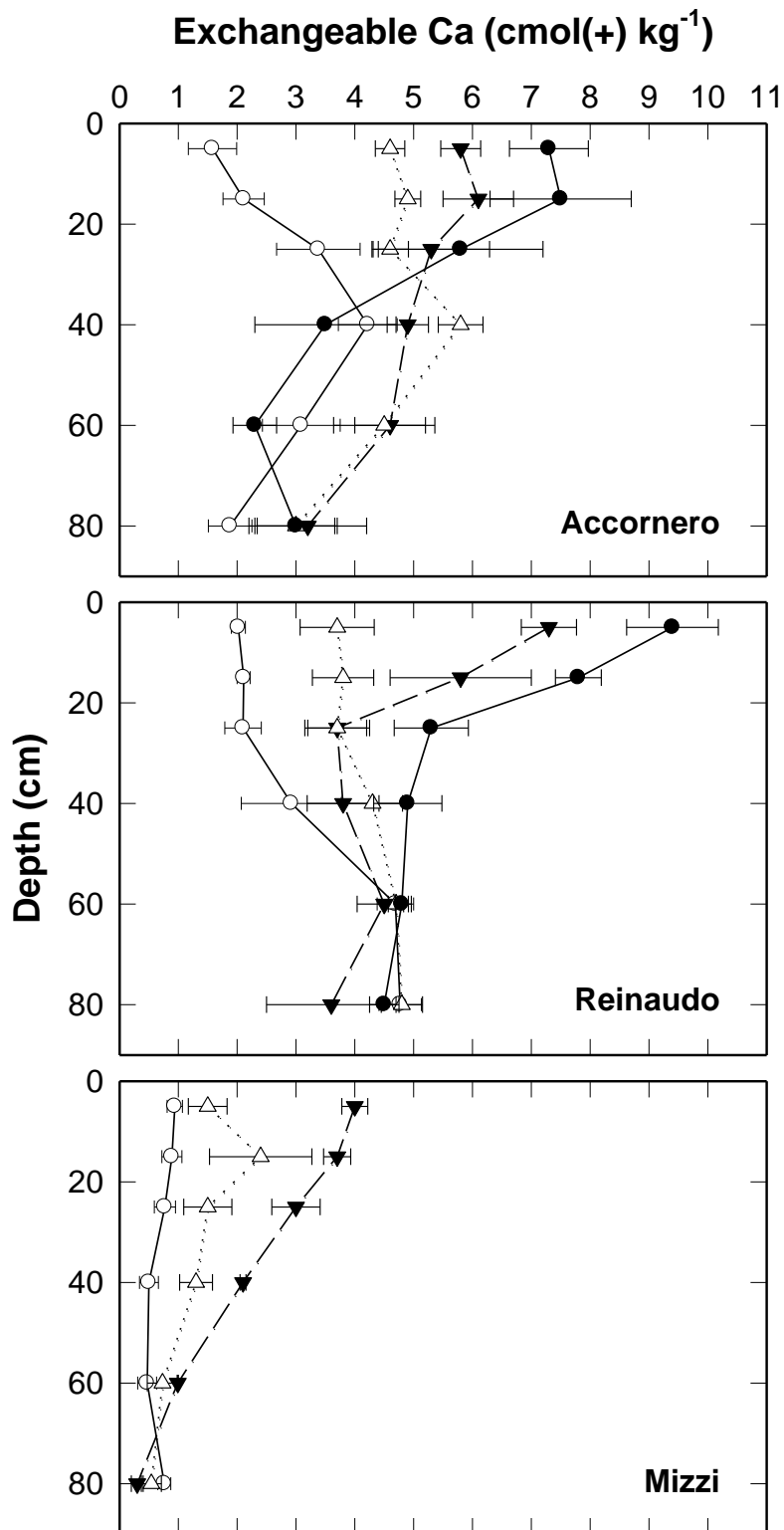


Figure 7.3. Exchangeable calcium status of the three lime trial soils prior to establishment of the trials (○) and one year after application of 15 t lime ha⁻¹ (◆), 15.2 t gypsum ha⁻¹ (Δ), or 15 t lime plus 15.2 t gypsum ha⁻¹ (●). Horizontal bars denote standard errors of the mean.

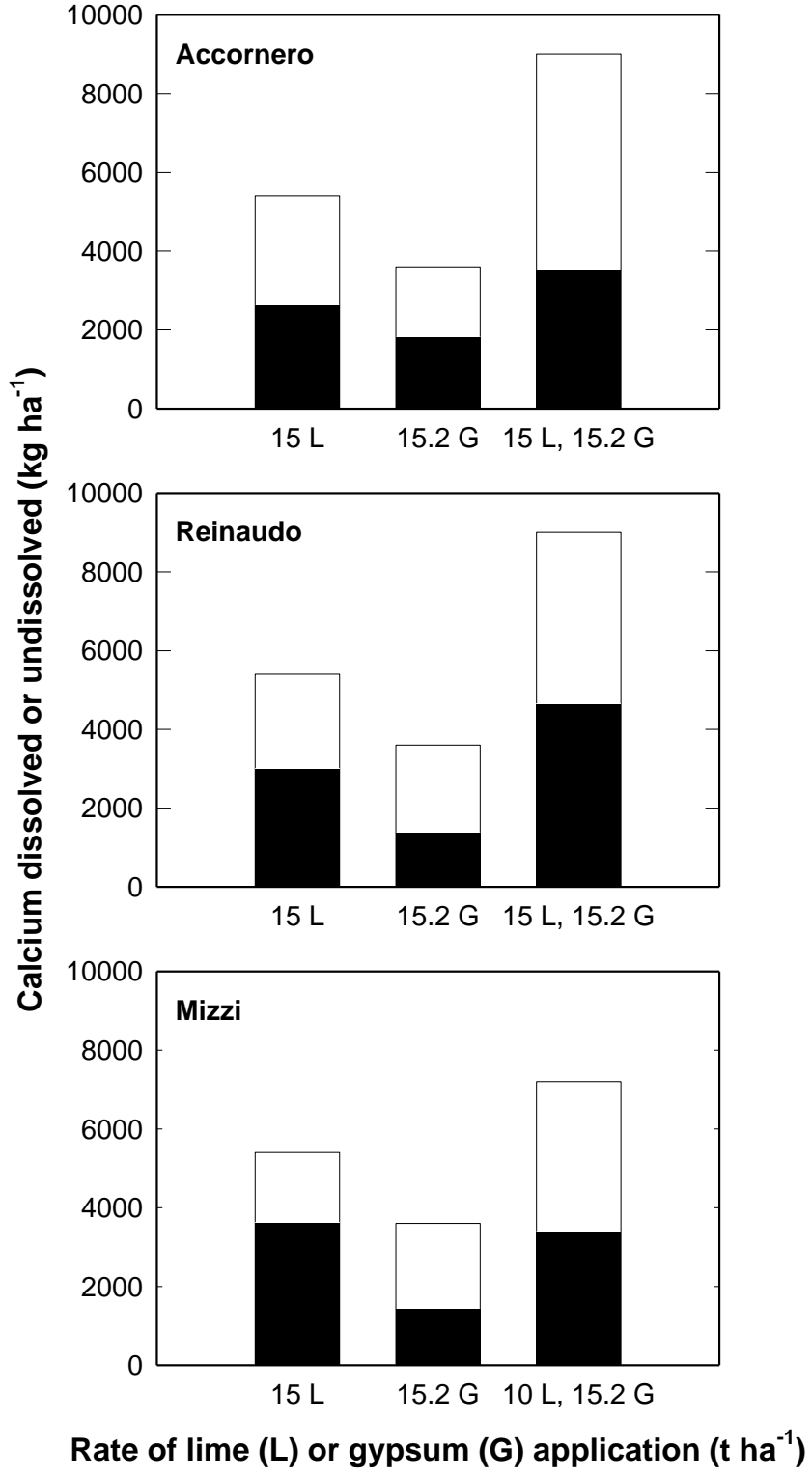


Figure 7.4. Estimates of the amount of Ca that has dissolved (solid shading) or remains undissolved (no shading) one year after application of lime or gypsum at the highest rates used in the lime trials. Note that the total height of each bar denotes the total Ca addition based on XRD analyses which indicated that the lime and gypsum contain 36 and 23.6 % Ca respectively.

Discussion

These results have several important implications for users of lime and gypsum in the sugar industry and in other agricultural industries in Queensland. First, even in the absence of any data on cane yield response, the present work suggests that the economics of lime application need to be evaluated over more than one, and probably several years for the cost-benefit of lime use to be properly assessed. Much of the previous published work on liming sugar cane soils (eg. Haysom *et al.*, 1986; Ridge *et al.*, 1980) focussed solely on cane yields in the year after lime application. However, Quinan and Wood (1989) demonstrated that the economic benefits of lime use were still apparent four harvests after application of lime to soils in the region to the south of Cairns, and yield responses were still occurring more than 7 years after application (Quinan and Wood, 1993). Similarly, Mallawaarachchi *et al.* (1998) have demonstrated that an economic response to lime application in a long term trial near Tully was not obtained until 4 years after the initial application, but that it was subsequently maintained for several years. Figure 7.4 also shows that much of the benefit of lime application can be expected to accrue more than one year after application.

Second, because the methodology for assessment of neutralizing value does not take account of the time required for the full neutralisation process to occur in field soils, it is important that growers understand that the effectiveness of a liming product is not necessarily indicated by its neutralising value. Factors affecting solubility must also be taken into account.

Third, as Figure 7.4 shows, a freely draining soil such as that at the Mizzi site, which presumably offers the opportunity for movement of particulate lime into the subsoil, has the capacity to dissolve more lime than less well drained sites, in spite of a much lower buffering capacity for Ca addition (i.e. lower CEC) and lower pH buffer capacity, simply because the lime can react with a larger volume of soil water moving through the profile than in the case of a heavier or more poorly drained clay, such as that at the Accornero site.

For some time, the relationship between the particle size of lime products and their solubility has been taken into account (eg. Tisdale *et al.*, 1985) in the measurement of effectiveness relative to pure CaCO₃. In Victoria, the State Chemistry Laboratory use the concept of *Effective Neutralising Value* (ENV) in registering the effectiveness of lime materials (K. Peverill, Victorian State Chem. Lab. - personal communication). ENV is calculated by adjusting the neutralising value on the basis of the proportions of product passing through 300 and 850 µm sieves. The lime used in these experiments had particle size fractions as shown in Table 7.3 which also illustrates the calculation of ENV. Thus, the lime used in our experiments had an ENV of approximately 72%.

Table 7.3. Estimation of ENV for lime used in the Herbert lime trials¹.

Sieve	ENV factor	% sample by mass	Neutralising value	ENV
>850 µm	0.1	18.1	94.25	1.7
300-850 µm	0.6	18.0	“	10.2
<300 µm	1.0	63.6	“	59.9
Total ENV				71.8

¹ENV = Σ [ENV factor × (% sample by mass/100) × Neutralising value]

Figure 7.4 suggests that at the Reinaudo site, approximately 2 t Ca ha⁻¹ had dissolved in the year between application and sampling. On the basis of Figure 7.2, this would suggest that

the pH in the top 15 cm should have risen to approximately 5.5. Figure 7.1 shows that the pH in that layer rose to only 5.3 which is consistent with the fact that the effects of the lime are integrated over about 25 cm rather than the top 15 cm. On the other hand, dissolution of approximately 2.5 and 3.0 t ha⁻¹ at the Accornero and Mizzi sites (Figure 7.4) ought to have increased soil pH to 6.1 and 7.5 (Figure 7.2). Clearly the pH shift was much less than this (Figure 7.1) and this reduction cannot be accounted for by the ENV of 72%. The apparent mismatch between Figure 7.1, Figure 7.4 and Table 7.3, suggests that even less lime has dissolved than we have estimated here, and also suggests that the relationship between ENV and lime solubility is not linear.

Noble *et al.* (1997) have recently argued on theoretical grounds that, liming strategies in the sugar industry should focus on (i) maintenance of the soil pH at 5.6 or greater, in order to counter the progressive downward movement of H⁺ from the topsoil to the subsoil, and (ii) on offsetting the removal of alkalinity associated with sending cane to the mill. The present results suggest that whilst the latter may be achievable on an annual basis, liming to a target pH of 5.6 using the lime source used in this work should be seen as a long term goal in view of the marginal pH shift achieved in one year in this study. Alternatively, other products such as Ca(OH)₂ or quicklime (CaO) could be used to achieve an initial pH shift, followed by regular smaller additions of lime targeted at mitigating soil acidification and the maintenance of soil pH close to the target value of 5.6. The fact that the mean topsoil pH in the Herbert is only 4.9, and that long term sugarcane monoculture may result in marked soil acidification (Bramley *et al.* 1996), suggests that the industry faces a resource sustainability issue in relation to soil acidity, and that in particular, growth of other crops in these acidic sugarcane soils may be problematic as a result.

Our results support the view that with respect to amelioration of soil pH, the lime used in this work was relatively ineffective over the 12 months following application. On the other hand, Aitken *et al.* (1998) concluded that typical commercial application rates of approximately 2 t lime ha⁻¹ were unlikely to increase soil pH by more than 0.5 pH unit in most south Queensland soils, even when a high quality lime is used. Further, one could argue that from the point of view of the Ca nutrition of the crop, the lime used in these experiments is a useful source of slowly available calcium which has a high residual value and is therefore ideal for supplying calcium over the duration of a crop cycle. It has been suggested (Calcino, 1994; Hetherington *et al.*, 1986; Kingston and Aitken, 1996) that sugarcane is tolerant of low soil pH and that lime is therefore required in order to satisfy the nutritional demand for Ca; note that none of the sites would be deemed lime-responsive on the basis of the current recommendations (Calcino, 1994; Kingston and Aitken, 1996), in spite of all having soil pH values well below 5.6. Nevertheless, in our view, the instigation of a quality assurance (QA) program would be of value to the sellers and purchasers of lime and gypsum in Queensland since there is clearly a marked difference in effectiveness between the lime used in this work and that used by Kingston and Aitken (1996), for example. Figure 7.4 also suggests that the derivation of an improved suite of indicators of lime requirement, which account for soil texture and structure, in addition to soil chemical properties and the characteristics of the liming material to be used, would be of value to the sugar industry, especially if amelioration of soil acidity is adopted as a long term goal aimed at enhancing the sustainability of the industry.

8. GREEN MANURE CROPS IN INITIAL TRIALS

At the original three trials, crops of cowpeas were established immediately following the application of lime and gypsum. The cowpea crops grew well and marked differences in growth and colour of the foliage were soon noticeable between the plots that had not received any lime and all the other plots. The growth of the cowpeas in the plots where gypsum but no lime had been applied appeared to be no better than in the plots that had received no lime or gypsum, suggesting that the growth response was due more to differences in soil pH rather than calcium availability. The growth of cowpeas in plots receiving the highest rate of lime application were visually no better than that in plots with the lowest rate of lime. The growers were asked to notify us before discing in the green manure crops so that the response of the cowpeas to the lime and gypsum treatments could be measured. This occurred at Accornero's and Reinaudo's but not Mizzi's. The cowpea crops were sampled in May 1996, but by then the crops had started to deteriorate and the results for dry matter yield (Tables 8.1 and 8.2) did not reflect the marked yield differences that were apparent a few weeks earlier.

Table 8.1. Effect of lime and gypsum application on the dry matter yield of cowpeas, N content and N uptake at the Accornero trial site, Ingham 1996.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
Dry matter yield (t ha ⁻¹)						
Gypsum (t/ha)						
0	3.27	3.98	4.09	3.82	4.31	
3.8	2.82	4.30	4.27	4.09	4.09	
15.2	3.38	3.90	3.84	3.90	3.70	0.73
N content (%)						
0	2.28	2.89	2.37	3.11	3.12	
3.8	1.89	3.18	3.18	2.94	2.89	
15.2	2.09	2.80	2.78	2.61	2.62	0.68
N uptake (kg ha ⁻¹)						
0	74.8	114.9	97.7	119.6	136.0	
3.8	52.8	137.4	137.9	123.7	118.7	
15.2	72.4	110.5	107.7	102.4	98.1	40.54

Table 8.2. Effect of lime and gypsum application on the dry matter yield of cowpeas, N content and N uptake at the Reinaudo trial site, Ingham 1996.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
Dry matter yield (t ha ⁻¹)						
Gypsum (t ha ⁻¹)						
0	4.43	4.90	5.08	3.12	4.41	
3.8	4.87	4.31	4.64	4.07	2.29	
15.2	4.24	4.40	3.92	4.42	4.23	2.09
N content (%)						
0	1.85	2.08	2.15	2.19	2.04	
3.8	2.16	2.16	2.32	2.17	0.81	
15.2	2.01	2.18	2.29	2.25	2.21	0.77
N uptake (kg ha ⁻¹)						
0	82.5	103.2	109.8	67.7	89.2	
3.8	104.9	93.6	108.0	88.1	36.8	
15.2	85.3	94.7	89.5	99.5	94.5	39.0

The cowpea crop at Accornero's showed a significant response to the lowest rate of lime application in terms of dry matter yield, nitrogen content and nitrogen uptake (Table 8.3; Figure 8.1). However, there were no significant differences between treatments for the cowpea crop sampled at Reinaudo's (Table 8.2).

Table 8.3. Main effects of lime on the yield of cowpeas, N content and N uptake at the Accornero trial site, Ingham 1996.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
Dry matter yield (t ha ⁻¹)						
	3.16	4.06	4.07	3.94	4.03	0.42
N content (%)						
	2.05	2.96	2.77	2.89	2.88	0.39
N uptake (kg ha ⁻¹)						
	66.7	120.9	114.4	115.2	117.6	23.4

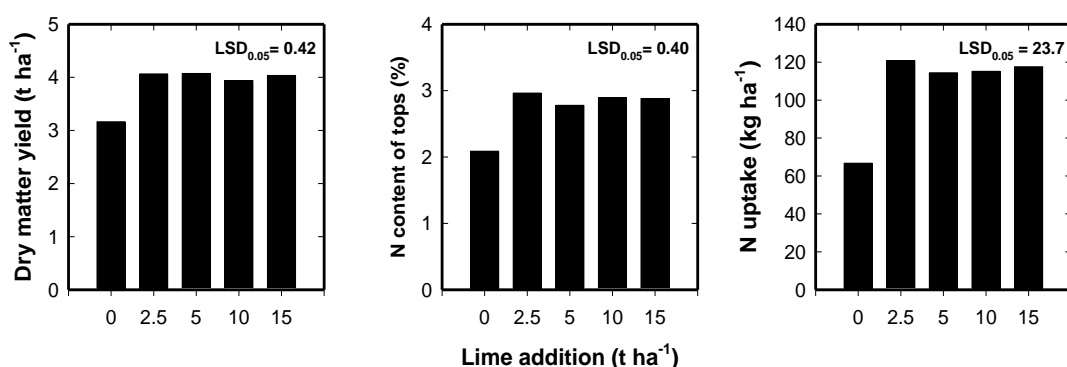


Figure 8.1. Response of cowpeas to lime at the Accornero site

The rapid response to lime addition in the cowpea crops is interesting particularly in view of the slow reactivity of the lime noted in the previous section. There must have been sufficient, relatively pure calcium carbonate in the lime applied at the lowest rate to have reacted rapidly in the soil to produce an improvement in soil pH which impacted on cowpea growth. The improved conditions for growth in the limed plots also resulted in the cowpeas being able to capture more nitrogen from the atmosphere, resulting in higher nitrogen contents in the leaves and stems.

These findings have important implications for fallow or break crops being grown in association with sugarcane. If leguminous crops are to be grown in fallow sugarcane fields, attention needs to be given to making sure that surface soil pH has not become too acidic. Low application rates of lime appear to have a rapid and significant benefit not only on the growth of fallow legumes but also on their ability to fix atmospheric nitrogen.

9. SUGARCANE YIELDS AND CCS

Harvest Year 1997

Results from the harvest of plant cane in the three initial trials in 1997 showed no significant responses to lime and/or gypsum (Tables 9.1 – 9.3). The Mizzi trial (Table 9.1), in particular, had a very high LSD for cane yield suggesting considerable yield variability between plots.

Table 9.1. Effect of lime and gypsum application on the yield of millable stalks and ccs at the Mizzi trial site, 1997 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	LSD _(0.05)	
millable stalk yield (t ha ⁻¹)						
Gypsum (t ha ⁻¹)						
0	95.0	148.2	128.7	120.7		
3.8	156.5	104.6	163.0	127.2		
15.2	123.3	127.7	142.7	155.6	55.8	
ccs						
0	15.5	15.7	16.0	15.7		
3.8	16.0	15.3	15.4	15.3		
15.2	15.6	14.6	15.6	15.5	1.2	

Table 9.2. Effect of lime and gypsum application on the yield of millable stalks and ccs at the Reinaudo trial site, 1997 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)	
millable stalk yield (t ha ⁻¹)							
Gypsum (t ha ⁻¹)							
0	143.2	129.4	134.1	130.0	126.0		
3.8	126.4	135.3	132.7	134.6	129.6		
15.2	127.4	125.5	123.2	141.1	124.9	15.5	
ccs							
0	13.5	14.8	14.4	14.7	13.5		
3.8	14.7	14.7	14.2	14.7	14.1		
15.2	14.7	14.4	14.7	14.4	14.2	1.1	

Table 9.3. Effect of lime and gypsum application on the yield of millable stalks and ccs at the Accornero trial site, 1997 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)	
millable stalk yield (t ha ⁻¹)							
Gypsum (t ha ⁻¹)							
0	126.8	120.2	128.5	129.3	130.3		
3.8	134.6	131.6	136.5	141.8	135.1		
15.2	134.4	127.0	133.7	139.0	131.0	19.4	
ccs							
0	15.0	15.1	15.1	14.3	14.4		
3.8	14.4	14.3	15.7	14.9	15.4		
15.2	14.7	15.2	14.7	14.8	14.5	1.2	

Harvest Year 1998

First ratoon yield data were obtained from only one trial in 1998 due to disruptions to harvesting caused by a very wet harvesting season. Yields at the Reinaudo trial (Table 9.4) were much higher than in plant cane but showed no responses to lime and/or gypsum application. In addition, the ccs data from Reinaudo's and Accornero's showed no signs of depression with lime application (Tables 9.4 and 9.5).

Table 9.4. Effect of lime and gypsum application on the yield of millable stalks and ccs at the Reinaudo trial site, 1998 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
millable stalk yield (t ha ⁻¹)						
Gypsum (t ha ⁻¹)						
0	167.0	178.0	166.5	162.5	180.1	
3.8	172.0	161.8	167.5	171.1	144.5	
15.2	160.2	169.0	162.5	177.2	170.9	25.0
ccs						
0	14.2	13.9	13.7	14.0	14.1	
3.8	14.2	12.7	14.1	13.0	14.4	
15.2	13.7	13.9	13.2	14.1	13.2	1.1

Table 9.5. Effect of lime and gypsum application on ccs at the Accornero trial site, 1998 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
ccs						
Gypsum (t ha ⁻¹)						
0	13.6	13.2	13.2	12.7	13.3	
3.8	12.7	13.8	13.0	13.0	13.4	
15.2	12.8	13.3	13.2	12.9	13.1	0.8

Harvest Year 1999

Second ratoon yield data from the hand harvest of the initial three trials indicated no significant interactive responses to lime and/or gypsum (Tables 9.6, 9.7 and 9.9). Cane yields at Reinaudo's (Table 9.7) were much lower than in the previous year, probably due to stool damage and compaction caused by harvesting the trial under wet conditions in 1998. The high LSD in the Reinaudo trial suggested that the wet weather harvest damage was probably localised and did not have a uniform impact over the whole trial. Yields at Accornero's were also quite low compared to the high plant crop yields and may also have been affected by the wet conditions at harvest. Whilst there were significant main effects of lime treatments on cane yields at the Accornero trial (Table 9.8), these are most likely due to variability in stalk number between plots and cannot be attributed to the lime treatments. The gaps that developed in some plots following the excessively wet harvest season in 1998 became a major constraint on obtaining good data from these trials in later years.

Table 9.6. Effect of lime and gypsum application on the yield and ccs of millable stalks at the Mizzi trial site, 1999 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	LSD _(0.05)
	millable stalk yield (t ha ⁻¹)				
Gypsum (t ha ⁻¹)					
0	74.3	93.3	111.1	100.9	
3.8	96.4	93.9	110.3	100.9	
15.2	94.2	102.3	84.3	93.1	35.4
	ccs				
0	14.1	15.1	13.7	15.1	
3.8	15.4	12.7	13.4	12.8	
15.2	14.5	13.6	15.6	14.8	2.3

Table 9.7. Effect of lime and gypsum application on the yield and ccs of millable stalks at the Reinaudo trial site, 1999 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
	millable stalk yield (t ha ⁻¹)					
Gypsum (t ha ⁻¹)						
0	57.6	57.0	53.2	43.1	65.3	
3.8	42.8	62.3	60.2	53.7	61.5	
15.2	54.4	41.1	60.6	44.6	37.1	27.1
	ccs					
0	12.3	12.9	13.0	12.7	13.1	
3.8	13.0	13.4	12.6	13.0	12.6	
15.2	13.2	12.1	13.2	12.4	12.7	0.9

Table 9.8. Main effects of lime treatments on millable stalk yield and stalk number at the Accornero trial site, 1999 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
	millable stalk yield (t ha ⁻¹)					
	58.04	56.27	44.62	60.17	46.64	11.56
	Stalk number (per 10m row)					
	70.2	73.4	58.7	65.4	62.0	7.7

Table 9.9. Effect of lime and gypsum application on the yield and ccs of millable stalks at the Accornero trial site, 1999 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
	millable stalk yield (t ha ⁻¹)					
Gypsum (t ha ⁻¹)						
0	57.7	45.8	38.6	67.0	41.9	
3.8	58.5	54.5	43.3	57.4	45.3	
15.2	57.8	68.4	51.8	56.1	52.6	20.0
	ccs					
0	14.0	13.73	14.0	13.43	13.4	
3.8	13.4	13.8	13.9	13.6	13.7	
15.2	13.0	12.7	13.3	13.2	13.5	1.3

Plant crop yields from the trial at DiBella's showed no significant responses to lime and/or gypsum despite the low soil calcium levels (Table 9.10). Also there was no sign of a depression in ccs due to lime application.

Table 9.10. Effect of lime and gypsum application on the yield and ccs of millable stalks at the DiBella trial site, 1999 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	LSD _(0.05)
millable stalk yield (t ha ⁻¹)					
Gypsum (t ha ⁻¹)					
0	92.8	90.4	95.0	95.6	
3.8	98.1	93.9	100.3	105.6	
15.2	97.1	102.3	91.9	101.1	17.7
ccs					
0	16.1	15.6	15.9	16.0	
3.8	13.7	15.9	15.7	15.8	
15.2	15.9	15.5	15.8	15.1	2.2

Harvest Year 2000

Cane yields for the third ratoon crop harvested in 2000 at the Mizzi trial (Table 9.11) were greatly reduced from the second ratoon crop and were poor across the whole trial. Neither cane yield nor ccs showed a response to lime and/or gypsum. At the Reinaudo and Accornero trials (Tables 9.12 and 9.13) yields were higher than in the previous year but again there were no responses to lime and/or gypsum.

Table 9.11. Effect of lime and gypsum application on the yield and ccs of millable stalks at the Mizzi trial site, 2000 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	LSD _(0.05)
millable stalks (t ha ⁻¹)					
Gypsum (t ha ⁻¹)					
0	23.7	25.0	35.7	29.3	
3.8	30.3	23.0	34.3	28.3	
15.2	28.3	27.3	37.3	32.7	18.1
ccs					
0	15.3	13.9	13.7	14.3	
3.8	13.6	14.2	14.1	13.7	
15.2	14.0	15.6	14.4	13.2	2.3

Table 9.12. Effect of lime and gypsum application on the yield and ccs of millable stalks at the Reinaudo trial site, 2000 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
	millable stalks (t ha ⁻¹)					
Gypsum (t ha ⁻¹)						
0	84.3	72.7	76.3	67.7	77.3	
3.8	76.3	80.0	77.3	82.0	74.3	
15.2	72.3	71.7	69.3	74.0	69.3	12.61
	ccs					
0	15.2	15.4	14.3	15.1	14.8	
3.8	14.6	14.4	14.6	15.2	15.3	
15.2	15.1	14.7	14.7	14.7	15.0	1.1

Table 9.13. Effect of lime and gypsum application on the yield and ccs of millable stalks at the Accornero trial site, 2000 harvest.

Lime (t ha ⁻¹)	0	2.5	5.0	10.0	15.0	LSD _(0.05)
	millable stalks (t ha ⁻¹)					
Gypsum (t ha ⁻¹)						
0	60.7	59.0	64.7	75.7	61.3	
3.8	62.3	51.7	57.3	66.3	56.3	
15.2	69.0	69.7	51.7	70.3	68.3	19.29
	ccs					
0	15.7	15.1	15.1	13.2	15.8	
3.8	13.9	15.8	15.3	14.5	15.5	
15.2	14.4	14.4	15.4	14.5	15.2	1.6

Discussion

A total of eleven harvests from four different lime and gypsum trials failed to show any significant response in terms of cane yield or ccs. This raises a key question as to why none of the trial sites were responsive even though they had very acidic surface horizons.

It has already been noted that in evaluating the responsiveness of different soils to lime and/or gypsum, it is important to consider the amount of Ca²⁺ on the soil's exchange complex. All three of the initial trial sites had soil exchangeable calcium levels that exceeded the critical level of 0.55 cmol_c kg⁻¹ Ca at all depths in the soil profile down to 90 cm. Consequently it can be argued that the sugarcane crops were able to access sufficient calcium from the soil profile and therefore did not respond to additional calcium applied as either lime or gypsum.

The DiBella site was different from the others in having soil exchangeable calcium below the critical level at all depths down to 90 cm. This site would be expected to be responsive to applied calcium. However it was unfortunate that only plant crop yields could be measured as the ratoon crops were too badly affected by external influences such as waterlogging, pests and diseases. The lack of response to applied calcium in the plant crop at DiBella's was not unusual as is shown in the following section where sugarcane on an acidic, calcium deficient site in north Queensland took 4 years to show a significant response to lime (see section 11).

10. INFLUENCE OF LIME AND GYPSUM APPLICATIONS AND SOYBEAN RESIDUE MANAGEMENT ON SOIL CHEMICAL PROPERTIES

Introduction

The incorporation of a legume crop species, in particular cowpea (*Vigna unguiculata*), as a break crop between plough-out of an old ratoon and re-planting to sugarcane the following autumn is an accepted practice within the Australian sugar industry. The legume crop provides a break from continual sugarcane cropping that has a beneficial effect in reducing disease build up (Pankhurst *et al.* 1999) and provides nitrogen for the subsequent sugarcane crop (Garside *et al.*, 1996). Further, a legume break provides ground cover for erosion and weed control over the wet season.

Over the past 5 years a considerable amount of research has gone into selecting suitable legume species and developing management strategies to maximise their benefits. In this respect, soybean (*Glycine max* L. Merrill) has been found to be well suited since it fixes considerably more nitrogen than other potential legume species (Garside and Bell, 1999), has a relatively short growing season, and large biomass production (Garside *et al.*, 1996, 1998). However, with the incorporation of a soybean crop as a green manure there is potential for significant losses of mineralised nitrogen under conditions conducive to leaching and/or denitrification. The movement of nitrate nitrogen down the soil profile following the incorporation of soybean residue was reported by Garside *et al.* (1998) from previous studies. The results clearly demonstrated that on incorporation of residue, rapid mineralisation of nitrogen occurred and that this nitrate nitrogen moved down the profile. By 137 days after incorporation the nitrate bulge was at 50 cm.

In an effort to address the problem of nitrate losses through leaching associated with legume break crops, a study was initiated at Feluga, north Queensland in association with a lime and gypsum trial. This study was undertaken in collaboration with Dr Alan Garside and the Yield Decline Joint Venture

Materials and methods

Site

The trial was established in November 1997 at the Sugar Yield Decline Joint Venture sub-station at Feluga, near Tully, north Queensland (17° 59'S; 145° 56' E). The long-term mean annual rainfall for the area is approximately 4300 mm, being concentrated between October and March. The rainfall at the site in 1998 was 3850 mm. The soil was a granite gravel of the Thorpe series (Murtha, 1986) classified as an Acidic Dystrophic Yellow Dermosol (Isbell, 1996).

Experimental design

This experiment was a factorial experiment established to measure the effect of lime and gypsum and residue management on the growth of a soybean cover crop and subsequent sugarcane crop (Table 10.1). There were three replications. Hence the design for this experiment was a randomised block with three residue management treatments and three replications. The residue management treatments were residue incorporated, residue standing and residue slashed and left on the surface.

The lime and gypsum treatments were surface broadcast and incorporated using a disc plough to a depth of 20 cm in November 1997 prior to planting soybeans. Replicates were separated

by a 5 metre discard and 1.5 metres was left between individual plots within replicates. Inoculated seed of soybean variety Leichardt was sown into raised ridges, 75 cm apart on December 16, 1997. The vegetative biomass of the soybean crop was measured on the 19 February 1998 (65 days after planting) and at physiological maturity of the crop on April 16 (118 days after planting). Nitrogen content of the soybean tops was determined on these samples. Soybean residue treatments were imposed on June 11, 1998. In plots where the soybean crop was incorporated, the crop was ploughed under to a depth of 20 cm using a disc plough. In plots receiving surface residue management treatments, the crop was cut using a rotary slasher and left on the surface, whilst those treatments having residue standing were left intact. Sugarcane (variety Q117) was planted over the entire area on August 6, 1998. The plots having standing and surface soybean residue were direct planted without any cultivation. Potassium at 100 kg/ha as muriate of potash and phosphorus at 20 kg/ha as single superphosphate was applied at planting. No nitrogen fertilizer was applied to the sugarcane. The plant cane crop was harvested during the 1999 and 2000 seasons using the methodology as described previously.

Table 10.1. Treatment combinations imposed along with the management of the soybean residue at the Feluga site.

Treatment	Lime (t ha ⁻¹)	Gypsum (t ha ⁻¹)	Soybean residue management
1.	0	0	Incorporated
2.	0	5.0	Incorporated
3.	2.5	0	Incorporated
4.	2.5	5.0	Incorporated
5.	5.0	0	Incorporated
6.	10.0	5.0	Incorporated
7.	0	0	Standing
8.	0	0	Surface applied
9.	5	0	Incorporated +140 kg N ha ⁻¹

Soil analysis

Soil samples were collected to 110 cm depth from each of the plots prior to the establishment of lime and gypsum treatments in November 1997. Samples were obtained using a 50 mm diameter truck-mounted hydraulic core sampler and composite samples for each depth interval were formed from three cores per plot. Cores were sectioned into the following depth intervals: 0-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-110 cm. Prior to chemical analysis, soils were air-dried and ground to pass a 2 mm sieve. Soil pH was determined in both water (pH_w) and 0.01 M CaCl₂ (pH_{Ca}) in a 1:5 soil-to-solution ratio. Selected soil chemical properties were measured on samples as discussed previously and presented in Table 10.2. Soil extractable inorganic nitrogen was determined using the methodology of Rayment and Higginson (1992).

Further soil samples were collected from the soybean residue treatments at physiological maturity of the soybean (April 16, 1998), and on May 25 (Day 1), August 3 (day 70) and October 8 (Day 136). The May 25 sample was taken just prior to the establishment of the stubble management treatments on June 11, while the August 3 sample was just prior to sugarcane planting on August 6. The sampling strategy was as described previously and pH and mineral nitrogen was determined on samples.

Table 10.2. Chemical properties of treatments collected prior to the implementation of lime and gypsum treatments in November 1997 at Feluga. Each data point is the mean of 18 replicates.

Depth	pH _w	pH _{Ca}	EC (dS m ⁻¹)	Exchangeable cations				H Al Al+H (cmol _c /kg)			CEC	ECEC	AEC
				Ca	Mg	K	Na	H	Al	Al+H			
0-10	5.38	4.59	0.067	0.991	0.317	0.394	0.209	0.209	0.375	0.58	2.21	2.49	0.17
10-20	5.31	4.55	0.067	0.983	0.337	0.353	0.182	0.182	0.400	0.58	2.15	2.43	0.14
20-30	5.23	4.47	0.062	0.901	0.251	0.267	0.183	0.183	0.570	0.75	2.07	2.35	0.13
30-40	5.03	4.32	0.053	0.68	0.154	0.239	0.187	0.187	0.906	1.09	1.96	2.35	0.25
40-60	4.95	4.31	0.054	0.547	0.105	0.203	0.190	0.190	1.076	1.26	1.84	2.30	0.30
60-80	4.89	4.24	0.053	0.356	0.076	0.198	0.163	0.163	1.135	1.29	1.73	2.08	0.24
80-100	4.86	4.24	0.052	0.264	0.070	0.203	0.195	0.195	1.191	1.38	1.58	2.11	0.25
100-120	4.68	4.08	0.052	0.239	0.077	0.251	0.175	0.175	1.027	1.20	1.57	1.94	0.22

Net Acid Addition estimates

In an effort to quantify the net acid addition (NAA) between May and October samplings over the 0-30 cm depth interval, a modified Helyar and Porter (1989) model was used.

$$\text{NAA} = [(\text{pH}_M - \text{pH}_O) \times \text{pH}_{BC}] \times \text{BD} \times V \quad (1)$$

where the subscripts M and O refer to the pH_{Ca} as measured in 0.01 M CaCl₂ in May 1998 and October 1998; pH_{BC} is the pH buffering capacity of the soil (kmol H⁺/kg.pH unit); BD is soil bulk density (kg/m³); V is the soil volume in the depth interval under consideration (m³/ha). pH buffering capacity was estimated using a pedo-transfer function described by Merry (personal communication), that takes into account soil organic carbon and field texture. Soil bulk density measurements previously undertaken by M.V. Braunack (personal communication) on the site were used in the calculation.

Statistical Analysis

Statistical analysis of the data was undertaken using Genstat 5 (Genstat Committee, 1993). 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 and discussion

Initial soil chemical characteristics

Selected soil chemical attributes prior to the implementation of treatments are presented in Table 10.2. Soil pH declined from 5.38 in the surface horizon to 4.68 at 110 cm, clearly indicating the acidic nature of the profile. Contrasting this, exchangeable Ca ranged from 0.99 cmol_c/kg in the surface horizon and declined to a low of 0.23 cmol_c/kg in the subsoil. These values traversed the critical value of 0.50 cmol_c/kg as described by Calcino (1994), suggesting sub-optimal levels of Ca in the subsoil that could limit the production of sugarcane. It is of note that the ECEC values are greater than the measured CEC, suggesting that there a portion of exchangeable cations that are not associated with the exchange complex. Clearly with depth and the associated decline in soil pH, exchangeable Al became the dominant cation on the exchange complex.

Soybean growth

A significant vegetative biomass response to gypsum and lime was observed at the first sampling of the soybean crop on February 19, 1998 (Table 10.3). With increased additions of both lime and gypsum there was a corresponding increase in above ground biomass, suggesting that soybean was responding to elevated soil Ca levels. Indeed, mean soil Ca levels down the entire soil profile prior to the application of amendments was 0.62 cmol_c/kg,

which would be classified as marginal for sugarcane production (Calcino, 1994). However, these initial responses did not persist to final biomass assessment at physiological maturity on the 16th April 1998. There were no significant treatment effects with respect above ground biomass production and its nitrogen concentration on 16th April 1998. The above ground dry matter production for this sampling was 6933 kg/ha at a nitrogen concentration in the tops of 3.91%. Hence a mean value of 271 kg N/ha was estimated as being potentially available in the soybean tops for mineralisation and conversion to inorganic nitrogen.

Table 10.3. Soybean biomass responses to lime and gypsum applications 65 days after establishment.

Growth parameter	Lime rate (t ha ⁻¹)				LSD _(0.05)
	0	2.5	5.0	10	
Biomass (kg ha ⁻¹)	1183	1314	1392	1510	231
	Gypsum rate (t ha ⁻¹)				
	0	5			
Biomass (kg ha ⁻¹)	1235	1464			163

Changes in soil nitrate under residue management.

The soil mineral nitrate profiles for the three soybean residue management treatments are presented in Figure 10.1. At time 0 (May 25), two weeks prior to incorporation of soybean residue on June 11, the nitrate profiles were similar for all residue management treatments and concentrations of NO₃-N ranged from 1 to 2.1 mg/kg (Figure 10.1a). By day 70 (August 3), just prior to planting the cane crop on August 6, significant differences between the incorporated treatment and the other two non-incorporated treatments were clearly evident (Figure 10.1b). Significantly higher concentrations of mineral NO₃-N (range 2-32 mg/kg) were observed to 80 cm depth under the incorporated treatment compared to the other two treatments (range 4-14 mg kg⁻¹), suggesting that under the incorporated treatment there were considerably higher rates of mineralisation. By day 136 (October 8), the NO₃-N bulge had moved from 15 cm to 60 cm down the profile under the incorporated treatment, presumably due to leaching whereas there was a less prominent bulge and it was still in the 20 – 40 cm depth for the two non-incorporated treatments (Figure 10.1). The depth of the bulge for the incorporated soybean residue treatment at 136 days is similar to that measured at this site previously (Garside *et al.*, 1998)

In an effort to establish the degree of nitrogen mineralisation and potential losses, the concentration of nitrate nitrogen down the entire profile (0 – 110 cm) from May 25 (Day 1) through to October 8 (Day 136) for the three treatments was calculated (Table 10.4). By day 70 (August 3) the NO₃-N content in each of the profiles had increased by 183.6, 39.0 and 60.4 kg ha⁻¹ for the incorporated, surface retained and standing treatments, respectively (Table 10.4). However, by day 136 the NO₃-N content in the residue incorporated treatment had declined to 101.6 kg ha⁻¹ whilst in the surface retained and standing treatments it had increased to 93.6 and 97.4 kg ha⁻¹ respectively (Table 10.4). Subtracting NO₃-N contents between days 70 and 136 offers an insight into the dynamics of the mineralisation process. In the case of the residue incorporated treatment the net addition of mineralised nitrate to the profile had declined to reflect a loss of 104.5 kg NO₃-N ha⁻¹ from the system over this period. In contrast, the surface retained and standing treatments showed net increases of 35.2 and 15.5 kg NO₃-N ha⁻¹ respectively over the same period. This would suggest that mineralisation of nitrogen was occurring at a faster rate than losses in the surface retained and standing treatments during this period.

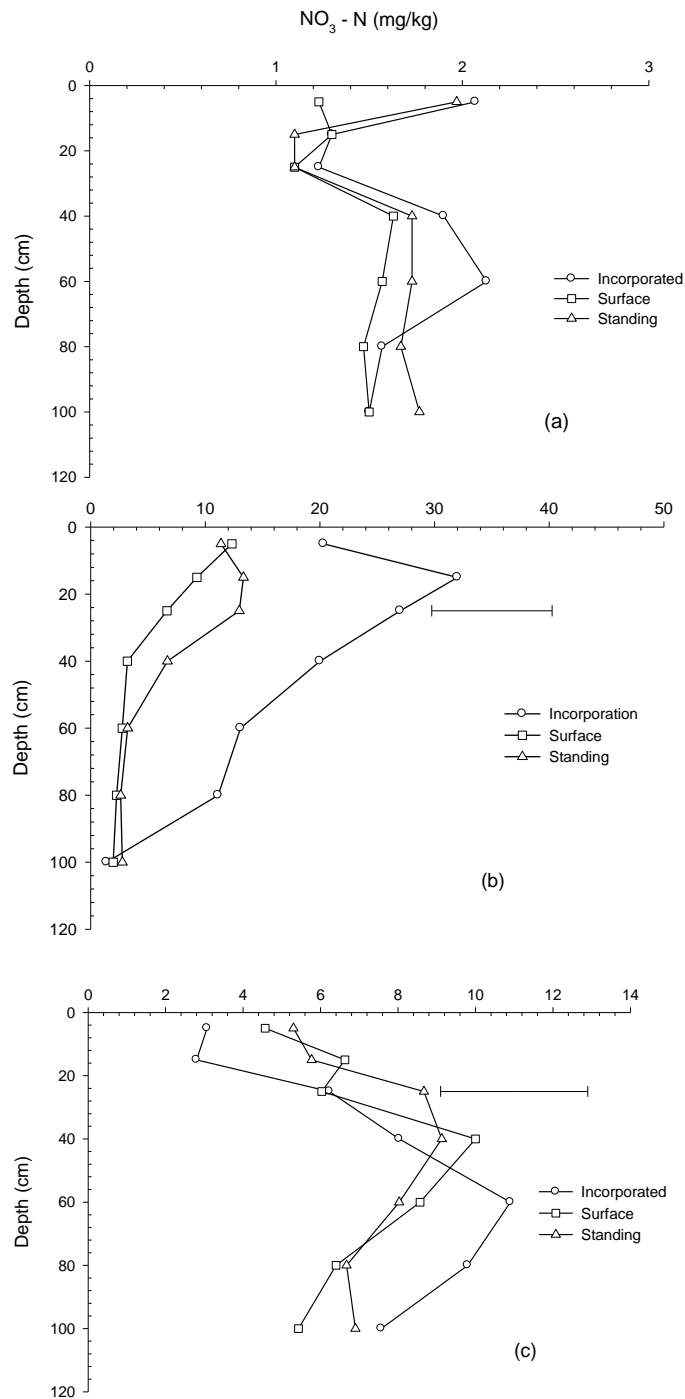


Figure 10.1. Soil nitrate profiles under different soybean residue management systems at (a) time 0 (just prior to incorporation of material), (b) 70 days after incorporation (just prior to establishment of a cane crop) and (c) 136 days after incorporation. Horizontal bars represent the least significant difference $p < 0.05$.

Clearly the substantial loss of mineralised nitrate in the case of the incorporated treatment represents a significant ‘waste’ of the potential 271 kg N ha^{-1} initially added in the soybean crop. Virtually none of this nitrogen is likely to have been used by the cane crop as by day

136 the cane crop had only been in the ground for 63 days and took at least 30 days to emerge.

Table 10.4. Nitrate nitrogen contents of soil profiles to 110 cm under different residue management systems. Positive changes in NO₃-N content between days 70 and 136 represent a net loss from the profile, whilst a negative value reflects a net addition to the profile.

Residue management	Days after incorporation of soybean crop			Difference between 70 and 136 days
	0	70	136	
	kg NO ₃ -N ha ⁻¹			
Incorporated	22.5	206.1	101.6	104.5
Surface retained	19.1	58.4	93.6	-35.2
Standing	21.5	81.9	97.4	-15.5

Changes in soil pH under residue management

Temporal changes in soil pH were monitored at each sampling date for the selected treatments and are presented in Figure 10.2. With time there was a gradual decrease in soil pH down the entire profile indicating that the mineralisation of organic nitrogen, along with the uptake of cations, resulted in net proton addition. The degree of acidification from November 1997 to May 1998 appeared greater and more extensive under the incorporated treatment. This may in part be attributed to temporal fluctuations and variability between sampling dates since the imposition of residue management treatments did not occur until May 1998. Between May 1998 and October 1998 all treatments showed declines in soil pH to depth. However, in the case of the incorporated treatments, the shape of the curve in October 1998 differed from the two non-incorporated treatments (Figure 10.2). This can be ascribed to the neutralising influence of the incorporated residue that had been mixed with the top 25 cm of soil. The net acid addition (NAA) over the 0-30 cm depth interval for the incorporated, surface retained and standing treatments was estimated to be 15.8, 21.5 and 21.5 kmol H⁺ ha⁻¹ respectively. The lower net acid addition observed under the incorporated treatment is indicative of the influence of the decomposing residue and the release of alkalinity that would effectively neutralize a portion of the acidity generated during nitrogen mineralization. Increased acid generation in surface soils as observed in the two non-incorporated treatments is commonly observed in no-tillage production systems (Phillips and Young, 1973).

Yield response of sugarcane

Responses to applied treatments on the sugarcane crop and selected yield components for the 1999 and 2000 crops are presented in Table 10.5. No significant differences in yield and ccs were observed over the treatment range. However, selected treatments appear to have out-performed the control treatment during the 1999 season although there were no clear trends.

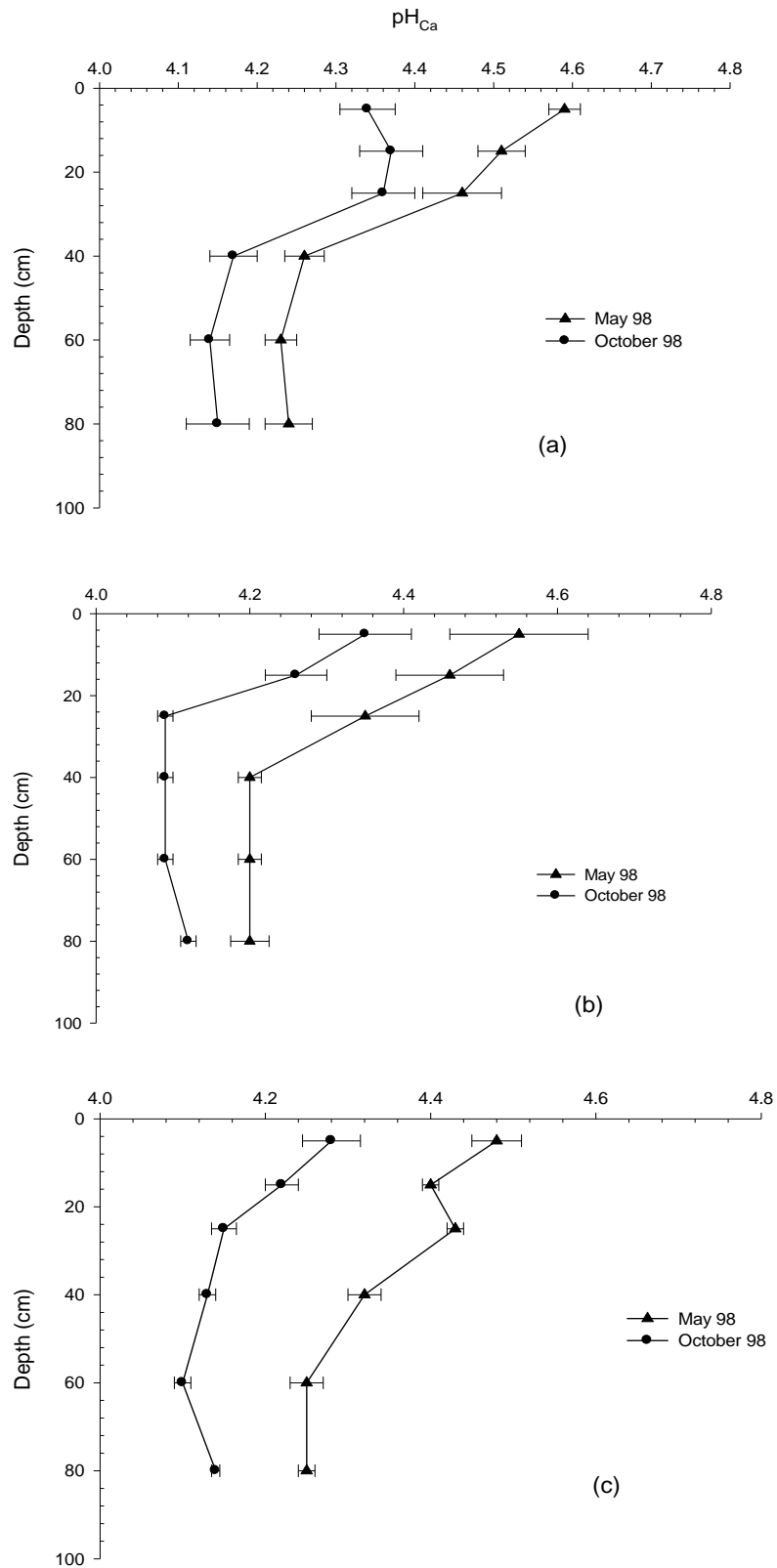


Figure 10.2. Temporal changes in soil pH_{Ca} associated with (a) the incorporation of soybean residue, (b) surface retention and (c) standing residue. Horizontal bars represent the stand error of the mean.

Table 10.5. Yield response to applied treatments over the 1999 and 2000 growing season at Feluga.

Treatment	Lime	Gypsum	Soybean residue management	Yield	CCS	Yield	CCS
	(t/ha)	(t/ha)		1999		2000	
				(t/ha)	(%)	(t/ha)	(%)
1.	0	0	Incorporated	53.9	12.3	70.7	9.5
2.	0	5.0	Incorporated	60.0	12.1	71.1	10.7
3.	2.5	0	Incorporated	60.7	12.3	66.2	10.5
4.	2.5	5.0	Incorporated	71.2	11.3	59.1	10.6
5.	5.0	0	Incorporated	79.4	11.2	56.8	9.3
	5.0	5.0	Incorporated	61.6	10.9	63.7	10.4
6.	10.0	0	Incorporated	69.9	12.1	70.7	10.9
7.	10.0	5.0	Incorporated	68.6	10.7	68.2	10.0
8.	0	0	Standing	63.9	11.4	72.7	9.7
9.	0	0	Surface applied	58.6	12.4	76.6	10.2
10.	5	0	Incorporated +140 kg N/ha	77.0	11.7	64.1	9.7
LSD (0.05)				16.4	1.0	13.1	1.2

General Discussion and Practical Implications

The results from this study clearly demonstrate that the addition of soybean residue to the soil results in significant amounts of nitrate nitrogen generation that is readily available for plant uptake. However, at least on the wet tropical coast, residue management significantly influences the efficacy of this legume nitrogen. Data presented here shows that the traditional practice of incorporating the residue results in rapid mineralisation and subsequent movement down the profile through leaching. Contrasting with this, the retention of residue either on the soil surface or as a standing crop reduces the rate of mineralisation and subsequent release of nitrate thereby resulting in significantly reduced leaching. Although processes other than leaching, such as denitrification and surface runoff, which may result in significant nitrate losses have not been taken into account, it is unlikely that they contributed significantly to the nitrogen dynamics in this study. Associated with these mineralisation processes and subsequent leaching of nitrate is a significant decline in soil pH.

There are several field implications for sugarcane farming systems on the wet tropical coast that emerge from this study. First, to effect maximum utilisation by the plant cane crop of nitrogen generated from soybean residue, establishment of the sugarcane crop should occur as soon as possible after the maturity of the break crop. Second, the soybean residue should not be incorporated but should be maintained on the soil surface. Third, a practical means of reliably establishing a sugarcane plant crop without land preparation will be necessary to accommodate these two requirements. Such technology is now becoming available with the development of strategic tillage (Braunack *et al.*, 1999). It is not hard to envisage the removal of the old ratoon with herbicide or a narrow line of cultivation, the establishment of a soybean crop through direct drilling several rows into the old cane mound, and the direct planting of sugarcane into surface retained soybean residue. In such a system significant benefits in timeliness of operations are likely to be realised (McPhee *et al.*, 1995).

The data presented here came from a single legume species grown on a relatively permeable soil in a high rainfall area. The wider application of these results requires further evaluation. However, some leads as to their general applicability can be gained from other rotation studies being conducted as part of the Sugar Yield Decline Joint Venture. First, in a previous study at this site (Garside *et al.*, 1998) it was shown that the mineralisation and movement

down the profile of nitrate nitrogen from incorporated peanut residue followed a similar pattern to that from soybean residue. This suggests that the trends measured here are not specific to soybean, but are applicable to other legumes. Second, the results from rotation experiments conducted in lower rainfall, higher latitude areas, such as Mackay and the Burdekin, clearly indicate that soybean can grow as well and contribute as much nitrogen in these environments as on the wet tropical coast (Garside *et al.*, 1999). Finally, the major differences between more southerly cane growing areas and the wet tropical coast are that the former has lower annual rainfall and less permeable soils. Both of these factors would tend to suggest that surface maintenance of legume residues as opposed to incorporation is unlikely to result in the same benefits in these more southerly cane growing areas, but this needs to be evaluated. Regardless, providing there is no adverse effect on the growth of the following sugarcane crop, advantages associated with reduced tillage and the timely establishment of the sugarcane crop are likely to be realised with surface management of legume residues.

11. LONG TERM EFFECTS OF LIME ADDITIONS ON SUGARCANE YIELDS AND SOIL CHEMICAL PROPERTIES

Introduction

Since it was not considered worthwhile to follow the long-term effects of lime and gypsum on cane yields and soil chemical properties in the trials established in the Herbert as part of this project due to their lack of responsiveness, it was decided to use some long-term data gathered by Andrew Noble from a lime trial established by BSES at their research station at Tully, north Queensland. This dataset allows the effects of lime additions on sugarcane yields and on soil chemical properties to be examined over a time period of 18 years.

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 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 were evaluated with reference to changes in surface and sub-soil chemical characteristics, and productivity over an 18 year period after the initiation of treatments.

Methodology

Site

The trial was established in November 1978 at the BSES experiment farm, Tully, north Queensland ($17^{\circ} 59'S$; $145^{\circ} 56' E$). 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 watercourses 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 %).

Experimental design and analysis

The experiment consisted of five replications of a randomised 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 (calcitic) additions are considered in this study (Table 11.1). The lime treatments were surface broadcast in November 1978 prior to planting of the plant cane crop in 1979 and incorporated using a plough and disc to a depth of 20 cm. The lime source used had a neutralising 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 m by 11.0 m. Blocks were separated by a 5 m buffer. 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 applied at standard rates recommended for the sugar industry and were as follows:

Nitrogen: 140 and 165 kg/ha N for plant and ratoon crops respectively.

Phosphorus: 45 and 30 kg/ha P for plant and ratoon crops respectively.

Potassium: 100 and 120 kg/ha of K for plant and ratoon crops respectively.

Table 11.1. Treatment codes and combinations as applied from 1978 to 1990.

Treatment Code	Year treatments applied		
	1978	1983	1990
T1	nil	nil	nil
T2	5t ha ⁻¹ Lime	nil	nil
T3	5t ha ⁻¹ Lime	5t ha ⁻¹ Lime	5t ha ⁻¹ Lime

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 diameter truck-mounted hydraulic core sampler and composite samples for each depth interval were 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 Ca²⁺, Mg²⁺, K⁺ and Na⁺ were extracted using 0.1 M BaCl₂/0.1 M NH₄Cl (Gillman and Sumpter, 1986) and determined by atomic absorption spectroscopy (Ca²⁺ and Mg²⁺) and flame emission spectroscopy (K⁺ and Na⁺). Exchangeable acidity (Al³⁺ + H⁺) was determined after extraction with 1 M KCl and extracts titrated against 1 M NaOH (Rayment and Higginson, 1992). Soil pH was determined in both water (pH_w) and 0.01 M CaCl₂ (pH_{Ca}) in a 1:5 soil-to-solution ratio. Mineral nitrogen (N) in the soil profile was determined by extracting 10 g of air dried soil in 2 M 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 study. However, due to logistical problems, composite treatment samples were only analysed thereby preventing any rigorous statistical analysis of the 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 standardise 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 and the two lime treatments is presented in Figure 11.1. There was a consistent and significant increase in yields in those treatments receiving lime. While yield differences were lower in years 1985 and 1992, which coincided with plant crops, there was in general an increase in the differences in yield over the control with successive ratoons. The influence on yield of a single application of lime made in 1978 (T2) was still evident 17 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 (Figure 11.1). As discussed previously, the magnitude of the response increased with time (Mallawaarachchi *et al.*, 1998; see section 12). 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 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; see section 12).

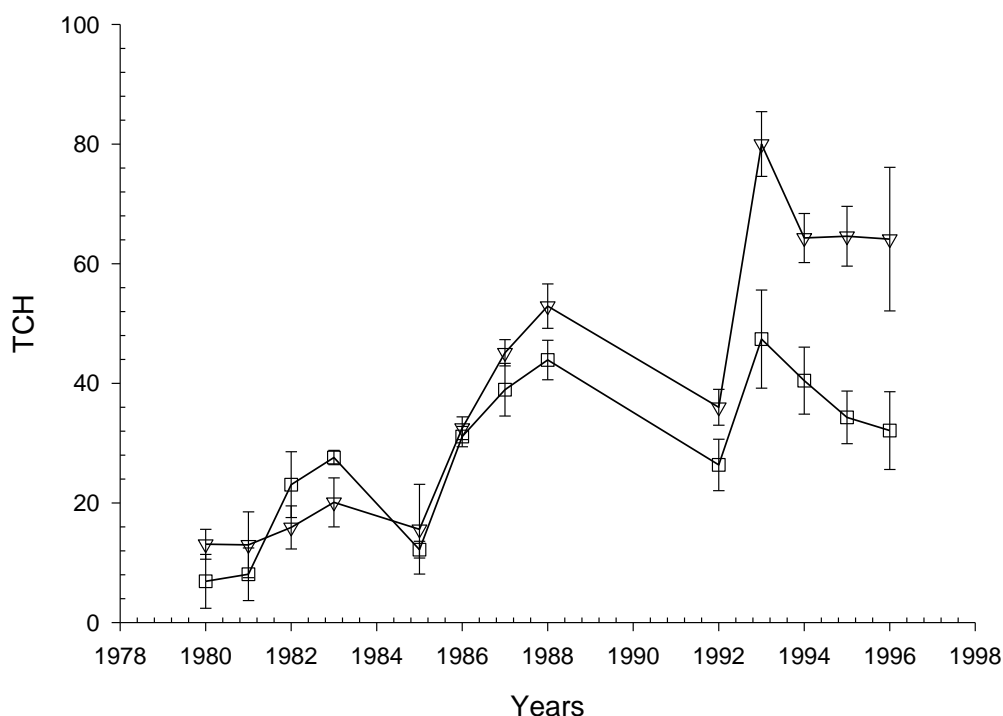


Figure 11.1. Yield differences (tonnes cane harvested - TCH) over time between a single application of lime and the control (T1) (□) and between repeated applications of lime and the control (∇). Vertical bars represent the standard error (SE) of the mean.

Exchangeable Ca²⁺, Mg²⁺, K⁺ and Na⁺

The effects of lime additions are clearly reflected in terms of soil analytical data 17 years after the initiation of the study (Figure 11.2). Significant increases in exchangeable Ca²⁺ from 60 to 100 cm were observed in all treatments receiving additions of lime (Figure 11.2a). The greatest increase in Ca²⁺ 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 Ca²⁺ in the 0 to 50 cm depth interval suggesting that any previous effects of increased Ca²⁺ in the upper portion of the profile were no longer evident 17 years after application. This may be indicative of the higher levels 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 of soil (R. O. Nable personal communication). The extremely low level of exchangeable Ca²⁺ in the control treatment after 17 years of continuous production (profile mean concentration 0.07 cmol/kg) would suggest that this treatment is predisposed to severe Ca²⁺ deficiency since it falls well below the published critical value of 0.55 cmol/kg (Calcino, 1994). Similarly, those treatments receiving single and repeated applications of lime exhibited a mean profile Ca²⁺ concentration of 0.19 and 2.0 cmol/kg, suggesting that a total of 5 t of lime per hectare was insufficient to alleviate possible Ca²⁺ 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 Ca^{2+} availability down the profile. Indeed plots of yield against mean exchangeable Ca^{2+} levels in the 0-25 and 25-100 cm respectively showed significant correlations between this soil parameter and yield (Figure 11.3a and b).

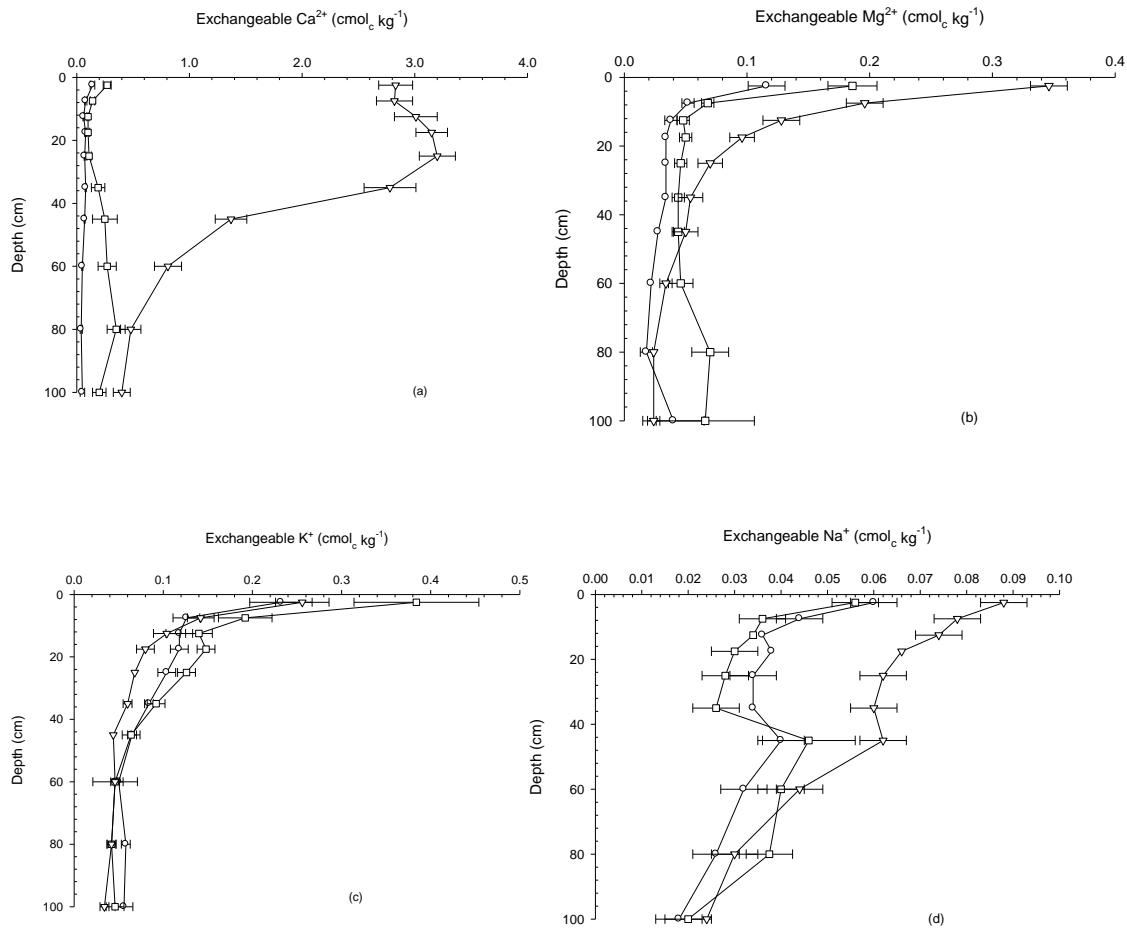


Figure 11.2. Long-term effect of lime additions on (a) exchangeable Ca^{2+} , (b) Mg^{2+} , (c) K^+ and (d) Na^+ ; (O) denotes the control treatment; (□) represents a single application of lime; (∇) represents multiple applications of lime. Horizontal lines represent the SE of the mean.

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 (Figure 11.2b). 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 likely on this site. In the current study, a significant relationship between exchangeable Mg^{2+} in the top 25 cm and yield was observed (Figure 11.4). However 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 and that the source of lime was classified as calcitic. However, it is clear that there must have been significant amounts of Mg in the lime used. 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 when compared to the control in the 20 to 50 cm depth interval (Figure 11.2c). This may in part be attributed to the increased Ca^{2+} and Mg^{2+} concentrations on the exchange complex in this treatment. The concentration of Na^+ on the exchange complex increased significantly in the 0-40 cm depth interval in those treatments receiving repeated lime additions. This again is thought to be due to possible impurities in the lime source (Figure 11.2d).

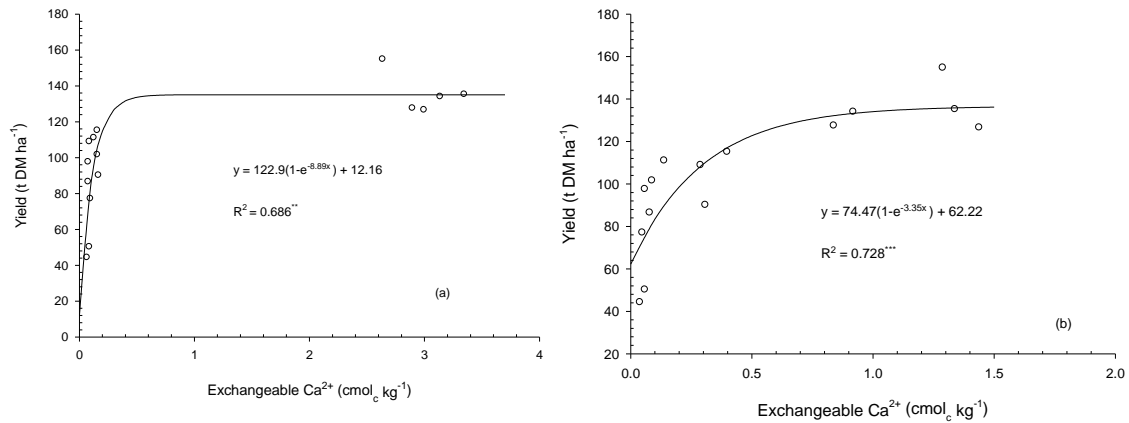


Figure 11.3. Relationship between yield of sugarcane and exchangeable Ca^{2+} as measured in (a) the 0-25 cm and (b) 25-100 cm depth intervals.

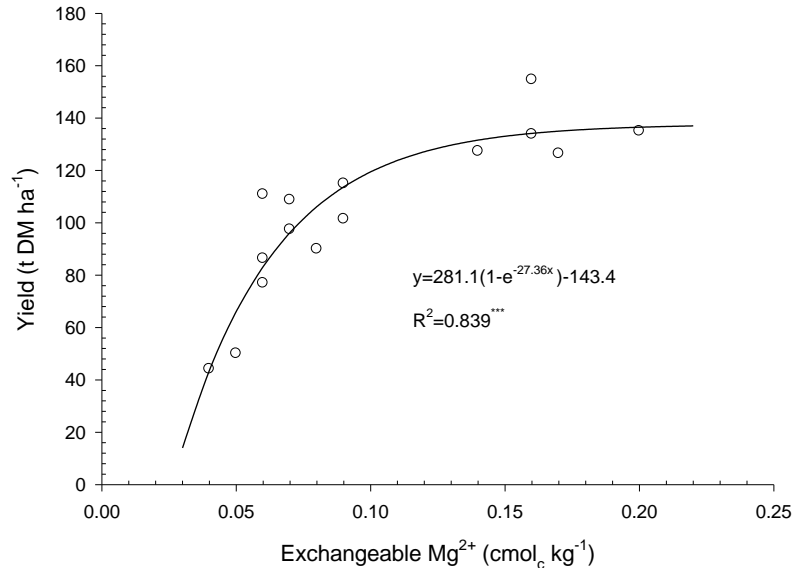


Figure 11.4. Relationship between exchangeable Mg^{2+} in the 0-25 cm depth interval and cane yield.

Soil pH and exchangeable acidity

In the treatment receiving no amendments (T1), the pH_w profile ranged from 4.6 in the upper horizons to 4.3 at 1 m (Figure 11.5a). This relatively uniform 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 pH_w to 100 cm when compared to treatment T1 (Figure 11.5a). This difference in pH_w at 100 cm was

approximately 0.5 of a pH unit between T1 and the limed treatments (T2 and T3). In contrast, the aforementioned differences between treatments were not as striking when pH_{Ca} values are compared (Figure 11.5b).

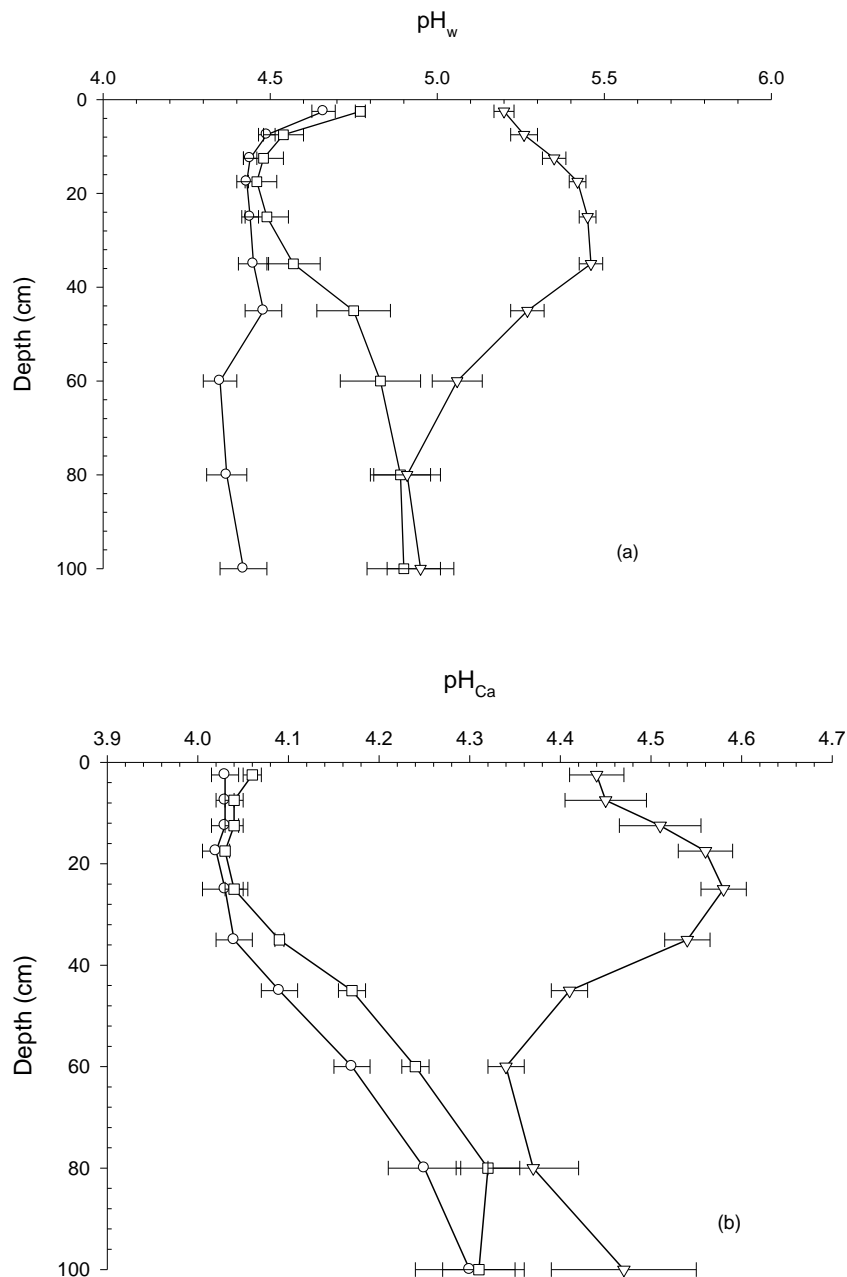


Figure 11.5. Long-term effects of lime additions on (a) pH_w in water and (b) pH_{Ca} in 0.01 M $CaCl_2$. (O) denotes the control treatment; (□) represents a single application of lime; (▽) represents multiple applications of lime. Horizontal lines represent the SE of the mean.

In this case at 100 cm significant differences were observed only in the treatment receiving repeated applications of lime. The differences observed in the 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 pH_w and pH_{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 (Figure 11.6). This decrease is due to a combination of increased Ca^{2+} and Mg^{2+} with depth resulting in increased base saturation (Table 11.2). In contrast, significant differences between T1 and T2 were only evident in the 40 to 60 cm horizon. 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 11.2). This is consistent with respect to a soil that is dominated by permanent charge and confirms previous determinations of charge characteristics for a similar soil by Gillman and Abel (1987).

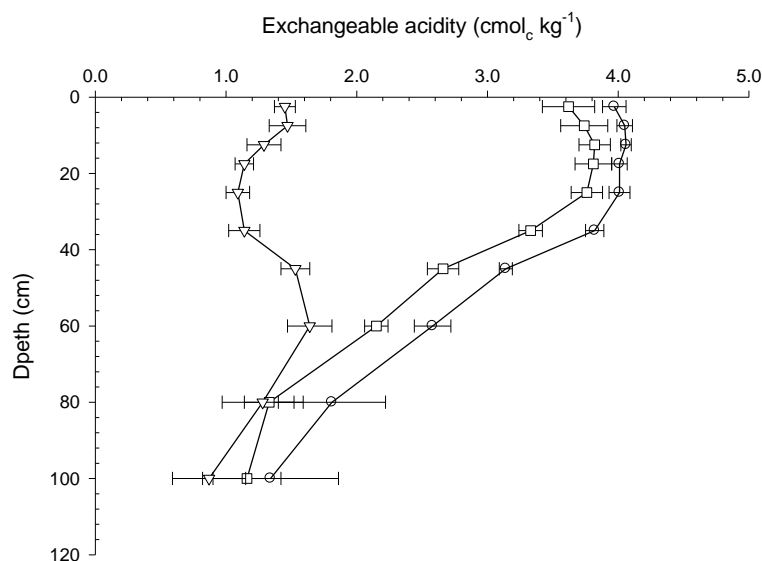


Figure 11.6. Long-term effects of lime additions on exchangeable acidity. (O) denotes the control treatment; (□) represents a single application of lime; (V) represents multiple applications of lime. Horizontal lines represent the SE of the mean.

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 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 in the form of HCO_3^- or OH^- must be transported by mass flow from surface horizons to the subsoil (Sumner, 1995). Notwithstanding the fact that the HCO_3^- ion is relatively unstable and decomposes to CO_2 and H_2O (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 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 11.2). In addition, in the current study pH_w did not rise above 5.5

thereby suggesting an alternative mechanism was operative that facilitated the significant downward movement of alkalinity and the observed increase in pH with depth.

Table 11.2. ECEC and base saturation values for each of the treatments.

Depth (cm)	Treatments		
	T1	T2	T3
	<u>ECEC (cmol_c kg⁻¹)</u>		
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
	<u>Base saturation (%)</u>		
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±8.3	35.2±15.8
90-110	16.5±5.1	22.0±8.2	41.7±16.3

The transfer of alkalinity to depth from surface application or incorporation of lime has been reported previously by several authors (Abruna *et al.*, 1964; Adams and Pearson, 1969). This is effected through the formation of Ca(NO₃)₂ in the limed topsoil in the presence of ammonium based fertilisers and its subsequent leaching to the subsoil, where the more rapid rate of assimilation of NO₃⁻ over Ca²⁺ 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(NO₃)₂ or NaNO₃. However, it has been demonstrated that in the absence of actively growing plants the application of Ca(NO₃)₂ as a means of remediating 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 Ca²⁺, and to a lesser degree Mg²⁺, was facilitated through the possible formation of ion pairs with NO₃⁻. Indirect evidence of this mechanism can be inferred from the mineral nitrate profiles of the individual treatments. Significant accumulations of NO₃ - N at depths greater than 60 cm in the profile of the T1 treatment were observed thereby inferring limited root activity (Figure 11.7).

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 Ca²⁺ (Ridge *et al.*, 1980). With the enhanced Ca²⁺ and Mg²⁺ status with depth a more

hospitable environment for root growth may have been created thereby facilitating the uptake of leached NO_3^- from depth with an associated increase in pH.

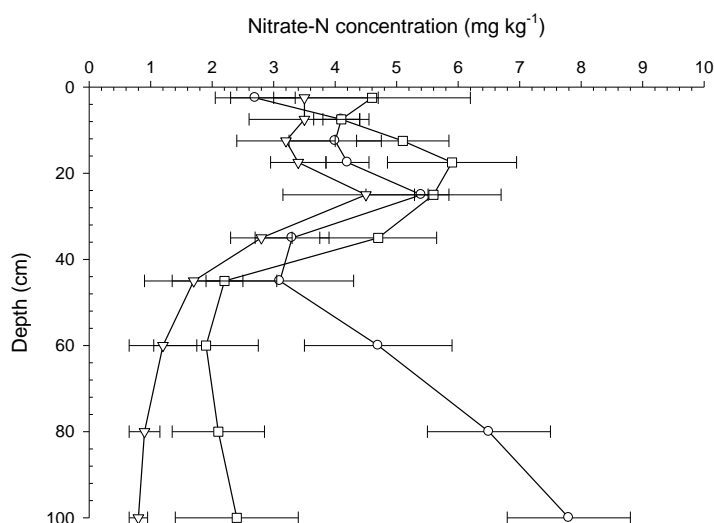


Figure 11.7. Effects of lime treatments on soil mineral nitrate profiles. (O) denotes the control treatment; (□) represents a single application of lime; (∇) represents multiple applications of lime. Horizontal lines represent the SE of the mean.

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

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

Of the 1846 and 5538 kg Ca^{2+} added in the form of lime to treatments T2 and T3 respectively, 879 and 1104 kg Ca^{2+} was not accounted for and is assumed to have been leached below 110 cm (Table 11.3). This estimation of a Ca^{2+} mass balance clearly indicates that significant leaching has occurred in this environment and if NO_3^- was the counter ion associated with Ca^{2+} , one would expect significant losses to have taken place.

Table 11.3. Estimated Ca budget for each of the treatments.

	T2	T3
Total amount of Ca^{2+} applied (kg ha ⁻¹)	1846	5538
Total Ca^{2+} in the soil profile (kg ha ⁻¹)	608	4035
Total Ca^{2+} exported in the crop (kg ha ⁻¹)	359	399
Total Ca^{2+} leached (kg ha⁻¹)	879	1104

The results demonstrate that considerable economic benefit is derivable from repeated lime additions under field conditions and emphasises the need for managers to consider lime applications routinely as part of their management inputs on these particular soils. After 17 years, repeated applications of lime (T3) resulted in a greater than 65 t/ha dry matter increase over 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 that 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^{2+} and Mg^{2+} for sugarcane that are currently in use (Calcino, 1994). These recommendations specifically address the issue of Ca^{2+} nutrition and should not be confused with the issue of remediating or preventing soil acidification. In the case of remediating a Ca^{2+} insufficiency the use of materials such as gypsum or phosphogypsum could be considered since these are far more effective sources of Ca^{2+} 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 remediating a Ca^{2+} deficiency and acidity problem. The results presented clearly show 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_w 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 characterised 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.

12. LONG TERM PROFITABILITY OF LIME ADDITIONS TO MANAGE SOIL ACIDITY

Introduction

Most of the soil orders that predominate in sugar producing areas of eastern Australia are inherently acidic and of a relatively low fertility (Ahern *et al.*, 1995). Almost 90 % of the soils used for cane production along the east coast of Australia are classified as naturally acidic ($\text{pH}_w < 5.6$) (Ahern *et al.*, 1995). Whilst soil acidification is not perceived as a high priority issue by most Australian farmers, it is a potentially significant resource degradation issue and is considered a major barrier to adoption of soil acidification amelioration methods (AACM, 1995). Currently within the sugar industry, \$ 3.5 million worth of lime is applied to 10 000 ha on an annual basis (Kingston and Aitken, 1996). But they have argued that this is far too low, and that 40 000 ha of cane land should be treated on an annual basis.

It has been clearly shown that long-term sugarcane monoculture results in a gradual decline in soil fertility that is associated with soil acidification (Bramley *et al.*, 1996; Garside *et al.*, 1997; Moody and Aitken, 1997). In this respect it has been clearly demonstrated that sugarcane varieties grown in Australia are relatively tolerant of acidity (ie. low pH and Al phytotoxicity), but are highly intolerant of low levels of soluble Ca^{2+} (Hetherington, 1986; Hurney, 1971; Haysom *et al.*, 1986; Ridge *et al.*, 1980). Reghenzani (1993) showed that 67% of the soils sampled in north Queensland were Ca^{2+} deficient. It has been conclusively shown that the remediation of a Ca^{2+} deficiency can result in significant increases in yield (Quinan and Wood 1989, 1993; Hurney, 1971; Haysom *et al.*, 1986; Ridge *et al.*, 1980). Whilst the advantages of applying lime to Ca^{2+} deficient soils has been clearly demonstrated, there is a paucity of economic data outlining the financial gains to be made in undertaking a routine liming strategy. Since the current set of trials established did not permit an assessment of the financial benefits associated with applied treatments, the long-term financial returns of various liming treatments using data collected from the previously discussed long-term liming trial established in 1978 are determined. This activity was undertaken in collaboration with Dr T. Mallawaarachchi (Resource economist in the CRC for Sustainable Sugar Production) and Mr Alan Hurney (BSES Tully), the latter being responsible for the setting up and maintenance of the trial.

Methods and Materials

Site characterisation

The site characteristics and treatments used in this evaluation are described in section 11, and for brevity the treatment combinations used in this analysis are presented in Table 12.1.

Statistical and Economic Analysis

Statistical analysis of the cane yield data was undertaken using Genstat5 following a simple ANOVA approach.

In undertaking an economic analysis of the yield responses observed over the 18 years of the trial, it has been assumed that the cane crop is sold at a market price of \$ 30/t and the ccs is fixed at 13. The analysis has not taken into account the fixed costs associated with production since it has confined itself to significant differences in yield between the control (T1) and lime treatments (T2-T5). In addition, all income streams are discounted by a 6 percent discount rate and all prices reflect 1996 values. Economic analysis was undertaken using the discounted cash flow analysis and partial budgeting approaches. The discounted cash flows were evaluated based on the net present value (NPV), and the partial budgeting results were presented as gross margins.

Discounted Cash Flow Analysis

Discounted cash flow analysis is a technique used to assess the current value of a future stream of payments. Payments can include both cash inflows (incomes) and outflows (costs). Net present value measures the current value of a stream of incomes and costs discounted by the rate of interest. This approach permits the evaluation of a series of payments on the basis of its current value so that alternative investment strategies leading to different streams of costs and benefits can be compared. In the analysis presented in this paper, different treatments of the liming experiment represent alternative investment strategies.

Gross Margin

Gross margin represents the difference between income and variable costs. The values are measured in current dollar terms and it is therefore more appropriate to measure single year activities. In this paper the gross margins are evaluated as an average over the duration of the experiment, primarily to illustrate the profitability differences amongst treatments. In addition, a sensitivity analysis was undertaken with respect to changes in the prices of cane and lime for the most economic treatment combination.

Results

Yield responses

The mean difference in tonnes of cane per hectare (TCH) from the control treatment are presented in Figure 12.1. It is of note that there was a lag period of 4 years before significant differences between the control (T1) and those treatments receiving lime additions were observed (Figure 12.1). The lack of significance over this period may in part be ascribed to severe lodging of the crop which made harvesting difficult. Thereafter there was a consistent and significant ($P < 0.05$) increase in yield between those treatments receiving lime when compared to the control. Whilst yield differences were lower in years 1985 and 1992, which coincided with plant crops, there was in general an increase in the differences in yield from the control with successive ratoons. Differences between those treatments receiving varying lime additions were not observed until 1993 when treatment T2 (lime 5 t/ha; 1978) showed significant ($P < 0.05$) decreases in yield. This trend has persisted through to the 1996 harvest.

It is clear from Figure 12.1 that the magnitude of the yield response increased with time. This increase probably reflects the progressive improvement in the soil fertility status, in particular an increase in Ca^{2+} on the exchange complex, and an arresting of the negative attributes associated with continued acidification (Noble *et al.*, 1997). In this respect, significant improvements in subsoil properties have been observed over the 18 year period with greater quantities of alkalinity and exchangeable bases being moved down the profile (Noble *et al.*, 1997). It is plausible that, depending on the longevity of the response to repeated applications of lime on soil chemical properties, that the cumulative benefits of lime addition 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 T2 (5 t/ha lime) made in 1978 no significant decline in yield was observed from those treatments receiving regular applications of lime until 1993. Consequently, due to the persistence of the observed responses through lime additions, the economics of applying lime on these soils would make liming an extremely attractive management option.

Economic analysis

Economic evaluation indicated that T3 (Lime 5 t/ha in 1978 + 1.25 t/ha in 1983 and 1990), was the most economically attractive option (Table 12.1). With an initial application of 5 t/ha of lime followed by repeated applications of 1.25 t/ha at plough out, T3 represented the least cost option. It is of note that there was a steady and significant decline in the yields in

T1 over the 17 year period when compared to the limed treatments, indicating a progressive deterioration in the ability of the soil resource to supply adequate nutrition (Figure 12.1). This practice (ie. cane production without liming) is clearly exploitative and unsustainable.

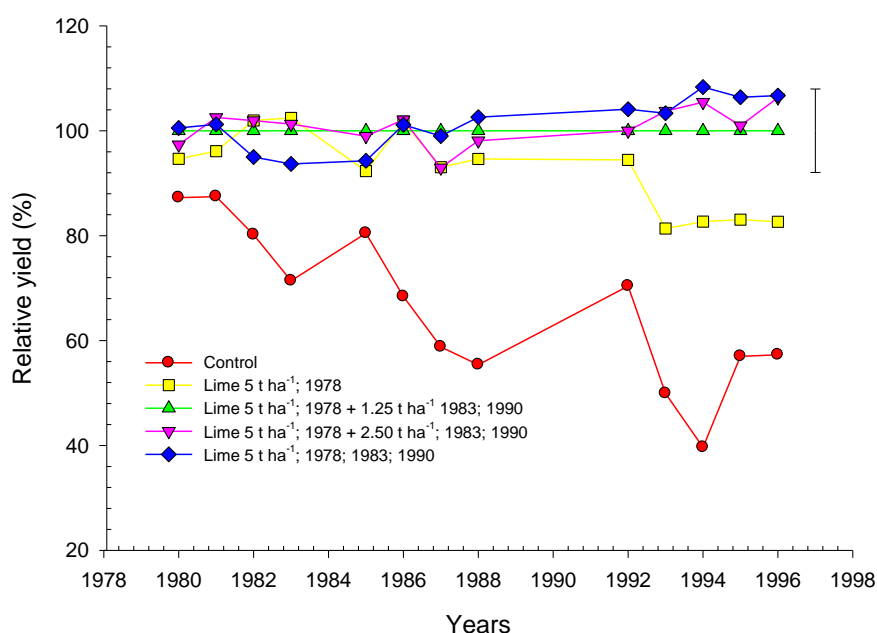


Figure 12.1. Yield differences from the control (zero application of lime) associated with varying rates of lime application over an 18 year period. The vertical bar represents the LSD ($P<0.05$) between treatment means.

Table 12.1. Net Present Value (NPV) of income streams per ha of sugar cane over 15 years

Treatment	Description	NPV \$
T1	Control; no liming	3686
T2	Lime 5 t/ha ; 1978	5329
T3	Lime 5 t/ha ; 1978 + 1.25 t/ha 1983, 1990	6088
T4	Lime 5 t/ha ; 1978 + 2.50 t/ha 1983, 1990	5993
T5	Lime 5 t/ha ; 1978 + 5.0 t/ha 1983, 1990	5824

The net revenue over the 18 year period was highest for T3 which yielded a cumulative net present value (NPV) of income per hectare of sugarcane of \$6088 as compared to T1, which yielded a mere \$3686 (Figure 12.2). The cumulative net present value of income per hectare also highlights the extent of revenue forgone by a grower for not adopting a soil acidity management plan (Figure 12.2). In this case the “do nothing” operator who adopted a strategy of not adding lime would have incurred a potential loss in profit of \$ 2402/ha over an 18 year period. In addition, the potential benefits that accrue due to lime application is further highlighted by comparing the costs associated with liming to the returns over an 18 year period. For example, the present cost of liming treatments ranged from \$241 in the case of T2 to \$437 in T5, with the liming costs associated with T3 being \$290. Whilst it may be argued that the differences between treatments receiving lime applications are not substantial per hectare of cane land, these differences would be significant for a farm size of 74 hectares.

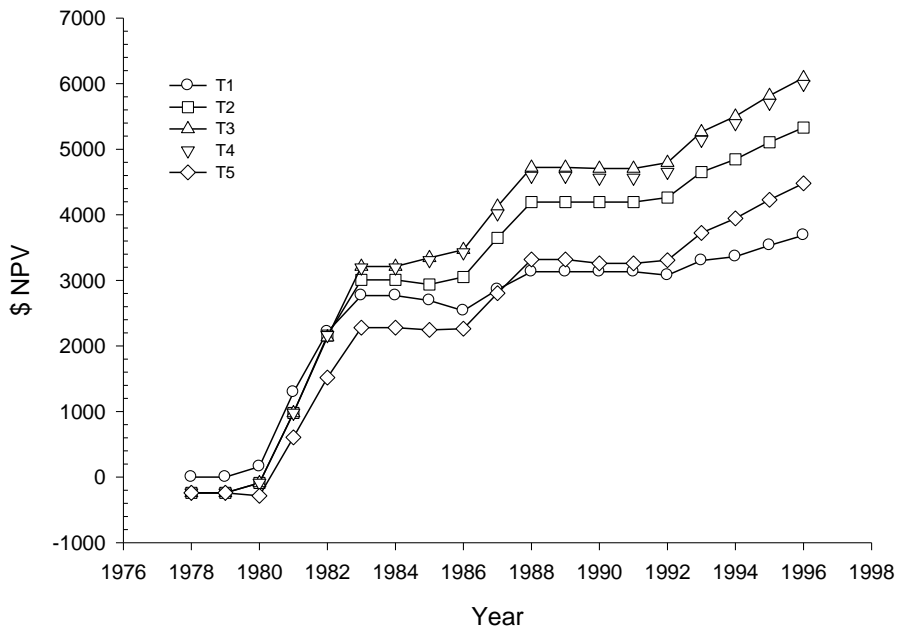


Figure 12.2. Profitability differences between treatments receiving varying rates of lime additions.

Conceptually, most growers are familiar with the term “gross margin” which effectively represents the difference between gross income received for the cane crop and the variable cost of producing the crop. In analysing the long-term benefits of liming with respect to average gross margins over the past 18 years it is clearly evident T1 was inferior to the other four treatments (Figure 12.3). The difference in average gross margins between treatments T1 and T3 was estimated to be \$756 per year which represents a substantial loss in net income to the grower.

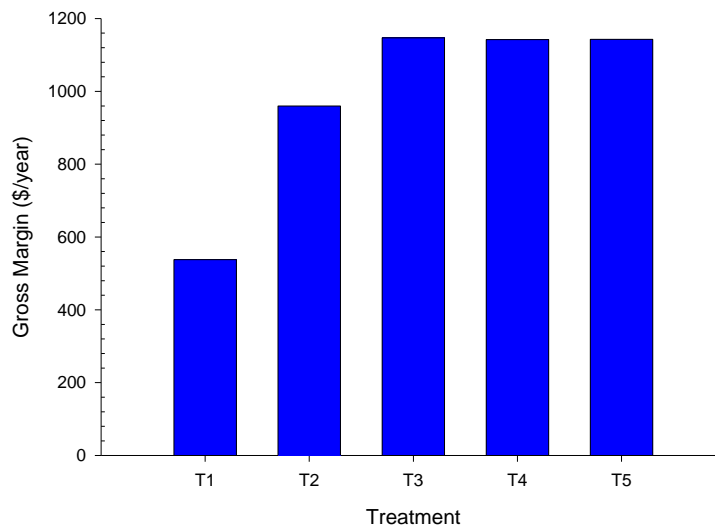


Figure 12.3. The average gross margins on an annual basis for the various treatments. T1 = Control (no liming); T2 = Lime 5 t/ha in 1978; T3 = Lime 5 t/ha in 1978 + 1.25 t/ha in 1983 & 1990; T4 = Lime 5 t/ha in 1978 + 2.50 t/ha in 1983 & 1990; T5 = Lime 5 t/ha in 1978, 1983 & 1990.

A sensitivity analysis of the data was undertaken in order to assess the influence of changes in the price of both of cane and lime on the profitability of the treatment T3 (Figure 12.4). As expected, the level of benefits associated with the application of lime were more sensitive to fluctuations in the price of cane than to the price of lime. In this respect, a 20 percent reduction in the price of cane would result in a net reduction in benefits of approximately 45 percent from \$6088 to \$3368/ha over the period of study. In contrast, a 10 percent increase in the cost of liming would result in less than a 1 percent decline in expected benefits based on the current price of cane (Figure 12.4). These results highlight the cost effectiveness of undertaking a strategic liming program. Canegrowers who maintain the fertility of their soil resource base through a prophylactic liming program would be better equipped to face the vagaries of a falling international sugar price or any such factor that affects net farm returns.

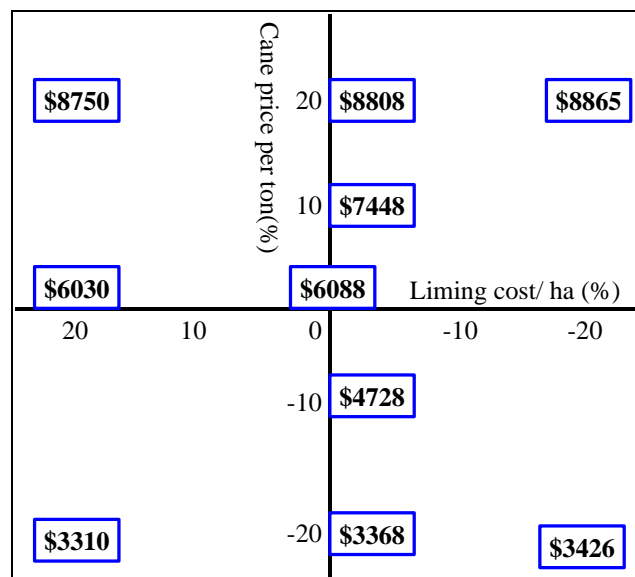


Figure 12.4. Sensitivity of net benefits of liming to changes in cane price and the cost of lime applied at a rate equivalent to T3; Lime 5 t/ha ; 1978 + 1.25 t/ha 1983, 1990.

The above analysis clearly shows that the level of investment required by a grower to maintain sustainable cane yields on a soil that is highly responsive to lime is very small. In contrast, the direct benefit associated with this small investment appears to be substantial. However, the yield responses observed between treatments cannot be entirely attributable to the addition of lime as there are other external factors such as climate that may have contributed to yield variations.

In evaluating the relative proportion of costs associated with liming as a proportion of the average annual variable costs associated with growing a cane crop, the average annual variable costs of a farm in the Herbert River District was used as a benchmark. If the average annual variable costs are taken to be \$1332/ha, the cost of applying lime at a rate equivalent to T3 would essentially account for 1.8 percent of the variable costs. If this is compared to the 8 percent costs associated with general fertilizer inputs, the contribution of liming to the overall variable costs of \$ 1332/ha is negligible. In terms of returns over the period that this study has been running, this investment leads to around a 200 percent increase in annual gross margins. The question that a grower should be asking is whether it is worth spending 2 per cent of annual returns to secure the future productive potential of the farm. One can only conclude that this is an extremely reasonable insurance premium to pay.

Discussion and Conclusions

Anthropogenic induced soil acidification under cane production systems is best described as an insidious process that is directly linked to current production activities. Increased net product removal from a paddock and the high level of nitrogenous fertilizer use are probably the major external factors contributing to soil acidification in the industry. The long-term consequences of uncontrolled accelerated acidification, is a decline in the quality of the soil resource base and associated productivity. This will inevitably result in lower farm income and declining resource rents to the society. Resource rents refer to net profits attributed to the use of the soil resource, where a decline in soil productivity would result in a decline in rents. There is a general perception amongst growers that strategic applications of lime are desirable in order to reduce the risk of declining yield. However, to date there has been a paucity of information on the economics associated with such strategies.

The results presented here provide clear evidence that surface incorporated lime applied in 1978 to a typical Ca^{2+} deficient soil found in the wet tropics, was effective in sustaining and increasing yields over the past 18 years. It is of note that there was a lag period of 2 years before significant differences were observed between the control treatments and those receiving lime. As previously discussed by Noble *et al.*, (1997), this site was classified as highly deficient in Ca^{2+} and the responses observed are most likely due to an amelioration of this insufficiency. It is suggested that the reason for the 2 year lag period before a significant response to the lime applications was observed may in part be explained by the severe lodging that was observed in those crops receiving lime treatments.

The economic analysis presented demonstrates that accelerated soil acidification with associated declines in exchangeable bases, is associated with direct potential costs to the canegrower. It can be argued that it is of public interest to manage soil acidification, as land resources are finite and a reduction in regional resource endowment through acidification imposes potential public costs. Numerical analysis of agronomic data confirms that the level of investment required by a farmer to maintain sustainable cane yields on a soil with a high level of acidity risk is very small. In contrast, the direct benefit associated with this investment appears very large. The risk of acidification of cane-land under different agronomic management regimes can vary considerably. However, in the absence of such information on specific cane paddocks, this analysis at least provides canegrowers with a rough guide for choosing the appropriate level of expenditure, and indicates the range of likely benefits of undertaking prophylactic lime treatment of cane paddocks.

Depending on soil characteristics and management regimes, the rate of acidification will vary between paddocks. In addition, the cost of amelioration of soil acidity is likely to increase at an exponential rate as soil pH decreases and exchangeable bases, in particular Ca^{2+} , are lost from the exchange complex. In order to avoid the long term negative effects of acid soil infertility, routine prophylactic applications of lime should be undertaken by growers. As outlined by Noble *et al.*, (1997) a possible long-term strategy to reduce the consequences of downward acidity movement in a profile, is to maintain the surface soil pH above 5.6.

It is quite conceivable that with a prophylactic liming strategy, this target will be reached over time. The results of this analysis offer guidance for canegrowers to prioritise their treatment plans, following a “prevention is better than cure” attitude, where greater benefits would be obtained by commencing treatment of those lands that have yet to develop the problem. Profits gained through such treatment can then be channelled for further treatment of paddocks with increasing levels of acidity as long as the value of future net benefits from treatment compensates for the treatment costs. In this manner canegrowers would be able to minimise the impact of soil acidification and its associated problems on sustained cane-farm

profitability. In all situations, combining beneficial agronomic practices with lime treatment would offer greater rewards as there are likely to be synergistic benefits. Further research on agronomic management and farming system development would provide the necessary input for guiding such decisions.

13. GENERAL DISCUSSION AND CONCLUSIONS

Most sugarcane soils in the wet tropics north of Townsville are already moderately to highly acidic and are becoming progressively more acidic due to heavy applications of nitrogen fertilizer and the removal of cane to the mill. Conclusive evidence of accelerated soil acidification under sugarcane cropping has been collected as part of the research conducted within the Sugar Yield Decline Joint Venture. Soil acidification is a degradation process and continued input of acidic additions will not only continue to acidify surface soil horizons but will also progressively acidify the lower parts of soil profiles, making amelioration much more difficult and costly. Low soil pH not only reduces the availability of some nutrients to plants but can also reduce soil surface charge resulting in a permanent reduction in the capacity of soil to hold nutrients. Since many soils in the wet tropics already have a low cation exchange capacity, further reductions in CEC due to accelerated acidification may lead to sub-optimal levels of exchangeable calcium, magnesium and potassium which will have a direct impact on sugarcane yields.

Whilst the application of both lime and gypsum had a marked effect on some soil properties, their overall effect was somewhat limited during the period in which the trials were observed. In the case of lime, increasing additions resulted in significant increases in the pH of surface horizons. However the fact that these changes were confined to surface horizons clearly indicates the difficulties of transferring alkalinity to depth in these soils over a relatively short period of time. As outlined previously, in order to generate excess alkalinity the soil pH has to increase to >5.5 , the pH at which most of the soluble Al^{3+} is neutralised. Added to this, the generation of variable charge associated with the edges of clays and organic matter would influence the degree of alkalinity that moves freely. This is clearly demonstrated when one analyses the charge fingerprints of surface horizons from the control plots. Significant amounts of charge are developed over the range of pH values imposed. Associated with the increase in pH and charge generation was an increase in exchangeable Ca^{2+} . Evidence of the movement of Ca down the profile to depth was observed at all sites suggesting that the movement is associated with counter ions other than CO_3^{2-} . The amount of Ca accounted for was estimated in a mass balance undertaken for the Mizzi trial site between the initiation of the trial and the 1998 soil sampling. The total amount of Ca exported in the crop was estimated to be 23.59 kg ha^{-1} (assuming cane yields of 134.5 and 98.3 t ha^{-1} ; Ca content of $338 \text{ mg Ca kg}^{-1}$ and moisture content of 70%) for the plant and first ratoon crops. The shift in Ca down the profile associated with the application of 10 t ha^{-1} lime between the initial sampling and second sampling was 866 kg ha^{-1} (assuming a bulk density of 1200 kg m^{-3}). The total amount of Ca applied, assuming the lime had a 36% Ca content, was equivalent to $3600 \text{ kg Ca ha}^{-1}$. Clearly a significant proportion of the Ca is unaccounted for and it is suggested that it may have been lost through leaching and transient lock-up associated with trash. In addition, a significant proportion of the alkalinity applied would have been consumed through the neutralisation of acidity generated via nitrogen mineralisation. Clearly the application of relatively large amounts of lime and gypsum had a limited overall effect on soil chemical properties over the study period, indicating the importance of routine and frequent applications to maintain a desirable environment for the growth of cane.

Applications of lime are required every crop cycle in order to neutralise the acidifying effects of nitrogen mineralisation and crop harvest.

The increases in soil pH and exchangeable calcium measured in the initial three trials in the Herbert were much lower than that expected on the basis of preliminary laboratory-based experiments which included an assessment of soil pH buffer capacity, the neutralising value of the lime and the solubility of lime. The lime used was shown to have a solubility only 80% that of pure $CaCO_3$ and as a consequence was much slower in its rate of reaction. The

gypsum too was shown to contain significant amounts of silica, suggesting that some of the calcium in the gypsum was present as insoluble CaSiO_3 rather than soluble CaSO_4 . It is therefore not surprising that the effects of lime and gypsum application need to be evaluated over several years and that economic responses to lime even on responsive sites, may not appear until up to four years after the initial application. The results also suggest that a Quality Assurance program for lime and gypsum would be of value to both sellers and users of these soil ameliorants.

Commercially available lime is less soluble than pure calcium carbonate and will be slow to react. Increases in soil pH and economic responses to lime may take several years to achieve.

A lack of yield response associated with the application of lime and gypsum in the Herbert trials was not surprising as exchangeable calcium levels were marginal at the Mizzi site but well above the critical level at the other two sites. However a response had been expected at the DiBella trial, although for the reasons mentioned above the trial was probably not monitored for long enough. A plausible reason for the lack of response on sites with marginal soil calcium levels in the Herbert is the distribution of Ca down the profile, as exchangeable Ca levels commonly increase down the profile. Current liming recommendations are based largely on satisfying a Ca requirement and not on neutralising acidity, this being largely associated with the tolerance of current cultivars to acid infertile soils. However, if one reviews the Ca status of the long-term liming trial established at Tully Experiment Station, it is clearly evident that Ca levels in the control plots were sub-optimal over the entire depth sampled. One can therefore conclude that in order to illicit a response to lime additions, sub-optimal Ca levels must exist to a depth of at least 120 cm. The implications of this are that in order to test a soil for responsiveness to lime and gypsum applications, both top- and sub-soil sampling would need to be undertaken. This argument is based on satisfying a Ca requirement rather than influencing intrinsic soil chemical properties. If the objective of a liming program is to enhance the quality of the soil resource base, the results from the charge fingerprint analysis have significant relevance. It is of note that on all soil types the CEC_b and CEC_T charge curves converge and come together to form a single curve at pH 5.6. At this pH one has eliminated all acidic components and has therefore attained base saturation. From an agronomic perspective this is an ideal state in that crop growth would be unrestricted by acidity (ie Al^{3+}). In addition, to increase the pH above this level may in the short-term exacerbate possible micronutrient problems.

Sugarcane crop responses to lime can only be expected if exchangeable soil calcium levels are suboptimal throughout the soil profile.

None of the Herbert trials showed a depression of ccs with liming and it was therefore not possible to investigate the reasons behind this phenomenon. The results support the conclusion that a depression in ccs can only be expected to occur in highly responsive sites, presumably those with very low exchangeable calcium levels to a depth of at least 120 cm.

A depression in ccs with additions of lime can only be expected to occur in responsive sites.

It was disappointing that the state of the crop at Dibella's trial only allowed cane yield results to be collected for the plant crop. The low exchangeable calcium down to 90 cm suggested that this site would probably have been responsive to lime in later ratoon crops. As far as the distribution of potentially responsive sites in the Herbert is concerned, an analysis of the CSR Soil Survey analytical database indicates that 166 soil sampling sites out of a total of 1054, or 15.7 %, had soil surface (0-20 cm) exchangeable calcium levels of $<0.55 \text{ cmol}_c \text{ kg}^{-1}$. Of these,

only 80, or 7.6 % of sampling sites, had exchangeable Ca levels of $<0.55 \text{ cmol}_c \text{ kg}^{-1}$ in the subsoil (40-60 cm). With most soil profiles in the Herbert having an increase in both clay content and exchangeable calcium occurring down the profile, only certain soil types are likely to have a high probability of being responsive to lime. These are likely to be those developed on acid volcanic rock types, which occur mainly along the eastern parts of the Cardwell Range, and also some of the very sandy soils of granitic origin.

More than 90% of sites in the Herbert are unlikely to be responsive to lime. Most have an increase in exchangeable soil calcium down the soil profile.

The results from the study undertaken at Feluga, whilst indicating no responses to lime or gypsum applications, for the same reasons as outlined above, clearly demonstrate the mobility of mineralised nitrogen from a legume break crop. By not having a growing crop present to make use of this mineralised nitrogen, a significant quantity can be leached from the rooting zone. Clearly, management of the incorporated trash from legume crops is extremely important in these management systems.

Legume break crops need to be carefully managed to avoid leaching of significant amounts of nitrate.

On responsive soils with acidic characteristics (low pH and low exchangeable Ca^{2+}), such as those at the trial site at BSES Tully Experiment Station, regular applications of lime each crop cycle is an economically viable long-term strategy for growers. Consequently sugar industry agricultural advisers would have no problem in justifying to growers that additions of lime not only make good economic sense but also contribute to the sustainability of their farming system. It is much more difficult to justify continued applications of lime on increasingly acidic but non-responsive soils such as those occurring over the majority of the Herbert River District. Sugarcane crop responses are unlikely and it is only when growers attempt to grow some other crop, particularly a legume crop, that they will realise just how degraded their soils have become.

On soils with suboptimal exchangeable calcium levels frequent lime applications represent an economically viable long-term strategy for cane growers.

If we are to design a sugarcane production system that is sustainable both from an economic viewpoint and an environmental viewpoint it appears that legume fallows need to be an essential component if the pest and disease problems of sugarcane monoculture are to be reduced. The experimental work in the Sugar Yield Decline Joint Venture has clearly demonstrated that legume break crops are successful not only in reducing sugarcane pests and diseases but also in improving soil health and fertility. Whilst sugarcane is tolerant of acidic soils and low soil pH, most other crops are not. If leguminous fallow crops are to be grown as part of sugarcane farming systems then attention needs to be paid to raising soil pH to a target level of approximately 5.6 so that the production system is sufficiently flexible to be able to produce crops other than sugarcane.

Legume fallows, which are an essential component of a sustainable sugarcane production system, are very sensitive to low soil pH and require soils with a pH >5.5 .

Current Australian sugarcane varieties are clearly tolerant of low soil pH and moderate to high levels of Al^{3+} and Mn^{2+} . The tolerance has presumably been bred into our varieties over long periods of time. Variety selection trials are normally conducted on experiment stations for the early stages of selection and on commercial farms for the later stages, and generally no attempt is made to manage the soil environment through regular liming programs to ensure

that varieties are being evaluated under conditions of optimal soil pH. The outcome has been the selection of a range of cultivars with tolerance to acid soil infertility. The question needs to be asked as to whether we have lost genetic potential for increased yields and/or CCS by breeding for degraded soils. It is interesting to note that sugarcane varieties from other countries such as South Africa and Brazil appear to be much more responsive to increases in soil pH and a reduction in exchangeable aluminium levels than Australian varieties. As a consequence, liming recommendations in these countries take into account both aluminium saturation (soil pH) and exchangeable calcium.

Current Australian sugarcane varieties have been selected for acidic soils. Genetic potential for increased sugar yields may have been lost by breeding for degraded soils.

Current sugar industry recommendations, which have been based on economic crop responses, consider only the level of exchangeable Ca^{2+} in the soil surface. Consequently applications of lime would be recommended for only around 15% of sites as noted earlier. Lime would not be recommended for the other 85% of sites, even though the surface soil pH maybe as low as 4.3. The recommendations thus ignore the continued acidification and degradation of the soil resource in areas like the Herbert. This is clearly inconsistent with the principles of sustainable agriculture. Continued acidification of the surface soil horizons will eventually cause proton movement to depth leading to subsoil acidification, which is extremely difficult to ameliorate. Also there is increasing concern that a low soil pH will cause irreversible degradation of clay minerals in soils.

In areas like the Herbert, current sugar industry recommendations ignore the continued acidification and degradation of the soil resource which is clearly inconsistent with the principles of sustainable agriculture.

From the sustainability perspective it is clear that the Australian sugar industry needs to develop a strategy to deal with the increasing problem of acid soil infertility. Both exchangeable calcium and either exchange acidity or soil pH need to be taken into account when formulating liming strategies. The convergence of soil charge curves at pH 5.5 clearly indicates that there is little soluble aluminium above this pH and that exchangeable base cations dominate the surface charge. Thus by liming surface soils to a pH of 5.6 the amount of soluble aluminium and manganese is minimised as well as the potential for downward proton movement and the risk of subsoil acidification. In addition, the liming recommendations need to take soil pH buffering capacity and CEC into account as far more lime is required to raise the pH of a clay soil with a high CEC and buffering capacity than a sandy soil.

The industry needs liming recommendations that aim to achieve a soil pH of 5.6 and that take into account differences in soil pH buffering capacity and CEC between soils.

Acid soil infertility not only restricts the range of crops that can be grown but also affects the availability of nutrients in soils. The rate of nitrogen mineralisation is slower in acidic soils due to a more restricted range of bacteria present. The flush of mineralised nitrogen resulting from enhanced soil microbiological activity may well be part of the explanation for the depression in CCS that has been observed in many sugarcane liming trials. The availability of phosphorus may also be restricted in highly acidic soils due to the solubilizing of Fe, Al and Mn. The reduced surface charge (CEC) at low pH in soils with substantial amounts of variable charge can limit the amounts of Ca, Mg and K cations that can be held on negatively charged surfaces. Suboptimal levels of any of these nutrients in low CEC soils can have a direct impact on crop yields.

Acid soil infertility is critical to nutrient availability particularly in low CEC tropical soils that are low in exchangeable cations and organic matter.

In conclusion, liming recommendations for the Australian sugar industry can no longer be based solely on an economic crop response. The industry has a responsibility to at least maintain or if possible improve the quality of its soil resources and ensure that sugar production systems are sustainable in the long term. It is proposed that frequent additions of liming products are required to neutralise the acidifying effects of nitrogen fertiliser use and crop removal and that additional applications of liming products are required to increase surface soil pH, particularly where this is well below pH 5.5.

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ANALYSIS OF OUTPUTS AND OUTCOMES COMPARED WITH OBJECTIVES

The five original objectives are considered below in terms of outputs and outcomes:

1. The current sugar industry recommendations for applying lime are based on the results of numerous field lime trials conducted by BSES. Most of the data comes from far north Queensland as the majority of responsive soils are located in this area (Ridge et al, 1980). The crop response data clearly show that $0.55 \text{ cmol}_c \text{ kg}^{-1}$ exchangeable Ca is appropriate as a critical level for soil calcium. Thus current industry recommendations are to apply 5 t/ha lime if exchangeable calcium in the top 20 cm of soil is $<0.55 \text{ cmol}_c \text{ kg}^{-1}$ and 2.5 t/ha lime if it is between 0.55 and $1.25 \text{ cmol}_c \text{ kg}^{-1}$ Ca. No lime is recommended for topsoils with an exchangeable calcium level of $>1.25 \text{ cmol}_c \text{ kg}^{-1}$.

If crop response is the only criterion for applying lime to sugarcane soils then the exchangeable calcium level in the top 20 cm of soil is a reasonably effective indicator of whether a sugarcane crop response to lime can be expected. The results from the trials in the Herbert, where soil exchangeable calcium levels commonly increase down the soil profile to depths that can still be accessed by plant roots, suggest that it would be more precise to include a measurement of subsoil exchangeable calcium at $>50 \text{ cm}$ depth, although this would add to soil sampling costs and would be unlikely to be adopted as a routine procedure. However, it is strongly argued that crop response should not be the sole criterion for applying lime. A sustainable sugarcane production system must include regular applications of lime to neutralise the acidifying effects of nitrogen fertiliser use and crop removal. We therefore advocate that sugarcane soils should be limed to achieve a target pH_{water} (pH_w) in the top 20 cm of soil of 5.6, in order to minimise soluble aluminium and manganese as well as the potential for subsoil acidification. A soil database compiled for the Herbert shows that very few soils (16%) have a pH as high as this and that average pH_w for the 0-20 cm layer is <5.0 . In addition, in order to achieve more precise recommendations that apply to the wide range of different soils being used for sugarcane production in the Herbert, the amount of lime required in a particular situation will depend not only on the magnitude of the soil pH increase required but also on the soil pH buffering capacity and CEC as far more lime will be required to raise the pH of a clay or organic soil with a high CEC than a sandy soil with a low CEC.

2. The long-term impact of the amelioration of soil acidity on sugarcane growth and crop productivity at a responsive site has been documented in section 11 where the effects of various liming treatments on sugarcane yields and soil chemical properties at the BSES Tully Sugar Experiment Station have been measured over an 18 year period. This clearly shows a consistent and significant increase in yields in those treatments receiving lime. It was not considered worthwhile to follow the long-term effects of lime and gypsum application on cane yields and soil chemical properties in the trials established in the Herbert due to their lack of responsiveness.

3. An explanation of the effects of raising soil pH on soil chemical properties is given in sections 5 and 11 of this report. Whilst an increase in soil pH_w to above pH 6 was not achieved in any of the Herbert experiments or in the experiment at Tully BSES, significant changes in soil pH did occur with a single application of lime. The greatest increase in soil pH generally occurred at the sites with the lowest soil pH buffering capacity. Thus at the Mizzi site, three years after lime application, soil pH in the 0-10 cm depth increment had increased from 4.64 in the control treatment to 5.24 in the 10t lime/hectare treatment. At the DiBella site, approximately 18 months after lime application, soil pH in the 0-10 cm depth increment increased from 4.43 in the control treatment to 5.56 in the 5t lime/hectare

treatment. These increases in surface soil pH were accompanied by significant increases in soil exchangeable Ca and CEC and a corresponding reduction in exchangeable acidity. At the Accornero site, with its much higher pH buffering capacity, the change in pH_w was much less, though still significant, as were the changes in exchangeable Ca, CEC and exchangeable acidity.

Charge fingerprints produced for the four different soils taken from the Ingham experiments show that there is considerable variable charge generated when the soil pH is increased. They also show that at a pH_w of about 5.5, the surface charge is dominated by exchangeable bases such as Ca, Mg and K and that exchangeable acidity is relatively small. Consequently, from a sustainability and an agronomic perspective, pH_w of 5.5 is regarded as an appropriate target for sugarcane growers to aim for in their liming programmes. It was calculated from the pH buffer capacity curves that 1.2, 1.4, 1.8 and 3.9 tonnes lime/hectare would be required at the Mizzi, DiBella, Reinaudo and Accornero sites respectively. However, the results reported from the trials in Sections 5 and 7 of this report suggest either that a much longer time period is required to achieve this than previously thought, due to a low solubility of commercial lime supplies, or that the calculations based on pure $CaCO_3$ do not account for impurities occurring in commercial lime supplies and therefore underestimate the amount of lime required to achieve the target soil pH.

4. It was not possible to investigate the reasons behind the depression in ccs sometimes associated with lime application because on no occasion was ccs significantly affected by lime application in the trials that were monitored.

5. An economic analysis of the responses to lime addition was conducted using data from the long-term liming experiment at BSES Tully Experiment Station. The results clearly show that accelerated soil acidification on a typical calcium deficient soil from the wet tropics of north Queensland is associated with a direct cost to the cane grower and that frequent prophylactic applications of lime following an initial 5 t/ha lime application represent a cost effective insurance premium to maintain sustained yields. This philosophy is more difficult to justify on the higher base status soils of the Herbert River District where sugarcane yield responses to lime cannot be expected in the majority of situations because of the tolerance of current varieties to highly acidic conditions. However, it has already been noted that if we are to put a value on the health and fertility of our soils, then frequent applications of lime can be justified in order to maintain soil pH levels above 5.5 and thus retain the flexibility to be able to produce crops other than sugarcane.

Additional objectives for the project were discussed at the SRDC project review in May 2000. One of these involved sampling selected treatments for wet aggregate stability analysis to determine whether there had been any treatment effects on soil physical properties. This is reported for the DiBella site in section 6 of this report.

POTENTIAL BENEFITS AND LIKELY INDUSTRY IMPACT

The following benefits are likely to arise from this project and impact on the Australian Sugar Industry:

- Strategies to arrest the long-term degradation of sugarcane soils due to accelerated acidification.
- Improved fertility of acid sugarcane soils arising from increased nutrient availability and soil charge resulting from a higher soil pH.
- A basis for making more precise lime recommendations for the Australian Sugar Industry based on the specific properties of different soil types.
- Strategies to ameliorate subsoil acidity in different sugarcane soils through the movement of alkalinity down through the soil profile.
- Enhanced sustainability of sugarcane production through successfully incorporating leguminous fallow crops into the sugarcane production system, which will help reduce the pest and disease problems associated with sugarcane monoculture.
- Improved knowledge of the soil characteristics of sites that are likely to be responsive and non-responsive, in terms of sugarcane yields, to lime applications.
- Improved characterisation of commercially available lime and gypsum sources that reflect their effectiveness in reducing soil acidity and supplying calcium, and the time lag between lime application and soil amelioration.

RECOMMENDED FUTURE RESEARCH NEEDS

The following research needs to be undertaken in order to build on the major findings of this project:

1. Very little long-term data exist for the Australian Sugar Industry to demonstrate acidification rates on different soils and the effectiveness of lime applications in ameliorating soil chemical properties. The Tully lime trial data presented in this report is the only long-term dataset available. More long-term experiments are required, preferably located on experiment stations rather than on farmers' fields, so that they can be closely monitored and so that no problems are encountered with harvesting, as occurred with the Ingham experiments. Longer term monitoring is also important in some situations because of the lag time between lime application and crop response, which can be up to four years.

2. It was not possible in this project to investigate the reasons for a depression in ccs that is commonly associated with lime application on responsive sites. Whilst Kingston *et al.* (1996) have reported on this phenomenon using data from southern Queensland, there is clearly a need for further investigations of the causes of reduced sucrose yield in responsive sites. Experimental sites are required with low exchangeable calcium levels down to a depth of 1.2m for these investigations.

3. Whilst it has been demonstrated that an appropriate target soil pH for sugarcane is approximately pH 5.5, the amount of lime required to achieve a given pH increase on soils with different soil pH buffer capacities and CEC's needs to be demonstrated. For a preliminary investigation it is suggested that soils in the Herbert can be grouped into three categories:

- Sandy soils with a low pH buffer capacity and a low CEC ($<3 \text{ cmol}_c \text{ kg}^{-1}$)
- Intermediate soils with a moderate pH buffer capacity and moderate CEC ($3\text{-}6 \text{ cmol}_c \text{ kg}^{-1}$)
- Clay soils with a high pH buffer capacity and high CEC ($>6 \text{ cmol}_c \text{ kg}^{-1}$).

Recommendations for lime provided by some soil testing laboratories already take soil pH buffering capacity into account.

4. It has been clearly shown that the effectiveness of liming materials used in the sugar industry depends not only on their neutralising value but also on their solubility. It is suggested that further work needs to be conducted to measure the effectiveness of different liming materials and that their registration for use on sugarcane soils be based on a characteristic such as Effective Neutralising Value as mentioned in section 7.

5. Further work is needed to investigate whether genetic potential for increased cane yields and ccs has been lost by selecting varieties that are adapted to acidic soils. It is suggested that a common set of unselected varieties should be evaluated in trials with both limed and unlimed treatments. It is possible that variety selection sites in areas like the Herbert should be managed to a common pH of 5.5.

EXTENSION ACTIVITIES

The following extension activities have been conducted to promote the activities and major findings of this project:

- A presentation on the objectives and methodology of this project was given at a combined meeting of the Macknade and Victoria Mill Suppliers Committee when the project commenced in July 1996.
- Presentations on this project were made at the 1997 BSES Herbert Field Day in May 1997 where 2 posters were displayed: 'Soil acidity in the Sugar Industry – The problem' and 'Soil acidity in the Sugar Industry – The solution'.
- Presentations and project updates were presented to the Herbert Catchment Group in March 1998 and April 2000.
- Numerous meetings were held with the growers who assisted with the project to advise them on progress and results from the project.
- Presentations were given at Sugar Yield Decline Venture Information Days at Bundaberg in September 1997 and at Mackay in February 1998.
- Communications presenting results from the project were sent to members of the Sugar Yield Decline Joint Venture and to the growers and suppliers of lime and gypsum who assisted with the project.
- A presentation based on the findings of this project "Are quality assurance procedures needed for lime and gypsum in Queensland?" was given at the ASPAC conference in Tasmania in November 1997.
- Presentations based on work in this project were given at the 1997 ASSCT Conference in Cairns ('Sugarcane and soil acidity – Why should we be worried?'), the 1998 ASSCT Conference in Ballina ('Is lime doing what we want it to?') and the 2003 ASSCT Conference in Townsville ('The development of site-specific nutrient management guidelines for sustainable sugarcane production').
- Selected datasets were contributed to the National Soil Acidity Audit.
- Data from this project were used to develop soil analysis interpretation guidelines to define liming recommendations for the sugar industry. These guidelines appeared in a workbook developed for training courses in 'An integrated approach to sustainable nutrient management' and in a 'Soil Reference Booklet for the Herbert District – Soil Specific Management Guidelines for Sugarcane Production'.
- The soil analysis interpretation guidelines are being discussed with growers in the Herbert at the 26 Productivity Forums run by the Herbert Cane Productivity Initiative (August – November 2003). They will be reinforced at further meetings in the Herbert following the release of the Soil Reference Booklet.

Presentations given at various training courses on sustainable nutrient management have incorporated information from this project. These have included:

- Soils module at Abergowrie College for senior chemistry students (1999 – 2002).
- Five short courses on 'Sustainable Nutrient Management' run by the CRC for Sustainable Sugar Production (1999-2002).
- Two short courses on 'Managing soils, nutrients and the Environment' run by the CRC for Sustainable Sugar Production (2001-2002).
- A short course on 'Cane Farming and the Environment' run by Herbert River Canegrowers (2002).
- Five short courses on 'Maintaining Soil Fertility' run by BSES in the Herbert (2001-2003).
- Short course on 'An integrated approach to sustainable nutrient management for sugarcane'. This has been offered at least 6 times in the Bundaberg region and once in the Herbert.

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 - Thilak Mallawaarachchi conducted the economic analyses reported in section 12

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PUBLICATIONS ARISING FROM THIS PROJECT

Published papers

Bramley, R.G.V., Noble, A.D., Muller, D.E. and Wood, A.W. (1997). Are quality assurance procedures needed for lime and gypsum in Queensland? *Australian Soil and Plant Analysis Council, Second National Conference and Workshop*, Launceston, pp. 146-148.

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Noble, A.D. and Hurney, A.P. (2000) Long-term effects of lime additions on sugarcane yield and soil chemical properties in north Queensland. *Expl. Agric.* 36: 397-413.

Poster papers

Bramley, R.G.V., Noble, A.D. and Wood, A.W. (1997) Soil acidity in the Sugar Industry - The problem. BSES Field Day Ingham.

Noble, A.D., Bramley, R.G.V., Hurney, A.P. and Wood, A.W. (1997) Soil acidity in the Sugar Industry - The solution. BSES Field Day Ingham.