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CSIRO Land and Water

Final Report

SRDC Project CLW009

Improving yield and ccs in sugarcane through the application of silicon based amendments

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Project Title: Improving yield and ccs in sugarcane through the application of silicon based amendments

Organisations: CSIRO Land and Water
BSES
Mossman Productivity Board
Sugar Yield Decline Joint Venture

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Executive Summary

Under high leaching environments common to the wet tropics, soils undergo significant weathering, which, when combined with accelerated chemical and physical degradation due to soil perturbation and crop removal, results in increased soil acidification and dissolution of the aluminosilicate clay minerals (de-silication). The consequences are both a loss of plant available Si through leaching and a decline in cation exchange capacity and hence an inability to retain essential plant nutrients.

The current project has highlighted that large areas of cane-growing soils in North Queensland have sub-optimal levels of plant-available Si. Based on the current soil test, some 85% of soils that were evaluated in the six mill areas on the wet tropical coast have sub-optimal to marginal levels of available Si. Hence the implications of silicon deficiency for substantial areas under sugarcane production, and therefore the benefit of prophylactic applications of silicate materials may have a significant impact on productivity.

One of the primary objectives of this study was to quantify responses in cane yield and CCS to Si application. To address this objective, three field trials were established in Bundaberg, Innisfail and Mossman, using a range of application rates of calcium silicate slag. At Innisfail, over the 2 years of the trial, a rate of 9t/ha Ca-silicate gave a 32% increase in total cane yield (189 t/ha) when compared to the control treatment (128 t/ha). At Mossman, a rate of 12 t/ha gave a 35% total yield increase (161 t/ha) compared to the control (105 t/ha) over the same period. At Bundaberg, over a crop cycle of 3 years, the 12 t/ha rate of Ca-silicate resulted in a 23 % increase (278 t/ha) compared to the control (213 t/ha). The results clearly indicate that Si should be treated as an integral part of any fertilizer strategy associated with cane production on these soils.

In addition, detailed investigations into changes in soil chemical attributes undertaken at the Mossman and Innisfail trials demonstrated significant increases in CEC in all treatments receiving Ca-silicate additions. Therefore, in addition to improved Si nutrition, the results suggest that the increase in CEC due to the application of Ca-silicate slag may contribute to the observed yield increases of sugarcane on these degraded and Si deficient soils.

The soil survey study and the field rate trials have clearly demonstrated a significant correlation between soil Si levels and top visible dewlap (TVD) tissue levels of Si and as such provide the basis of a useful diagnostic tool. A strong and significant relationship exists between relative cane yield and TVD Si status ($r^2 = 0.73$). The asymptotic function provided by the regression analysis predicts that 95% of the maximum yield (Y_{max}) will be achieved with a TVD of 0.55% Si.

A focus of the project has been in developing reliable laboratory soil tests to adequately determine sub-optimal soil Si levels, and also cane responsiveness to silicate amendments. Results indicate that the current soil tests used to determine Si status of the soil is effective, particularly for the light textured soils. Using 95% of Y_{max} as the response threshold, the rate trial data supports the current recommendations of 10mg Si/kg soil in a 0.01M CaCl₂ extract and 100mgSi/kg in

0.005M H₂SO₄ extract. However, interpretation of soil and plant data for soils with a higher clay content, high sorptive ability due to significant quantities of Al and Fe oxides and hydroxides, and possibly soils with poor drainage, high levels of organic matter, and alkaline or sodic soils, still needs to be investigated.

Grower and industry interest in the outcomes of this research is evidenced as a number of commercial laboratories are now offering soil Si testing as part of their routine soil tests. However, it is felt that further work still needs to be undertaken to define responsive soils, as, although some soils clearly have sub-optimal levels of soil Si, other soil properties associated can minimize the response to Si additions. Future research should focus on refining soil-testing techniques to enable not only the prediction of 'sub-optimality', but importantly 'responsiveness' to silicate additions.

Another important focus has been developing a reliable laboratory test to provide an estimate of the potential value of a silicate source to remediate Si sub-optimalities. Considerable progress has been made using laboratory tests combined with soil incubation experiments to predict both the potential and possible application rates necessary for field applications.

Considerable progress was made in identifying locally available silicate materials, although none of the silicate materials tested within the scope of this project compared in efficacy with the calcium silicate slag imported from the USA. Identifying and testing further potential products is on-going, and before recommendations can be made on any products, comprehensive field testing needs to be undertaken on a range of soils showing sub-optimal Si levels. The need to identify suitable locally available products is an important issue as the importation of calcium silicate slag on a commercial basis at present is likely to be uneconomic.

1. Introduction and Project Background

A major causal factor associated with declining yields has been attributed to the loss of productive capacity of sugarcane-growing soils under long-term monoculture (Garside *et al.*, 1997). Although, recent trends since 1990 have seen an increase in sugar yields compared to the yield plateau encountered during the previous 20 years, this has been largely attributed to expansion onto better quality soil and/or irrigation, and an increase in harvesting efficiency (Garside *et al.*, 1997). Despite this improvement in production trends, declining soil fertility continues to be a significant problem for long-term sustainability of the sugar industry.

Industry development has intensified the monoculture system, with a concurrent increase in the use of major nutrient elements such as nitrogen and phosphorus. During this period, calcium and magnesium deficiencies (Ridge *et al.*, 1980) and zinc deficiency (Reghenzani, 1990; Reghenzani, 1993) have been identified as nutrient factors affecting cane yield, particularly in north Queensland. For sustainable crop production, nutrient monitoring and management is essential. It is well recognised that sugarcane requires regular additions of nitrogen (N) phosphorus (P) and potassium (K), as well as other macro and micronutrients for optimum crop production. However, a nutrient that is not normally considered to be essential for sustained sugarcane production is silicon (Si). Like many grasses, sugarcane actively accumulates Si, suggesting both a physiological and morphological role in growth. A 12 month crop can accumulate 380 kg/ha Si in the above ground tissues, compared to 180 kg/ha K, 140 kg/ha N and 20 kg/ha P (Samuels, 1969). Although it can grow normally with small amounts of Si, its ability to absorb large quantities suggests that Si may be necessary, or at least beneficial, for optimal growth. As such, Si is recognised as an agronomically essential element for sustainable sugarcane production (Savant *et al.*, 1999).

Agronomic effects of inadequate Si nutrition

A number of the factors associated with declining sugarcane yields are also factors linked with inadequate Si nutrition. An example is the association of adequate levels of plant tissue Si with increased resistance to disease and insect pressure and improved root growth and structural strength (Epstein, 1994; Epstein, 1999).

Physical and Physiological Effects

Silicon is an integral part of cell walls, and has a similar role to lignin, in that it provides compression-resistance and rigidity in cell walls, thus providing structural strength to the plant. An ample supply of Si has been reported to reduce lodging (drooping, leaning or becoming prostrate) in grass crops due to improved mechanical strength. The improved rigidity of the cell walls also promotes a more erect habit and disposition of the leaves, resulting in better light interception and photosynthetic efficiency (Jones and Handreck, 1967; Kaufman *et al.*, 1985; Adatia and Besford, 1986). Alexander (1968a) suggested that sugarcane cultivars high in Si may also show enhanced sucrose synthesis, due to improved photosynthesis, as shoots are not as likely to become prostrate following wind and rain.

Varieties have changed substantially between 1970 and 1990, and lodging, once a factor selected against, is now considered a less important selection criterion, with the use of mechanical chopper harvesters (Garside *et al.*, 1997). Consequently, plant-breeding programmes may have been inadvertently selecting varieties with lower concentrations of Si in the stalk. As there is evidence that lodging can result in loss of cane yield and reduction in sugar content (Hurney, 1984; Muchow *et al.*, 1995; Garside and Nable, 1996), this highlights the possibility that low plant and soil Si levels may be a causal factor in declining sugarcane yields observed over recent years.

Adequate Si nutrition may also assist crops withstand the effects of drought conditions in areas reliant on rainfall, or declining water quality in irrigation areas. Plants with a well-thickened layer of Si associated with the cellulose in cell walls of epidermal cells have been observed to be less prone to wilting and have improved drought resistance. Silicon may also reduced stress to salt in a similar way that it alleviates water stress. Work with cereal crops suggest that Si can both increase photosynthesis and decrease the permeability of plasma membranes of leaves of salt-stressed plants. In addition, Si has been shown to inhibit the uptake of Na and increase the uptake of K, thus alleviating the effect of salt toxicity and improving vegetative growth (Liang *et al.*, 1996).

Reduced Resistance to Biotic Stresses

Improved resistance to disease and pathogenic fungal attack, due to Si applications, has been reported for a number of crops (Jones and Handreck, 1967; Adatia and Besford, 1986; Yamauchi and Winslow, 1987; Raid *et al.*, 1992). It is generally agreed that as most parasitic fungi penetrate the host by boring through the epidermal cell wall, Si in these walls may act as a mechanical barrier. In addition, Si may also protect the plant by its association with the cell wall constituents, minimizing the enzymatic degradation that accompanies the penetration of the cell wall by the fungal hyphae. The highly silicified leaves of grasses can not only make the plant more resistant to attack by pathogenic fungi, but also to attack by predaceous chewing insects, as they can suffer a high mortality when their mandibles and maxillae become worn down, rendering their mouthparts ineffective (McNaughton and Tarrant, 1983).

It is relevant, therefore, that recent history of yield decline in sugarcane dates back to the recognition of 'Northern Poor Root Syndrome' (NPRS) as a problem in sugarcane on Queensland's wet tropical coast (Egan *et al.*, 1984). Although, it has been suggested that the build-up and susceptibility to root pathogens may be the ultimate expression of other factors being out of balance in the farming system (Garside, 1995), it is plausible that low soil and plant Si levels have allowed increased susceptibility to pathogen attack.

Increased Susceptibility to Abiotic Stresses

Adequate Si nutrition is reported to have a major effect on the absorption and translocation of some macronutrient and micronutrient elements, assist in the negative effects resulting from nutrient imbalances, and also have the ability to alleviate, or in some cases to eliminate, the adverse effects of heavy metals, excess phosphorus and salinity.

Current sugarcane production systems often apply nitrogen at rates far in excess of what may be considered necessary for maximum yield, and with high soil concentrations of phosphorus, may result in unbalanced nutrient supply on many sugarcane soils (Garside *et al.*, 1997). In discussing declining yields in rice (another crop with a high agronomic requirement for Si), Savant *et al.* (1997a) commented that yield decline can be temporarily reversed by increasing N fertilizer rates to soil Si-depleted systems. However, for sustained yields, Si fertilisation is required to balance applied nutrients, particularly N, when high rates can result in increased problems with lodging. Although Si additions are reported to improve P nutrition, conversely, continued use of superphosphate may have also resulted in accelerated depletion of soil Si reserves, since P effectively competes with Si for specific sorption sites, thereby resulting in the loss of Si through leaching.

Soil Si status, indicative of potential soil productivity

Silicon is recognized as a major constituent of soils. It is present in the solid phase of soils as aluminosilicate clay minerals and crystalline minerals, and also in a number of amorphous forms such as plant phytoliths. In the soil solution, or liquid phase, Si is present as mono- and poly-silicic acids, and also present as complexes with inorganic and organic compounds (Figure 1.1 and Figure 1.2). While it is the mono-silicic acid component that is taken up by plants and has a direct influence on crop growth, the poly-silicic acids, and probably the inorganic and organic Si complexes, are important as sources/sinks of Si which can replenish the soil solution following crop use, but importantly, they can have a significant effect on soil properties such as improving soil aggregation and increasing soil water holding capacity and also increasing the exchange and buffering capacity of soils (Figure 1.2) (Matichenkov and Bocharnikova, 1999). It has also been suggested that the organosilicic compounds play a specific role in organic matter formation (Matichenkov and Bocharnikova, 1999).

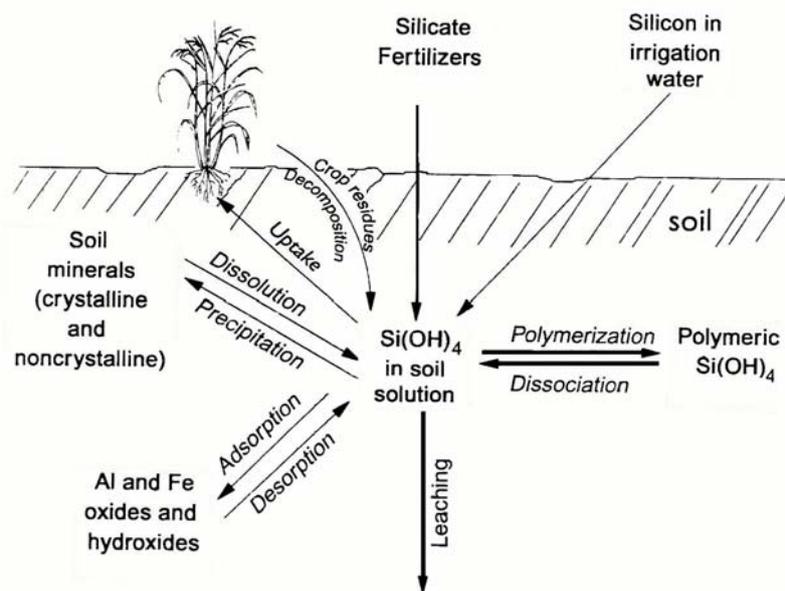


Figure 1.1. The main transformations/processes influencing Si concentration in the soil solution (from Savant *et al.*, 1997).

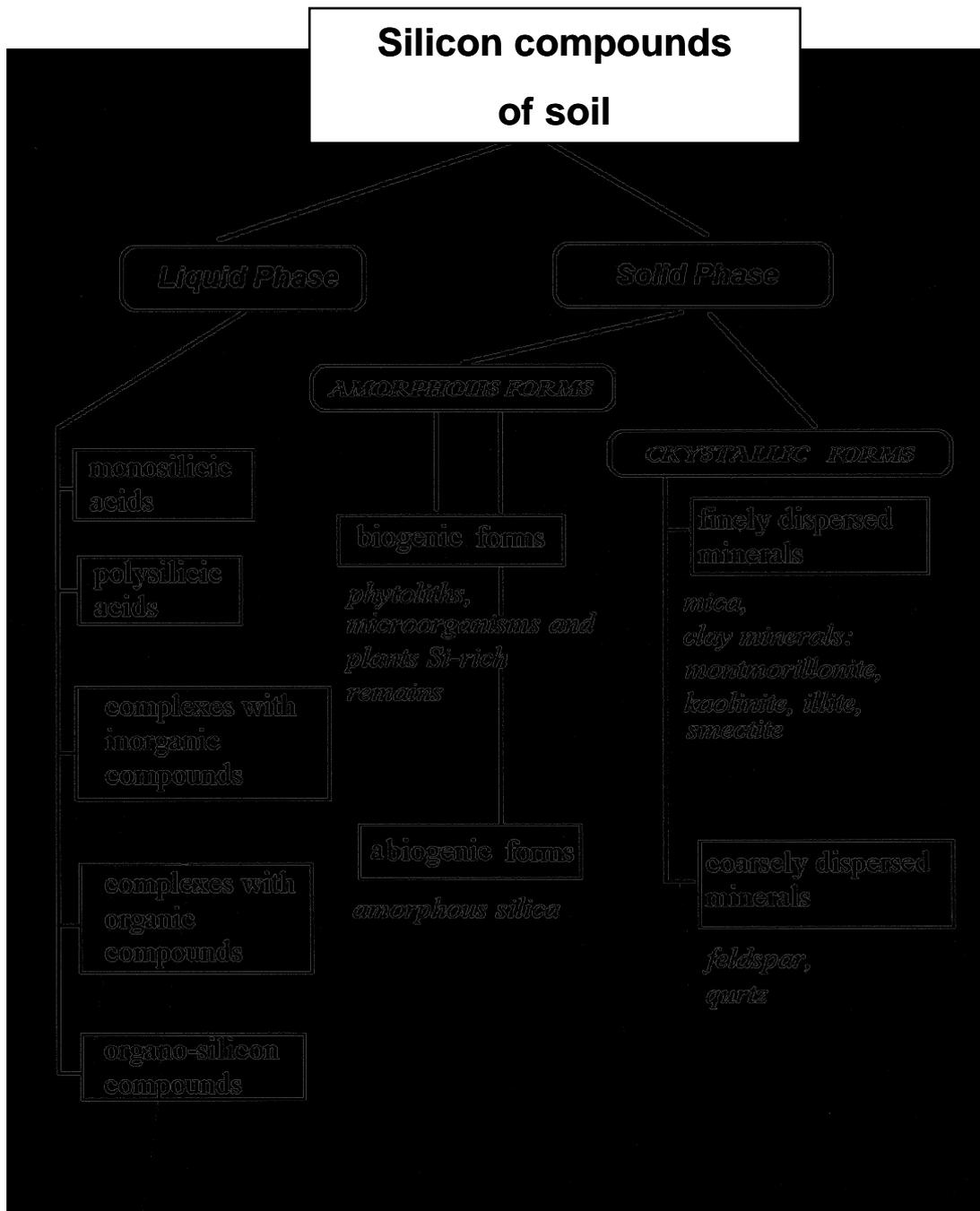


Figure 1.2. Forms of Si in the soil (from Matichenkov and Bocharnikova, 1998)

In this regard, Si, in all its forms can be regarded as a basic building block of soils. Savant et al. (1997) observed that high soil productivity was generally associated with an adequate supply of soil Si. This indicates that soil Si supply, as distinct from its role as a plant nutrient, but due to its effect on other soil properties, can be an important factor associated with maximum production.

Quantity of plant-available Si in soils

In general, most soils have appreciable amounts of primary silica minerals (quartz) and alumino-silicate clays. Consequently, the total Si content of soils may appear to be adequate for crop growth. Although quartz is a major source of Si in many soils, the rate of dissolution of this mineral is very slow and therefore does not contribute significantly to the labile pool of soluble Si. For plant growth the important forms of soil Si are the soluble forms, mainly monosilicic acid ($\text{Si}(\text{OH})_4$), various polymers and silica gels, Si adsorbed onto sesquioxidic surfaces, and that present in crystalline and amorphous soil minerals. The quantity present in each of these forms is largely controlled by the dominant soil mineral and the amount of Si lost (desilication) through weathering. The solubility of Si in the soil is influenced by several factors including, particle size, soil pH, organic complexes, the presence of aluminium, iron and phosphate ions, temperature, exchangeable/dissolution reactions, and soil moisture (McKeague and Cline, 1963a, 1963b, 1963c; Beckwith and Reeve, 1963, 1964; Jones and Handreck, 1963, 1965).

Desilication of soils is a natural process associated with pedogenesis and is favoured in humid tropical environments as a direct consequence of the high rainfall and temperature associated with these regions. Under these conditions, basic cations (Ca^{2+} , Mg^{2+} , K^+ and Na^+) are stripped from the exchange complex resulting in acidification of the soil and the dissolution of aluminosilicate clay minerals with the concomitant leaching of Si. Thus soils of the wet tropics that have undergone significant weathering invariably have inherently low levels of plant available Si and consequently may have sub-optimal levels for maximum biomass and sugar production.

An indication that many soils in the wet tropics may have inherently low levels of plant-available Si was highlighted in a previous study on soils from the Tully-Innisfail cane-growing area (Berthelsen *et al.*, 1999). This study suggested that the majority (up to 67%) of soils in this region had marginal to sub-optimal levels of plant-available Si, and that it was possible that these levels were insufficient to maintain optimum crop growth. The map produced from this study was based on soils from undisturbed sites. Hence it detailed the inherent levels of soil Si prior to the establishment of agricultural enterprises. In other studies on new and old land paired sites (Berthelsen *et al.*, 1998) demonstrated a considerable decline in available Si after long-term sugarcane production. As sugarcane accumulates large amounts of Si, and a considerable component of the crop, and therefore the accumulated silicon, is permanently exported from the paddock, this resultant depletion of plant-available Si on sugarcane growing soils could possibly be a further limiting factor contributing to declining yields.

Measurement of Si in soils and plants

To reliably estimate the percentage of soils with potentially sub-optimal concentrations of plant-available Si, and to develop dependable 'critical' levels that reflect sub-optimality, and thus predict soils likely to respond to amelioration through additions of silicate materials, consideration must be given to the most appropriate form of laboratory extractant and measurement. While the forms of Si in the soil can be defined as total, extractable and soluble, it is the concentration of soluble Si in soils

that is agronomically important, and this can have no relationship to the total Si content of the soil. In addition, the concentration of soluble Si in soils is dynamic. Although changes in moisture content related to wetting-drying cycles in the soil, and leaching of Si from the soil and plant uptake are important processes in determining Si concentrations, for an individual soil type, the equilibrium concentration of Si is largely controlled by adsorption / desorption reactions. Silica, when added to a soil, reacts rapidly with amorphous surfaces. The amount and rate of Si adsorption is dependent on the sesquioxide content of the soil, soil pH, and the presence of other anions (Jones and Handreck, 1963).

A number of different extracting solutions have been used to estimate plant available soil Si. In general, the most successful extractants for determining the amount of 'extractable' Si in the soil are acid rather than neutral solutions, and dissolution is further increased by the addition of chelating agents (due to decreased Si sorption resulting from the lower concentration of Al and Fe in solution). However, as a number of factors, including the mineralogy of the clay component in the soil, amorphous Si coatings formed due to dehydration and precipitation, and aluminosilicate compounds of variable composition influence the concentration of Si in the soil solution, the 'extractable' soil Si concentration may not always be a reliable estimate of the 'plant-available' soil Si. Although water has often been used to estimate readily soluble Si, dispersion due to low solution ionic strength can cause problems and solubility of Si can vary greatly with time of shaking, pH and other factors (Lindsay, 1979). As most of the soluble Si below pH 8 is uncharged Si(OH)_4 , changes in ionic strength should not significantly alter extractable levels in most soils. In this respect, Elgawhary and Lindsay (1972) recommend the use of 0.02M CaCl_2 as the reactive media to equalize ionic strengths and facilitate ready flocculation of colloidal Si. Lindsay (1979) states that when the soil is extracted with 0.02 M CaCl_2 , the measured Si in the soil solution corresponds more closely to the levels of Si(OH)_4 expected from solubility predictions.

Leaf Si is an adequate indicator of the Si status of sugarcane, and is highly correlated with yield (Bair, 1966; Meyer, 1996). It is generally recognized that the level of Si accumulated by the plant is a reflection of the amount of plant available soil Si (Anderson *et al.*, 1991; Deren *et al.*, 1993). Attempts have been made to determine 'critical' plant levels of Si required for optimum growth. However, because of the close association between 'plant-available' soil Si levels and plant Si accumulation, both these measures used simultaneously, could be effective in delineating areas currently under sugarcane production that may be predisposed to sub-optimal Si levels.

Application of silicate materials

The application of silicate materials to soils low in soluble Si has produced dramatic field responses in both cane and sugar yields in many countries, including Hawaii, Mauritius, South Africa, Puerto Rico and Florida (Fox *et al.*, 1969; Samuels, 1969; du Preez, 1970; Wong You Cheong and Halais, 1970; Elawad *et al.*, 1982a). Yield results have consistently shown significant increases in plant height and weight, stem diameter and number of millable stalks.

The multiple benefits that have been attributed to applications of silicate slags or other silicate materials to sugarcane can be summarised as follows:

- 1) neutralizes soil acidity
 - this has a beneficial effect on microbial activity and enhances the release of organically bound N, P and S
 - reduced toxicity of Fe, Al, Mn and other metals in the soil solution
- 2) supplies large amounts of Ca and Si, and smaller and variable amounts of many other nutrients, including P, K, Mg, S and micronutrients, depending on the source of the silicate material
- 3) increases both cane and sugar yields
 - increased plant height, stem diameter and number of millable stalks
 - increased number of green functioning leaves
 - greater growth index
- 4) controls 'leaf freckle' symptoms, thereby improving photosynthesis and chlorophyll production
- 5) acts as an enzyme regulator in sugar synthesis, storage and retention within the plant
- 6) provides structural strength
 - reduces lodging
 - promotes a more erect growth habit, and as a consequence a more efficient use of sunlight
- 7) improves the plants resistance to damage from insects and disease
- 8) decreases the levels of leaf transpiration, resulting in increased water-use efficiency
- 9) decreases Mn toxicity by preventing localized accumulations of Mn in the leaf
- 10) improved P nutrition
 - reduction in fertilizer P fixation
 - greater solubility of soil P
 - possibly increased efficiency of P utilization within the plant
- 11) benefits the plant, possibly in an essential role, to improve plant vigour and longevity.

While the first two points are often a consequence of the silicate material added, the remaining benefits are usually attributed directly to Si.

Although applications of silicate materials have not been routinely practiced in Australia, early trials in north Queensland and the Mackay district in the 1970's using silicate materials indicated responses that may have been attributable to Si (Hurney, 1973; Haysom and Chapman, 1975). In most of these early studies, cement was used as the Si source. Although responses appeared to be strongly dependent on soil type, these studies did not clearly differentiate between responses associated with enhanced Si levels to those associated with changes in soil Ca or pH. Therefore, the lack of adoption by the industry to amend soils with silicate materials on a routine basis can in part be attributed to the confounding influence of associated cations accompanying the Si source (eg. Ca^{2+}), and the inability to predict responsive soils.

However, recent studies in the wet tropics of north Queensland have demonstrated significant increases in both cane and sugar yield with the addition of Si-based amendments on soils that had sub-optimal levels for cane growth (Rudd and Berthelsen, 1998). These studies indicated that the increases in yield of 38% were

due to enhanced soil Si status (Rudd and Berthelsen, 1998). Similarly, Kingston (1999) reported significant positive responses to Si on a gleyed podzolic soil in the Isis district.

Silicate materials

Silicon exists in a wide variety of forms and has a wide variety of stabilities. It is estimated to represent about 28 percent of the earth's crust. While Si is an abundant element it is not found free in nature, but always combined, usually as oxides or silicates. Many sources have been assessed for use as an agricultural amendment, both those found as natural deposits, such as wollastonite (calcium silicate rock) or olivine (magnesium silicate rock), or as by-products from various industrial processes (eg. various blast furnace slags).

Before any source can be considered useful for agricultural applications it must meet a number of criteria, such as solubility, availability, suitable physical properties and be free of, or have acceptably low levels of contaminants (Gascho, 2001). One of the most important criteria, and often the most difficult to achieve is solubility, as many natural sources are always combined with other elements and are largely insoluble. Generally solubility of many materials increases as particle size decreases, but producing a product of fine particle size can introduce other problems with field application and human health issues. An important consideration with silicate sources derived from industrial by-products is the possible high levels of heavy metals associated with their origin or processing. From a cost:benefit aspect, it is also important that the product is available at a reasonable distance from where it is required as generally large quantities of material are needed. Finding a silicate source that has all these criteria demonstrates the difficulty of selecting a material suitable for agricultural purposes.

The difficulty of selecting suitable silicate materials is further compounded as there are no proven methods for adequately assessing the availability of Si in the potential Si source. While a number of chemical extractant methods have been used to estimate both total and soluble Si in silicate materials, often the results obtained do not correlate well with plant uptake of Si once the material is applied to the soil. In addition to the effect of particle size on solubility, other chemical characteristics of the material such as pH, molar ratio of CaO:SiO₂ have been shown to influence Si availability (Ma and Takahashi, 2002). Once a product is added to the soil, soil chemical reactions, eg. the increase in soil pH due to the dissolution of Ca and Mg from the material can further influence the solubility and hence availability of Si (Ma and Takahashi, 2002). Consequently, it is possible that there is not a universal extractant that is suitable for determining available Si that will cover all types of materials, and for all soils and soil conditions (Gascho, 2001).

While various chemical extractants may provide the first estimate of the potential value of a silicate source, a more reliable means of determining the solubility and chemical reactivity of a silicate material is through indirect chemical extraction after soil incubation, and by determining plant uptake after a short-term bioassay (Savant *et al.*, 1999).

Project Objectives

It was speculated that there were large areas of the far north and southern Queensland that would benefit from prophylactic applications of Si based amendments. This project aimed to develop a set of recommendations for cane growers to address the problem of declining ccs and cane yield through the application of silicon (Si) based amendments. Objectives of this study were predominantly achieved through field based surveys and trials. A major component of the project was the establishment of 6 field trials to assess the efficacy of selected Si based amendments and the development of optimal rates and response functions. In addition, soil and plant data collected from a nutrient survey of sugarcane areas in north Queensland provided information for the development of a Si risk assessment map for the region from Tully to Mossman. It is anticipated that the outcomes of this research can have significant impact on the profitability of the sugar industry through increases in yield and ccs in specific areas of the sugar industry. The project has build on and added value to outcomes already achieved in the Sugar Yield Decline Joint Venture.

Specific objectives defined at the outset of the project were:

1. Evaluate the current Si status of cane growing soils in the Tully to Mossman regions with the objective of identifying soils most likely to be responsive to prophylactic applications of Si.
2. Quantify responses in cane yield and ccs to Si application in Queensland's cane growing regions, through the establishment of (a) Si rate trials and (b) trials designed to evaluate the efficacy of various sources of Si in both northern and southern growing regions.
3. Establish plant and soil diagnostic norms for use in the sugar industry.
4. Undertake a comprehensive extension initiative to create an awareness of the role of Si in sugarcane production.

Additional funding to the project was provided for the period August 2000 to July 2002 to enable the assessment of acidulated metal silicates. Preliminary laboratory investigations based on dissolution studies indicated that these materials were significantly more soluble with respect to Si than the current range of products being evaluated in the original field trials, and consequently may have a potential use as high analysis fertilizers supplying both Si and basic cations. The additional funding allowed field trials to be established in each of the three regions where the original Si trials were being carried out. The objectives of this further study was to:

5. Undertake further assessments of these acidulated products in laboratory and greenhouse studies;
6. Undertake field assessment of acidulated metal silicates as a Si source, specifically looking at the efficacy of acidulated materials against a standard Si source currently being assessed in the field trials (ie. Ca-silicate), and the effect of placement of acidulated materials (ie. broadcast application versus banding).

The project achieved all stated objectives and was also extended to include additional areas of research that were considered relevant to the outcomes of the project.

Additional research

As the project progressed additional areas of research, not specifically outlined in the original objectives, were identified and pursued to add value to the outcomes of the project, and to assist in providing direction for future research work.

1. As part of the overall yield response resulting from the additions of silicate materials may be due to an overall improvement of soil fertility, as distinct from a direct plant nutritional response, a detailed study was made of the changes in soil chemical parameters associated with prophylactic applications of Si based amendments, in this instance calcium silicate slag. It was felt that a better understanding of these processes would enable future research work to not centre entirely on the direct plant nutritional aspects, but be more encompassing of other benefits of Si additions.
2. When the original Product trials were established there was only a limited number of potential Si sources identified and commercially available, and there was only limited capacity to field test those that were considered to have the most potential. However as the project progressed, attention was drawn to a large number of alternative locally available Si products. Many products may contain high amounts of total Si but this does not necessarily equate with available Si. This highlighted the importance of having a reliable laboratory based method to 'rapidly' assess the potential of any product to supply available Si. To this end, a detailed study, examining various documented chemical extraction methods, incubation and bioassay methods was carried out. Knowledge of reliable and appropriate laboratory methods was considered to be an important output, and essential for any future research into the use and benefit of silicate materials in agriculture.

3. Parties Involved and Linkages

This project was developed as a multi-disciplinary and multi-institutional initiative involving CSIRO Land and Water, BSES and Cane Pest and Productivity Board (CPPB). Each investigator was able to bring unique qualities to the project through their affiliation to their own organization.

Andrew Noble (CSIRO Land and Water) was the overall project co-ordinator with extensive experience in soil chemistry in particular acidic highly leached soils.

Alan Hurney (BSES) brought wide knowledge and experience in sugarcane nutrition with expertise in the soils of the Tully/Innisfail area, and was responsible, with the assistance of David Grace, for the establishment and maintenance of field trials in this area. In addition, Alan had been involved with earlier work in Si nutrition in sugarcane in Australia.

Graham Kingston (BSES) again brought considerable experience in sugarcane nutrition and soil chemistry to the project, and was responsible, with the assistance of Monika Anink, for the establishment and maintenance of field trials in southern Queensland.

Alan Rudd (Mossman CPPB) had been responsible for recent Si amendment trials in the Mossman area that had measured significant yield increases and rekindled interest in Si nutrition in that area. He was also responsible for the establishment and maintenance of trials in that district.

Peter Lawrence (BSES), and later David Calcino (BSES), were responsible for extension and technology transfer.

Suzanne Berthelsen (CSIRO Land and Water) brought considerable experience in Si research, including development of soil extraction methods to assess the Si status of soils, evaluation of plant Si levels, and production of Si status maps of the Tully/Innisfail area.

The project was also strongly linked to and associated with other SRDC funded activities, including the Sugar Yield Decline Joint Venture (SYDJV), which had strongly supported early work in Si nutrition and its impact on yield decline. Alan Garside and John Berthelsen (SYDJV) assisted in the running and data collection from the field trials in north Queensland. Also linked to this project was another SRDC funded Travel Project to enable Suzanne Berthelsen to present a keynote address at the First Silicon Conference held in Florida in 1999, and to visit key personnel responsible for Si research in Hawaii and Mauritius. This has helped to develop strong links with major researchers in Si nutrition in other parts of the world, including USA, Brazil, Hawaii, Mauritius, Russia and Japan. These links have been further strengthened by Suzanne Berthelsen and Graham Kingston also being involved and presenting outcomes from this project at the Second Silicon Conference in Japan in 2002. This has resulted in the work carried out in Australia as part of this project, being well recognized and considered to be a significant contribution to research worldwide. In addition, knowledge transfer from these linkages has strongly and directly benefited this project.

4. Methodology

Initial research into Si nutrition of sugarcane in Queensland was undertaken in the central region and on the wet tropical coast of north Queensland during the 1970's (Haysom and Chapman, 1975; Hurney, 1973). In most of these early studies cement was used as the Si source. Although responses appeared to be strongly dependent on soil type, these studies did not clearly differentiate between responses associated with enhanced Si levels to those associated with changes in soil Ca or pH. In more recent preliminary studies undertaken in the Mossman district using Ca-silicate slag, cement and lime it was shown that increases in yield of 38% were due to enhanced soil Si status (Rudd and Berthelsen 1998). Similarly, Kingston (1999) reported significant responses to Si on a gleyed podzolic soil in the Isis district. A recent soil survey/mapping exercise of soil Si status in the Tully/Innisfail cane growing districts concluded that 67% of the cane growing region had sub-optimal levels of plant available Si (Berthelsen *et al.*, 1999). Hence, it was suggested that significant areas under sugarcane in the wet tropics have inadequate levels of Si to maintain optimum crop growth. Consequently two major objectives of this project were, (1) to extend the previous soil mapping exercise and evaluate the current Si status of the cane-growing soils between Tully and Mossman; and (2) to quantify responses in cane yield following Si application to soils identified as likely to be responsive.

Evaluation of the current Si status of cane growing soils in the Tully – Mossman regions

In the previous study on soils from the Tully-Innisfail area, Berthelsen *et al.* (1999) showed that the majority of soils had marginal to sub-optimal levels of Si. The map produced from this study was based on soils from undisturbed sites. Hence it detailed the inherent levels of soil Si prior to the establishment of agricultural enterprises. In other studies on new and old land paired sites Berthelsen *et al.* (1998) demonstrated a considerable decline in available Si after long-term sugar cane production. The success of the original soil mapping exercise encouraged an expansion of the survey area. In this survey all sugarcane cropping areas north of Tully were evaluated for soil Si status.

The previously described mapping exercise for the Tully-Innisfail Si status map was based on critical plant available soil Si levels using 0.01 M calcium chloride (CaCl_2) extractant, as suggested by Chapman *et al.* (1981). This is only one of several chemical extractant procedures that have been developed to determine plant available soil Si status (Fox *et al.*, 1967; Haysom and Chapman, 1975; Khalid *et al.*, 1978; Medina-Gonzales *et al.*, 1988; Snyder, 1991; Savant *et al.*, 1999). Therefore, an additional challenge is to develop and adopt a simple-to-use, but dependable, soil testing procedure that is appropriate for a given agro-climate (Savant *et al.*, 1999). Previous studies of Ca-silicate additions to sugarcane in central and northern Queensland determined soil Si levels using either 0.01 M CaCl_2 and 0.005 M H_2SO_4 (Hurney, 1973; Haysom and Chapman, 1975). As it was considered that routine testing of soil Si status is likely to be adopted in the near future, another objective of this study was to evaluate the two different analytical chemical methods for measuring soil Si in order to identify the most robust method, and one that was best correlated with plant tissue levels.

Soil and plant sampling

Soil and plant ‘top visible dewlap’ (TVD) samples were collected from approximately 200 sites in the Tully, South Johnstone, Mourilyan, Babinda, Mulgrave, Mossman and Atherton Tableland mill areas. Extension staff of BSES, under the supervision of Mr A. Hurney, undertook the collection of the samples. The selection of sites from each mill area was based on dominant soil types. Soil samples were collected to a depth of 25 cm from the centre of the interrow. Each sample consisted of 10 bulked cores taken either along a diagonal or in a zig-zag pattern across the field to ensure that a representative sample was collected. Samples were collected following harvest of the plant crop, air dried and sieved to pass a 2 mm sieve prior to chemical analysis.

Leaf samples were collected from the same cane block during the period of maximum crop growth (February to April 2000), and collected again in 2001 from most of the blocks previously sampled. To avoid possible confounding effects due to varietal variation, wherever possible, sampling was restricted to first ratoon crops of the variety Q152. Where this was not possible, second ratoon crops or variety Q158 were chosen. On the Atherton Tableland only one variety, Q124, was sampled. Leaf samples, collected randomly throughout the block, were taken from stalks of average height and consisted of the middle 20 cm section of the top visible dewlap (TVD) leaf. After sampling the blades were stripped from the mid-rib, dried at 70°C and ground to pass through a 1 mm sieve using a hammer mill in preparation for analysis.

Plant available soil Si was determined following extraction with 0.01 M CaCl₂, using a modified approach to the blue silicomolybdous acid procedure (Weaver *et al.*, 1968). In brief, soil was shaken for 16 hours on an end-over-end shaker at 18 rpm, at a ratio of 1 g soil to 10 ml 0.01 M CaCl₂, centrifuged and supernatant retained for analysis. In addition, soil Si was determined after extraction with 0.005 M H₂SO₄ to provide an estimate of the capacity of soils to supply Si. This extraction is used for the determination of acid-extractable phosphorus, using the method of Kerr and von Stieglitz as described by Rayment and Higginson (1992). Following extraction at a ratio of 1:200 with 0.005 M H₂SO₄ for 16 hours, Si in the supernatant was determined using the blue silicomolybdous acid procedure. Determination of Si in the TVD leaf samples used a modified approach to the blue silicomolybdous acid procedure following the ‘Auto-clave digestion’ procedure described by Elliott and Snyder (1991).

Using latitude and longitude data for each site, samples were allocated to appropriate soil map coverages. Soil maps of the ‘Tully-Innisfail’ (Murtha, 1986), ‘Mossman-Cape Tribulation’ (Murtha, 1989), Cardwell-Tully’ (Cannon *et al.*, 1992), ‘Babinda-Cairns’ (Murtha *et al.*, 1997), and the ‘Atherton -Mareeba’ area (Enderlin *et al.*, 1997) were used to provide details and descriptions of the soils collected in the survey.

Quantification of responses in cane yield and ccs to Si applications

In order to quantify the potential Si response in these areas, a series of field experiments were established during the 1999 planting season in the Mossman and Innisfail districts of the wet tropics and the Bundaberg district of southern Queensland. Two series of experiments were established – ‘Rate trials’ and ‘Product trials’. In the Rate trials a range of rates of Ca-silicate from zero to 12 t/ha were

applied, while in the Product trials a number of different potential sources of Si were evaluated.

Selection of field sites and site characterization

Rate and Product trials

A large number of potential sites were examined before final selection of the field sites for the Rate and Product trials. Sites were selected on a number of criteria. Contrasting soil types and climatic conditions were important considerations, but the predominant criteria was that the soils had sub-optimal levels of soluble Si (<10mg Si/kg following extraction with 0.01M CaCl₂) and extractable Si (<100 mg Si/kg following extraction with 0.1M citric acid (initially used as an alternative extractant to 0.005M H₂SO₄)).

Both sites in north Queensland have characteristically humid summers and relatively mild dry winters. Although the annual rainfall of approximately 3000 to 3500 mm has a strong summer dominance, significant rainfall events can still occur at any time during the year. The mean monthly temperatures range from a maximum of 31°C in January to a minimum of 16°C in July (Murtha, 1986; Murtha, 1989).

At Innisfail, both Rate and Product trials were established close to each other on R. Cecchi's property on the Palmerston Highway (17°35'S, 145°59'E), in the South Johnston Mill Area. The soil is a krasnozem, a deep soil formed *in situ* from basaltic material and classified as a Ferrosol using the New Australian Classification System (Isbell, 1996). The soil has been further classified by the local soil series name, Pin Gin (Murtha, 1986). It is a red gradational textured soil with a dark reddish brown, friable clay loam 'A' horizon, gradually changing to a dark red friable clay loam to light clay 'B' horizon which generally has a massive to weak structure. The profile is dominated by clay (65 to 80%) and silt (13 to 20%).

The Mossman trials were again established close to each other, and situated on Reynold's property 'Brie Brie' (16°17'S, 145°24'E) in the Daintree area. In contrast to the Innisfail site, these trials were established on a well-developed podzol formed on a remnant beach ridge and classified as a Tenosol (Isbell, 1996). The soil is locally classified as a Daintree soil series Murtha (1989). It is characterized by a very dark grey fine sand to loamy sand 'A' horizon, approximately 30 to 40 cm thick, with a clear change to a dark grey brown mottled 'B' horizon. The entire soil profile is dominated by sand (>80%) with generally 60 to 70% being fine sand.

The Bundaberg trials were established at two different locations. The Rate trial was established at Relmay Pty. Ltd, Elliott Plain on a gleyed podsolic soil, classified as a Hydrosol (Isbell, 1996), while the Product trial was established on D. Trebbin's property on Gillens Creek Road on a yellow podzolic soil.

Although the pedological characteristics of the three sites are very different, all sites are characterized by a general low fertility status with low pH, low levels of

Table 4.1. Selected soil chemical properties of field trial sites prior to the application of silicate materials. Each value is the mean of 3 replicates

| Depth (cm) | pH _w | pH _{Ca} | EC (dS/m) | Organic C (%) | Exchange properties (cmol _c /kg) | | | | | | | | BSES P (mg/kg) | Si (CaCl ₂) (mg/kg) | Si (Citric) (mg/kg) |
|------------------|-----------------|------------------|--------------|------------------|---|------------------|----------------|-----------------|--------|------|------|------|-------------------|------------------------------------|---------------------------|
| | | | | | Ca ²⁺ | Mg ²⁺ | K ⁺ | Na ⁺ | Al + H | CEC | AEC | ECEC | | | |
| Bundaberg | | | | | | | | | | | | | | | |
| 0-10 | 6.12 | 5.52 | 0.04 | 0.65 | 1.83 | 0.39 | 0.07 | 0.06 | 0.06 | 2.47 | 0.04 | 2.42 | 50 | 9.0 | 49 |
| 10-20 | 6.15 | 5.60 | 0.05 | 0.60 | 1.63 | 0.33 | 0.07 | 0.10 | 0.12 | 2.27 | 0.03 | 2.24 | 46 | 7.8 | 63 |
| 20-30 | 5.82 | 5.22 | 0.05 | 0.48 | 0.94 | 0.20 | 0.04 | 0.12 | 0.06 | 1.53 | 0.02 | 1.36 | 37 | 6.2 | 31 |
| 50-70 | 5.93 | 5.40 | 0.07 | 0.24 | 0.72 | 0.51 | 0.03 | 0.19 | 0.05 | 1.27 | 0.06 | 1.50 | 3 | 10.1 | 54 |
| Innisfail | | | | | | | | | | | | | | | |
| 0-10 | 4.84 | 4.67 | 0.11 | 2.73 | 1.07 | 0.26 | 0.13 | 0.07 | 0.18 | 0.74 | 0.99 | 1.54 | 56 | 8.6 | 68 |
| 10-20 | 4.83 | 4.62 | 0.11 | 2.87 | 1.09 | 0.26 | 0.11 | 0.05 | 0.19 | 0.76 | 0.88 | 1.52 | 58 | 9.2 | 61 |
| 20-30 | 4.64 | 4.52 | 0.07 | 2.43 | 0.48 | 0.12 | 0.06 | 0.05 | 0.22 | 0.17 | 1.60 | 0.72 | 46 | 8.1 | 57 |
| 50-70 | 4.43 | 4.86 | 0.04 | 1.10 | 0.08 | 0.00 | 0.02 | 0.04 | 0.05 | 0.00 | 3.33 | 0.13 | 25 | 5.1 | 75 |
| Mossman | | | | | | | | | | | | | | | |
| 0-10 | 5.49 | 4.33 | 0.02 | 1.43 | 1.90 | 0.17 | 0.13 | 0.04 | 0.50 | 2.40 | 0.06 | 2.24 | 82 | 4.2 | 25 |
| 10-20 | 5.50 | 4.53 | 0.02 | 1.40 | 2.60 | 0.08 | 0.07 | 0.04 | 0.35 | 2.73 | 0.09 | 2.79 | 86 | 4.4 | 36 |
| 20-30 | 5.57 | 4.67 | 0.02 | 1.10 | 1.80 | 0.05 | 0.05 | 0.03 | 0.29 | 1.77 | 0.10 | 1.92 | 65 | 4.0 | 104 |
| 50-70 | 5.07 | 4.45 | 0.02 | 0.41 | 0.17 | 0.02 | 0.04 | 0.03 | 0.35 | 0.24 | 0.05 | 0.26 | 16 | 6.4 | 255 |
| Bundaberg | | | | | | | | | | | | | | | |
| 0-10 | 6.07 | 5.47 | 0.04 | 0.57 | 1.60 | 0.23 | 0.04 | 0.04 | 0.05 | 1.95 | 0.03 | 1.91 | 34 | 5.4 | 30 |
| 10-20 | 5.98 | 5.39 | 0.05 | 0.55 | 1.60 | 0.24 | 0.07 | 0.04 | 0.04 | 2.03 | 0.03 | 1.95 | 35 | 5.0 | 31 |
| 20-30 | 6.19 | 5.60 | 0.05 | 0.55 | 1.65 | 0.27 | 0.07 | 0.04 | 0.04 | 1.83 | 0.01 | 2.03 | 38 | 5.5 | 23 |
| 50-70 | 5.23 | 5.01 | 0.04 | 0.26 | 0.66 | 0.15 | 0.02 | 0.05 | 0.11 | 0.75 | 0.03 | 0.89 | 2 | 7.1 | 70 |
| Innisfail | | | | | | | | | | | | | | | |
| 0-10 | 4.89 | 4.63 | 0.11 | 2.83 | 1.23 | 0.28 | 0.18 | 0.06 | 0.17 | 1.19 | 0.66 | 1.74 | 79 | 9.1 | 63 |
| 10-20 | 4.79 | 4.58 | 0.09 | 2.70 | 0.87 | 0.20 | 0.12 | 0.05 | 0.19 | 1.05 | 1.02 | 1.24 | 80 | 8.1 | 60 |
| 20-30 | 4.52 | 4.51 | 0.06 | 2.05 | 0.32 | 0.08 | 0.06 | 0.05 | 0.19 | 0.29 | 2.13 | 0.51 | 58 | 8.0 | 60 |
| 50-70 | 4.38 | 4.68 | 0.04 | 1.19 | 0.07 | 0.02 | 0.02 | 0.03 | 0.09 | 0.00 | 4.18 | 0.15 | 29 | 5.9 | 72 |
| Mossman | | | | | | | | | | | | | | | |
| 0-10 | 5.14 | 4.25 | 0.02 | 1.58 | 0.91 | 0.12 | 0.11 | 0.04 | 0.81 | 1.88 | 0.08 | 1.17 | 113 | 4.3 | 62 |
| 10-20 | 5.12 | 4.26 | 0.02 | 1.70 | 0.97 | 0.09 | 0.10 | 0.04 | 0.86 | 1.58 | 0.06 | 1.20 | 108 | 4.0 | 64 |
| 20-30 | 5.09 | 4.37 | 0.02 | 1.28 | 0.42 | 0.05 | 0.06 | 0.03 | 0.68 | 0.76 | 0.04 | 0.55 | 50 | 4.5 | 163 |
| 50-70 | 4.83 | 4.38 | 0.02 | 0.41 | 0.13 | 0.03 | 0.04 | 0.02 | 0.31 | 0.24 | 0.12 | 0.21 | 7 | 6.6 | 122 |

exchangeable cations, low cation exchange capacity and relatively low levels of organic carbon (Table 4.1). All sites have been under continual sugarcane production for more than 30 years.

Soil chemical properties prior to the implementation of treatments for each of the trials and locations are presented in Table 4.1. Soil pH as measured in water was highest in soils from the Bundaberg area and lowest in the Innisfail soils with the Mossman soils being intermediate. Exchangeable Ca^{2+} levels were at an adequate level in all trials over the depth interval 0-20 cm. However, in the case of the Mossman and Innisfail sites, although the levels were greater than the critical value of 0.55 cmol/kg (Calcino, 1994) they may still be considered slightly marginal (Table 4.1). Similarly exchangeable Mg^{2+} levels followed the same trend, with the Bundaberg and Innisfail sites exhibiting adequate Mg^{2+} levels in the surface soils, while those at Mossman were in the marginal range (0.10 to 0.25 cmol/kg) (Calcino, 1994). At all sites the levels of exchangeable K^+ were below the critical level of 0.24 cmol/kg as reported by Calcino (1994). Fertilizer at standard recommended rates was applied at planting to remediate sub-optimal nutrient levels. The amount of Si extracted using 0.01 M CaCl_2 at all sites was less than the critical value of 10 mg/kg as described by Haysom and Chapman (1975). Concentrations of Si extracted using 0.01 M citric acid are usually comparable to that extracted with other dilute acid extractants such as 0.005 M H_2SO_4 , and the levels reported suggest that the Si reserves in these soils are also low. It is notable that in samples collected from the 50-70 cm depth interval at Mossman the levels of citric acid Si were elevated. This source of Si is associated with poorly crystalline/amorphous materials. Indeed it was noticeable that significant amounts of concretionary material were present in this depth layer and it is assumed that the elevated citric acid Si levels were associated with this material. It is of note that on the Ferrosol site (Innisfail), there is an increase in anion exchange capacity (AEC) with depth (Table 4.1). The presence of a significant AEC would enhance the retention of Si on the exchange complex in these soils.

Additional trials to assess acidulated metal silicates

In 2000, additional trial sites were established close to the original trial sites to undertake field assessment of acidulated metal silicates as a Si source. While results from early laboratory-based dissolution studies suggested that these products were very high in soluble Si when compared to other sources of silicate materials, their ability to significantly increase the Si concentration in the soil solution was unknown. Therefore these field studies were initiated to investigate the efficacy of these materials and their effect on soil chemical properties.

At Mossman a plant cane crop was established on a Si deficient sand, prior to the imposition of treatments. However, due to the patchy establishment of the plant cane crop the trial site was abandoned. As the planting season had come to an end, it was decided to apply these treatments to an established ratoon crop, situated beside the existing Rate and Product trials. The soil chemical attributes of this site were similar to that of the existing Rate and Product trials (Table 4.1).

In the Tully – Innisfail area, a site was chosen at the Yield Decline Joint Venture site at Feluga (17°52'S, 145°57'E). The soil at this site is classified as a well-drained coarse sandy yellow Kandosol (Isbell, 1996), and locally classified as a Thorpe soil series (Murtha, 1989). The soil chemical attributes prior to the imposition of treatments are shown in Table 4.2.

Table 4.2. Soil chemical properties of the Feluga field trial site prior to the application of silicate materials. Each value is the mean of 3 replicates

| Depth cm | pH water | pH CaCl ₂ | EC dS/m | Organic Carbon % | Charge Properties | | | | | | | Si | | |
|-------------|-------------|-------------------------|------------|------------------------|-------------------|------|------|------|------|------|------|--------|--------------------------------|-------------------|
| | | | | | Ca | Mg | K | Na | H+Al | CEC | AEC | Citric | H ₂ SO ₄ | CaCl ₂ |
| | | | | | cmol(c)/kg | | | | | | | mg/kg | | |
| 0-10 | 5.34 | 4.60 | 0.04 | 0.76 | 1.70 | 0.42 | 0.11 | 0.09 | 0.26 | 1.90 | 0.09 | 155 | 98 | 6.0 |
| 10-20 | 5.28 | 4.63 | 0.04 | 0.78 | 1.53 | 0.39 | 0.11 | 0.10 | 0.36 | 2.03 | 0.06 | 148 | 98 | 7.3 |
| 20-30 | 4.77 | 4.47 | 0.03 | 0.81 | 0.70 | 0.19 | 0.07 | 0.07 | 0.91 | 1.44 | 0.09 | 161 | 111 | 8.0 |
| 30-50 | 4.57 | 4.18 | 0.03 | 0.57 | 0.45 | 0.10 | 0.10 | 0.08 | 1.39 | 1.67 | 0.20 | 190 | 116 | 12.5 |
| 50-70 | 4.49 | 4.12 | 0.03 | 0.46 | 0.32 | 0.07 | 0.09 | 0.07 | 1.67 | 1.70 | 0.39 | 189 | 119 | 11.3 |

Three trials were established in the Bundaberg district in the 2000 spring planting season. Two of the trials were designed to assess the efficacy of the acidulated olivine whilst the third trial assessed various locally available source of Si. The main trial, using similar treatments as used in the Mossman and Tully trials was situated at Relmay, Elliott Plain on a gleyed podzolic soil, and had soil chemical characteristics as those described for the Rate trial previously established on this property (Table 4.1). The two other trials were established on G. McCarthy's property, North Gregory, Childers on a yellow podsol soil. While one trial (Block 8) included an acidulated Mg silicate material, the treatments imposed at both of these sites were designed to assess a wide range of various available sources of Si.

In the 2001 season, three further trial sites were established in the Bundaberg district, namely at D. Schulte's property, Moore Park Rd., Bundaberg, D. Morris's property, Boonaroo Rd., Maryborough, and K. Franettovich's property, Mackay. The site at Franettovich's, Mackay was considered an unusual site as the H₂SO₄ extractable Si concentrations were very low while the CaCl₂ soluble Si levels were >10 mg/kg (which was nominally set as the critical level below which a response to silicate additions could be expected) (Table 4.3). These trials were designed to assess a range of potential silicate materials including acidulated Mg silicate, and to also investigate alternative methods of applying silicated materials (ie. broadcast application versus banding).

Table 4.3. Initial soil chemical properties of the Franettovich field trial site

| Depth | pH | EC | Charge Properties | | | | P | Si | |
|-------|------|------|-------------------|------|-------|-------|-------------|--------------------------------|-------------------|
| | | | Ca | Mg | K | Na | (acid BSES) | H ₂ SO ₄ | CaCl ₂ |
| cm | | dS/m | cmol(c)/kg | | | | mg/kg | mg/kg | |
| 0-25 | 5.95 | 0.02 | 0.80 | 0.20 | 0.094 | 0.024 | 34 | 24 | 13.0 |
| 25-50 | 5.43 | 0.01 | 0.39 | 0.08 | 0.056 | 0.028 | 36 | 26 | 13.0 |

Experimental details

Rate and Product trials

All trial sites were established in 1999, with the silicate materials being applied approximately one month before planting. At all three sites, the Rate trials comprised of applications of Ca-silicate at rates of 0, 1.5, 3.0, 4.5, 6.0, 9.0 and 12.0 t/ha. The trial design was a randomised complete block with four replications, giving a total of 28 plots. The Ca-silicate used was a by-product phosphorous furnace slag obtained from Rhodia Inc. Total elemental analysis of the product, determined using X-ray fluorescence spectrometry (XRF) is presented in Table 4.4. In addition to the Ca-silicate treatments, at Innisfail, 2.5t/ha of lime was also applied prior to planting. Nitrogen (N), phosphorus (P) and potassium (K) fertilizer was applied at rates equivalent to 146, 19 and 96 kg/ha in the plant crop (2000) and at 151, 21 and 102 kg/ha in the first and second ratoon crops (2001 and 2002). Although lime was not applied to the Mossman site, N, P and K were applied at similar rates as previously described.

Table 4.4. Total elemental analysis of the calcium-silicate product used in the trials, determined using X-ray fluorescence spectrometry

| Si | Al | Fe | Mg | Ca | Na | K | Ti | P | Mn |
|-------|------|------|------|-------|------|------|------|------|------|
| % | | | | | | | | | |
| 21.47 | 1.56 | 1.33 | 0.36 | 31.48 | 0.59 | 0.38 | 0.08 | 1.17 | 0.03 |

The Product trials compared various locally available sources of Si, including mill ash, mud ash, cement, cement building board by-product (Hi-Yield), rock dust (Min Plus), thermo-phosphate (CalPhos), soluble potassium silicate and two imported Ca-silicate products (supplied by Rhodia Inc. and Calcium Silicate Corp.), both of which are by-product phosphorous furnace slags. Details of the various treatments used at the three sites are provided in Table 4.5. Rates of application in these trials were 0, 3 and 6 t/ha except for mill and mud ash. With these products, 25 and 50 t/ha (dry weight) of both the mill ash and mud ash were applied at Bundaberg, while rates of 30 and 60 t/ha (dry weight) of mill ash were used at Mossman. The experimental design was a randomized complete block with 3 replications.

In both the Rates and Products trials all treatments were broadcast and incorporated into the top 10 - 20 cm using an off-set disc plough or rotary. Trial details, including planting and

harvesting dates, are provided in Table 4. Plot widths ranged from 8 rows (12 m) for the trials established at Bundaberg, 7 rows (10.85 m) at Innisfail and 6 rows (9 m) at Mossman. Gross plot lengths of 15 m and 20 m were used in the Product and Rate trials respectively in all districts. The trials at Innisfail and Mossman were planted to Q158 in September and October 1999, whilst Q182 and Q124 were established on the Rate and Products trials at Bundaberg, respectively (Table 4.6).

Table 4.5. Details of the various Products used in the Product trials at Mossman, Innisfail and Bundaberg

| Mossman | Rate (t/ha) | Innisfail | Rate (t/ha) | Bundaberg | Rate (t/ha) |
|--|--------------------|---|--------------------|--|--------------------|
| 1. Untreated Control | 0 | 1. Untreated Control | 0 | 1. Untreated Control | 0 |
| 2. Calcium Silicate (Rhodia Inc.) | 3, 6 | 2. Calcium Silicate (Rhodia Inc.) | 3, 6 | 2. Calcium Silicate (Rhodia Inc.) | 3, 6 |
| 3. Calcium Silicate (Calcium Silicate Corp.) | 3, 6 | 3. Calcium Silicate (Calcium Silicate Corp.) | 3, 6 | 3. Calcium Silicate (Calcium Silicate Corp.) | 3, 6 |
| 4. Cement | 3, 6 | 4. Cement | 3, 6 | 4. Cement | 3, 6 |
| 5. Hi-Yield | 3, 6 | 5. Hi-Yield | 3, 6 | 5. Hi-Yield | 3, 6 |
| 6. Min Plus | 3, 6 | 6. Min Plus | 3, 6 | 6. Mill ash | 25, 50 |
| 7. Mill ash | 30, 60 | 7. Potassium Silicate solution (AG-SIL) ** | 10, 20 L/ha | 7. Mud ash | 25, 50 |
| | | | | 8. CalPhos | 300, 600 kg/ha |

** Mill Ash was to be used at this site, but due to wet weather and difficulty obtaining product, soluble potassium silicate was applied to plots in early January 2000

Table 4.6. Details of number of plots, plot size, and dates of planting and biomass assessment operations for the Rate and Product trials at Mossman, Innisfail and Bundaberg

| Trial details | Mossman | | Innisfail | | Bundaberg | |
|----------------------------------|---------------------|---------------------|------------------------|------------------------|----------------------|----------------------|
| | Rate trial | Product trial | Rate trial | Product trial | Rate trial | Product trial |
| Number of plots | 28 | 39 | 28 | 39 | 28 | 45 |
| | 7 trts x 4 reps | 13 trts x 3 reps | 7 trts x 4 reps | 13 trts x 3 reps | 7 trts x 4 reps | 15 trts x 3 reps |
| Plot size | 180m ² | 135m ² | 206m ² | 152m ² | 240m ² | 180m ² |
| | 6 rows: 9m x 20m | 6 rows: 9m x 15m | 7 rows: 10.9m x 19m | 7 rows: 10.9m x 14m | 8 rows: 12m x 20m | 8 rows: 12m x 15m |
| Variety | Q158 | Q158 | Q158 | Q158 | Q182 | Q124 |
| Planted | October-99 | October-99 | September-99 | September-99 | August-99 | September-99 |
| Biomass assessment* - plant crop | May-00 | May-00 | May-00 | May-00 | August-00 | September-00 |
| Biomass assessment* - ratoon 1 | July-01 | July-01 | September-01 | not harvested | July-01 | |
| Biomass assessment* - ratoon 2 | not harvested | not harvested | July-02 | not harvested | September-02 | November-02 |

* hand - harvest

Additional trials to assess acidulated metal silicates

Experimental details of the additional trials are provide below:

District: Mossman

Site/Grower: Brie Brie

Variety: Q158

Plot size: 135m² (4 rows: 6m x 15m)

Number of plots: 27 (3 reps x 9 treatments)

Treatments: untreated control; calcium silicate at 4t/ha; cement at 500 kg/ha; Growforce acidulated olivine at 250, 500, 1000 kg/ha; Incitec acidulated serpentine at 250, 500, 1000 kg/ha

Application method: All treatments applied to surface of drill with no subsequent cultivation to an established ratoon crop

Establishment dates: Treatments applied 1/12/2000

Harvest details: Attempts were made to hand-harvest the plant crop in July 2001. The yields were extremely poor and the plots very weedy with a highly variable plant stand. The trial was abandoned and ploughed in following harvest.

District: Tully

Site/Grower: Feluga Yield Decline Rotation site

Variety: Q158

Plot size: 90m² (6 rows: 9m x 15m)

Number of plots: 27 (3 reps x 9 treatments)

Treatments: untreated control; Growforce acidulated olivine at 50, 100, 250, 500 kg/ha; Incitec acidulated serpentine at 50, 100, 250 kg/ha; cement at 500 kg/ha

Application method: The treatment containing Ca-silicate slag was broadcast and incorporated. The cement and acidulated treatments were applied to the drill to young cane in December 2000 prior to hilling up. These applications were not applied at the most desirable time due to the late arrival of product and the inclement wet conditions prior to the December application.

Establishment dates: The plant cane crop was established in August 2000, calcium silicate broadcast prior to planting and all other treatments applied in December 2000.

Harvest details: The plant crop was machine harvested in July 2001 and the first ratoon crop hand-harvested in June 2002.

District: Bundaberg

Site/Grower: Relmay, Elliott Plain, Block 17A

Variety: Q170

Plot size: 135m² (4 rows: 6m x 15m)

Number of plots: 45 (3 reps x 15 treatments)

Treatments: untreated control; calcium silicate at 4t/ha; cement at 500 kg/ha; Growforce acidulated olivine product 1 at 250, 500, 1000 kg/ha; Incitec acidulated serpentine at 250, 500, 1000 kg/ha; CalPhos at 150, 300, 600 kg/ha; Growforce acidulated olivine product 2 at 250, 500, 1000 kg/ha

Application method: The treatment containing Ca-silicate slag was broadcast and the remainder of the treatments applied as row dressings

Establishment dates: The treatment containing Ca-silicate slag was broadcast and incorporated on 14/9/2000 and the remainder of the treatments applied on 18/10/2000, except for the Growforce acidulated olivine product 2 which was applied on 5/12/2000

Harvest details: The plant crop was harvested in 4/10/2001 and the first ratoon crop on 20/9/2002.

District: Bundaberg

Site/Grower: McCarthy, McCarthy's Rd. North Gregory, Childers, Block 8

Variety: Q138

Plot size: Strip trial – 6 strips of 13 rows x approximately 400m

Number of plots: 6 strips with no replication

Treatments: two untreated controls; Growforce acidulated olivine at 415 kg/ha; filter mud/ash at 100t/ha (fresh); diatomaceous earth at 2 t/ha; CalPhos at 486 kg/ha

Application method: Filter mud/ash and diatomaceous earth incorporated and the other treatments applied as row dressings and hilling-up

Establishment dates: Broadcast treatments applied and incorporated in first week of September 2000 and row dressings applied 1/12/2000

District: Bundaberg

Site/Grower: McCarthy, McCarthy's Rd. North Gregory, Childers, Block 18

Variety: Q138

Plot size: 99m² (6 rows: 9m x 11m)

Number of plots: 36 (3 reps x 12 treatments)

Treatments: untreated control; calcium silicate at 4t/ha; diatomaceous earth at 0.5, 1, 2, 6 t/ha; CalPhos at 150, 300, 600 kg/ha; mineral potassium silicate at 150, 300, 600 kg/ha

Application method: Calcium silicate and the two highest rates of diatomaceous were broadcast and incorporated, and the other treatments applied to the open row after planting and then incorporated by 'cotton king' discing.

Establishment dates: Broadcast treatments applied and incorporated on 4/9/2000 prior to planting on 11/9/2000, and row dressings applied 13/10/2000

District: Bundaberg

Site/Grower: Des Schulte, Moore Park Rd.

Variety: Q151

Plot size: 141m² (6 rows: 9.4m x 15m)

Number of plots: 57 (3 reps x 19 treatments)

Treatments: two untreated controls; calcium silicate at 0.5, 1, 2, 4t/ha; cement at 0.5, 1, 4 t/ha; Pacific Lime at 0.5, 1, 4 t/ha; diatomaceous earth (Silconite) at 0.5, 4 t/ha; Growforce acidulated olivine product 2 at 100, 200, 400 kg/ha; diatomaceous earth (Maidenwell) at 2 t/ha; diatomaceous earth (Maidenwell + bugs) at 2 t/ha

Application method: The two highest rates of Ca-silicate slag and the highest rates of cement, Pacific Lime and Silconite were broadcast and incorporated. The remainder of the treatments were applied to the row.

Establishment dates: The broadcast treatments were applied before planting which took place on 6/8/2001.

District: Maryborough

Site/Grower: Des Morris, Boonaroo Rd.

Plot size: 148.5m² (6 rows: 9.9m x 15m)

Number of plots: 42 (3 reps x 14 treatments)

Treatments: two untreated controls; blast slag at 4 t/ha; calcium silicate at 4, 8 t/ha; cement at 4 t/ha; Pacific Lime at 0.5, 1, 4 t/ha; diatomaceous earth (Silconite) at 3.4 t/ha; lime kiln dust (ELM_plus) at 2.69 t/ha; Growforce acidulated olivine product 2 at 100, 200, 400 kg/ha

Application method: All treatments were broadcast and incorporated except for the two lowest rates of Pacific Lime and the Growforce acidulated olivine product 2, which were applied to the row.

District: Mackay

Site/Grower: Keith Franettovich

Number of plots: 48 (3 reps x 16 treatments)

Treatments: untreated control; calcium silicate at 0.5, 1, 2, 4 t/ha; cement at 0.25, 0.5, 1, 4 t/ha; Pacific Lime at 0.25, 0.5, 1, 4 t/ha; diatomaceous earth (Silconite) at 0.5, 4 t/ha; soft rock phosphate at 1 t/ha

Application method: The three highest rates of calcium silicate and the highest rate of cement, Pacific Lime and Silconite (diatomaceous earth) were broadcast and incorporated before planting and the remaining treatments were applied to the row.

Soil sampling and analysis

In 1999, soil samples were collected prior to the imposition of treatments from all control plots to a depth of 90 cm. Samples were air dried and sieved to pass a 2-mm mesh before chemical analysis was carried out on the 0-10, 10-20, 20-30 and 50-70 cm depth increments. Soil pH was measured in both water and 0.01 M CaCl₂ using a 1:5 soil:solution ratio. Electrical conductivity (EC) was determined on the supernatant of the water suspension prior to the pH measurement. 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⁺). The cation exchange capacity (CEC) and anion exchange capacity (AEC) were determined using the compulsive exchange method of Gillman and Sumpter (1986). Soil organic carbon was determined by wet oxidation using the Walkley and Black method as modified by Rayment and Higginson (1992). Phosphorous (P) was measured using the acid-extractable method of Kerr and von Stieglitz (1938) and determined using the colorimetric method of Murphy and Riley (1962). Plant available soil Si is considered to be the soil Si that is readily soluble (Si_{sol}), and was determined following extraction with 0.01 M CaCl₂, using a modified approach to the blue silicomolybdous acid procedure (Weaver *et al.*, 1968). Soil Si (Si_{cit}) was also determined after extraction with 0.1 M citric acid to provide an estimate of the capacity of soils to supply Si. Initial soil chemical properties for each of the trial sites prior to the implementation of treatments are presented in Table 4.1.

At the end of the first (2000) and second (2001) growing seasons soil samples were again collected from all treatments and submitted for chemical analysis. At Mossman and Innisfail, during these sampling periods soil was only collected to 40 cm, as it was anticipated that most soil chemical changes would have occurred within, and possibly just below the incorporation layer of the calcium silicate material. Three cores per plot were bulked and then divided into 10 cm increments. At Bundaberg, at the end of the first growing season (2000) soil samples were collected to 50 cm, and divided into 0-10, 10-20, 20-30 and 30-50 cm depth increments. At the end of the second growing season (2001), soil was only collected from 0-25 cm increment.

Soil was air dried and sieved to pass a 2-mm mesh before chemical analysis was carried out. On the first three depth increments (0-10, 10-20 and 20-30 cm) chemical analysis included pH measured in both water and 0.01 M CaCl₂, EC, basic exchangeable cations (Ca²⁺+Mg²⁺+K⁺+Na⁺), readily soluble soil Si (Si_{sol}) and P using the methods described above. Extractable soil Si (Si_{ext}) was also determined on the acid extraction used for determining P as recommended by Hurney (1973) and Haysom and Chapman (1975), as an alternative means of assessing plant available soil Si levels. Readily soluble soil Si (Si_{sol}) was also determined on the deeper depth increment (30-40 cm at Mossman and Innisfail, or 30-50cm at Bundaberg) to determine if there had been any vertical movement of Si.

Charge fingerprint analysis using the methodology described by Gillman and Sumpter (1986), was undertaken on composite samples to examine the effect the calcium silicate

amendment may have had on the surface charge characteristics and buffer capacity of the soil. Composite samples were prepared for the soils collected at both the end of the first and second growing seasons, by bulking the four replicate samples for the 0-10 cm increment of the control, 4.5, 9 and 12 T/ha treatments only. All charge fingerprint analyses were duplicated and the results reported are a combination of the duplicates.

Charge fingerprints are curves describing the total cation exchange (CEC_T), base cation exchange (CEC_B) and anion exchange capacity (AEC) over a range of pH values. The CEC_B is of agricultural significance, as it is a measure of the maximum amount of exchangeable basic cations that can be retained in exchangeable form. In brief, soils are first saturated with Ca^{2+} before being brought to equilibrium in a 0.002M $CaCl_2$ matrix. The pH of the suspension is adjusted to six values over the pH range of agronomic interest, generally pH 4 to pH 7. After equilibrium is attained, the Ca^{2+} , Al^{3+} and Cl^- are displaced with NH_4NO_3 . The Al^{3+} content is determined using the pyrocatechol-violet method (Bartlett *et al.*, 1987) and the Cl^- using methodology described by Rayment and Higginson (1992). 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.

Estimates of the pH buffering capacity were also made on the same composite samples used for charge fingerprint analysis, using the method of Aitken and Moody (1994). Briefly, titration curves are established by adding incremental amounts of either NaOH or HCl to a 1:5 soil:water suspension. For each titration 4 g of soil was weighed into each of 11 centrifuge tubes. Varying amounts of 0.003M $CaCl_2$ or deionized water were added such that once the acid and alkali additions are made the final volume was 20 mL with a solution concentration of 0.002M $CaCl_2$. The alkali and acid solutions are 0.04M (standardised) and for each soil additions of 0, 0.2, 0.4, 0.6, 1.2 and 2.4 mL were made. Chloroform (0.25 mL) was also added and the suspensions equilibrated for 24 h on an end-over-end shaker. The suspensions were then removed from the shaker and left to equilibrate for a further 6 days. During this period the samples are re-suspended daily by shaking for 2 minutes. After equilibration the pH of each suspension is read. Soil pHBC is a measure of the rate of acid or alkali addition per unit change in soil pH (Helyar and Porter, 1989), and is approximately constant within the pH range 4.5 – 6.0 (Magdoff and Bartlett, 1985). Since buffer capacity is defined as the change in quantity with intensity, the reciprocal of the slope of the regression line is taken as a measure of pH buffer capacity. The amount of acid or base that has been added to the system as a result of amendment addition or over time can be determined by calculating the net acid addition rate, NAAR ($kmol\ H^+/ha$) by using the equation of Helyar and Porter (1989):

$$NAAR = [(pH_i - pH_f) \times pHBC \times BD \times V]/T$$

where the subscripts i and f refer to initial and final values, pHBC is the mean pH buffering capacity in $kmol\ H^+/kg.pH$ unit, BD is bulk density (kg/m^3), V is the soil volume in the 10 cm depth interval (m^3/ha) and T is time (years) since addition of amendment.

In addition, the point of zero charge, pH_0 , can be determined during the development of the charge fingerprint. After the soil sub-samples have been equilibrated over the required range of pH values at low ionic strength (0.002M $CaCl_2$), a small amount of concentrated $CaCl_2$

solution is added to each tube to raise the electrolyte concentration. When the change in pH for each sub-sample is plotted against suspension pH, the point where a change in electrolyte concentration does not cause a change in pH is nominally called pH_0 , and is the point where the net charge from all the variable charge components in the soil is zero. Consequently, at pH_0 any remaining charge is the net permanent charge, and can be determined by $CEC_T - AEC$. Once the amount of permanent charge is known, and as this does not change with a change in pH, the amount of variable charge at any pH can be determined.

At the end of the first growing season soil samples were collected from all treatments and submitted for chemical analysis.

Yield assessment, plant sampling and analysis

Leaf samples were collected from the top visible dewlap from all treatments approximately 7 months after the establishment of the trials. Samples were oven dried at 70°C and ground to a powder. The Si content was determined by wet digestion (Elliott and Snyder, 1991). The elemental composition of leaf samples was determined by x-ray fluorescence spectrometry (Norrish and Hutton, 1977) on a selection of samples.

An interim yield sample was undertaken approximately 8 months after planting at all sites. Sample quadrats were cut from each plot and consisted of 2 rows x 3 m in the Mossman trials. The number of stalks harvested and total fresh weight were recorded and a sub-sample of 20 stalks were split into millable stalk and green leaf plus cabbage. Millable stalk was defined as that part of the stalk below the fifth dewlap from the top. Weights of each of these components were recorded and a sub-sample was mulched for dry mass determination. At Innisfail and Bundaberg, numbers of stalks were determined from 2 rows x net plot length (14 or 19m) with weight being determined on a sub-sample of 20 stalks (2 rows x 10 stalks). The stalks were partitioned into stalks and tops and processed as per the Mossman samples. Six whole stalks were used for the determination of CCS. This was done following juice extraction with a hydraulic press (rates trials) and laboratory mill (products trials). In addition to the interim yield assessment at 8 months, final harvest yields were undertaken at all sites using a weighing machine. The Mossman and Innisfail sites were hand-harvested in May 2000, while the machine harvest was carried out in July and October at each of these sites respectively. At Bundaberg, again the crops were hand-harvested at approximately 8 months, and machine harvest took place for the Rate trial in August 2000 and the products trial in September 2000. CCS was determined from juice extracts with a laboratory mill or hydraulic press.

5. Evaluation of the current Si status of cane growing soils in the Tully to Mossman region

Introduction

Desilication is a natural process of soil pedogenesis and is favoured in humid tropical regions because of characteristically high rainfall and temperature. Under these conditions basic cations are stripped from the exchange complex resulting in acidification of the soil and dissolution of aluminosilicate clay minerals with the concomitant leaching of silica. Thus soils of the wet tropics that have undergone significant weathering invariably have inherently low levels of plant available silicon (Si) and consequently may have sub-optimal levels for maximum biomass and sugar production.

To evaluate the current soil Si status of the Tully to Mossman region (Figure 5.1) and to determine what percentage of soils may have sub-optimal Si concentrations, the methodology used to measure plant available soil Si is an important consideration. The forms of Si in the soil can be defined as total, extractable and soluble. Whilst it is the concentration of soluble Si in soils that is important for crop growth, this can have little relationship to the total Si content of soils. In addition, the concentration of soluble Si in soils is dynamic. Although leaching of Si from the soil and uptake by the plant are important processes in determining Si concentrations, for an individual soil type, the equilibrium concentration of Si is largely controlled by adsorption / desorption reactions. In addition, when Si is added to a soil, it reacts rapidly with amorphous surfaces. The amount and rate of Si adsorption is dependent on the sesquioxide content of the soil, soil pH, and the presence of other anions (Jones and Handreck, 1963).

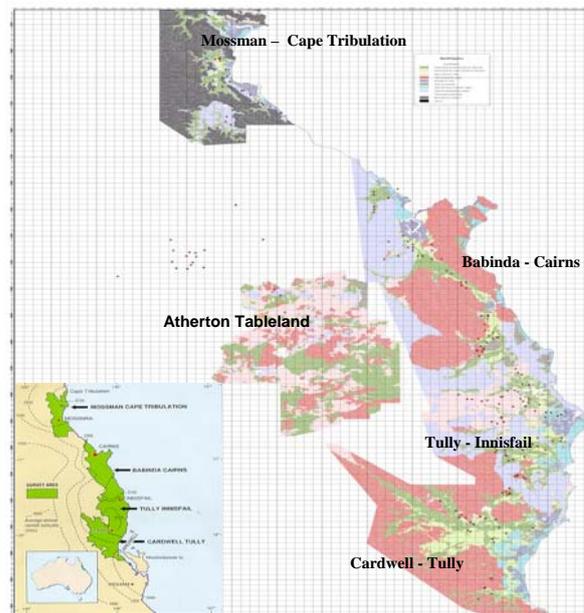


Figure 5.1. Soil distribution map areas of the Mossman, Babinda, South Johnston, Tully and Atherton Tableland regions

The previous mapping exercise for the Tully-Innisfail Si status map was based on critical plant available soil Si levels using 0.01 M calcium chloride (CaCl₂) extractant, as suggested by Chapman *et al.* (1981). This is only one of several chemical extractant procedures that have been developed to determine plant available soil Si status (Table 5.1). If routine testing of soil Si status is to be adopted, the challenge is to develop and adopt a simple-to-use, but dependable, soil testing procedure that is appropriate for a given agro-climate (Savant *et al.*, 1999). As previous studies of Ca-silicate additions to sugarcane in central and northern Queensland, determined soil Si levels using either 0.01 M CaCl₂ and 0.005 M H₂SO₄ (Hurney, 1973; Haysom and Chapman, 1975), an aim of this study was also to evaluate these two different analytical chemical methods for measuring soil Si in order to identify the most robust method, and one that was best correlated with plant tissue levels.

Results and Discussion

Plant available soil Si levels

The mean concentrations of readily soluble soil Si (extracted with 0.01 M CaCl₂) from sites sampled in the survey are presented in Table 5.2. The Si concentration was classified as sub-optimal (< 10 mg/kg Si) or marginal (10-20 mg/kg Si) based on levels suggested by Chapman *et al.* (1981), and used in the previous mapping exercise of the Tully-Innisfail area (Berthelsen *et al.*, 1999). Although the sites selected for the current survey covered only a limited range of the total number of soil series described on the wet tropical coast and the Atherton Tablelands, they do represent the dominant soil series present within the major soil types found in these areas. The results indicate that plant available Si levels on the majority of soils on the coastal plain are low. Greater than 50% of all sites sampled had sub-optimal soil Si levels (< 10 mg/kg), and in excess of 85% of all sites had Si levels that have the potential to limit production (< 20 mg/kg). In contrast, sites from the Atherton Tablelands had higher soil Si levels, with 50% of the soils sampled having soil Si concentrations greater than 20 mg/kg.

The majority of soils sampled on the Atherton Tablelands were from the Mareeba-Dimbulah area. These soils are predominantly of metamorphic and other meta-sedimentary rock origin (~53%), granite origin (~28%) and soil derived from basalt (~12%). Highest Si levels of soils sampled in this area were those derived from basalt (> 20 mg/kg), whilst the lowest were on the granite derived soils (≤ 10 mg/kg). Metamorphic soils were variable, with lower levels being on the soils with a neutral to acid reaction (average of 12 mg/kg), whilst more alkaline and sodic soils had considerably higher Si concentrations (> 20 mg/kg). This observation supports experimental work by Acquaye and Tinsley (1964) who demonstrated that while calcium reduced Si solubility under alkaline conditions, sodium enhanced solubility.

Although soils of the Atherton Tablelands need to be considered separately from soils of the wet coastal region, individual soil types and series of the Mossman, Babinda-Cairns and Tully-Innisfail mapping areas can, to some extent, be considered collectively as they have similar characteristics. We have chosen to consider the areas separately for preciseness (Table 5.2), although mean soil Si values (extracted both in 0.01 M CaCl₂ and 0.005 M H₂SO₄) of each of the soil series sampled in the survey are presented in Table 5.3. In the

Mossman district, which is the most northern section of the humid lowland cane growing area of north Queensland, the soils are formed on low grade metamorphic and granite, and on mixed alluvium derived from these parent materials. The predominant soil series described by Murtha (1989) are the well-drained alluvial soils (~42%) and soils derived from metamorphic material (~35%). As illustrated in Table 5.2, all the soils sampled in this area, which include those considered most suitable for sugarcane production (eg. Liverpool, Mossman and Tully soil series) (Wilson, 1991) are low in plant available soil Si, with concentrations of < 10 mg/kg.

Table 5.1 Methods used to determine soluble and extractable soil Si

| Extractant | Soil : Solution Ratio | Method | Suggested critical level | Reference |
|---|---|--|---|--|
| H ₂ O | pre-wet air-dry soil at a matric suction of 0.1 bar | incubate at 25°C for 1 day and centrifuge at 900g (RCF) for 1 hr. | | Gillman and Bell, 1978; Menzies and Bell, 1988 |
| H ₂ O | saturated paste | | 2 mg/kg | Fox and Silva, 1978 |
| H ₂ O | 1g : 1 mL | allow to stand 2 weeks with repeated shaking, filter and centrifuge | | Clements <i>et al.</i> , 1967 |
| H ₂ O | 10 g : 100 mls | continuous shaking for 4 hrs. and centrifuge at 24,000g (RCF) | < 0.9 mg/kg (deficient) < 2.0 mg/kg (marginal) 8.0 mg/kg | Fox <i>et al.</i> , 1967; Elawad <i>et al.</i> , 1982 |
| Phosphate acetate (pH 3.5) [500ppm P as Ca(H ₂ PO ₄) ₂ and 0.1 M (H,NH ₄)OAc] | 10 g : 100 mls | continuous shaking for 4 hrs. and centrifuge | < 50 mg/kg (deficient) 50-150 mg/kg (marginal - adequate) | Fox <i>et al.</i> , 1967 |
| Modified Truog - [0.01 M H ₂ SO ₄ containing 3 gms (NH ₄) ₂ SO ₄ /liter] | 1 g : 100 mls | continuous shaking for 30 minutes | < 40 mg/kg (deficient) 40-100 mg/kg (marginal - adequate) | Fox <i>et al.</i> , 1967 |
| 0.5 M NH ₄ OAc (pH 4.5-4.8) | 5 gms : 100 mls | continuous shaking for 1 hr. | < 20 mg/kg (deficient) 20-40 mg/kg (marginal - adequate) < 50 mg/kg (deficient) | Fox <i>et al.</i> , 1967 Wong You Cheong and Halais, 1970; Ayres, 1966 |
| 0.5 M NH ₄ OAc (pH 4.5-4.8) | 2.5 gms : 50 mls | 2.5 gm soil leached with 10 * 5 ml aliquots of extractant | | Bishop, 1967 |
| 0.01 M CaCl ₂ | 01:10 | continuous shaking for 16 hrs and centrifuged | < 20 mg/kg (deficient - marginal) | Haysom and Chapman, 1975 |
| 0.01 M CaCl ₂ | 01:25 | shake for 7 days, with a few drops of chloroform on a reciprical shaker at 250 C | | Wickramasinghe, 1994 |
| 0.005 M H ₂ SO ₄ | 1 : 200 | continuous shaking for 16 hrs and centrifuged | < 100 mg/kg (deficient-marginal) | Hurney, 1973 |
| 0.5 M Acetic acid | 01:10 | 1 hr shake, rest 15 minutes, decant and filter, rest 12 hrs before analysis | < 15 mg/kg (deficient) | Snyder, 1991 Korndorfer, G. (per. comm.) |
| 0.1 M Citric acid | 01:50 | 2 hr shake, rest O/N, 1 hr shake, centrifuge | | Acquaye and Tinsley, 1964 |

Table 5.2 Plant available soil Si levels (extracted with 0.01M CaCl₂) from sites sampled in the survey. The values represent the means of all sites sampled in each mill area ± standard error (SE.), and the percent of samples that may be classified as sub-optimal or marginal.

| Soil mapping areas | Mill Districts | Average soil Si concentration (mg/kg) (±SE.) | % sub-optimal (<10 mg/kg Si) | % marginal (10-20 mg/kg Si) | % soils with soil Si levels that may limit cane production |
|--|-----------------------------|--|------------------------------|-----------------------------|--|
| Mossman - Cape Tribulation (Murtha, 1989) | Mossman (n = 30) | 7.0 ± 0.5 | 87 | 7 | 94 |
| Babinda - Cairns (Murtha, 1997) | Babinda (n = 30) | 10.7 ± 0.8 | 70 | 20 | 90 |
| | Mulgrave (n = 29) | 10.8 ± 0.6 | 51 | 49 | 100 |
| Tully - Innisfail (Murtha, 1986) | Sth Johnstone (n = 30) | 11.6 ± 0.9 | 53 | 40 | 93 |
| | Mourilyan (n = 34) | 11.1 ± 0.9 | 59 | 38 | 97 |
| | Tully (n = 35) | 9.9 ± 1.0 | 60 | 26 | 86 |
| Atherton - Mareeba (Enderlin <i>et al.</i> , 1997) | Atherton Tableland (n = 20) | 17.7 ± 1.6 | 15 | 35 | 50 |

The soils of the Babinda – Cairns area are similar to those of the Mossman area (~ 24% well drained alluvials and ~21% metamorphic soils). The majority of soils are friable and free draining, acidic and have a low base status. The lowland soils can be diverse depending on drainage and profile wetness and there are extensive areas of freshwater and mangrove swamps (Murtha, 1989; Murtha *et. al.*, 1997). Fourteen percent of the soils series classified in this area consist of soils emanating from swamps. While the majority of soils sampled, particularly those derived from metamorphic parent material, had soil Si values < 10 mg/kg, some soils, notably the organic swamp soil of the Babinda series, had Si levels between 15 and 20 mg/kg. The role of organic matter in Si dissolution is complex, and therefore determining plant availability on these soils with high levels of organic matter can be difficult. In this respect it has been suggested that humus can both protect soil Si from dissolution while at the same time preventing it from sorption by the soil (Sadzawka and Aomine, 1977).

In contrast to the Mossman and Babinda-Cairns areas, a higher proportion of the soils in the Tully-Innisfail area are formed from granite (~24%) rather than metamorphic material (~10%), with large areas of soil formed from basalt present in the South Johnstone area. Considerable areas of mixed alluvium (~25% well-drained and ~17% poorly-drained) are derived from these parent materials. In this area the soils formed from granite, metamorphic and beach ridge material were all generally sub-optimal in soil Si levels, many soils containing < 5 mg/kg Si. The basalt soils (predominantly Pin Gin series) and the well-drained alluvial derived soils (predominantly Tully series) were generally higher, but more variable, with Si concentrations ranging from 10 – 20 mg/kg. The Si levels in the poorly

Table 5.3. Mean soil Si concentrations (and 95% confidence limits*), determined following extraction with both 0.01M CaCl₂ and 0.005M H₂SO₄, and the ratio 0.005M H₂SO₄ extracted Si to that extracted with 0.01M CaCl₂, for the range of soil types sampled in the survey.

* Confidence limits have only been determined where > 2 sites were sampled for each soil series.

| Parent Material | Soil Series | Number sites sampled | Mean soil Si (CaCl ₂) (mg/kg) ± confidence limits | Mean soil Si (H ₂ SO ₄) (mg/kg) ± confidence limits | Ratio of Si (H ₂ SO ₄) to Si (CaCl ₂) |
|---|-------------------|----------------------|---|--|--|
| <i>Wet Tropical Coastal (Tully - Mossman)</i> | | | | | |
| basaltic | Eubenangee | 8 | 10.8 ± 2.6 | 130 ± 35 | 12 |
| | Mundoo | 6 | 12.3 ± 6.5 | 144 ± 66 | 12 |
| | Pingin | 13 | 15.4 ± 3.1 | 232 ± 76 | 15 |
| beach ridges | Brosnan | 10 | 7.3 ± 1.9 | 135 ± 80 | 18 |
| | Daintree | 2 | 4.1 | 116 | 28 |
| granitic | Banyan | 2 | 3.3 | 166 | 50 |
| | Lugger | 4 | 8.8 ± 2.7 | 412 ± 909 | 47 |
| | Malbon | 8 | 9.3 ± 1.4 | 186 ± 25 | 20 |
| | Thorpe | 16 | 7.4 ± 1.9 | 198 ± 57 | 27 |
| | Tyson | 1 | 8.5 | 80 | 9 |
| metamorphic | Clifton | 7 | 7.1 ± 2.6 | 121 ± 31 | 17 |
| | Edmonton | 1 | 8.8 | 124 | 14 |
| | Galmara | 6 | 6.1 ± 2.3 | 83 ± 49 | 14 |
| | Mission | 4 | 11.0 ± 3.9 | 97 ± 65 | 9 |
| | Weatherby | 6 | 6.9 ± 3.1 | 99 ± 73 | 14 |
| poorly drained alluvial | Bulgun | 5 | 14.3 ± 7.8 | 1014 ± 1382 | 71 |
| | Coom | 12 | 12.8 ± 3.5 | 520 ± 521 | 41 |
| | Hewitt | 1 | 7.4 | 2756.00 | 374 |
| | Inlet | 4 | 9.2 ± 2.4 | 113 ± 34 | 12 |
| | Newell | 6 | 6.0 ± 3.0 | 170 ± 97 | 28 |
| | Timara | 1 | 23.4 | 248 | 11 |
| well drained alluvial | Innisfail | 6 | 12.9 ± 4.2 | 185 ± 91 | 14 |
| | Jarra | 1 | 7.3 | 148 | 20 |
| | Liverpool | 10 | 10.3 ± 2.6 | 138 ± 31 | 13 |
| | Mossman | 7 | 10.6 ± 2.8 | 170 ± 70 | 16 |
| | Tully | 29 | 11.0 ± 1.9 | 212 ± 43 | 19 |
| | Virgil | 2 | 9.1 | 185.00 | 20 |
| swamps | Babinda | 6 | 14.9 ± 5.8 | 801 ± 325 | 54 |
| <i>Atherton Tableland</i> | | | | | |
| basaltic | Tolga | 4 | 23.7 ± 5.7 | 596 ± 68 | 25 |
| granitic | Nicotine/Algoma | 4 | 9.7 ± 1.8 | 40 ± 24 | 4 |
| metamorphic | Arriga | 4 | 22.2 ± 9.2 | 227 ± 227 | 10 |
| | Penman/Leadingham | 3 | 23.9 ± 7.3 | 215 ± 122 | 9 |
| | Mulligan/Murphy | 5 | 11.9 ± 4.8 | 66 ± 27 | 6 |

drained alluvial soils were variable and strongly related to drainage, with the more poorly drained series having much higher Si levels.

Extraction and Measurement of Plant Available Si

While Si compounds such as quartz, various crystalline silicate minerals, silicate clays and amorphous silica compounds dominate the solid phase of all soils, the soluble forms in the soil solution consist of monosilicic and polysilicic acids, and complexes with organic and inorganic compounds. Monosilicic acid ($\text{Si}(\text{OH})_4$) is the form actively absorbed by growing plants and will remain in solution in the monomeric state in neutral and weakly acid solutions. However, rapid polymerization occurs at high solution concentrations, with increasing soil pH and in the presence of oxides and hydroxides of aluminium and iron. Monosilicic acid in solution can only be measured by the silicomolybdate blue colour method (Iler, 1979). When determining the amount of Si available for plant growth, the quantity of Si solubilized by different methods varies depending on the strength of the extracting solution. Although water extracts have often been used to estimate readily soluble Si this is generally not a suitable method since the low ionic strength of the solution will cause dispersion (Lindsay, 1979). As most of the soluble Si below pH 8 is uncharged monosilicic acid, changes in ionic strength should not significantly alter extractable levels in most soils. In this respect, Elgawhary and Lindsay (1972) recommend the use of 0.02 M CaCl_2 as the reactive media to equalize ionic strengths and facilitate ready flocculation of colloidal Si. Soils extracted with dilute CaCl_2 measure Si in the soil solution, and corresponds more closely to the levels of $\text{Si}(\text{OH})_4$ expected from solubility predictions (Lindsay, 1979). While dilute salt solutions (e.g. 0.01 M CaCl_2) provide a measure of the readily available Si, stronger extractants (e.g. 0.005 M H_2SO_4) will solubilize the slightly available and more insoluble structural forms of Si. Although this may provide an indication of the total capacity of the soil Si pool, it may not be related to the concentration of soluble Si in the soil solution, as this tends to be controlled by the solubility of the most soluble silicate mineral, regardless of the amount present (Herbillon *et al.*, 1977).

A comparison of the soil Si levels after extraction with 0.01 M CaCl_2 and 0.005 M H_2SO_4 are presented in Table 5.3 and Figure 5.2. It is clear that some soils, notably the basalt soils from the Atherton Tablelands (Figure 5.1, (a)), and the poorly drained soils (eg. Banyan, Lugger, Bulgun, Coom, Hewitt and Babinda soil series) from the wet coastal regions (Figure 5.2, (c) and (d)) have considerably larger reserves of soil Si. With soils from the Atherton Tablelands, 0.005 M H_2SO_4 extracted approximately 25 times more Si from the basalt soils compared to that extracted with 0.01 M CaCl_2 (Table 5.3). Soil Si reacts readily with Al and Fe oxide and hydroxide surfaces found in basalt soils, and the solubility of the Si from these compounds may be low. In contrast, the granite and metamorphic soils from this district have relatively low Si reserves compared to their plant available soil Si levels, in particular the granitic Nicotine/Algoma series. Although granitic soils are high in total Si in the form of quartz, this form of Si is insoluble, and its ability to replenish the soluble Si levels in the soil solution following plant uptake is limited.

Most of the soil series sampled from the mapping areas on the wet coast had an average of 15 times more Si extracted with 0.005 M H_2SO_4 than 0.01 M CaCl_2 (Table 5.3), the exception being soils from low lying, poorly drained areas or swamplands (Table 5.3 and Figure 5.2).

As discussed previously, the high levels of 0.005 M H₂SO₄ extractable Si in these poorly drained soils, relative to the Si readily soluble in 0.01 M CaCl₂, may in part be attributed to higher levels of organic matter present in many of these soils. In many of these soils the levels of readily soluble Si were also higher than average (eg. Babinda, Bulgun, Coom and Timara series). The high water retention capacity of these soils assists the slow dissolution of the crystalline Si material, which when combined with a reduced leaching rate, can result in higher soluble soil Si levels (Gibson, 1994).

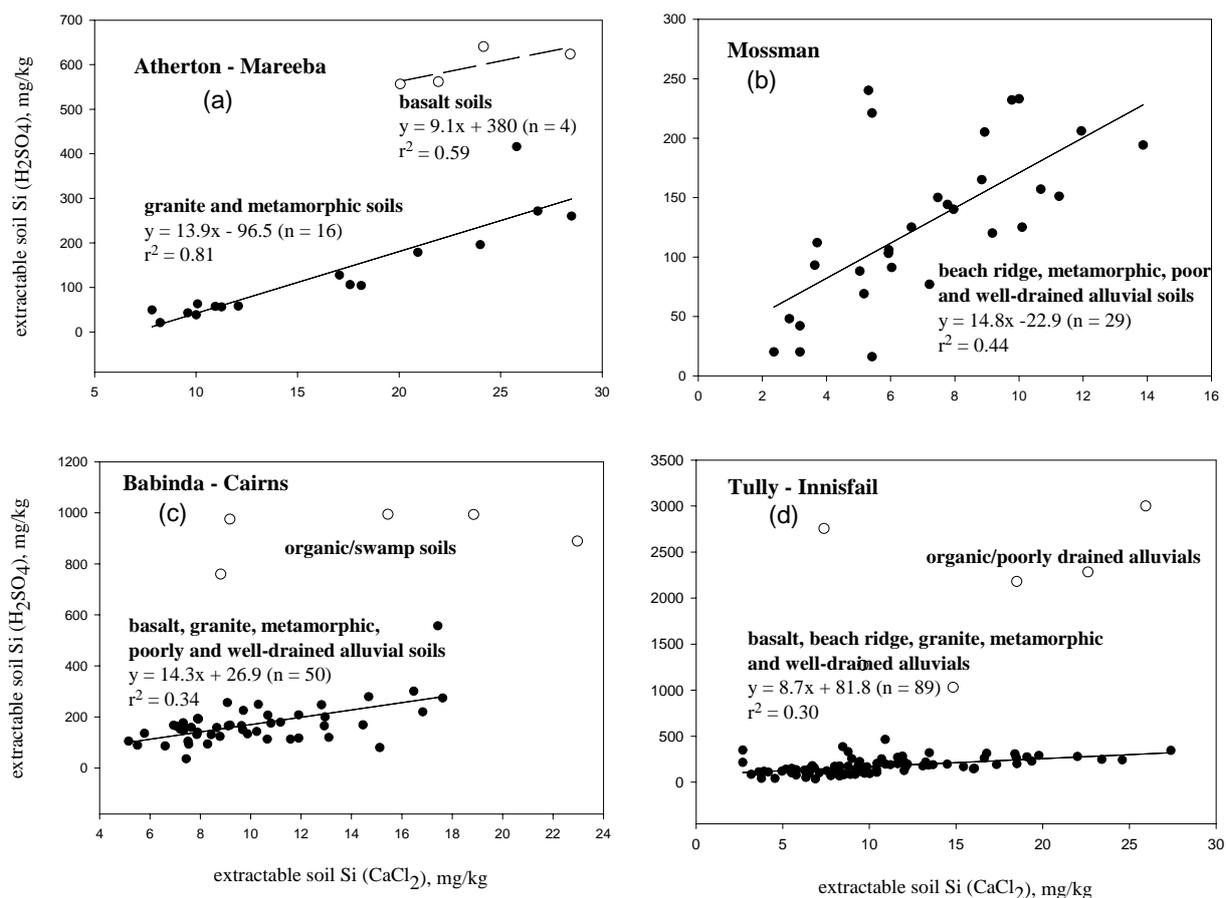


Figure 5.2. The relationship between soil Si levels after extraction with 0.01M CaCl₂ and 0.005M H₂SO₄ for the soil mapping areas (a) Atherton – Mareeba, (b) Mossman, (c) Babinda – Cairns and (d) Tully - Innisfail. The equation for the regression line and the coefficient of determination (r^2) are reported if the relationship was significant at the 5% level of significance.

The results from this study indicate that although a general relationship between the two soil extractants may be applied to many soils, soil Si data obtained after extraction with 0.005 M H₂SO₄ may not be as sensitive in determining sub-optimality, as data obtained with 0.01 M CaCl₂. The variability observed between all the soils sampled in this survey suggests that interpreting soil Si status using 0.005 M H₂SO₄ extraction data should be done with caution, particularly on soils with poor drainage or high Si sorption ability (eg. high sesquioxide content and high organic matter content). In addition, extraction with 0.005 M H₂SO₄ may underestimate the need for silicate fertilization on soils that have been previously amended

with silicate amendments or lime. Many silicate fertilizers have inherently low solubility, and a stronger extractant like 0.005 M H₂SO₄ may dissolve non-available Si from the silicate amendment previously added to the soil (Savant *et al.*, 1997). The increase in soil pH following liming promotes polymerization of Si and the formation of aluminosilicate compounds, which can have a marked influence on the solubility and availability of Si. In this respect, the acid extractant again may overestimate the Si available for plant growth, by dissolving these compounds of lower solubility. If a single measure of soil Si is required, these results would suggest that 0.01 M CaCl₂ extractable Si is probably preferable. The overall general relationship observed between 0.01 M CaCl₂ and 0.005 M H₂SO₄ suggest that the Si concentration in the soil solution is linked to ‘capacity’, and it is unlikely that readily available Si will be high unless there is sufficient ‘capacity’. Silica extracted with 0.01 M CaCl₂ represents the Si in the soil solution available for plant growth, and also reflects the effects of the sorption/desorption reactions that control solubility, thus giving a measure of current availability.

Table 5.4. Concentration of Si in the top visible dewlap (TVD) leaf blade for the various soil types in the four mapping areas. The values represent the mean value for each soil type ± standard error (SE.). For each soil mapping area the regression equation between plant Si (%) and extractable soil Si (mg/kg) and the correlation coefficient (r²) has been reported if the relationship was significant at a 5% level of significance.

| Soil mapping area | Soil types | Number sites sampled | Mean % Si (TVD leaf) ± SE. | Overall mean % Si (TVD leaf) for each mapping area | Regression equation of plant Si (%) to extractable soil Si (mg/kg), and correlation coefficient (r ²) | |
|--|-------------------------|----------------------|----------------------------|--|---|---------------------------------------|
| | | | | | 0.01M CaCl ₂ | 0.005M H ₂ SO ₄ |
| Wet Tropical Coastal (Tully - Mossman) | | | | | | |
| Mossman | beach ridge | 5 | 0.29 ± 0.04 | 0.39 | n.s. | n.s. |
| | metamorphic | 10 | 0.37 ± 0.04 | | | |
| | poorly drained alluvial | 4 | 0.26 ± 0.02 | | | |
| | well drained alluvial | 5 | 0.63 ± 0.06 | | | |
| Babinda - Cairns | basaltic | 4 | 0.22 ± 0.03 | 0.29 | y = 0.029x + 0.02 r ² = 0.45 | n.s. |
| | granitic | 13 | 0.26 ± 0.03 | | | |
| | metamorphic | 6 | 0.34 ± 0.03 | | | |
| | poorly drained alluvial | 10 | 0.26 ± 0.03 | | | |
| | well drained alluvial | 6 | 0.22 ± 0.03 | | | |
| | organic/swamps | 16 | 0.37 ± 0.04 | | | |
| Tully - Innisfail | basaltic | 19 | 0.28 ± 0.03 | 0.26 | y = 0.015x + 0.10 r ² = 0.47 | n.s. |
| | beach ridge | 4 | 0.24 ± 0.06 | | | |
| | granitic | 13 | 0.22 ± 0.02 | | | |
| | metamorphic | 6 | 0.14 ± 0.03 | | | |
| | poorly drained alluvial | 13 | 0.31 ± 0.05 | | | |
| | well drained alluvial | 33 | 0.26 ± 0.02 | | | |
| Atherton Tableland (Atherton - Mareeba) | | | | | | |
| Atherton - Mareeba | basaltic | 4 | 0.91 ± 0.1 | 0.81 | y = 0.032x + 0.23 r ² = 0.66 | n.s. |
| | granitic | 4 | 0.60 ± 0.07 | | | |
| | metamorphic | 5 | 0.59 ± 0.10 | | | |
| | metamorphic (sodic) | 7 | 1.04 ± 0.09 | | | |

Relationship of extractable soil Si to plant uptake

The Si concentration (%) of the TVD leaf blade, from leaf samples collected during the period of maximum crop growth are presented in Table 5.4. Plant Si concentrations from sites sampled on the wet tropical coast (average 0.30%) are considerably lower than those measured from the Atherton Tablelands (average 0.81%). Critical plant concentrations reported in Reuter and Robinson (1997) suggest values in the range of 0.83-1.23 % Si to be marginal, and 1.40-1.52 % Si to be adequate in a sugarcane plant crop. Samples collected in this survey were in the most part from first ratoon crops. Anderson *et al.* (1991) observed that plant Si levels decline with successive ratoons, and suggested either a physiological response that reduces crop requirement, or a decline in uptake reflecting general declining plant health and vigour due to ageing or a decline of other nutrients. In this respect, critical plant concentrations reported in Reuter and Robinson (1997) for ratoon crops to be in the range of 0.31-0.53 (marginal) or 0.68-0.76 (adequate). Based on these critical levels the crops on the wet coast are generally marginal in plant Si concentration, while those from the Atherton-Mareeba area could be considered adequate. As there are also genotypic differences in the ability of sugarcane to accumulate Si, differences in plant concentrations between the Atherton Tableland (where Q124 was sampled) and the coastal districts (predominantly Q152), could in part be due to varietal differences.

The marginal levels of plant Si recorded in the coastal districts correspond to the overall low extractable soil Si levels. It is notable that plant Si levels are significantly related to readily soluble soil Si levels (0.01 M CaCl₂) but show no relationship to soil levels obtained using the stronger acid extractant (0.005 M H₂SO₄) (Table 5.4). Similar observations have been reported by Fox *et al.* (1967) and Medina-Gonzales *et al.* (1988), who observed highly significant relationships between plant Si and water extractable Si, but not with any other soil extractant.

Establishment of soil diagnostic norms for use in the sugar industry

This work has clearly demonstrated a significant correlation between soil Si levels and top visible dewlap tissue levels and as such provides the basis of a useful diagnostic tool. When examining the inherent soil Si level of a non-amended soil, and if a single measure of soil Si is required the results suggest that the most appropriate extractant is 0.01 M CaCl₂. Silica extracted with 0.01 M CaCl₂ represents the Si in the soil solution available for plant growth, and also reflects the effects of the sorption/desorption reactions that control solubility, thus giving a measure of current availability.

At the initiation of this project many commercial laboratories began to offer a soil Si test for sugarcane soils based on extraction with 0.005 M H₂SO₄, using a critical value of <100mg/kg as indicative of sub-optimal levels, as this test uses the same extractant used to measure phosphorus (P_{BSES} method), and this procedure did not involve any additional sample preparation in the laboratory. However, the results from this survey have shown that the method of extraction is important for determining the level of available Si in the soil and that caution should be taken when assessing results obtained solely with 0.005 M H₂SO₄.

Depending on the soil type, the Si extracted using these 2 different extractants can be poorly correlated. However, it is also clear from the relationship observed between 0.01 M CaCl₂ and 0.005 M H₂SO₄ that the Si concentration in the soil solution is linked to ‘capacity’, and it is unlikely that readily available Si will be high unless there is sufficient ‘capacity’. While dilute salt solutions such as 0.01 M CaCl₂ provide a measure of the readily available Si, stronger extractants like 0.005 M H₂SO₄ will solubilize the slightly available and more insoluble amorphous forms of Si. Although this may provide an indication of the total capacity of the soil Si pool, it may not be related to the concentration of soluble Si in the soil solution, as this tends to be controlled by the solubility of the most soluble silicate mineral, regardless of the amount present.

Although these two tests, depending on the laboratory, are currently being used to predict ‘sub-optimality’, neither test on its own may be a reliable test to assess the ‘responsiveness’ of soils to applications of Si-based amendments. From results obtained in this survey, it was hypothesised that a combination of both tests may be a better indication of ‘responsiveness’. By plotting the results of one test against the other, the resulting graph could be divided into four quadrats based on the critical values of 10 mg/kg (CaCl₂) and 100 mg/kg (H₂SO₄), as demonstrated in Figure 5.3 (graphs prepared from survey data for the Mossman, Mourylian, South Johnstone and Tully districts). The four quadrats may represent: (1) highly responsive; (2) marginally or variably responsive depending on specific soil properties that may minimize response; (3) non-responsive; and it is unlikely that soils would fall into quadrat (4) as it would be considered unusual or doubtful that high readily soluble Si would occur in the presence of low supply or capacity.

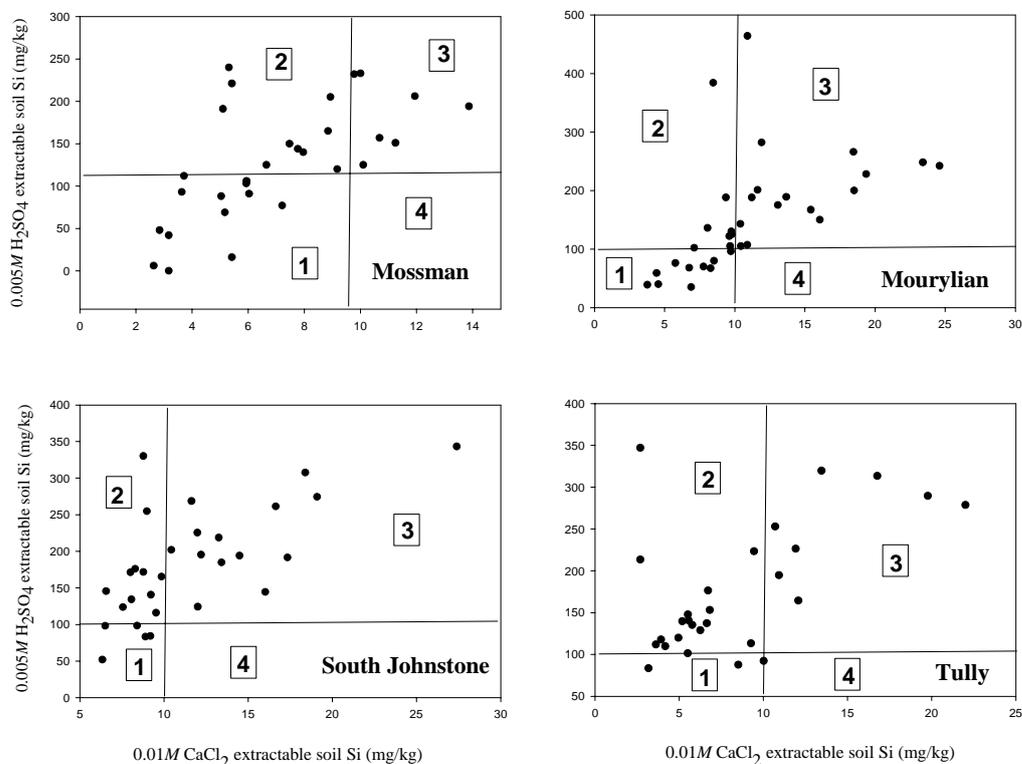


Figure 5.3. Relationship between 0.005M H₂SO₄ and 0.01M CaCl₂ extractable soil Si for the Mossman, Mourylian, South Johnstone and Tully regions.

The soils that fall into quadrat 2 may have a variable response to silicate additions for differing reasons, but most likely due to differing mineralogies. Soils will differ in their ability to adsorb added Si, predominantly due to the reactivity of the oxidic surfaces of Al and Fe oxides, and to a lesser extent silicated surface of the clay minerals (Gallez *et al.* 1977). This differing ability to adsorb added Si can be determined using an Index of Silica Reactivity (ISR), and this may prove to be a useful research tool in understanding and developing application rates of silicate amendments on these soils. Gallez *et al.* (1977) found that the ISR was related to the specific surface area of the soil. However, it was not only sensitive to the magnitude of the specific surface area, but also to the nature of the sorbing surface and the presence of amorphous Al and Fe compounds. They grouped the active sorption surfaces into two categories: 1) the surfaces of oxides and hydrous oxides of Fe and Al, which exhibit a strong affinity for soluble Si, and 2) the surfaces of the silicated minerals in the clay fraction. Results from a subsample of soils from the Tully region are consistent with the ISR data discussed by Gallez *et al.*, (1977) and it was found that ISR was significantly correlated with % clay and the amount of Al and Fe present (Figure 5.4).

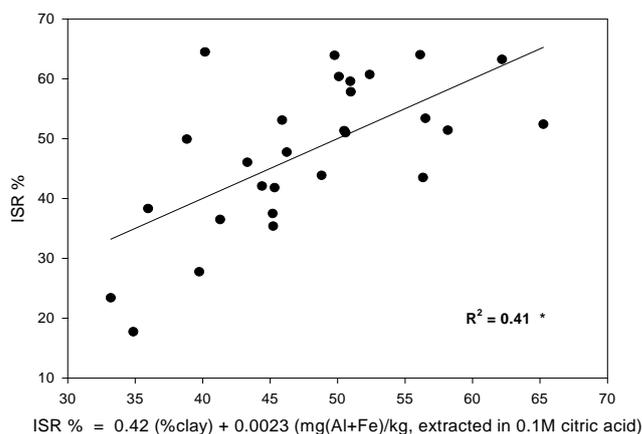


Figure 5.4. The relationship between the ISR %, as determined using the methodology of Gallez *et al.* (1977), and that calculated using the % clay and the soil concentration of Al + Fe (mg/kg) following extraction with 0.1 M citric acid. The linear relationship is significant at the 5% level of significance (n = 28)

This current project has established reliable analytical methodology for determining plant-available soil Si, and has estimated that approximately 85% of soils evaluated in the six mill areas on the wet tropical coast have marginal to sub-optimal levels of available Si. As Si is likely to be a substantial limiting factor in many cane growing areas on the wet tropical coast, future work needs to further refine these soil testing techniques to enable not only the prediction of 'sub-optimality', but more importantly 'responsiveness' to silicate additions. This could be based on the hypothesised '2-test' approach for soil testing, changing the parameters that define the quadrats if necessary, and determine if this is an effective means of

identifying Si-responsive soils. A wide range of soils that fall into the different quadrats (1, 2 and 3) should be tested through both greenhouse and field based bio-assessment studies.

Acknowledgements

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6. Yield Response to calcium silicate materials - Silicon Rate trials

Introduction

One of the objectives of this project was to quantify the response in cane yield and CCS to Si application in Australia's cane growing regions. As part of that process, Si rates trials were established in the Mossman, Innisfail and Bundaberg cane growing areas during the 1999 planting season. The Si source for these trials was an imported calcium (Ca) silicate slag (product A) that had been shown to increase sugarcane yields in studies overseas.

Results and Discussion

Initial soil chemical characteristics

Prospective trial sites were soil sampled to determine if they were potentially responsive to Si amelioration and to determine what other nutrients would be required to ensure nutritional requirements of the crop would be adequately supplied. For example, Blend 3 (32% Ca; 3% Mg) was applied to the Innisfail site at 2.5 t/ha in August 1999 because soil calcium and magnesium were below the critical levels. This avoided any confounding of potential responses since a calcium product was being used as the silicon source. The selected sites were again sampled immediately prior to implementation of treatments. Soil chemical properties for each of the trials and locations are presented in Table 6.1.

Soil pH as measured in water was highest in soils from the Bundaberg area and lowest in the Innisfail soils with the Mossman soils being intermediate. Exchangeable Ca^{2+} levels were at an adequate level in all trials over the depth interval 0-20 cm. However, in the case of the Mossman and Innisfail sites, although the levels were greater than the critical value of 0.55 cmol/kg (Calcino, 1994), they may still be considered marginal (Table 6.1). Similarly exchangeable Mg^{2+} levels followed the same trend, with the Bundaberg and Innisfail sites exhibiting adequate Mg^{2+} levels in the surface soils, while those at Mossman were in the marginal range (0.10 to 0.25 cmol/kg) (Calcino, 1994). At all sites the levels of exchangeable K^+ were below the critical level of 0.24 cmol/kg reported by Calcino (1994). Fertilizer at standard recommended rates was applied at planting to remediate sub-optimal nutrient levels.

The amount of Si extracted using 0.01 M CaCl_2 at all sites was less than the critical value of 10 mg/kg as described by Haysom and Chapman (1975). Concentrations of Si extracted using citric acid are usually comparable to that extracted with other dilute acid extractants such as 0.005 M H_2SO_4 , and the levels reported (Table 4.1) suggest that Si reserves in these soils are also low. It is notable that in samples collected from the 50-70 cm depth interval at Mossman the levels of citric acid Si were elevated. This source of Si is associated with poorly crystalline/amorphous materials. Significant amounts of concretionary material were present in this depth layer and it is assumed that the elevated citric acid Si levels were associated with this material. It is of note that on the Ferrosol site (Innisfail), there is an increase in anion exchange capacity (AEC) with depth (Table 6.1). The presence of a significant AEC would enhance the retention of Si on the exchange complex in these soils.

Table 6.1 Selected soil chemical properties of field trial sites prior to the application of silicate materials. Each value is the mean of 3 replicates.

| Depth (cm) | pH _w | pH _{CaCl2} | EC (dS/m) | Organic C (%) | Exchange properties (cmol _c /kg) | | | | | | | | BSES P (mg/kg) | Si (CaCl ₂) (mg/kg) | Si (Citric) (mg/kg) |
|------------------|-----------------|---------------------|--------------|------------------|---|------------------|----------------|-----------------|--------|------|------|------|-------------------|------------------------------------|---------------------------|
| | | | | | Ca ²⁺ | Mg ²⁺ | K ⁺ | Na ⁺ | Al + H | CEC | AEC | ECEC | | | |
| Bundaberg | | | | | | | | | | | | | | | |
| 0-10 | 6.07 | 5.47 | 0.04 | 0.57 | 1.60 | 0.23 | 0.04 | 0.04 | 0.05 | 1.95 | 0.03 | 1.91 | 34 | 5.4 | 30 |
| 10-20 | 5.98 | 5.39 | 0.05 | 0.55 | 1.60 | 0.24 | 0.07 | 0.04 | 0.04 | 2.03 | 0.03 | 1.95 | 35 | 5.0 | 31 |
| 20-30 | 6.19 | 5.60 | 0.05 | 0.55 | 1.65 | 0.27 | 0.07 | 0.04 | 0.04 | 1.83 | 0.01 | 2.03 | 38 | 5.5 | 23 |
| 50-70 | 5.23 | 5.01 | 0.04 | 0.26 | 0.66 | 0.15 | 0.02 | 0.05 | 0.11 | 0.75 | 0.03 | 0.89 | 2 | 7.1 | 70 |
| Innisfail | | | | | | | | | | | | | | | |
| 0-10 | 4.89 | 4.63 | 0.11 | 2.83 | 1.23 | 0.28 | 0.18 | 0.06 | 0.17 | 1.19 | 0.66 | 1.74 | 79 | 9.1 | 63 |
| 10-20 | 4.79 | 4.58 | 0.09 | 2.70 | 0.87 | 0.20 | 0.12 | 0.05 | 0.19 | 1.05 | 1.02 | 1.24 | 80 | 8.1 | 60 |
| 20-30 | 4.52 | 4.51 | 0.06 | 2.05 | 0.32 | 0.08 | 0.06 | 0.05 | 0.19 | 0.29 | 2.13 | 0.51 | 58 | 8.0 | 60 |
| 50-70 | 4.38 | 4.68 | 0.04 | 1.19 | 0.07 | 0.02 | 0.02 | 0.03 | 0.09 | 0.00 | 4.18 | 0.15 | 29 | 5.9 | 72 |
| Mossman | | | | | | | | | | | | | | | |
| 0-10 | 5.14 | 4.25 | 0.02 | 1.58 | 0.91 | 0.12 | 0.11 | 0.04 | 0.81 | 1.88 | 0.08 | 1.17 | 113 | 4.3 | 62 |
| 10-20 | 5.12 | 4.26 | 0.02 | 1.70 | 0.97 | 0.09 | 0.10 | 0.04 | 0.86 | 1.58 | 0.06 | 1.20 | 108 | 4.0 | 64 |
| 20-30 | 5.09 | 4.37 | 0.02 | 1.28 | 0.42 | 0.05 | 0.06 | 0.03 | 0.68 | 0.76 | 0.04 | 0.55 | 50 | 4.5 | 163 |
| 50-70 | 4.83 | 4.38 | 0.02 | 0.41 | 0.13 | 0.03 | 0.04 | 0.02 | 0.31 | 0.24 | 0.12 | 0.21 | 7 | 6.6 | 122 |

Silicate responses in the plant crop

No treatment effects were noted during the early growth phases of these trials. However, visual responses in height to increasing application rates of Ca-silicate were noted during February and March 2000. This has been the usual experience under Queensland conditions with responses to Ca-silicate application. Stalk populations and heights were measured in the Innisfail trial in March. Calcium silicate application had no significant effect on stalk population but did have a positive effect on stalk height although this just failed to reach significance (Table 6.2). The crops at all three sites were affected by orange rust infection (*Puccinia kuehnii*). The Bundaberg experiment was severely infected and it was considered orange rust might have adversely affected yields at this site. The two northern trials were also infected by yellow spot fungus (*Mycovellosiella koepkei*). An interim harvest was undertaken in the two northern trials in May to ensure potential responses were not masked by lodging, which had already commenced in those trials. This was particularly necessary with the Innisfail trial because the crop was also showing signs of cane grub damage.

Table 6.2 Influence of increasing rate of Ca-silicate application on stalk height and number in Q158 plant cane at Innisfail

| Ca-silicate rate (t/ha) | Stalk height (cm) | Number of stalks (stalks/m ²) |
|----------------------------|----------------------|--|
| 0 | 242 | 6.5 |
| 1.5 | 248 | 6.7 |
| 3.0 | 251 | 7.0 |
| 4.5 | 254 | 6.9 |
| 6.0 | 245 | 6.7 |
| 9.0 | 262 | 7.4 |
| 12.0 | 260 | 7.1 |
| Probability | 0.054 | 0.41 |

The interim harvest yield (8 months) at the Mossman and Innisfail sites showed that application of Ca-silicate resulted in significant increases in millable stalk yields. The maximum response was achieved at a rate of 9 t/ha of Ca-silicate with yield increases of 22 and 39 t/ha over the control at the Innisfail and Mossman sites, respectively (Table 6.3). This was due to a significant increase in stalk weight due to silicate treatment at both the Innisfail (P=0.02) and Mossman (P=0.04) sites (data not shown). This increase in weight at Innisfail was probably associated with the increase in stalk height noted at this site (Table 6.2). Although the application of increasing amounts of Ca-silicate resulted in a decline in ccs at Mossman and Innisfail for the interim sample, there was no significant difference by final harvest (Table 6.3). The early positive responses to increasing applications of Ca-silicate were evident at final harvest at Mossman and Bundaberg, but not at Innisfail (Table 6.3). It is thought that the lack of response at Innisfail was due to severe cane grub damage late in the experiment. Although additions of Ca-silicate had no effect on ccs at Mossman (Table 6.3), significant increases in both cane and sugar yield were observed from applications as low as 1.5 t/ha Ca-silicate. In contrast, at Bundaberg significant increases in cane yield were only observed at the highest rate of Ca-silicate

application (12 t/ha). However, infestation by orange rust may have influenced the final yields at Bundaberg.

Table 6.3. Concentration of Si (%) in the top visible dewlap (TVD) leaf at approximately 7 months at Mossman, Innisfail and Bundaberg; responses in millable stalks, ccs and top fresh weight 8 months after planting at Mossman and Innisfail; and final yield of cane, ccs and sugar associated with varying rates of Ca-silicate applied to trials at Mossman, Innisfail and Bundaberg.

| Ca-silicate rate (t/ha) | % Si TVD* leaf at ~ 7 months | Interim harvest at 8 months | | | Final harvest | | |
|-----------------------------|------------------------------|-----------------------------|---------|--------------------------|-------------------|---------|--------------------|
| | | Millable stalks (t/ha) | CCS (%) | Fresh weight tops (t/ha) | Cane yield (t/ha) | CCS (%) | Sugar yield (t/ha) |
| Mossman | | | | | | | |
| 0 | 0.14 | 51.4 | 12.55 | 7.0 | 50.5 | 14.70 | 7.41 |
| 1.5 | 0.25 | 66.6 | 12.71 | 9.5 | 57.0 | 15.19 | 8.66 |
| 3 | 0.36 | 70.3 | 11.91 | 10.2 | 60.8 | 15.04 | 9.14 |
| 4.5 | 0.42 | 86.9 | 11.70 | 12.8 | 71.1 | 15.41 | 10.95 |
| 6 | 0.47 | 72.8 | 11.21 | 11.1 | 69.1 | 15.16 | 10.47 |
| 9 | 0.63 | 90.4 | 11.10 | 13.6 | 73.9 | 15.34 | 11.32 |
| 12 | 0.73 | 86.1 | 10.12 | 13.6 | 79.6 | 14.63 | 11.61 |
| LSD_(0.05) | 0.10 | 11.4 | 1.30 | 1.9 | 6.0 | n.s. | 0.91 |
| Innisfail | | | | | | | |
| 0 | 0.29 | 64.4 | 7.04 | 9.7 | 63.2 | 13.26 | 8.37 |
| 1.5 | 0.38 | 70.1 | 7.10 | 10.8 | 59.0 | 13.69 | 8.09 |
| 3 | 0.43 | 73.1 | 6.46 | 11.0 | 64.1 | 14.34 | 9.35 |
| 4.5 | 0.51 | 78.1 | 7.28 | 11.5 | 67.4 | 14.04 | 9.51 |
| 6 | 0.53 | 77.3 | 6.74 | 11.3 | 62.6 | 14.04 | 8.94 |
| 9 | 0.69 | 86.5 | 6.80 | 12.8 | 73.8 | 14.16 | 10.46 |
| 12 | 0.68 | 78.7 | 6.27 | 11.9 | 63.8 | 13.83 | 8.86 |
| LSD_(0.05) | 0.11 | 11.2 | ns | ns | ns | ns | ns |
| Bundaberg | | | | | | | |
| 0 | 0.47 | na | na | na | 99.6 | 9.25 | 9.22 |
| 1.5 | 0.65 | na | na | na | 104.8 | 8.58 | 9.78 |
| 3 | 0.66 | na | na | na | 105.2 | 10.23 | 9.91 |
| 4.5 | 0.79 | na | na | na | 105.8 | 10.45 | 10.56 |
| 6 | 0.74 | na | na | na | 105.1 | 11.06 | 10.76 |
| 9 | 0.99 | na | na | na | 101.1 | 11.65 | 11.47 |
| 12 | 0.95 | na | na | na | 117.8 | 10.81 | 12.61 |
| LSD_(0.05) | 0.13 | | | | 9.3 | ns | ns |

* The critical level recorded for Si is 0.80% (Reuter and Robinson , 1997)

The failure to achieve an increase in ccs following silicate application was disappointing as there were indications in the literature that Si could have a positive effect on sugar accumulation. However, the fact that ccs was not depressed at final harvest by silicate application could be considered a positive result. Generally ccs tends to decline as yields increase, which was not the case in these trials. The responses obtained at the Mossman site resulted in an increase in sugar yield of 3.5 t/ha at an application rate of 4.5 t/ha of Ca-silicate slag, increasing to a sugar yield increase of 4.2 t/ha at an application rate of 12 t/ha. Whilst the magnitude of the responses was not as large at Bundaberg and Innisfail, they were probably influenced

by external factors (orange rust and cane grubs, respectively) and thus should not necessarily be regarded as poorly responsive sites.

Increasing rates of Ca-silicate had a direct effect on plant uptake of Si at all sites as indicated by the concentration of Si (%) in the top visible dewlap leaf (Table 6.3). The only nutrient element in the plant that was present in deficient concentrations was Si, and the ‘critical’ concentration was only approached at the highest rate of Ca-silicate application. Since varying rates of Ca-silicate additions had minimal effect on the uptake of nutrients measured in the plant, and as all other nutrients other than Si were present at concentrations deemed sufficient, it seems plausible that the positive yield responses recorded are directly associated with an improvement in soil Si availability, and the consequent effect on Si status in the plant

Silicate effects on lodging and leaf diseases

It was considered that since silica is accumulated in structural components of the plant this might have led to benefits such as increased structural strength resulting in decreased lodging. There was a slight trend towards higher fibre content in the stalks with increasing Ca-silicate application although it did not achieve significance at the 5% level (Table 6.4). However, this definitely had no influence on lodging. The incidence of lodging tended to increase with cane yield and consequently silicate application. This effect of increased lodging as yields increased following silicate application has been noted previously (Hurney, 1973).

Table 6.4. Fibre content (%) of millable stalks at Mossman and Innisfail and percent leaf infected by orange rust and yellow spot at Innisfail 8 months after planting as influenced by different rates of Ca-silicate application

| Ca-silicate rate (t/ha) | Stalk fibre (%) | | Percent of leaf infected ¹ | |
|-------------------------|-----------------|-----------|---------------------------------------|-------------|
| | Mossman | Innisfail | Orange rust | Yellow spot |
| 0 | 12.5 | 9.7 | 18 | 50 |
| 1.5 | 13.1 | 10.0 | 15 | 48 |
| 3 | 13.6 | 9.7 | 17 | 49 |
| 4.5 | 13.6 | 10.2 | 17 | 49 |
| 6 | 13.5 | 10.4 | 12 | 51 |
| 9 | 14.6 | 10.4 | 14 | 49 |
| 12 | 13.9 | 10.4 | 13 | 45 |
| Probability | 0.06 | 0.12 | 0.22 | 0.95 |

¹ Rating conducted on leaf 7 on 6 stalks/plant

All trials were infected with orange rust in the plant crops, particularly Q182[Ⓛ] in the Bundaberg trial. The Q158 in the northern trials was also infected with yellow spot, particularly at Innisfail. The level of disease infection was rated in May in the Innisfail trial by BSES Pathology staff. The incidence of yellow spot was much higher than orange rust in this trial and varying the rates of Ca-silicate application had no influence on the incidence of either disease (Table 6.4). It was hoped that increasing concentration of Si in the leaf (Table 6.3) might improve the plant’s resistance to fungal attack. However, the data in Table 6.4 would suggest this is unlikely under the heavy infection pressure experienced at this site. The incidence of

disease on the younger leaves did appear to be lower at the higher silicate application rates during the recovery phase. Unfortunately disease ratings were not carried out during that phase of growth.

Residual response to silicates

There were a strong residual responses to the Ca-silicate applied prior to planting in both the first and second ratoon crops at the Bundaberg site. Results in Table 6.5 show there was a linear response in cane yield up to 9 t/ha of Ca-silicate with this treatment producing an additional 20.3 and 29.2 tonnes of cane than the untreated control in the first and second ratoon crops respectively. The magnitude of the response increased through the crop cycle and by the second ratoon, the untreated plots were extremely short and had major gaps in the stool population. There was no significant effect on lower cane ccs in either crop. Results in Table 6.5 summarises the crop cycle situation. The response pattern is similar to first and second ratoon results. The 9 t/ha of Ca-silicate produced an additional 52 tonnes of cane than the untreated control over the three crops.

Table 6.5. First ratoon and cumulative (plant + first ratoon) cane yields at Innisfail and first, second ratoon and crop cycle cane yields at Bundaberg from trials treated with different rates of Ca-silicate

| Ca-silicate rate (t/ha) | Cane yield (t/ha) | | | | |
|-------------------------|-------------------|--------|-----------|------|-------------------------|
| | Innisfail | | Bundaberg | | |
| | 1R | P + 1R | 1R | 2R | Crop cycle ¹ |
| 0 | 63.4 | 128 | 76.9 | 36.9 | 213 |
| 1.5 | 60.5 | 131 | 80.1 | 40.9 | 226 |
| 3 | 92.8 | 166 | 83.7 | 45.5 | 234 |
| 4.5 | 83.7 | 162 | 88.7 | 52.7 | 247 |
| 6 | 91.4 | 169 | 90.6 | 55.1 | 251 |
| 9 | 102.3 | 189 | 97.2 | 66.1 | 265 |
| 12 | 93.7 | 172 | 93.4 | 67.3 | 278 |
| LSD _(0.05) | 20.1 | 26 | 6.8 | 7.9 | 15 |

¹ Crop cycle = plant (P) + first ratoon (1R) + second ratoon (2R) cane yields (t/ha)

Growth was extremely variable in the young first ratoon crop at Innisfail as a result of the grub damage suffered in the plant crop. This increased the variability of the first ratoon yields although there was still evidence of a strong residual response to the pre-planting application of calcium silicate. As observed in the plant crop, continued responses to Ca-silicate additions at rates greater than 1.5 t/ha were observed with the highest yield being observed at a rate of 9 t/ha (Table 6.5). The increase over the control treatment was 38.9 t/ha. No significant differences in ccs were observed. The second ratoon crop was again severely infested by cane grubs and, although the trial was harvested, the results were too variable to be of any value. The cumulative yield response over the plant and first ratoon crops is presented in Table 6.5. The highest yield was observed at 9 t/ha of calcium silicate resulting in an overall yield increase over the control of 61 t/ha for the two crops. This site was more responsive than the Bundaberg site despite having higher soil Si levels but it may be related to the retention of more Si on the exchange complex because of the higher AEC of the Ferrosol soil at the Innisfail site.

The Mossman trial was badly infested with weeds in the first ratoon crop and produced quite variable yield results. There were clear indications of residual response to Ca-silicate treatment but the results were too variable to draw any conclusions. The grower ploughed out the trial after the first ratoon harvest.

An economic analysis of the Bundaberg data showed that the silicate product would need to be applied prior to planting for \$130/t for a break even situation for 6 and 9 t/ha rates over the crop cycle, based on a sugar price of \$300/t. No other comparisons were possible as the Bundaberg trial was the only one with sufficient data available for this type of comparison. The Ca-silicate product used in these experiments cannot be imported and delivered for the above price. Currently there are no suitable, economic products available in Queensland.

The importance of Si for sugarcane production has been confirmed by these experiments. The results clearly indicate that Si should be treated as an integral part of any fertiliser strategy associated with cane production. The high rate of calcium silicate needed to produce a significant response is a concern or this has economic implications. Results from northern and southern trials show yields increasing up to the 9t/ha application rate. It is unknown if this is due to the quantity/intensity relationships because of the low solubility of calcium silicate or related to soil chemical attributes. These factors need to be unravelled to enable an effective remediation program to be developed.

7. Use of soil and plant analysis to interpret yield response to silicate amendments

Response of soils to calcium silicate

Calcium silicate slag was applied to the “rates” trials at Mossman, Innisfail and Bundaberg in 1999 at 0, 1.5, 3.0, 4.5, 6.0, 9.0 and 12.0 t/ha. Soils were analysed from all sites after harvests in 2000 and 2001 and from the Bundaberg site only after harvest of the second ratoon in 2002. In this section we discuss only the data from 0-20cm or 0-25cm zones, because of relevance to the plough layer and use for industry nutrient advice.

All soils had less than 10 mg $\text{Si}_{(\text{sol})}$ /kg (extracted in 0.01 M CaCl_2) in the untreated controls and there was little change in values in the assessment period. (Figure 7.1a). The values for $\text{Si}_{(\text{ext})}$ (extracted in 0.005 M H_2SO_4) in untreated soil in 2000 varied between 51 and 60 mg/kg (Figure 7.1b). Only at the Bundaberg site was there a large drop in $\text{Si}_{(\text{ext})}$, 51 to 21 mg/kg across the assessment period (NB this was 2000-2002 compared with 2000-2001 at other sites).

There was a significant ($p < 0.05$) response in levels of $\text{Si}_{(\text{sol})}$ and $\text{Si}_{(\text{ext})}$ at all sites to applied calcium silicate (Figure 7.1a & b). In addition, there was a major difference in the levels of $\text{Si}_{(\text{sol})}$ and $\text{Si}_{(\text{ext})}$ achieved in the different soils for any given rate of calcium silicate. The Innisfail Ferrosol showed the highest rate and level of response in both fractions of soil Si to applied silicate. The Hydrosol at Bundaberg gave an intermediate response to $\text{Si}_{(\text{sol})}$ followed by the Tennosol at Mossman. Levels of $\text{Si}_{(\text{sol})}$ in these soils remained below 10 and 5 mg/kg respectively until rate of calcium silicate was greater than 6 t/ha (Figure 7.1a). Levels of $\text{Si}_{(\text{sol})}$ in these soils were significantly greater than 10 mg/kg for the Hydrosol in 2000.

The Ferrosol also demonstrated the highest rate and level of response in $\text{Si}_{(\text{ext})}$ of the three soils (Figure 7.1b). The Tennosol showed a greater response in the $\text{Si}_{(\text{ext})}$ fraction than did the Hydrosol. At least 4.5 and 6.0 t/ha of calcium silicate was required to elevate $\text{Si}_{(\text{ext})}$ in the Ferrosol and Tennosol, respectively, above the suggested threshold of 100 mg/kg. At no stage or rate of calcium silicate was the level of $\text{Si}_{(\text{ext})}$ significantly greater ($p < 0.05$) than 100 mg/kg.

These responses are thought to reflect the different clay contents and charge properties across soils that influence the dynamics between $\text{Si}_{(\text{sol})}$ and less available pools, as well as capacity of the soil to retain Si especially within the first 12 months after application. The higher clay and sesquioxide content of the Ferrosol are likely to be the key properties. Clay content for the 0-20cm zone was 5, 50 and 3% respectively for the Tennosol, Ferrosol and Hydrosol soils respectively. The site characterisation data revealed that this depth interval also supported anion exchange capacity of 0.07, 0.84 and 0.03 cmol_c/kg for the Tennosol, Ferrosol and Hydrosol soils respectively.

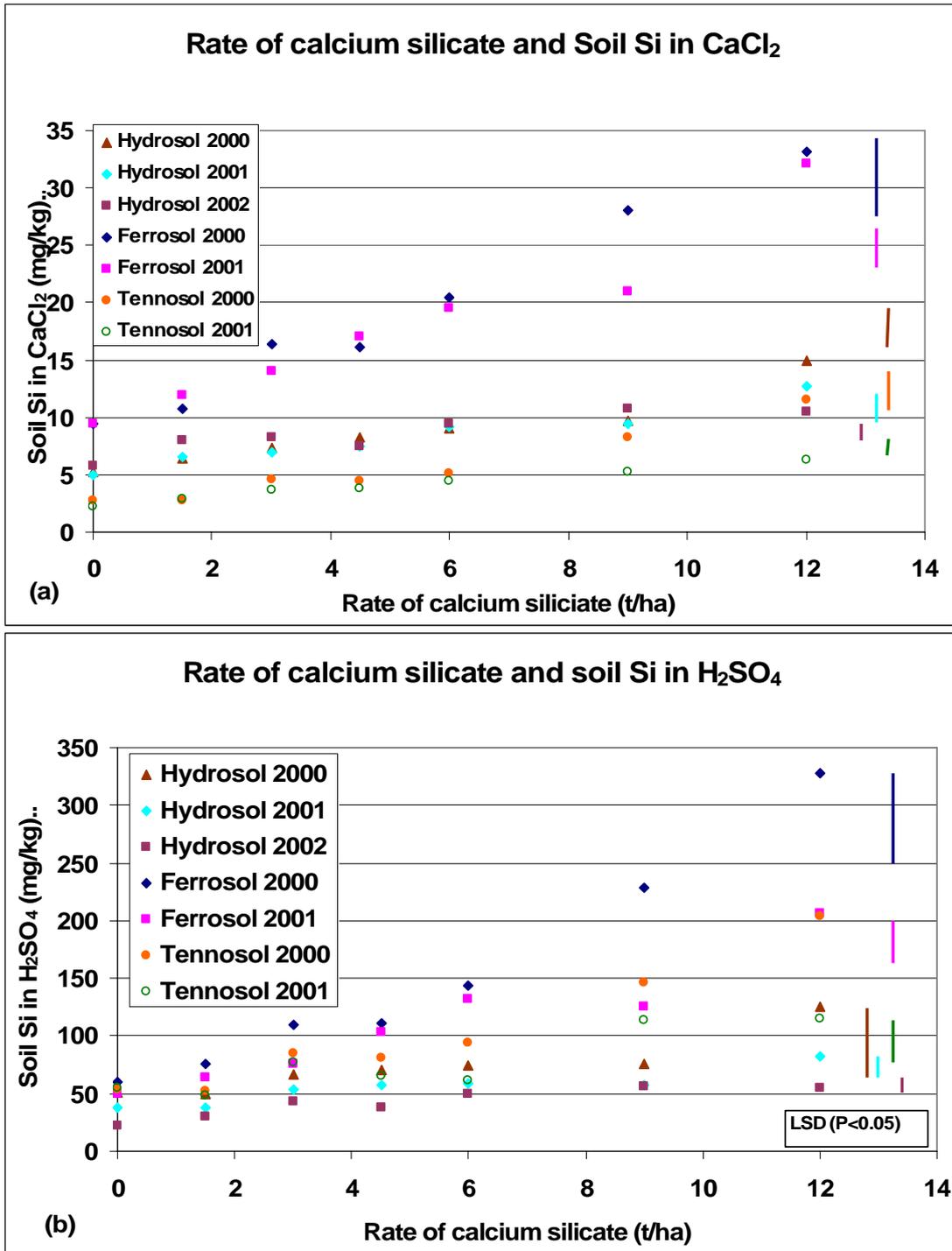


Figure 7.1. Response of soil silicon status in the 0-20 cm zone to rate of applied calcium silicate slag three years after application to a Hydrosol soil and for two years after application to Tենnosol and Ferrosol soils. (a) Extraction in 0.01 M CaCl₂ indexes the Si_(sol) fraction, while (b) extraction in 0.005 M H₂SO₄ indexes the Si_(ext) fraction. LSD bars are applicable to each soil within years.

Cane yield response to soil silicon status.

The absolute response of sugarcane yield parameters to rate of applied calcium silicate slag was discussed in Chapter 6. Here we discuss relationships between cane yield and indices of plant available silicon in an attempt to provide guidance to the sugar industry and agri-business on criteria to be used to determine the need for management intervention to improve Si fertility of soils.

The role of $Si_{(sol)}$ and $Si_{(ext)}$ from extraction in 0.01 M $CaCl_2$ and 0.005 M H_2SO_4 , respectively, as indices of plant available Si were discussed previously. In order to examine the role of these indices across soil and years it was necessary to present cane yield as relative cane yield (mean yield for each treatment is expressed as a percentage of the maximum yield at each site for each year). This concept was considered valid because generally there was little change in soil Si status from each rate of calcium silicate across years (Figure 7.1 a & b).

Relative cane yield response to both $Si_{(sol)}$ and $Si_{(ext)}$ for the sandier Tennoisol and Hydrosol soils is described by an asymptotic function (Figure 7.2. a & b). Functions describe the response of yield on both soils to each soil silicon index. If we use 95% of Y_{max} as the response threshold, it is clear that our data support the current recommendations of 10 mgSi/kg soil in 0.01 M $CaCl_2$ extract and 100 mg Si/kg in 0.005 M H_2SO_4 extract for the light textured soils. The Ferrosol data have a different distribution from those for the previous soils, particularly for the $Si_{(sol)}$ fraction in the calcium chloride extract (Figure 7.2a). In addition to the physical separation, the response function is not asymptotic because of the decline in yield at the highest rate of calcium silicate. No explanation is currently available for this response pattern. It is however unlikely to be associated with a change in the availability status of soil Si, as TVD data suggest an asymptotic response for the two higher levels of soil Si.

If the Ferrosol yield and soil Si relationships in Figure 7.2a & b were asymptotic (*ie.* non consideration of yield decline at highest soil silicon) it may suggest the thresholds for $Si_{(sol)}$ and $Si_{(ext)}$ could be higher than 10 and 100mg/kg respectively. This issue and the general separation of the Ferrosol data from the other soils were explored by further examination of soil silicon and relative cane yield data in terms of additional knowledge of soil properties. The Hydrosol has a clay content of 3% and anion exchange capacity (AEC) of 0.03 $cmol_{(c)}/kg$ (recent analysis and Berthelsen *et al.* 2001, respectively) and the Tennoisol and Ferrosol soils have clay values of 5% and 50% (Murtha, 1986) and AEC values and 0.07 and 0.84 $cmol_{(c)}/kg$, respectively.

The data for $Si_{(sol)}$ and $Si_{(ext)}$ were first normalised for clay content by converting values in mg/kg of soil to mg/100g clay. This caused further separation of the $Si_{(sol)}$ data for the Ferrosol from the other soils and also increased the separation of $Si_{(sol)}$ yield responses on the Tennoisol and Hydrosol soils (Figure 7.3. a), but provided little additional understanding of issues. This might be expected with a simple scaling divisor. The sulfuric acid extraction /100g clay still provides a clear separation of the Ferrosol data from other soils (Figure 7.3 b), but the Tennoisol and Hydrosol populations are more homogeneous. This might be expected as the sulfuric acid procedure is in fact measuring both $Si_{(sol)}$ and $Si_{(ext)}$.

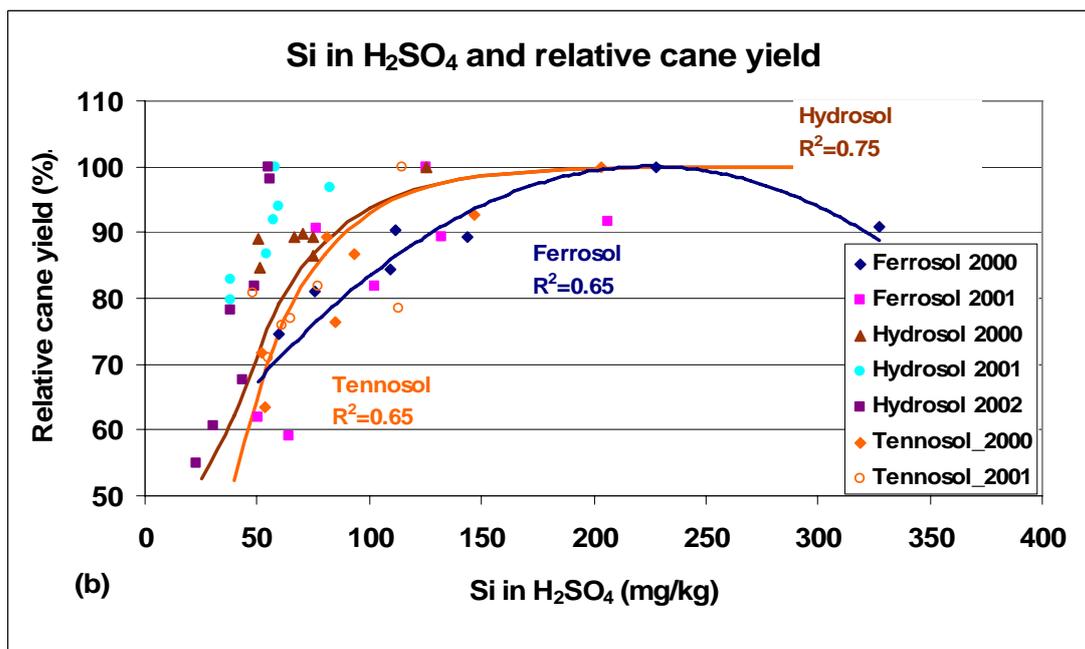
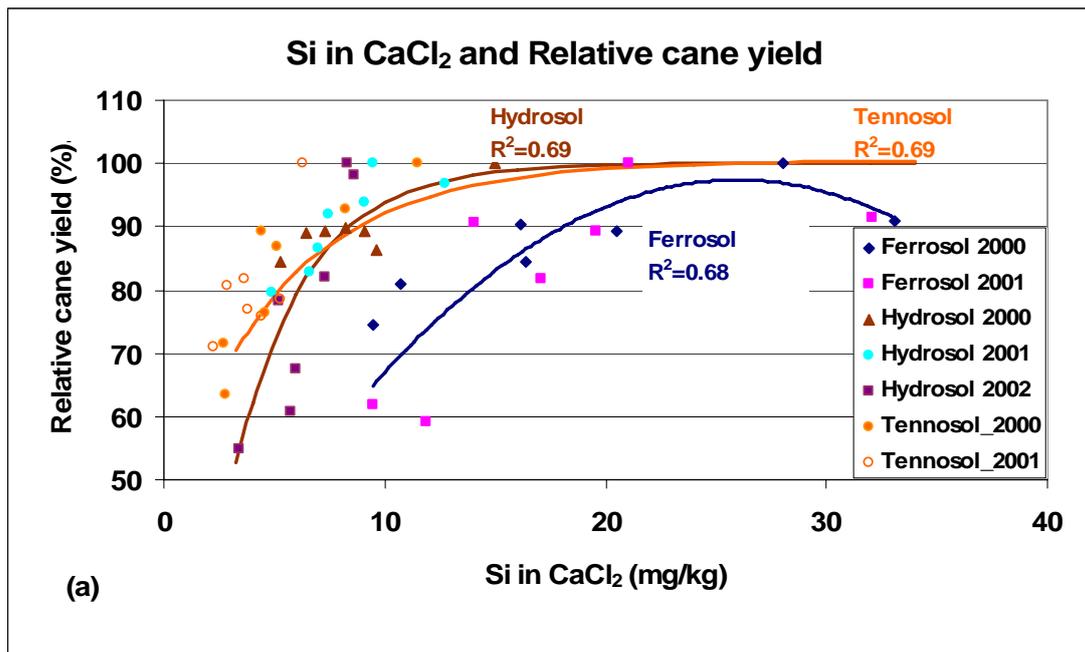


Figure 7.2. Relationships between relative cane yield and indices of plant available silicon across three years on a Hydrosol soil and across two years on a Tennenosol and Ferrosol soil. (a) Si_(sol) from extraction with 0.01 M CaCl₂ and (b) Si_(ext) from extraction with 0.005 M H₂SO₄.

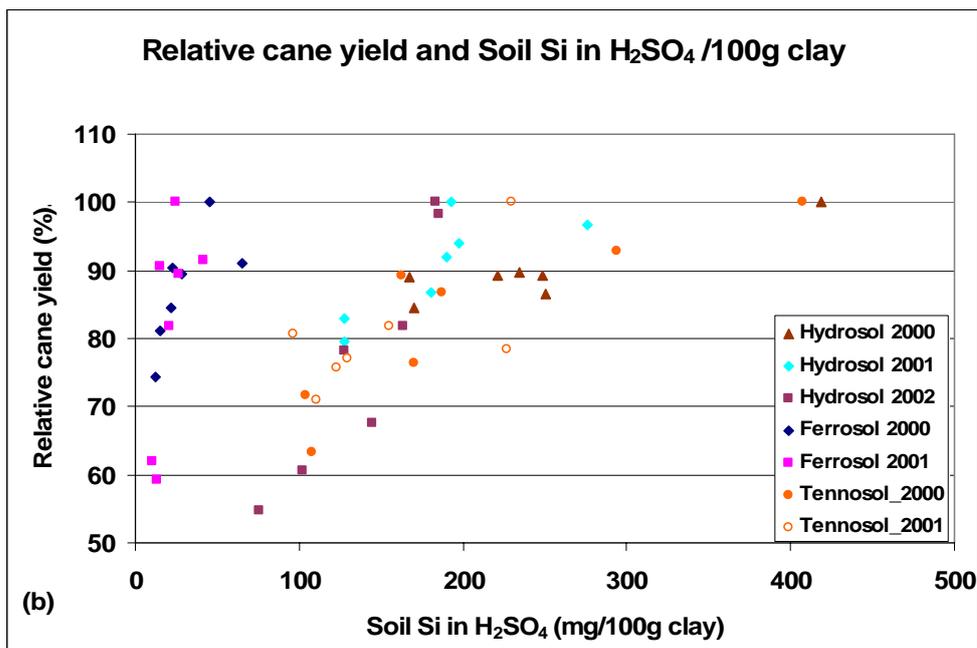
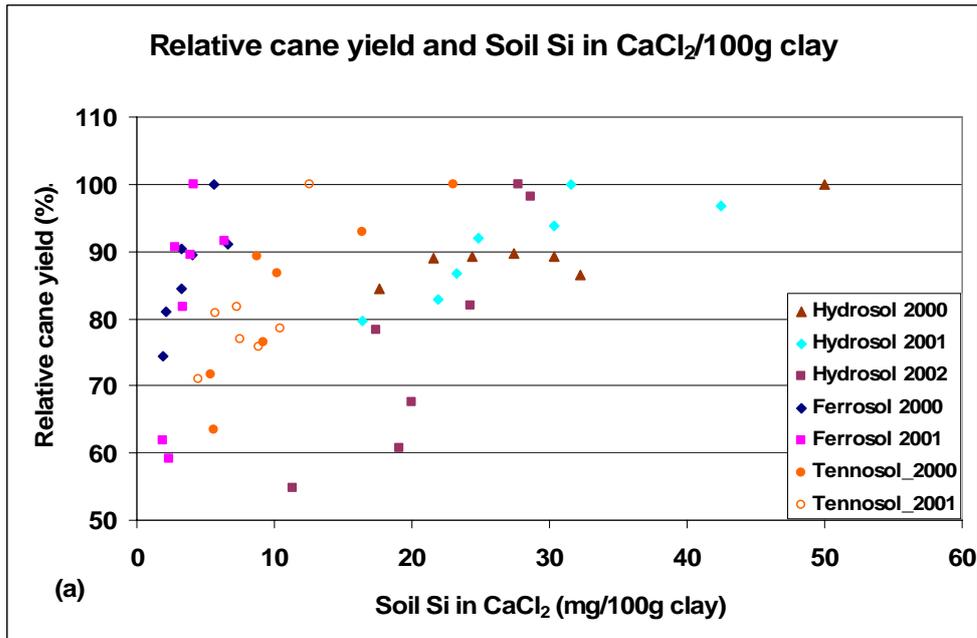


Figure 7.3. Relationships between relative cane yield and indices of plant available silicon / 100g clay across three years on a Hydrosol soil and across two years on a Tennenosol and Ferrosol soil. (a) $\text{Si}_{(\text{sol})}$ from extraction with 0.01 M CaCl_2 and (b) $\text{Si}_{(\text{ext})}$ from extraction in 0.005 M H_2SO_4 .

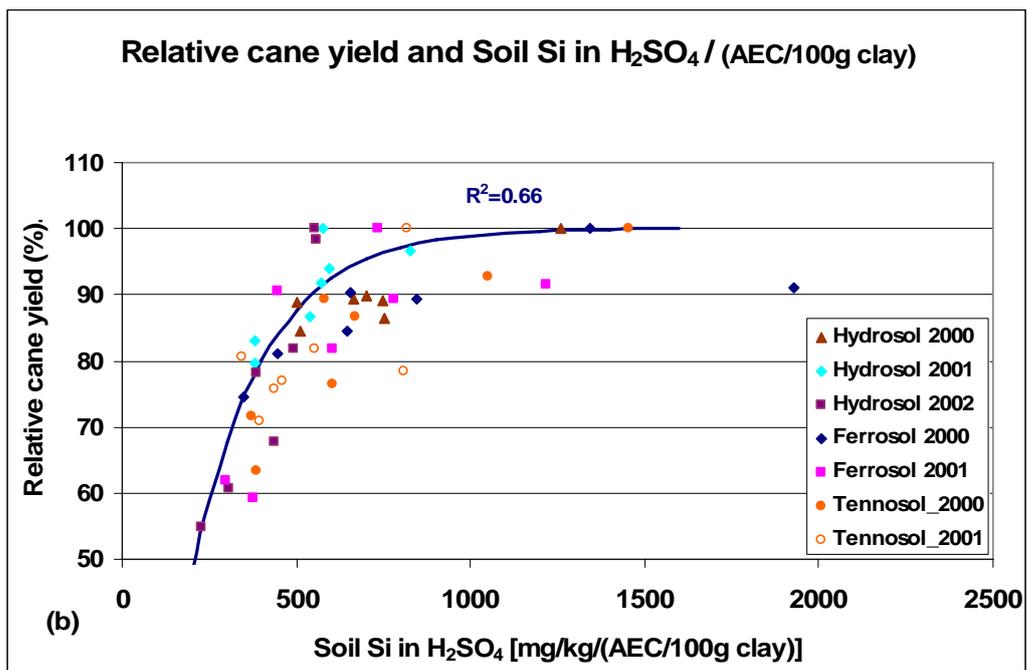
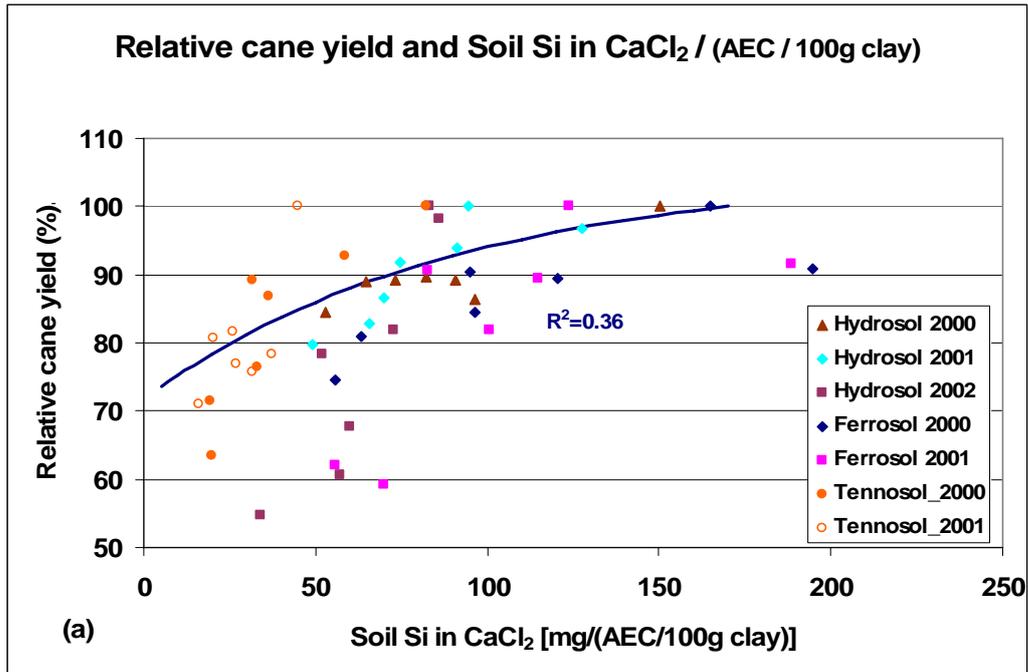


Figure 7.4. Relationships between relative cane yield and indices of plant available silicon / (AEC / 100g clay) across three years on a Hydrosol soil and across two years on a Tennesol and Ferrosol soil. (a) $Si_{(sol)}$ from extraction with 0.01 M CaCl₂ and (b) $Si_{(ext)}$ from extraction with 0.005 M H₂SO₄.

Utilisation of another normalising factor based on the (AEC / 100g clay) was justified because of the importance of clay in supplying soils with plant available silicon and the role that AEC from sesquioxide surfaces plays in the retention of silicate and phosphate anions in soils. Effects of this transformation are summarised in Figure 7.4a & b). There is clear evidence of a tendency for greater homogeneity of the data, especially for the sulfuric acid extraction. (Figure 7.4b). The alignment of relative yield data with normalised soil silicon data improves as Y_{max} falls below 100%, suggesting that the sulfuric acid extraction may be the most useful technique for providing management information about the critical part of the response curve, as this methodology measures both the $Si_{(sol)}$ and $Si_{(ext)}$ fractions in soil. Untransformed data in Figure 7.3b also lends support to this proposition, but additional experiments are required across a range of soil textures and AEC values for confirmation. Ability to use a non-transformed soil assay is a highly desirable outcome for extension purposes.

Uptake of silicon by sugarcane crops

Soil analysis provides only empirical data about the availability of fractions of the Si in soils to plants. These data can only be interpreted after correlation with actual crop response (yield and acquisition of Si by the biomass). Yield parameters were discussed above. Here we examine the impact of rates of calcium silicate and silicate products on Si uptake by the crop.

Leaf silicon status

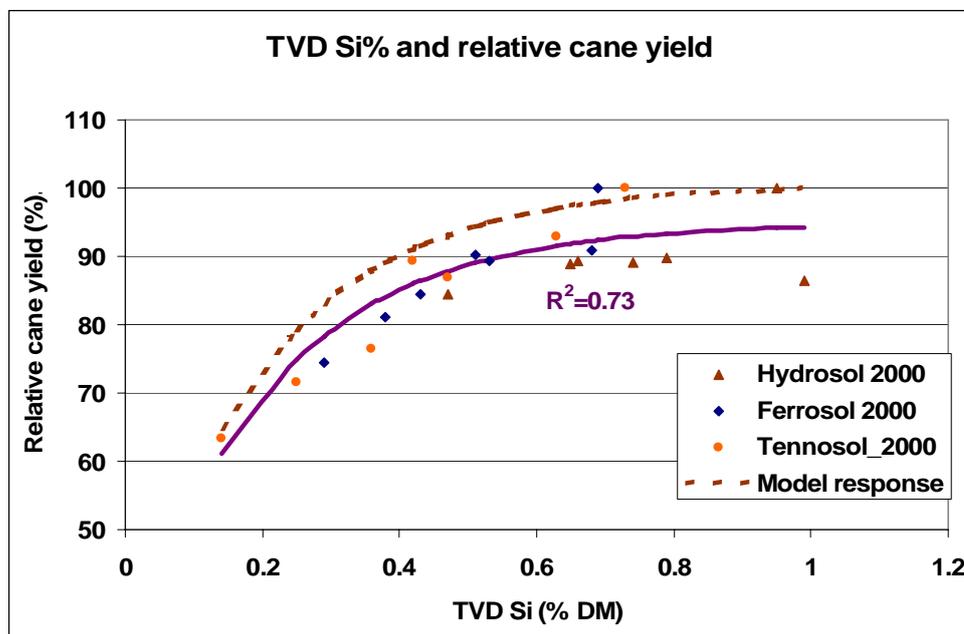


Figure 7.5. Relationship between relative plant cane yield and Si% in TVD leaves for all treatments in the Rates trials on a Hydrosol, Ferrosol and Tennesol soil types.

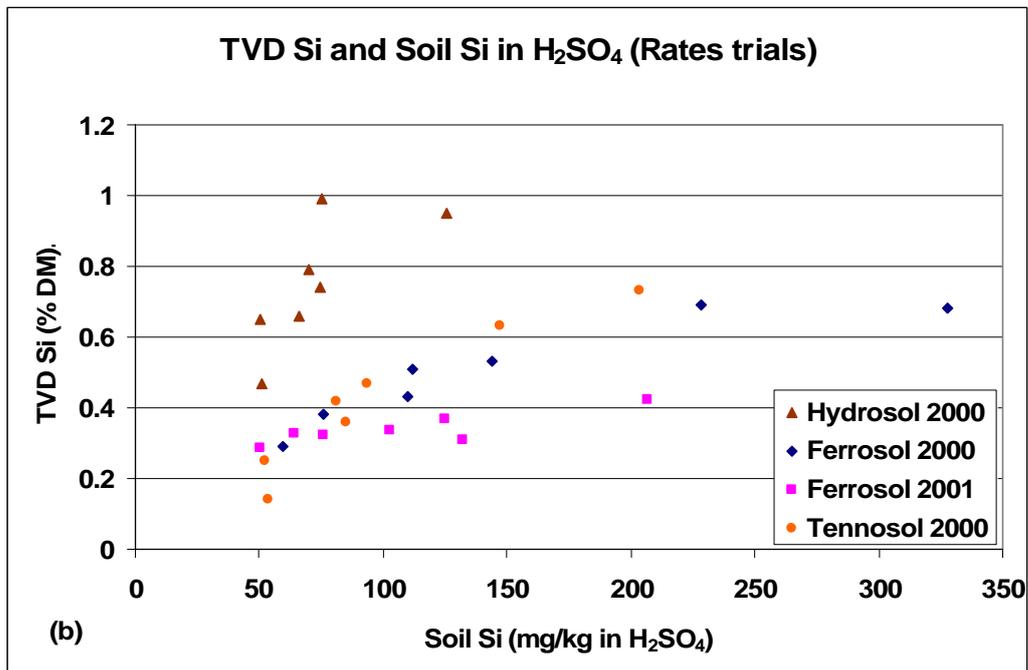
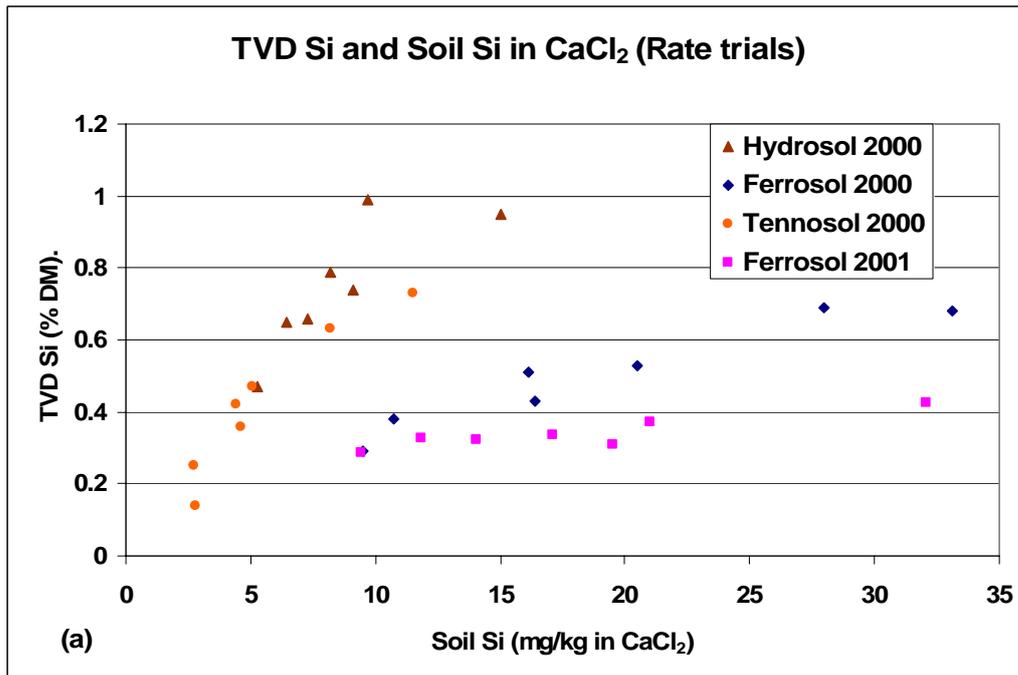


Figure 7.6. Relationships between TVD Si% and indices of plant available silicon on across three years on a Hydrosol soil and across two years on Tennesol and Ferrosol soils. (a) $Si_{(sol)}$ from extraction with 0.01 M CaCl₂ and (b) $Si_{(ext)}$ from extraction with 0.005 M H₂SO₄.

The relationship between relative plant cane yield and silicon content of TVD leaves for all treatments of the Rates trial is summarised in Figure 7.5. A strong and significant relationship exists between relative cane yield and TVD Si status ($R^2=0.73$, $P<0.05$). The asymptotic function provided by this regression analysis was then used to derive the “Model response” curve based on a single estimate of Y_{\max} . This function predicts that 95% of Y_{\max} will be achieved with a TVD of 0.53%, rounded to 0.55%.

Data for relative cane yield and TVD Si% are much more homogeneous across the three soils types than were distributions for untransformed $Si_{(sol)}$ and relative cane yield. Examination of TVD Si% in relation to indices of silicon availability in soils (Figure 7.6. a & b) provided a significant understanding of the values of the respective soil assays. TVD Si% on Hydrosol and Tenosol soils appear to respond similarly, however the Ferrosol soil supports a lower TVD Si% for comparable values of $Si_{(sol)}$ (Figure 7.6. a). This is interesting as Figure 7.5 data suggest there was no difference in the yield response to TVD Si% across soils. The explanation for this is provided by the sulfuric acid extraction data (Figure 7.6. b) that show that the crop on the Ferrosol is accessing reserve Si and soluble from the soil as plant available Si. The Tenosol and Hydrosol data separate in Figure 7.6b because the slightly higher clay and AEC values in the former soil place a higher proportion of the available silicon reserve in the $Si_{(ext)}$ fraction than in the Hydrosol. The data support the conclusion that the relatively low levels of Si in the Hydrosol are mostly present in the soluble or highly available form and have led to “luxury” values of silicon in the TVD leaves.

A role for silicon in leaf greenness

To date a definitive physiological role has not been identified in the literature to explain the growth response of most plants to Si. Possible roles have included increased resistance to fungal disease in rice, improved tolerance of salinity and improved control of water relations due to greater strength of bulliform cells around stomata, increased resistance of sugarcane to infestation by the stem borers *Eldana* and *Diatrea* etc. Stimulus for investigation for a possible role for silicon arose in Bundaberg in 2000. The plant crops of Q182 and Q124 in the rate and product trials respectively were affected by orange rust in 2000 (Plate 7.2) and the Q182 also showed symptoms of Brown strip top rot (Plate 7.3). As the epiphytotic was waning in the autumn of 2000 it was noted that plots treated with more than 3t/ha of calcium silicate in the Rates trial appeared to be producing more leaves with lower levels of disease than were the remaining treatments. The effect was not as evident in the products trial. In an attempt to quantify this observation we used a Minolta Leaf Chlorophyll Meter (Plate 7.1) which uses an infra-red mechanism to rank leaf greenness in dimensionless SPAD (Specific Photosynthetic Active Diode), where the maximum reading is ~44 units.

The leaf chlorophyll meter was used on the central portion of the lamina of 10 TVD leaves in each plot. Ten readings were taken on each leaf over a 15-20 cm section of the leaf (this corresponds to the portion sampled for nutrient analysis). The mean value for each plot was therefore the mean of 100 readings. SPAD readings were acquired for the plant, first and second ratoon crops in the Rates trial and the plant crop of the Products trial at Bundaberg and for the plant crop in the Products

experiment at Mackay. Values were interpreted against applied treatments and TVD nutrient parameters, where these were available.

There was a significant effect of rate of applied calcium silicate on leaf greenness in the Bundaberg experiment for plant, first and second ratoon crops (Table 7.1), where TVD leaves in plots which received more than 3.0 t/ha of calcium silicate were significantly greener than the untreated control. Values were similar within treatments for the plant and first ratoon crops. While there was a large drop in values for the second ratoon crop and the relativity between treatments was preserved, the treatment effect was significant only at $p=0.17$. This large drop in SPAD values between first and second ratoon was also associated with a large drop in cane yield.

Table 7.1. Effect of rate of applied calcium silicate on leaf greenness (SPAD units) in plant, first and second ratoon crops of Q182 in the Rates trial at Bundaberg.

| Rate of calcium silicate (t/ha) | Plant crop 2000 | First ratoon 2001 | Second ratoon 2002 |
|---------------------------------|-----------------|-------------------|--------------------|
| 12.0 | 37.1 | 37.5 | 27.4 |
| 9.0 | 37.5 | 35.8 | 28.0 |
| 6.0 | 36.3 | 36.1 | 27.4 |
| 4.5 | 36.3 | 36.1 | 27.2 |
| 3.0 | 33.8 | 34.2 | 25.5 |
| 1.5 | 32.5 | 34.8 | 24.7 |
| 0 | 32.3 | 34.1 | 24.7 |
| LSD ($p<0.05$) | 2.0 | 1.1 | 2.1 ($p=0.17$) |

nn = significantly greater than control



Plate 7.1. Minolta leaf chlorophyll meter for assessing leaf greenness in SPAD units.



Plate 7.2. Orange rust in canopy of Q124 plant cane in the Bundaberg Products trial – April 2000.



Plate 7.3. Brown stripe tp rot in Q182 plant cane in the Bundaberg Products Trial – April 2000.

Similar SPAD assessments were acquired from Q124 plant cane in the Bundaberg Products trial. Initial analysis of the data showed a range in SPAD values from 34.6 in a calcium silicate treatment to 29.2 in control plots. The treatment effect across all treatments was significant only at $p=0.22$. By reasoning that silicon may have been involved we then omitted from the analysis any treatments which did not have a significant or near significant ($p<0.05$) effect on leaf silicon (Ash, Calphos and Potassium silicate liquid). The treatment effect then achieved significance at $p=0.15$ (Table 7.2). All rates and sources of calcium silicate, both rates of cement and one rate of Cement board waste and Mud –ash resulted in significantly greener leaves than in the controls.

Table 7.2. Effect of applied silicate ameliorant on leaf greenness (SPAD units) in the plant crop of Q124 in the Products experiment at Bundaberg.

| Treatment | SPAD values |
|----------------------------|-------------|
| Calcium silicate (A) 3t/ha | 34.6 |
| Calcium silicate (B) 6t/ha | 34.4 |
| Calcium silicate (A) 6t/ha | 34.2 |
| Cement 3t/ha | 33.6 |
| Mud – Ash 25t/ha | 33.6 |
| Cement board waste 6t/ha | 33.2 |
| Cement 6t/ha | 32.8 |
| Calcium silicate (B) 3t/ha | 32.7 |
| Mud – Ash 50t/ha | 31.7 |
| Cement board waste 3t/ha | 31.2 |
| Control 1 | 29.9 |
| Control 2 | 28.4 |
| LSD ($p<0.15$) | 3.1 |

nn = significantly greater than average of controls

Similar logic was applied to studying the effect on SPAD values of products applied in the Mackay experiment. The treatment effect here was also significant only at $p=0.22$ (Table 7.3). The higher rates of calcium silicate and cement produced the greener leaves. Row dressings of cement at 0.25 and 0.5 t/ha also had no significant effect on leaf silicon levels, but were included in the analysis on an “effective products” basis. Calcium silicate at 0.5 t/ha in the row only just achieved statistical significance for a Si effect.

The association between application of silicate ameliorants and greener leaves does not directly imply a role for Si in this effect. Various levels of detail were available for TVD nutrient analysis across the experiments for which SPAD data were acquired. The plant crop of the Rates and Products trials at Bundaberg and Mackay had the full suite of nutrient assays, whereas the rates trial at Bundaberg had only TVD silicon assays completed.

A significant ($p<0.05$) and positive linear association was demonstrated between TVD Si% and SPAD values for the Bundaberg Rates and Products and for the Mackay Products trials ($r^2=0.76, 0.38$ and 0.65 , respectively). This association does not

provide guidance for any physiological role for silicon. Examination of associations between TVD Si status and other nutrients for the Bundaberg rates and Mackay products experiments revealed that significant relationships existed only for silicon and iron levels $r^2=0.49$ and 0.63 , $p<0.05$. for the respective sites (Figure 7.7). This relationship could not be demonstrated for the Products trial at Maryborough, where iron levels for all treatments were $< 50\text{mg/kg}$ and therefore in potential deficiency. This association provides some evidence of a physiological role for silicon, in that increased iron levels may be associated with higher levels of chlorophyll and greener leaves because of the importance of iron in the development of the chlorophyll molecule. Fortunately the data from the plant crops of the Bundaberg Rates and the Mackay Products trials also demonstrated significant associations ($r^2=0.58$ and 0.66 , $p<0.05$) between leaf greenness (SPAD units) and iron status of TVD leaves (Figure 7.8a & b).

Results from the Innisfail experiments also suggested more rapid recovery from yellow spot disease on plots treated with calcium silicate, but no relationship was apparent between yellow spot rating and silicated treatment. Thus the data from Bundaberg and Innisfail on recovery from disease and the limited data on association between SPAD values and higher iron levels with greater uptake of silicon provide interesting but inconclusive evidence of a role for silicon in sugarcane.

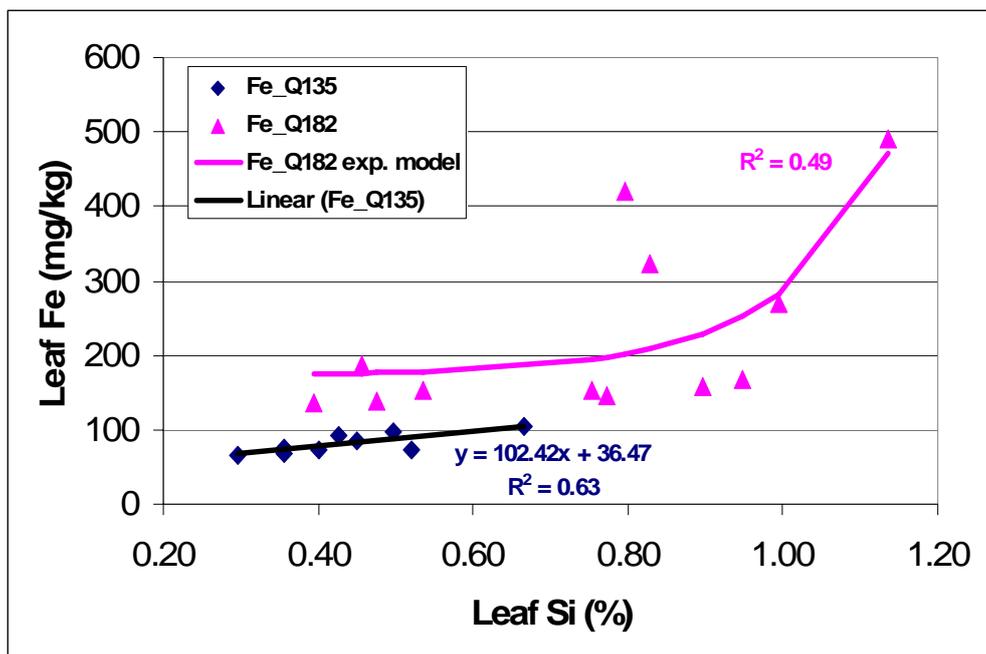


Figure 7.7. Relationship between levels of iron and silicon in TVD leaves in plant crops of the Rates trial at Bundaberg (Q182) and the Products trial at Mackay (Q135).

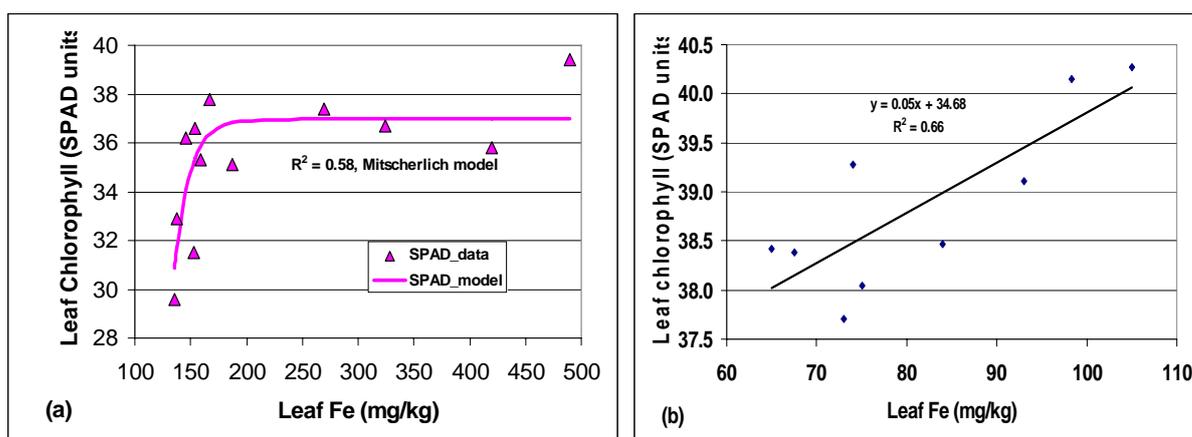


Figure 7.8. Association between leaf greenness (SPAD units) and iron concentration in TVD leaves for (a) Q182 plant cane in the Bundaberg rates experiment and (b) the Mackay Products trial.

Table 7.3. Effect of applied silicate ameliorant on leaf greenness (SPAD units) in the Q135 plant crop of the Products trial at Mackay.

| Treatment | SPAD values |
|-----------------------------------|-------------|
| Calcium silicate (A) 4t/ha | 40.3 |
| Cement 4t/ha | 40.1 |
| Calcium silicate (A) 2t/ha | 39.3 |
| Cement 1t/ha row | 39.1 |
| Calcium silicate (A) 1.0t/ha row | 38.5 |
| Control | 38.4 |
| Cement 0.25t/ha row | 38.4 |
| Cement 0.50t/ha row | 38.1 |
| Calcium silicate (A) 0.50t/ha row | 37.7 |
| LSD (p<0.22) | 1.4 |

nm = significantly greater than control

Silicon uptake by the biomass.

Silicon uptake by sugarcane biomass was monitored for the plant crop of the Rates trial on the Tenosol, Ferrosol and Hydrosol soil types at Mossman, Innisfail and Bundaberg, respectively. The summary data (Figure 7.9) shows that Si acquisition by sugarcane biomass is of the same order of magnitude as that considered for nitrogen. These results are the product of both biomass and Si% in dry matter response to rates of applied calcium silicate. Cane yield response to rate of calcium silicate was discussed previously. Summary data in Table 7.4 show a clear and significant (p<0.05) effect of the calcium silicate treatment on Si% in dry matter of biomass

components. There was similarity in the range of Si% within in components across sites. The trash component of biomass was not measured for the Tennesol and Ferrosol sites because estimates would have been unreliable due to the “free-trashing” nature of varieties used in these trials. Similarity of Si% in other biomass components suggested trash Si% and biomass trash% from the Hydrosol site could be used to estimate Si in trash at the other sites for total biomass acquisition of Si (Figure 7.9). On average untreated cane was able to extract 77kg of silicon/ha from soil. If the economic rate for applied calcium silicate equivalent is between 4.5 and 6.0 t/ha the average silicon content in biomass lies between 153 and 166 kg/ha. Thus an additional 76 to 89 kg/ha of silicon must be supplied from applied ameliorants on silicon deficient soils.

Table 7.4. Silicon % in biomass components for plant crops in the Rates trial on Tennesol, Ferrosol and Hydrosol soils.

| Site | Signif. of treatment | Range of Si% | | | Rank of Si% |
|----------|----------------------|----------------|-------------|-------------|-------------------------|
| | | Trash | Tops | Stalk | |
| Tennesol | P<0.05 | Not determined | 0.23 – 0.86 | 0.11 – 0.32 | By treatments |
| Ferrosol | P<0.05 | Not determined | 0.38 – 0.75 | 0.19 – 0.30 | Generally by treatments |
| Hydrosol | P<0.05 | 0.67 – 1.48 | 0.37 – 0.71 | 0.14 – 0.23 | By treatments |

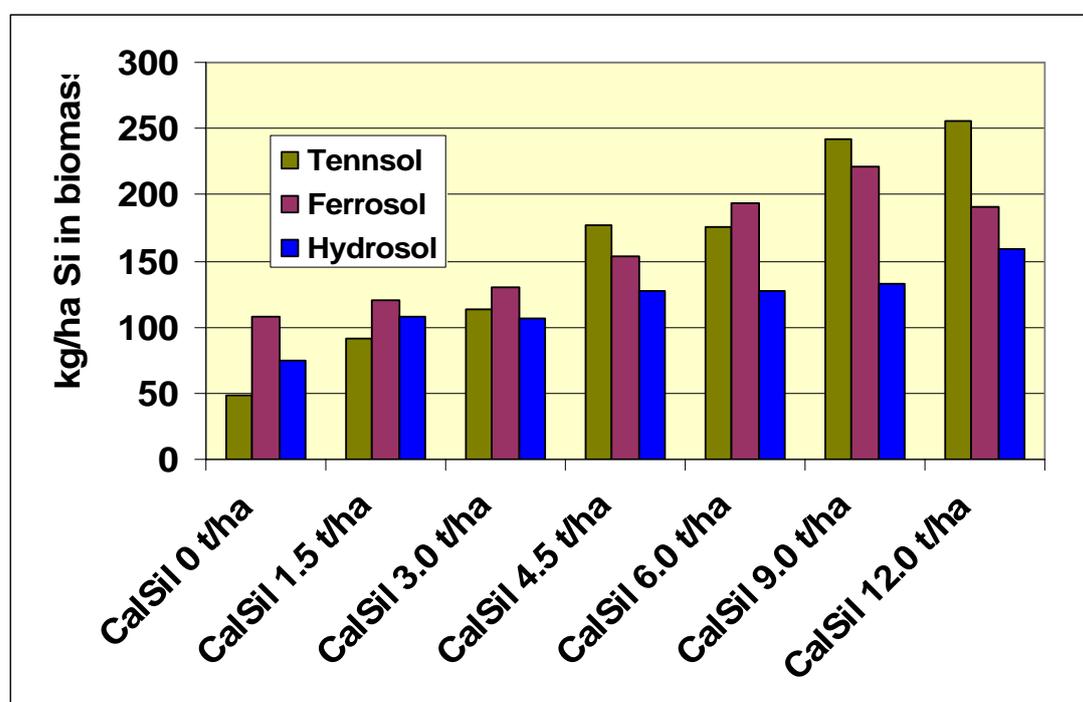


Figure 7.9. Uptake of silicon by plant cane biomass in relation to rate of applied calcium silicate Tennesol, Ferrosol and Hydrosol soils.

8. Effect of Ca-silicate amendments on soil chemical properties

Introduction

The application of silicate materials to soils low in soluble Si has produced dramatic field responses in both cane and sugar yields, and this has been demonstrated in many countries. There is no doubt that part of this response is nutritional, as the benefits to yield have been demonstrated by significant increases in plant height and weight, stem diameter and number of millable stalks, all of which have been strongly correlated with plant uptake of Si. However, as high soil productivity is generally associated with an adequate supply of soil Si (Savant et al., 1999), it is likely that the addition of silicates can also improve plant growth by associated beneficial effects on other soil properties, as distinct from a direct plant nutritional response.

The majority of agricultural soils of the wet tropical coast of north Queensland have been cropped to sugarcane for approximately 50 to 100 years. Under the high temperature, rainfall and leaching conditions of these environments, soils undergo significant weathering, resulting in the base stripping from the exchange complex and a decline in surface charge capacity. The consequences of these weathering processes, combined with accelerated chemical and physical degradation due to soil perturbation and crop removal, are increased soil acidification and dissolution of the aluminosilicate clay minerals (de-silication). This results in both a loss of plant available Si through leaching and a decline in cation exchange capacity and hence an inability to retain essential plant nutrients.

As many soils of the tropics are dominated by variable charged minerals, the net surface charge of soil colloids is a function of pH and electrolyte concentration. The point of zero charge (pH_0) is one of the most important parameters in a variable charged system as it determines the sign of the net surface charge, while the relationship between soil pH and pH_0 determines the magnitude (Uehara and Gillman, 1981). Consequently it is common practice to lime soils to increase pH and thus the soil's cation exchange capacity (CEC). However, due to the high pH buffering capacity of these soils, it is often uneconomic to increase the pH above 6.0. Under these circumstances, by lowering the pH_0 it may be possible to effect a substantial increase in surface charge capacity without raising the pH to levels that are uneconomic (Uehara and Gillman, 1981). Both silica and organic matter have inherently low pH_0 values and could therefore effect an increase in CEC on these soil types. Increasing soil organic matter under tropical conditions is often extremely difficult due to rapid mineralisation, particularly under conditions where the soil is regularly perturbed. However, the addition of inorganic amendments, such as silicates could possibly be of benefit in lowering pH_0 and thus increasing CEC. In addition, the application of amendments such as calcium silicate will increase soil pH and add both calcium (Ca^{2+}) and silicon (Si), both of which are important crop nutrients.

Silicon is recognized as a major constituent of soils. It is present in the soil as aluminosilicate clays, crystalline quartz and as amorphous forms such as plant phytoliths. In the soil solution, Si is present as mono- and poly-silicic acids, and as

complexes with inorganic and organic compounds. Whilst mono-silicic acid is taken up by plants and has a direct influence on crop growth, poly-silicic acids, and organic Si complexes, are important sources and sinks of Si, which can replenish the soil solution following crop use. In addition, these compounds can have a significant effect on soil properties such as soil aggregation, water holding capacity, and cation exchange and buffering capacities of soils (Matichenkov and Bocharnikova, 1999).

Within this project, the effect of additions of silicate materials on soil properties has been examined through a detailed study of the changes in soil chemical properties from contrasting soil types found in the field trials ('Rate' trials) at Innisfail and Mossman.

Despite the very different pedological characteristics of the two sites at Innisfail and Mossman, both sites are characterized by a general low fertility status with low pH, low levels of exchangeable cations, low cation exchange capacity and relatively low levels of organic carbon (refer to Table 4.1). The Innisfail site was established on a Ferrosol where the profile is dominated by clay (65 to 80%) and silt (13 to 20%). In contrast, the field trial site at Mossman was established on a well-developed podzol formed on a remnant beach ridge, and the entire soil profile is dominated by sand (>80%) with generally 60 to 70% being fine sand.

Details of the trial design, soil sampling techniques and soil chemical methodology are detailed in the Methodology section, but are briefly described here for convenience. The treatments for the Rate trials consisted of varying applications (0, 1.5, 3.0, 4.5, 6.0, 9.0 and 12.0 t/ha) of Ca-silicate, broadcast and incorporated to a depth of 10 - 20 cm using a rotary hoe prior to planting. The Ca-silicate used was a by-product phosphorous furnace slag obtained from Rhodia Inc.¹ In addition to the Ca-silicate treatments, at Innisfail, 2.5t/ha of "Blend 3" (32% Ca; 3% Mg) was also applied prior to planting. Nitrogen (N), phosphorus (P) and potassium (K) fertilizer was applied at rates equivalent to 146, 19 and 96 kg/ha in the plant crop (2000) and at 151, 21 and 102 kg/ha in the first ratoon crop (2001). Although liming material was not applied to the Mossman site, N, P and K were applied at similar rates as previously described.

Soil samples were collected prior to the imposition of treatments from all control plots to a depth of 90 cm, and then again at the end of the first and second growing seasons. During these later sampling periods, soil was collected to 40 cm, as it was anticipated that most soil chemical changes would have occurred within, and possibly just below the incorporation layer of the calcium silicate material. Detailed soil analysis was completed on all soil samples, and charge fingerprint analysis, to examine charge characteristics, and the determination of pH buffer capacity were completed on composite samples from the 0–10 cm depth increment from the control, 4.5, 9 and 12 t/ha treatments. In addition, the point of zero charge, pH_0 , was determined using the methodology of Gillman and Sumpter (1986a). Plant available soil Si, considered to be the soil Si that is readily soluble (Si_{sol}), was determined following extraction with 0.01 M $CaCl_2$, while extractable soil Si (Si_{ext}) was also determined on the acid extraction used for determining P as recommended by Hurney (1973) and Haysom and Chapman (1975), as an alternative means of assessing plant available soil Si levels.

¹ Rhodia Phosphate Products, Post Office Box 4439, Glen Allen, VA 23058-4439,

Results and Discussion

The results of changes in selected soil properties following the addition of Ca-silicate, from both 2000 and 2001, are presented in Tables 8.1 and 8.2. Of the selected chemical properties measured, significant differences between treatments were observed in $\text{pH}_{(\text{water})}$, $\text{pH}_{(\text{CaCl}_2)}$, exchangeable Ca, cation exchange capacity readily soluble $\text{Si}_{(\text{sol})}$, and to lesser extent extractable Si and P.

Changes in general soil properties

The application of 2.5t/ha lime in the control treatments at the Innisfail site, substantially increased exchangeable Ca^{2+} levels in the 10-20 and 20-30 cm in the control treatment between 1999 and 2000 (Table 4.1 and 8.1). However, by 2001 exchangeable Ca^{2+} had declined to levels below that of 1999. This is attributed to both the downward movement of Ca^{2+} through leaching and crop uptake. The addition of Ca-silicate resulted in significant increases in exchangeable Ca^{2+} in all depths by 2000, with the greatest responses being observed at rates ≥ 6 t/ha (Table 8.1 and Figure 8.1). However, at rates of < 6 t/ha Ca-silicate, the increase in Ca^{2+} is largely attributed to the applied lime. Increases in exchangeable Ca^{2+} persisted into 2001 in those treatments receiving > 6 t/ha Ca-silicate.

In contrast, at the Mossman site where no basal application of lime was applied, the effect of continued crop export and leaching resulted in a steady decline in exchangeable Ca^{2+} between 1999 and 2001 on the control treatments (Table 4.1 and 8.2). The effect of Ca-silicate is clearly evident over the two growing seasons (Table 8.2). In all cases the application of Ca-silicate increased exchangeable Ca^{2+} in 2000, the magnitude being contingent on the rate of application (Table 8.2). By 2001 exchangeable Ca^{2+} levels had declined over all depth intervals, this being attributed to crop export and/or leaching (Figure 8.1).

Applications of Ca-silicate and lime, in the case of the Innisfail site, had no effect on the Mg^{2+} status at both site (Table 8.1 and 8.2). However, over the two cropping cycles there was a general decline in exchangeable Mg^{2+} from the 1999 levels over all depth intervals (Table 4.1, 8.1 and 8.2). At the Innisfail site exchangeable Mg^{2+} levels were adequate for both 1999 and 2000 based on reported critical values of >0.25 cmol_c/kg (Calcino, 1994). By the end of the second cropping cycle, these values had declined to 0.19 cmol_c/kg , which would be considered marginal for sugarcane production (Calcino, 1994). Contrasting this, at the Mossman site Mg^{2+} levels were considered to be marginal over the entire study period. Similarly, exchangeable K^+ levels were generally inadequate at both trial sites (critical value: >0.24 cmol_c/kg , Calcino, 1994) despite annual routine applications of inorganic K^+ .

Table 8.1. Selected soil chemical properties of field trial site at Innisfail sampled at the end of the first (2000) and second (2001) growing seasons. Each value is the mean of 3 replicates, and significant differences between treatments are shown using 'least significant differences of the means' (lsd) at the 5% level of significance.

| soil chemical property | year | depth interval (cm) | Rate of application of Calcium silicate (t/ha) | | | | | | lsd 5% | |
|--|------|---------------------|--|------|------|------|------|------|--------|------|
| | | | 0 | 1.5 | 3 | 4.5 | 6 | 9 | | 12 |
| pH _(water) | 2000 | 0 - 10 | 5.45 | 5.59 | 5.53 | 5.62 | 5.91 | 6.01 | 6.23 | 0.32 |
| | | 10 - 20 | 5.24 | 5.44 | 5.41 | 5.52 | 5.75 | 5.43 | 6.2 | 0.45 |
| | | 20 - 30 | 4.97 | 5.17 | 5.11 | 5.14 | 5.22 | 5.28 | 5.34 | n.s. |
| | 2001 | 0 - 10 | 4.78 | 5.09 | 5.18 | 5.37 | 5.61 | 5.58 | 5.81 | 0.33 |
| | | 10 - 20 | 4.76 | 5.03 | 5.13 | 5.34 | 5.51 | 5.34 | 5.79 | 0.35 |
| | | 20 - 30 | 4.58 | 4.65 | 4.71 | 4.9 | 4.97 | 4.7 | 5.15 | n.s. |
| pH _(CaCl2) | 2000 | 0 - 10 | 4.89 | 5.09 | 5.04 | 5.07 | 5.34 | 5.18 | 5.33 | 0.22 |
| | | 10 - 20 | 4.9 | 5.05 | 5.12 | 5.07 | 5.21 | 5.09 | 5.55 | 0.28 |
| | | 20 - 30 | 4.81 | 4.97 | 4.99 | 4.93 | 5.07 | 5.06 | 5.1 | n.s. |
| | 2001 | 0 - 10 | 4.49 | 4.6 | 4.77 | 4.88 | 5.12 | 5.31 | 5.12 | 0.39 |
| | | 10 - 20 | 4.54 | 4.69 | 4.78 | 4.9 | 5.12 | 4.99 | 5.25 | 0.26 |
| | | 20 - 30 | 4.49 | 4.54 | 4.6 | 4.67 | 4.76 | 4.57 | 4.9 | n.s. |
| Si _(sol) , mg/kg | 2000 | 0 - 10 | 9.3 | 10.3 | 15.8 | 16.0 | 20.8 | 30.0 | 32.8 | 5.6 |
| | | 10 - 20 | 9.8 | 11.3 | 17.0 | 16.3 | 20.3 | 26.0 | 33.5 | 8.6 |
| | | 20 - 30 | 8.0 | 9.5 | 13.5 | 9.3 | 12.5 | 17.3 | 17.0 | 4.7 |
| | | 30 - 40 | 6.5 | 8.0 | 10.5 | 9.5 | 9.5 | 10.5 | 9.8 | 2.5 |
| | 2001 | 0 - 10 | 9.4 | 12.1 | 14.2 | 16.5 | 20.2 | 22.2 | 32.6 | 3.6 |
| | | 10 - 20 | 9.6 | 11.7 | 13.9 | 17.7 | 18.9 | 19.9 | 31.6 | 4.6 |
| Si _(ext) , mg/kg | 2000 | 0 - 10 | 57 | 72 | 100 | 107 | 165 | 234 | 256 | 76 |
| | | 10 - 20 | 62 | 80 | 119 | 116 | 123 | 223 | 299 | 96 |
| | | 20 - 30 | 67 | 66 | 93 | 72 | 100 | 128 | 123 | n.s. |
| | 2001 | 0 - 10 | 46 | 61 | 73 | 95 | 136 | 138 | 211 | 41 |
| | | 10 - 20 | 55 | 68 | 79 | 110 | 129 | 113 | 203 | 39 |
| | | 20 - 30 | 44 | 48 | 50 | 70 | 81 | 67 | 110 | 30 |
| P _(ext) , mg/kg | 2000 | 0 - 10 | 80 | 80 | 81 | 81 | 92 | 95 | 98 | 14 |
| | | 10 - 20 | 85 | 76 | 77 | 77 | 79 | 78 | 96 | n.s. |
| | | 20 - 30 | 89 | 63 | 62 | 63 | 68 | 73 | 71 | n.s. |
| | 2001 | 0 - 10 | 68 | 72 | 66 | 76 | 99 | 75 | 94 | n.s. |
| | | 10 - 20 | 66 | 67 | 63 | 75 | 84 | 68 | 103 | 19 |
| | | 20 - 30 | 44 | 40 | 40 | 48 | 45 | 46 | 59 | n.s. |
| Ca ²⁺ , cmol _c /kg | 2000 | 0 - 10 | 0.84 | 1.51 | 1.95 | 2.02 | 2.73 | 4.13 | 4.77 | 1.32 |
| | | 10 - 20 | 1.13 | 1.5 | 2.2 | 1.88 | 3.07 | 3.46 | 4.81 | 1.38 |
| | | 20 - 30 | 0.72 | 0.94 | 1.32 | 0.76 | 1.37 | 1.74 | 1.77 | n.s. |
| | 2001 | 0 - 10 | 0.59 | 1.48 | 1.58 | 2.11 | 3.23 | 3.02 | 4.73 | 1.21 |
| | | 10 - 20 | 0.7 | 1.45 | 1.50 | 2.26 | 2.89 | 2.32 | 4.46 | 1.05 |
| | | 20 - 30 | 0.37 | 0.53 | 0.56 | 1.03 | 1.4 | 0.79 | 2.02 | 1.05 |
| Mg ²⁺ , cmol _c /kg | 2000 | 0 - 10 | 0.20 | 0.23 | 0.25 | 0.23 | 0.25 | 0.30 | 0.29 | n.s. |
| | | 10 - 20 | 0.20 | 0.19 | 0.23 | 0.20 | 0.25 | 0.21 | 0.25 | n.s. |
| | | 20 - 30 | 0.15 | 0.14 | 0.16 | 0.11 | 0.13 | 0.13 | 0.12 | n.s. |
| | 2001 | 0 - 10 | 0.12 | 0.18 | 0.16 | 0.21 | 0.24 | 0.18 | 0.21 | n.s. |
| | | 10 - 20 | 0.09 | 0.13 | 0.10 | 0.13 | 0.15 | 0.08 | 0.16 | n.s. |
| | | 20 - 30 | 0.04 | 0.05 | 0.04 | 0.07 | 0.08 | 0.03 | 0.07 | n.s. |
| K ⁺ , cmol _c /kg | 2000 | 0 - 10 | 0.18 | 0.21 | 0.19 | 0.18 | 0.19 | 0.17 | 0.20 | n.s. |
| | | 10 - 20 | 0.12 | 0.13 | 0.11 | 0.09 | 0.11 | 0.09 | 0.11 | n.s. |
| | | 20 - 30 | 0.06 | 0.08 | 0.06 | 0.06 | 0.06 | 0.05 | 0.07 | n.s. |
| | 2001 | 0 - 10 | 0.07 | 0.07 | 0.07 | 0.08 | 0.08 | 0.07 | 0.06 | n.s. |
| | | 10 - 20 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | n.s. |
| | | 20 - 30 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.02 | n.s. |

Table 8.2. Selected soil chemical properties of field trial site at Mossman sampled at the end of the first (2000) and second (2001) growing seasons. Each value is the mean of 3 replicates, and significant differences between treatments are shown using 'least significant differences of the means' (lsd) at the 5% level of significance.

| soil chemical property | year | depth interval (cm) | Rate of application of Calcium silicate (t/ha) | | | | | | lsd 5% | |
|--|------|---------------------|--|------|------|------|------|------|--------|------|
| | | | 0 | 1.5 | 3 | 4.5 | 6 | 9 | | 12 |
| pH _(water) | 2000 | 0 - 10 | 5.00 | 5.06 | 5.52 | 5.81 | 5.56 | 5.66 | 5.99 | 0.31 |
| | | 10 - 20 | 4.98 | 5.08 | 5.35 | 5.42 | 5.52 | 5.39 | 5.91 | 0.44 |
| | | 20 - 30 | 4.99 | 4.88 | 5.18 | 5.1 | 5.1 | 4.9 | 5.21 | n.s. |
| | 2001 | 0 - 10 | 4.88 | 5.16 | 5.34 | 5.48 | 5.4 | 5.87 | 6.02 | 0.21 |
| | | 10 - 20 | 4.8 | 5.1 | 5.25 | 5.24 | 5.3 | 5.64 | 5.71 | 0.18 |
| | | 20 - 30 | 4.82 | 4.97 | 4.96 | 4.9 | 5.07 | 5.05 | 5.25 | n.s. |
| pH _(CaCl2) | 2000 | 0 - 10 | 4.39 | 4.47 | 4.84 | 4.85 | 4.96 | 5.07 | 5.28 | 0.24 |
| | | 10 - 20 | 4.42 | 4.42 | 4.7 | 4.89 | 4.84 | 4.78 | 5.36 | 0.33 |
| | | 20 - 30 | 4.42 | 4.35 | 4.46 | 4.47 | 4.49 | 4.45 | 4.7 | n.s. |
| | 2001 | 0 - 10 | 4.07 | 4.49 | 4.44 | 4.66 | 4.72 | 5.05 | 5.36 | 0.21 |
| | | 10 - 20 | 4.09 | 4.21 | 4.42 | 4.49 | 4.6 | 4.95 | 5.07 | 0.17 |
| | | 20 - 30 | 4.1 | 4.12 | 4.27 | 4.22 | 4.31 | 4.37 | 4.55 | n.s. |
| Si _(sol) , mg/kg | 2000 | 0 - 10 | 2.5 | 2.7 | 4.6 | 4.6 | 5.3 | 8.9 | 11.9 | 3.2 |
| | | 10 - 20 | 3.0 | 2.7 | 4.5 | 4.1 | 4.9 | 7.4 | 11.1 | 4.6 |
| | | 20 - 30 | 2.8 | 2.6 | 3.7 | 3.1 | 2.9 | 3.8 | 3.6 | n.s. |
| | | 30 - 40 | 3.6 | 3.8 | 3.7 | 3.6 | 4.6 | 4.5 | 4.6 | n.s. |
| | 2001 | 0 - 10 | 2.2 | 2.8 | 3.3 | 4.2 | 5.8 | 5.5 | 7.8 | 2.2 |
| | | 10 - 20 | 2.3 | 2.9 | 4.1 | 3.3 | 3.2 | 5.0 | 4.8 | 1.5 |
| Si _(ext) , mg/kg | 2000 | 0 - 10 | 50 | 42 | 75 | 86 | 91 | 138 | 155 | 67 |
| | | 10 - 20 | 55 | 32 | 72 | 68 | 94 | 111 | 160 | n.s. |
| | | 20 - 30 | 54 | 55 | 92 | 59 | 78 | 61 | 78 | n.s. |
| | 2001 | 0 - 10 | 54 | 50 | 78 | 68 | 76 | 124 | 130 | 49 |
| | | 10 - 20 | 57 | 47 | 77 | 62 | 47 | 103 | 100 | 42 |
| | | 20 - 30 | 61 | 45 | 133 | 58 | 70 | 68 | 80 | n.s. |
| P _(ext) , mg/kg | 2000 | 0 - 10 | 112 | 102 | 114 | 123 | 130 | 130 | 137 | 20 |
| | | 10 - 20 | 106 | 108 | 121 | 115 | 116 | 130 | 141 | 22 |
| | | 20 - 30 | 91 | 119 | 97 | 89 | 85 | 85 | 99 | n.s. |
| | 2001 | 0 - 10 | 107 | 104 | 105 | 118 | 109 | 135 | 143 | n.s. |
| | | 10 - 20 | 134 | 98 | 143 | 120 | 132 | 142 | 149 | n.s. |
| | | 20 - 30 | 130 | 134 | 177 | 152 | 103 | 156 | 148 | n.s. |
| Ca ²⁺ , cmol _c /kg | 2000 | 0 - 10 | 0.63 | 1.18 | 2.13 | 2.98 | 2.88 | 4.93 | 5.53 | 0.87 |
| | | 10 - 20 | 0.64 | 0.9 | 1.44 | 2.02 | 2.36 | 2.85 | 4.61 | 1.73 |
| | | 20 - 30 | 0.54 | 0.42 | 0.53 | 0.96 | 0.52 | 0.65 | 1.03 | n.s. |
| | 2001 | 0 - 10 | 0.54 | 1.04 | 1.73 | 2.51 | 2.46 | 4.44 | 4.83 | 0.69 |
| | | 10 - 20 | 0.49 | 0.95 | 1.52 | 1.9 | 1.93 | 3.91 | 3.72 | 0.96 |
| | | 20 - 30 | 0.46 | 0.55 | 0.66 | 0.97 | 0.72 | 1.65 | 1.63 | 0.85 |
| Mg ²⁺ , cmol _c /kg | 2000 | 0 - 10 | 0.12 | 0.13 | 0.13 | 0.16 | 0.13 | 0.13 | 0.14 | n.s. |
| | | 10 - 20 | 0.11 | 0.11 | 0.08 | 0.15 | 0.13 | 0.14 | 0.19 | n.s. |
| | | 20 - 30 | 0.06 | 0.06 | 0.05 | 0.11 | 0.07 | 0.08 | 0.1 | n.s. |
| | 2001 | 0 - 10 | 0.10 | 0.12 | 0.14 | 0.22 | 0.16 | 0.17 | 0.19 | n.s. |
| | | 10 - 20 | 0.07 | 0.11 | 0.09 | 0.14 | 0.08 | 0.09 | 0.08 | n.s. |
| | | 20 - 30 | 0.05 | 0.06 | 0.06 | 0.08 | 0.04 | 0.05 | 0.06 | n.s. |
| K ⁺ , cmol _c /kg | 2000 | 0 - 10 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.05 | n.s. |
| | | 10 - 20 | 0.07 | 0.06 | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | n.s. |
| | | 20 - 30 | 0.06 | 0.06 | 0.04 | 0.05 | 0.04 | 0.04 | 0.04 | n.s. |
| | 2001 | 0 - 10 | 0.05 | 0.07 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | n.s. |
| | | 10 - 20 | 0.05 | 0.05 | 0.04 | 0.04 | 0.16 | 0.04 | 0.03 | n.s. |
| | | 20 - 30 | 0.04 | 0.05 | 0.04 | 0.05 | 0.03 | 0.04 | 0.03 | n.s. |

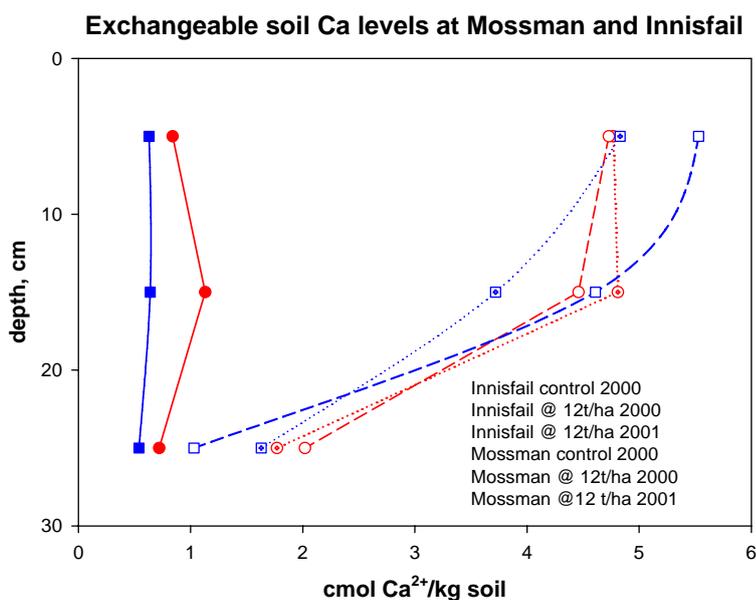


Figure 8.1 Exchangeable soil Ca levels at Mossman and Innisfail, in 2000 and 2001, following additions of Ca-silicate. Only results for the control plots in 2000 and the highest application rate of 12t/ha for both 2000 and 2001 are shown.

At both sites there was a small but significant increase in extractable P as a result of the higher application rates of Ca-silicate (Table 8.1 and 8.2). It is plausible that this may have arisen due to Si dislodging P from the exchange sites, an increase in P solubility resulting from an increase in soil pH and the application of Ca-silicate which contained 1.2% P (Table 4.4).

At both sites, the background concentration (control treatment) of readily soluble Si ($Si_{(sol)}$) did not change from 1999 to 2001 (average of 9.2 mg/kg at Innisfail and 3 mg/kg at Mossman) (Tables 8.1 and 8.2). Increasing application rates of Ca-silicate significantly increased $Si_{(sol)}$ over all depths. The increases at Mossman were considerably less than at Innisfail (a maximum of 11.9 mg/kg at Mossman compared to 32.8 mg/kg at Innisfail), and differences due to amendment addition were only significant at application rates of 9 and 12 t/ha (Table 8.2). In contrast, at Innisfail, all application rates of > 3 t/ha resulted in significant increases from the control (Table 8.1). In addition, the levels of $Si_{(sol)}$ were maintained at the same level at Innisfail over both years, whereas, at Mossman there tended to be a decline in $Si_{(sol)}$ over all rates between 2000 and 2001 (Figure 8.2.), to the point where by the end of 2001 the $Si_{(sol)}$ in the plots receiving 12 t/ha of Ca-silicate were only 7.8 mg/kg which is below the 'critical' soil level that is recommended to maintain optimum growth (Haysom and Chapman (1975)).

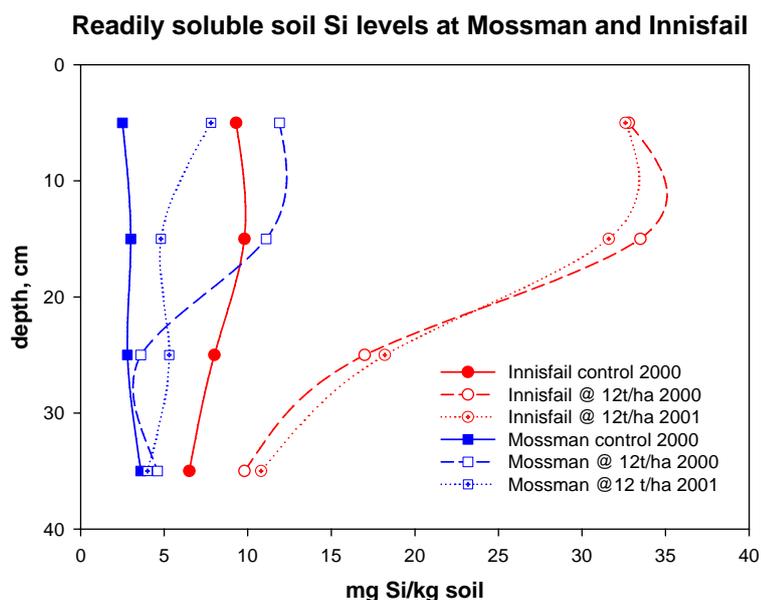


Figure 8.2. Readily soluble soil Si levels at Mossman and Innisfail, in 2000 and 2001, following additions of Ca-silicate. Only results for the control plots in 2000 and the highest application rate of 12t/ha for both 2000 and 2001 are shown.

Soluble Si ($Si_{(sol)}$) and extractable Si ($Si_{(ext)}$) were well correlated over all depth increments, in both years, at Innisfail (Table 8.3). It is interesting to note, that while the $Si_{(sol)}$ and $Si_{(ext)}$ were well correlated in the surface layers at both sites, the magnitude of this relationship was site dependent (Table 8.3). At Innisfail, $Si_{(ext)}$ was approximately eight times greater than $Si_{(sol)}$, while at Mossman $Si_{(sol)}$ represented a much smaller proportion of $Si_{(ext)}$, with $Si_{(ext)}$ being on average 13 times $Si_{(sol)}$ in 2000 and increasing to 21 times at 10–20 cm in 2001. These differences are an indication of the type of solid phases in the soil that are acting as Si sinks/sources, available to replenish the soluble Si in the soil solution following depletion through leaching loss or plant uptake. The concentration of Si in the soil solution is controlled by exchange/dissolution reactions in the soil, which can have no relationship to the total Si in the soil. Sorption/desorption reactions by sesquioxides and clays can result in faster equilibrium between the solid and liquid phases of Si in the soil than dissolution/precipitation reactions (McKeague and Cline, 1963a; Beckwith and Reeve, 1964; Jones and Handreck, 1963). It is suggested that the close relationship and magnitude between $Si_{(sol)}$ and $Si_{(ext)}$ at Innisfail may indicate the importance of amorphous aluminosilicate surfaces on the sesquioxides in supplying soluble Si. In contrast, it appears that the soil properties of the Mossman site are such that the levels of $Si_{(sol)}$ in the soil solution are more dependent on the dissolution of applied Ca-silicate, and that by the second year the solubility of this source had declined significantly. A laboratory incubation study supports the suggestion that amorphous silicate compounds had formed in the basaltic Innisfail soil but not in the sandy Mossman soil (Table 8.4). Soil collected from both sites was incubated with calcium silicate at a rate equivalent to 9t/ha. X-ray Diffraction (XRD) analysis on the samples after 4 months showed no change in the amorphous content in the soil in the Mossman sand, but an increase from 55 to 63% in the Innisfail basaltic krasnozem soil.

Table 8.3. Fitted regression equations describing the relationship between readily soluble Si ($Si_{(sol)}$) and extractable Si ($Si_{(ext)}$), for depth increments 0–10, 10–20 and 20–30 cm, at Innisfail and Mossman for years 2000 and 2001.

| Site | Depth increment | Equation | R ² |
|-------------------|-----------------|---------------------------------------|----------------|
| Innisfail 2000 | 0-10cm | $Si_{(sol)} = 0.12 Si_{(ext)} + 2.83$ | 0.99 |
| | 10-20cm | $Si_{(sol)} = 0.10 Si_{(ext)} + 5.07$ | 0.96 |
| | 20-30cm | $Si_{(sol)} = 0.14 Si_{(ext)} - 0.66$ | 0.96 |
| Innisfail 2001 | 0-10cm | $Si_{(sol)} = 0.13 Si_{(ext)} + 3.57$ | 0.99 |
| | 10-20cm | $Si_{(sol)} = 0.15 Si_{(ext)} + 1.95$ | 0.98 |
| | 20-30cm | $Si_{(sol)} = 0.15 Si_{(ext)} + 1.48$ | 0.96 |
| Mossman 2000 | 0-10cm | $Si_{(sol)} = 0.08 Si_{(ext)} + 1.52$ | 0.96 |
| | 10-20cm | $Si_{(sol)} = 0.07 Si_{(ext)} - 0.42$ | 0.95 |
| | 20-30cm | $Si_{(sol)} = 0.02 Si_{(ext)} + 1.98$ | 0.3 |
| Mossman 2001 | 0-10cm | $Si_{(sol)} = 0.05 Si_{(ext)} + 0.19$ | 0.72 |
| | 10-20cm | $Si_{(sol)} = 0.04 Si_{(ext)} + 0.91$ | 0.84 |
| | 20-30cm | $Si_{(sol)} = 0.01 Si_{(ext)} + 2.40$ | 0.43 |

Table 8.4. Amorphous and mineral phases present in the Mossman sand and the Innisfail basaltic soil following a 4 month incubation period with additions of 9 t/ha calcium silicate.

| Site / soil type | Treatment | Phases present | % |
|-------------------------------------|--------------------|---|----|
| Mossman 'Daintree' sand | control | Amorphous Content | 9 |
| | | Quartz (SiO ₂) | 86 |
| | | Potassium feldspar (KAlSi ₃ O ₈) | 5 |
| | CaSilicate @ 9T/ha | Amorphous Content | 7 |
| | | Quartz (SiO ₂) | 89 |
| | | Potassium feldspar (KAlSi ₃ O ₈) | 4 |
| Innisfail 'Pin Gin' krasnozem | control | Amorphous Content | 55 |
| | | Quartz (SiO ₂) | 6 |
| | | Potassium feldspar (KAlSi ₃ O ₈) | 1 |
| | | Gibbsite (Al(OH) ₃) | 17 |
| | | Tridymite (SiO ₂) | 0 |
| | | Cristobalite (SiO ₂) | 0 |
| | | Anatase (TiO ₂) | 4 |
| | | Goethite (FeO(OH)) | 18 |
| | CaSilicate @ 9T/ha | Amorphous Content | 63 |
| | | Quartz (SiO ₂) | 4 |
| | | Potassium feldspar (KAlSi ₃ O ₈) | 0 |
| | | Gibbsite (Al(OH) ₃) | 17 |
| | | Tridymite (SiO ₂) | 0 |
| | | Cristobalite (SiO ₂) | 0 |
| Anatase (TiO ₂) | 5 | | |
| Goethite (FeO(OH)) | 11 | | |

Changes in soil pH and pH buffer capacity

At both Innisfail and Mossman sites, $\text{pH}_{(\text{water})}$ and $\text{pH}_{(\text{CaCl}_2)}$ significantly increased with Ca-silicate additions during the first year of the study. Although there were small changes at 20 – 30 cm at both sites, significant changes were restricted to the incorporation layer of 0 – 20 cm. On average, at both sites, the increase was approximately one pH unit ($\text{pH}_{(\text{water})}$) from the control to the highest rate of Ca-silicate (12 t/ha) application. Contrasting this there was a significant decline in pH (0.3 – 0.4) at the Innisfail site between the first and second year of the study (Table 8.1). The influence of the 2.5 t/ha lime is clearly evident 12 months after application with the soil pH in the control treatments increasing from 4.89 to 5.45 (Tables 4.1 and 8.1). However, this increase in pH had declined to 4.78 by the end of the second cropping cycle in 2001 (Table 8.1).

In contrast at the Mossman site, soil pH declined between 2000 and 2001 at the lower rates of Ca-silicate application, whilst at 9 and 12 t/ha, pH was maintained or increased slightly over this period (Table 8.2).

The size of difference between $\text{pH}_{(\text{CaCl}_2)}$ and $\text{pH}_{(\text{water})}$ (ΔpH), and whether it is positive or negative, can give an indication of the polarity of net soil surface charge. In most soils, the system is dominantly negatively charged, causing the major exchange to be with the H^+ and Al^{3+} , causing the pH in 0.01M CaCl_2 to be more acid than that in water. At Mossman, the ΔpH values were considerably larger compared to those at Innisfail (-0.9 compared to -0.26, Table 4.1). This can be attributed to the high percentage of H^+ and Al^{3+} compared to the other basic cations, accounting for 70% of the ECEC at Mossman compared to only 10% at Innisfail. A high negative ΔpH value associated with high levels of extractable Al can indicate a soil high in permanent charge minerals, and in the case of an acid, sandy soil rich in quartz, like the Mossman soil, the high ΔpH value simply indicates that the surface charge density on the quartz is high and negative in sign (Uehara and Gillman, 1981). It is of note that at Mossman the ΔpH values tended not to change as a response to Ca-silicate addition, either with depth or over time. Any differences observed in ΔpH were not significant.

A ΔpH that is positive, zero, or a small negative (<-0.5), as is the case with the Innisfail soil, generally indicates a soil dominated by variable charge minerals (Uehara and Gillman, 1981). At Innisfail, in contrast to the Mossman site, there was a significant increase in ΔpH with increasing rates of Ca-silicate and this was maintained over the two years, although there was a slight decrease from 2000 to 2001. This increase in ΔpH is likely to be due to the development of amorphous aluminosilicate surfaces forming as a result of the amendment addition in the Innisfail soil.

Soil pHBC is an intrinsic property of a soil that effectively describes its ability to resist shifts in soil pH. It is generally agreed that this property is a function of soil pH and clay and organic matter content. Both soils demonstrated an increase in pH buffer capacity (pHBC) ($\text{cmol}(\text{H}^+)/\text{kg}\cdot\text{pH unit}$) with increasing rates of calcium silicate additions (Table 8.5 and Figure 8.3). The variable charge nature of certain soils (ie Ferrosols) will have a significant effect on pHBC. This is clearly demonstrated by the response in pHBC in the Innisfail soil to increasing rates of

calcium silicate. The higher buffer capacity of the Innisfail soil, compared to the Mossman soil, is due to the higher amount of variable charged clay present, and as it has the capacity to generate large amounts of surface charge from the sesquioxide surfaces, the buffer capacity increases with increasing rates of calcium silicate additions.

In contrast, the pHBC of the Mossman soil begins to plateau at rates of calcium silicate additions greater than 4.5 t/ha. At the lower rates of calcium silicate addition, a significant amount of exchange acidity present in the Mossman soil would effectively consume any base added to the system. However, at rates greater than 4.5 t/ha the exchangeable acidity is eliminated and there is little capacity in the system to buffer changes in pH, causing the response curve to plateau.

Table 8.5. Fitted regression equations describing the relationship between pH (y-axis) and cmol (H⁺)/kg (x-axis) for the various rates of calcium silicate additions, and pH buffer capacity (cmol (H⁺)/kg, at Innisfail and Mossman for years 2000 and 2001.

| Site | Treatment | pH (water) | Equation | R ² | pH buffer capacity (cmol H ⁺ /kg.pH unit) |
|-------------------|-----------|------------|----------------------|----------------|--|
| Innisfail 2000 | control | 5.45 | $y = 0.428 x + 5.19$ | 0.99 | 2.33 |
| | 4.5 t/ha | 5.62 | $y = 0.384 x + 5.57$ | 1.00 | 2.61 |
| | 9 t/ha | 6.01 | $y = 0.348 x + 6.02$ | 1.00 | 2.80 |
| | 12 t/ha | 6.23 | $y = 0.325 x + 6.13$ | 0.99 | 3.10 |
| Innisfail 2001 | control | 4.78 | $y = 0.397 x + 4.97$ | 1.00 | 2.52 |
| | 4.5 t/ha | 5.37 | $y = 0.393 x + 5.44$ | 1.00 | 2.55 |
| | 9 t/ha | 5.58 | $y = 0.368 x + 5.69$ | 1.00 | 2.72 |
| | 12 t/ha | 5.81 | $y = 0.322 x + 6.00$ | 1.00 | 3.10 |
| Mossman 2000 | control | 5.00 | $y = 0.681 x + 4.57$ | 1.00 | 1.47 |
| | 4.5 t/ha | 5.81 | $y = 0.564 x + 5.22$ | 1.00 | 1.77 |
| | 9 t/ha | 5.66 | $y = 0.525 x + 5.69$ | 1.00 | 1.90 |
| | 12 t/ha | 5.99 | $y = 0.547 x + 6.07$ | 1.00 | 1.83 |
| Mossman 2001 | control | 4.88 | $y = 0.688 x + 4.58$ | 1.00 | 1.45 |
| | 4.5 t/ha | 5.48 | $y = 0.555 x + 5.32$ | 0.99 | 1.80 |
| | 9 t/ha | 5.40 | $y = 0.511 x + 5.79$ | 0.99 | 1.96 |
| | 12 t/ha | 6.02 | $y = 0.513 x + 6.03$ | 0.99 | 1.95 |

At the Innisfail site 2.5 t/ha of 'Blend 3' (32% Ca; 3% Mg) was added to all plots prior to the imposition of the calcium silicate treatments. Assuming that 50 kg of pure CaCO₃ can neutralize 1 kmol H⁺, and if this is incorporated to a depth of 20 cm, this addition will contribute 25 kmol/ha of alkalinity to the top 10 cm of soil. The 'Blend 3' caused a pH shift in the control plots of 0.56 pH units (from pH 4.89 in 1999 to 5.45 in 2000). Based on the pH buffer capacity value of 2.33 (Table 8.5) it can be estimated that approximately 15 kmol/ha of base was required to effect this pH change. As 'Blend 3' would not have a neutralizing value of 100%, it is speculated that a large proportion of the base addition was consumed in the first year.

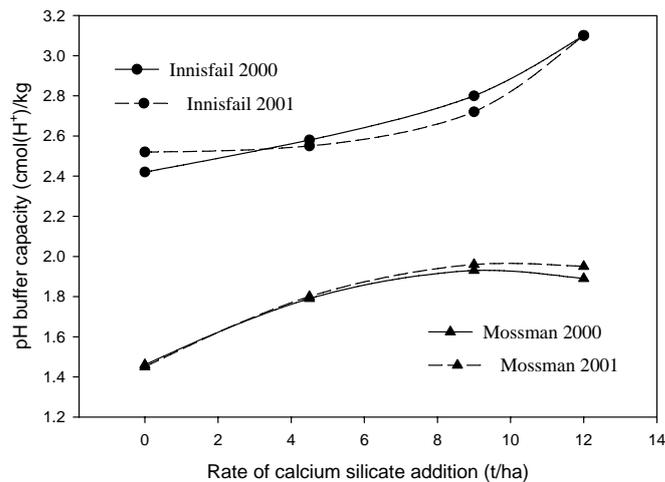


Figure 8.3. The response in pH buffer capacity to increasing rates of calcium silicate additions at Innisfail and Mossman in 2000 and 2001

The Net Acidification Rate ($\text{kmol}(\text{H}^+)/\text{ha}\cdot\text{year}$) of the two soil systems, calculated from the pH buffer capacity and the change in soil pH, are presented in Table 8.6, and the annual alkalinity ($\text{kmol}(\text{OH}^-)/\text{ha}\cdot\text{year}$) removed in the harvestable stalk material is presented in Table 8.7. The impact of the 2.5t/ha of ‘Blend 3’ is clear, as the control treatment at the Innisfail site had a net alkalinity input of 16 $\text{kmol}(-)/\text{ha}\cdot\text{yr}$ in 2000. This supports the suggestion that most of the base input in the form of ‘Blend 3’ was consumed in the first year in increasing soil pH, by 2001 this soil was now acidifying, with a net acid input of 19.50 $\text{kmol}(+)/\text{kg}\cdot\text{year}$, with a corresponding drop in pH from 5.45 to 4.78 (Table 8.1 and Table 8.6)). All rates of calcium silicate resulted in alkalinity input in the first year, and despite the effect of alkalinity removed with harvestable product (Table 8.7), and other soil acidification processes, the net effect after 2 years, except for the control plots, was alkalising. The Net Acidification Rate for the control plots was well balanced by the amount of alkalinity removed in the stalk material at both sites (Table 8.6 and table 8.7).

Gillman and Sumpter (1986b) observed that in soils of the wet tropics exhibiting variable charge characteristics, approximately 50% of the lime added to raise the pH of a soil suspensions from 4 to 6 can be consumed by generating cation exchange capacity and not in directly increasing soil pH. The total alkalinity added to the soils with the additions of calcium silicate varied from 0 to 5 $\text{cmol}(-)/\text{kg}$ at Mossman and 2.08 to 7.08 $\text{cmol}(-)/\text{kg}$ at Innisfail (Table 8.8). Less than half of this base input was used to increase pH in the first year. Even allowing for the alkalinity removed with the harvested material at the end of the plant crop in 2000, a considerable amount of alkalinity added to the system is unaccounted for. The addition of this excess alkalinity has undoubtedly contributed to the net increase in cation exchange capacity. The effect of calcium silicate additions on the charge characteristics of the soil is discussed in the next section.

Table 8.6. Net Acidification Rate (kmol (H⁺)/ha.year) for additions of 0, 4.5, 9 and 12 t/ha of calcium silicate, for Innisfail and Mossman, for 2000 and 2001, and an average value over the 2 years.

| Site | Treatment | Nett acidification rate (kmol (H ⁺)/ha.year) | | |
|-----------|-----------|---|-------|--------------|
| | | 2000 | 2001 | over 2 years |
| Innisfail | Control | -16.30 | 19.50 | 1.60 |
| | 4.5 t/ha | -21.24 | 7.74 | -6.75 |
| | 9 t/ha | -32.59 | 14.45 | -9.07 |
| | 12 t/ha | -38.99 | 15.62 | -11.69 |
| Mossman | Control | 2.86 | 2.45 | 2.66 |
| | 4.5 t/ha | -13.69 | 8.25 | -2.72 |
| | 9 t/ha | -10.63 | 7.03 | -1.80 |
| | 12 t/ha | -17.37 | -0.79 | -9.08 |

Table 8.7. Alkalinity (kmol (OH⁻)/ha.yr) removed with the harvested stalk material following additions of 0, 4.5, 9 and 12 t/ha of calcium silicate, for Innisfail and Mossman, for 2000 and 2001, and an average value over the 2 years. Alkalinity was determined using measured ash alkalinity values of 8 cmol/kg at Innisfail and 15 cmol/kg at Mossman.

| Site | Treatment | Dry weight stalks (t/ha) | | Alkalinity removed with stalk (kmol (OH ⁻)/ha.yr) | | |
|-----------|-----------|-----------------------------|-------|--|-------|--------------|
| | | 2000 | 2001 | 2000 | 2001 | over 2 years |
| Innisfail | Control | 19.58 | 24.59 | 1.567 | 1.967 | 1.767 |
| | 4.5 t/ha | 23.39 | 34.13 | 1.871 | 2.730 | 2.301 |
| | 9 t/ha | 25.57 | 33.03 | 2.045 | 2.642 | 2.344 |
| | 12 t/ha | 23.12 | 31.56 | 1.850 | 2.525 | 2.187 |
| Mossman | Control | 17.14 | 17.56 | 2.570 | 2.633 | 2.602 |
| | 4.5 t/ha | 29.23 | 21.95 | 4.385 | 3.292 | 3.838 |
| | 9 t/ha | 30.24 | 21.95 | 4.536 | 3.292 | 3.914 |
| | 12 t/ha | 28.90 | 26.73 | 4.334 | 4.010 | 4.172 |

Table 8.8. The balance of the alkalinity added with the lime and calcium silicate (cmol)/kg, and that removed through soil pH adjustment and in harvestable stalk material at Innisfail and Mossman in 2000.

| Site | Treatment | cmol (-)/kg | | | | | | | |
|-----------|-----------|------------------|-------|-------|--|---|--|-------------------------|---|
| | | Alkalinity added | | | Alkalinity needed to shift pH from initial pH (due to lime & Ca Sil) | Alkalinity needed to shift pH from pH of control plot to treatment pH (CaSil response only) | Alkalinity removed at end 2000 with stalk material | Total excess alkalinity | Excess 'residual' alkalinity derived from calcium silicate addition |
| | | Lime | Ca Si | Total | | | | | |
| Innisfail | control | 2.08 | 0.00 | 2.08 | 1.10 | 0.00 | 0.13 | 0.85 | 0.00 |
| 2000 | 4.5t/ha | 2.08 | 1.88 | 3.96 | 1.49 | 0.40 | 0.16 | 2.31 | 1.48 |
| | 9t/ha | 2.08 | 3.76 | 5.84 | 2.40 | 1.30 | 0.17 | 3.27 | 2.46 |
| | 12t/ha | 2.08 | 5.00 | 7.08 | 2.91 | 1.82 | 0.15 | 4.02 | 3.18 |
| Mossman | control | 0 | 0 | 0 | -0.21 | 0.00 | 0.18 | 0.03 | 0.00 |
| 2000 | 4.5t/ha | 0 | 1.88 | 1.88 | 0.98 | 1.19 | 0.31 | 0.59 | 0.69 |
| | 9t/ha | 0 | 3.76 | 3.76 | 0.76 | 0.97 | 0.32 | 2.68 | 2.79 |
| | 12t/ha | 0 | 5.00 | 5.00 | 1.25 | 1.46 | 0.31 | 3.44 | 3.54 |

Charge characteristics

The charge characteristics of the two sites are presented graphically in Figures 8.4, 8.5, 8.6, and 8.7, and the fitted quadratic equations for CEC_B are presented in Table 8.9. The CEC_B represents the total amount of basic cations, while the CEC_T is the total amount of both basic and acidic cations that can be retained in an exchangeable form at any particular solution pH. The curves depicted in Figures 8.4 and 8.5 clearly illustrate that at the Innisfail site most of the exchange complex is occupied by basic cations over the entire pH range. In contrast, at the Mossman site (Figures 8.6 and 8.7) a large proportion of the cation exchange capacity below pH 5.5 is occupied by acidic cations, predominantly Al^{3+} . As the soil pH of un-amended soil at Mossman is well below pH 5.5, it becomes clear that this increase in exchangeable Al^{3+} on the exchange complex, associated with a decline in exchangeable Ca^{2+} , Mg^{2+} and K^+ is likely to have had a significant impact on crop performance.

The surface charge fingerprints can be used to quantify the changes in the charge capacity of the soil associated with amendment applications. At both sites, significant increases in CEC were observed in all treatments receiving Ca-silicate one year after application, and these increases persisted into the second year. With increasing additions of Ca-silicate there was a vertical shift in the charge curve over the entire pH range, suggesting the increase in charge is not only associated with an increase in pH *per se*.

Table 8.9. Fitted regression equations describing the relationship between pH (x) and CEC_B (y) for the 0–10 cm increment from the control, 4.5, 9 and 12 t/ha Ca-silicate treatments from the Innisfail and Mossman sites for years 2000 and 2001.

| Site | Treatment | Equation | R ² |
|-------------------|-----------|---------------------------------------|----------------|
| Innisfail 2000 | control | $CEC_B = 0.968x^2 - 8.107x + 17.709$ | 0.994 |
| | 4.5 t/ha | $CEC_B = 0.458x^2 - 2.916x + 4.921$ | 0.993 |
| | 9 t/ha | $CEC_B = 0.138x^2 + 0.531x - 3.669$ | 0.988 |
| | 12 t/ha | $CEC_B = 0.191x^2 + 0.326x - 3.720$ | 0.985 |
| Innisfail 2001 | control | $CEC_B = 0.579x^2 - 4.328x + 8.329$ | 0.980 |
| | 4.5 t/ha | $CEC_B = 0.488x^2 - 3.520x + 6.955$ | 0.959 |
| | 9 t/ha | $CEC_B = 0.454x^2 - 2.935x + 4.858$ | 0.982 |
| | 12 t/ha | $CEC_B = 0.303x^2 - 1.028x - 0.477$ | 0.993 |
| Mossman 2000 | control | $CEC_B = 0.524x^2 - 3.975x + 8.297$ | 0.984 |
| | 4.5 t/ha | $CEC_B = 0.219x^2 - 0.839x + 1.063$ | 0.986 |
| | 9 t/ha | $CEC_B = 0.0030x^2 + 1.228x - 3.905$ | 0.974 |
| | 12 t/ha | $CEC_B = -0.054x^2 + 1.928x - 5.068$ | 0.935 |
| Mossman 2001 | control | $CEC_B = 0.568x^2 - 4.407x + 9.144$ | 0.994 |
| | 4.5 t/ha | $CEC_B = 0.130x^2 - 0.014x - 1.087$ | 0.994 |
| | 9 t/ha | $CEC_B = -0.048x^2 + 2.081x - 6.360$ | 0.979 |
| | 12 t/ha | $CEC_B = -0.230x^2 + 3.814x - 10.472$ | 0.992 |

Changes in charge capacity are summarized in Table 8.10. At Innisfail, CEC_B (at soil pH) the addition of 12 t/ha Ca-silicate resulted in an increase of 3.80 cmol_c/kg in the first year (2000), falling slightly by 2001 to 2.96 cmol_c/kg, when compared to the control. The increases in charge capacity at Mossman were in the same order as at Innisfail, being 3.06 and 2.73 cmol_c/kg at soil pH, in 2000 and 2001 respectively.

As previously discussed, and as illustrated in Table 8.10, ‘variable’ charge minerals dominate the Innisfail soil, and they represent approximately three quarters of the charge capacity. In contrast, in the Mossman soil the charge present is predominantly ‘permanent’, with the ‘variable’ component representing approximately a quarter of the total charge capacity. Despite this inherent difference in ‘permanent’ and ‘variable’ charge between the two soils, in both soils there was a depression in pH₀ with increasing additions of calcium silicate (Table 8.11) resulting in a small change in ‘permanent’ charge in both soils (Figure 8.8). It seems likely that the introduction of the Si anion onto the colloid surface has increased the negative charge, and this decrease in pH₀ combined with the increase in soil pH due to the ‘liming’ effect of the calcium silicate has resulted in a significant increase in the magnitude of the net surface charge. Most of the increase in CEC is associated with the variable charged surfaces, likely to be due to the development of amorphous alumino-silicate surfaces in the Innisfail soil, and possibly the formation of Al-Si gels/coatings on quartz surfaces at Mossman.

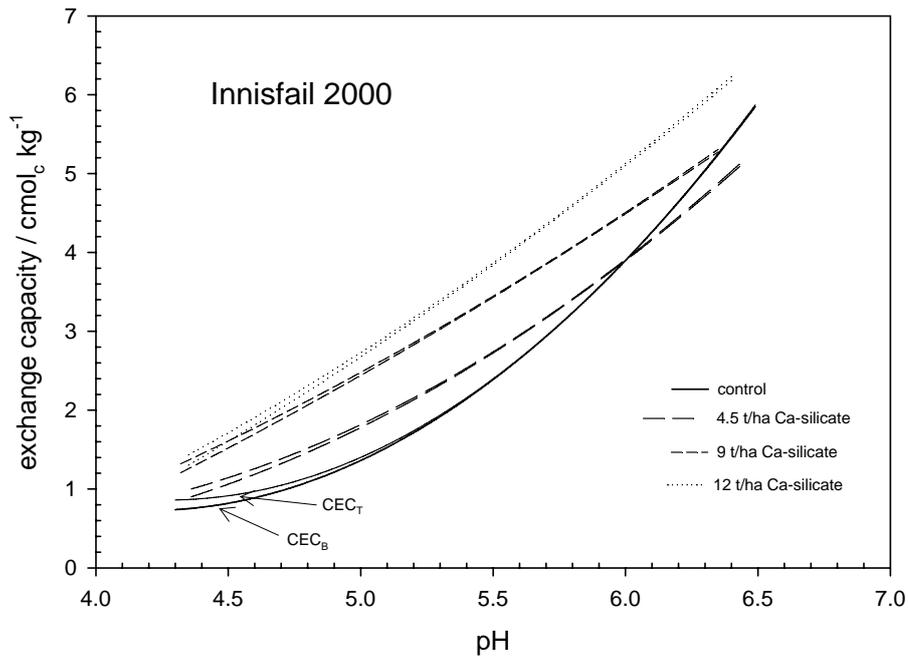


Figure 8.4. Surface charge fingerprints showing CEC_B and CEC_T for the 0 – 10 cm increment for the composite samples from the 0 – 10 cm increment from the control, 4.5 t/ha, 9 t/ha and 12 t/ha Ca-silicate treatments from the Innisfail for year 2000.

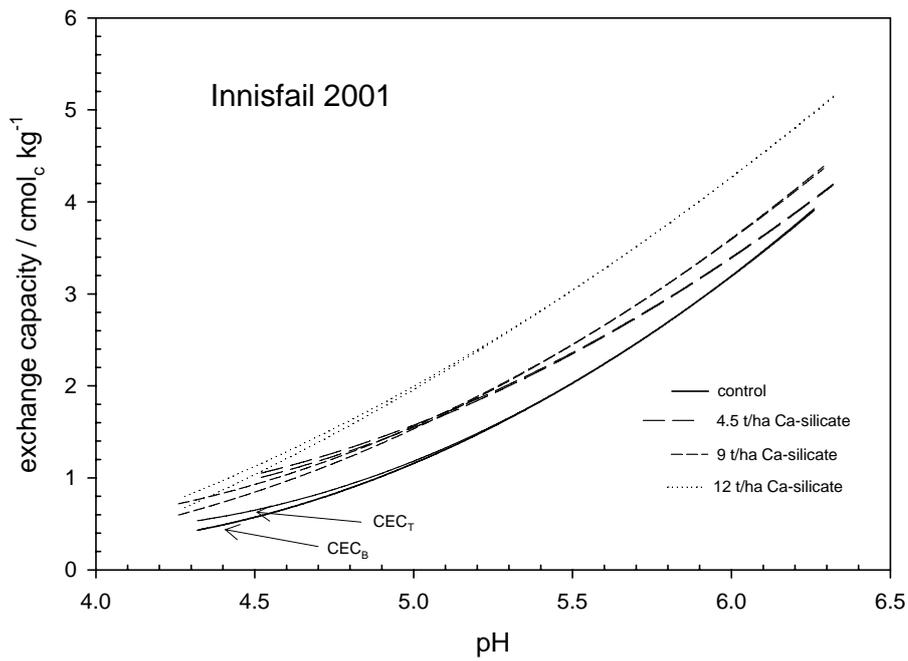


Figure 8.5. Surface charge fingerprints showing CEC_B and CEC_T for the 0 – 10 cm increment for the composite samples from the 0 – 10 cm increment from the control, 4.5 t/ha, 9 t/ha and 12 t/ha Ca-silicate treatments from the Innisfail for year 2001.

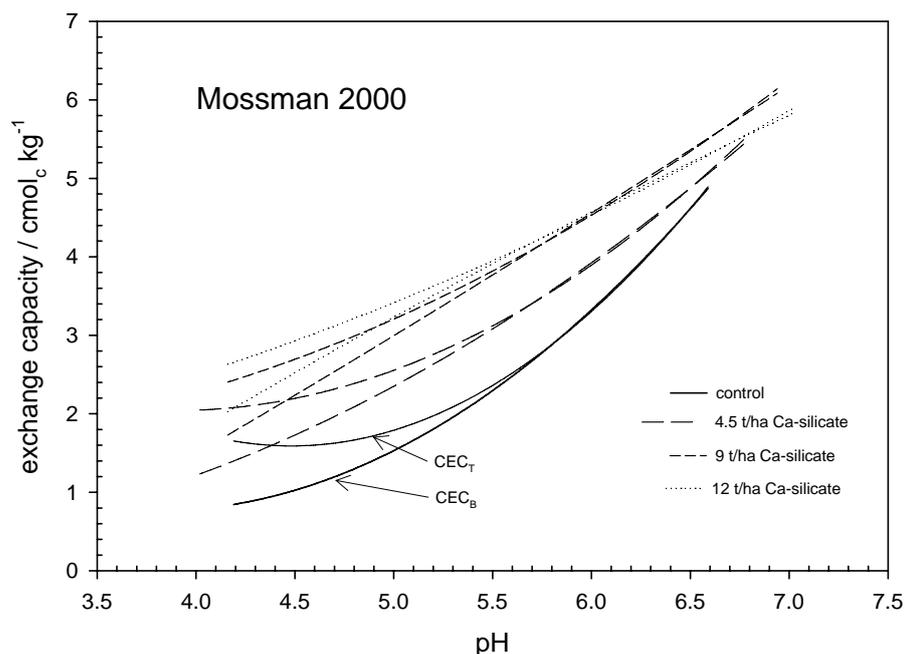


Figure 8.6. Surface charge fingerprints showing CEC_B and CEC_T for the 0 – 10 cm increment for the composite samples from the 0 – 10 cm increment from the control, 4.5 t/ha, 9 t/ha and 12 t/ha Ca-silicate treatments from the Mossman for year 2000.

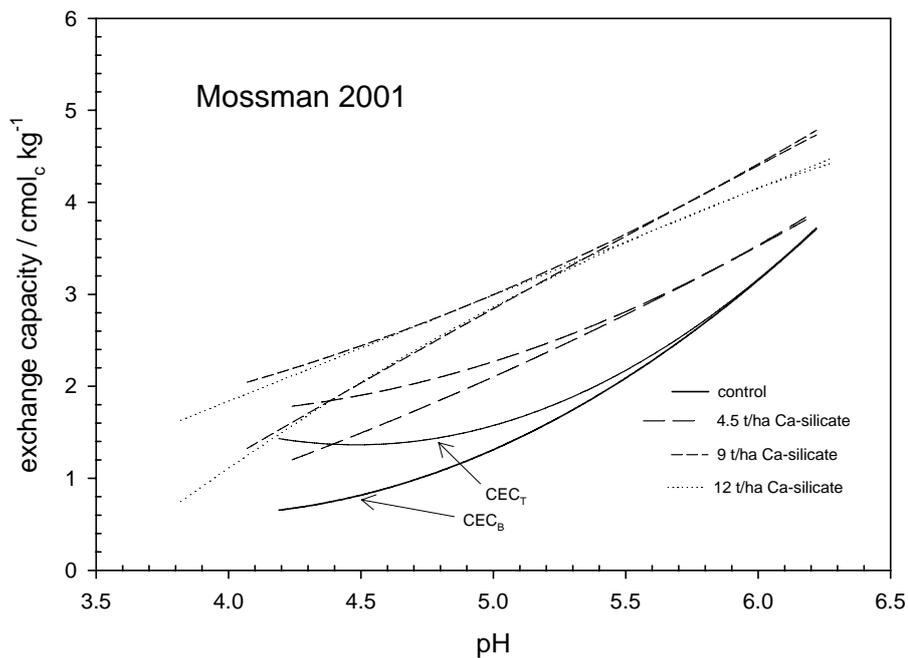


Figure 8.7. Surface charge fingerprints showing CEC_B and CEC_T for the 0 – 10 cm increment for the composite samples from the 0 – 10 cm increment from the control, 4.5 t/ha, 9 t/ha and 12 t/ha Ca-silicate treatments from the Mossman for year 2001.

Table 8.10 Changes in charge characteristics, CEC_T, CEC_B, AEC, pH₀ and the proportion of permanent and variable charge components due to additions of Ca-silicate, at the Innisfail and Mossman sites, after one (year 2000) and two (year 2001) years.

INNISFAIL 2000

| t/ha Ca-silicate | pH ₀ | CEC _T at pH ₀ | AEC at pH ₀ | permanent charge (CEC _T - AEC) | increase in permanent charge | soil pH | CEC _B soil pH | increase in CEC _B at soil pH | variable charge soil pH | CEC _B at pH _{5.5} | increase in CEC _B at pH _{5.5} | variable charge at pH _{5.5} |
|------------------|-----------------|-------------------------------------|------------------------|---|------------------------------|---------|--------------------------|---|-------------------------|---------------------------------------|---|--------------------------------------|
| | | cmol/kg | | | | | cmol/kg | | | cmol/kg | | |
| 0 | 4.45 | 0.895 | 0.372 | 0.523 | | 4.980 | 1.332 | | 0.809 | 2.389 | | 1.866 |
| 4.5 | 4.42 | 1.062 | 0.387 | 0.674 | 0.151 | 5.410 | 2.537 | 1.205 | 1.863 | 2.724 | 0.335 | 2.050 |
| 9 | 4.24 | 1.195 | 0.347 | 0.848 | 0.325 | 5.830 | 4.126 | 2.794 | 3.278 | 3.434 | 1.044 | 2.586 |
| 12 | 4.24 | 1.242 | 0.313 | 0.929 | 0.405 | 6.010 | 5.129 | 3.797 | 4.200 | 3.843 | 1.454 | 2.914 |

INNISFAIL 2001

| t/ha Ca-silicate | pH ₀ | CEC _T at pH ₀ | AEC at pH ₀ | permanent charge (CEC _T - AEC) | increase in permanent charge | soil pH | CEC _B soil pH | increase in CEC _B at soil pH | variable charge soil pH | CEC _B at pH _{5.5} | increase in CEC _B at pH _{5.5} | variable charge at pH _{5.5} |
|------------------|-----------------|-------------------------------------|------------------------|---|------------------------------|---------|--------------------------|---|-------------------------|---------------------------------------|---|--------------------------------------|
| | | cmol/kg | | | | | cmol/kg | | | cmol/kg | | |
| 0 | 4.58 | 0.711 | 0.355 | 0.357 | | 4.830 | 0.925 | | 0.568 | 2.030 | | 1.673 |
| 4.5 | 4.5 | 1.040 | 0.342 | 0.698 | 0.341 | 5.330 | 2.050 | 1.125 | 1.351 | 2.349 | 0.320 | 1.651 |
| 9 | 4.37 | 0.806 | 0.393 | 0.413 | 0.056 | 5.550 | 2.542 | 1.618 | 2.129 | 2.438 | 0.409 | 2.025 |
| 12 | 4.24 | 0.744 | 0.399 | 0.345 | -0.012 | 5.850 | 3.888 | 2.963 | 3.543 | 3.043 | 1.013 | 2.698 |

MOSSMAN 2000

| t/ha Ca-silicate | pH ₀ | CEC _T at pH ₀ | AEC at pH ₀ | permanent charge (CEC _T - AEC) | increase in permanent charge | soil pH | CEC _B soil pH | increase in CEC _B at soil pH | variable charge soil pH | CEC _B at pH _{5.5} | increase in CEC _B at pH _{5.5} | variable charge at pH _{5.5} |
|------------------|-----------------|-------------------------------------|------------------------|---|------------------------------|---------|--------------------------|---|-------------------------|---------------------------------------|---|--------------------------------------|
| | | cmol/kg | | | | | cmol/kg | | | cmol/kg | | |
| 0 | 3.91 | 1.834 | 0.054 | 1.780 | | 5.010 | 1.542 | | -0.237 | 2.295 | | 0.515 |
| 4.5 | 3.84 | 2.033 | 0.109 | 1.923 | 0.144 | 5.380 | 2.897 | 1.355 | 0.974 | 3.083 | 0.788 | 1.160 |
| 9 | 3.77 | 2.128 | 0.070 | 2.058 | 0.279 | 5.720 | 4.115 | 2.572 | 2.056 | 3.770 | 1.475 | 1.711 |
| 12 | 3.77 | 2.310 | 0.108 | 2.203 | 0.423 | 6.020 | 4.598 | 3.056 | 2.395 | 3.916 | 1.622 | 1.714 |

MOSSMAN 2001

| t/ha Ca-silicate | pH ₀ | CEC _T at pH ₀ | AEC at pH ₀ | permanent charge (CEC _T - AEC) | increase in permanent charge | soil pH | CEC _B soil pH | increase in CEC _B at soil pH | variable charge soil pH | CEC _B at pH _{5.5} | increase in CEC _B at pH _{5.5} | variable charge at pH _{5.5} |
|------------------|-----------------|-------------------------------------|------------------------|---|------------------------------|---------|--------------------------|---|-------------------------|---------------------------------------|---|--------------------------------------|
| | | cmol/kg | | | | | cmol/kg | | | cmol/kg | | |
| 0 | 3.97 | 1.566 | 0.119 | 1.447 | | 4.930 | 1.226 | | -0.221 | 2.092 | | 0.645 |
| 4.5 | 3.86 | 1.690 | 0.099 | 1.591 | 0.144 | 5.310 | 2.517 | 1.291 | 0.926 | 2.782 | 0.690 | 1.191 |
| 9 | 3.75 | 1.789 | 0.090 | 1.699 | 0.251 | 5.650 | 3.869 | 2.643 | 2.171 | 3.637 | 1.545 | 1.938 |
| 12 | 3.64 | 1.426 | 0.064 | 1.362 | -0.085 | 5.820 | 3.951 | 2.725 | 2.589 | 3.562 | 1.470 | 2.200 |

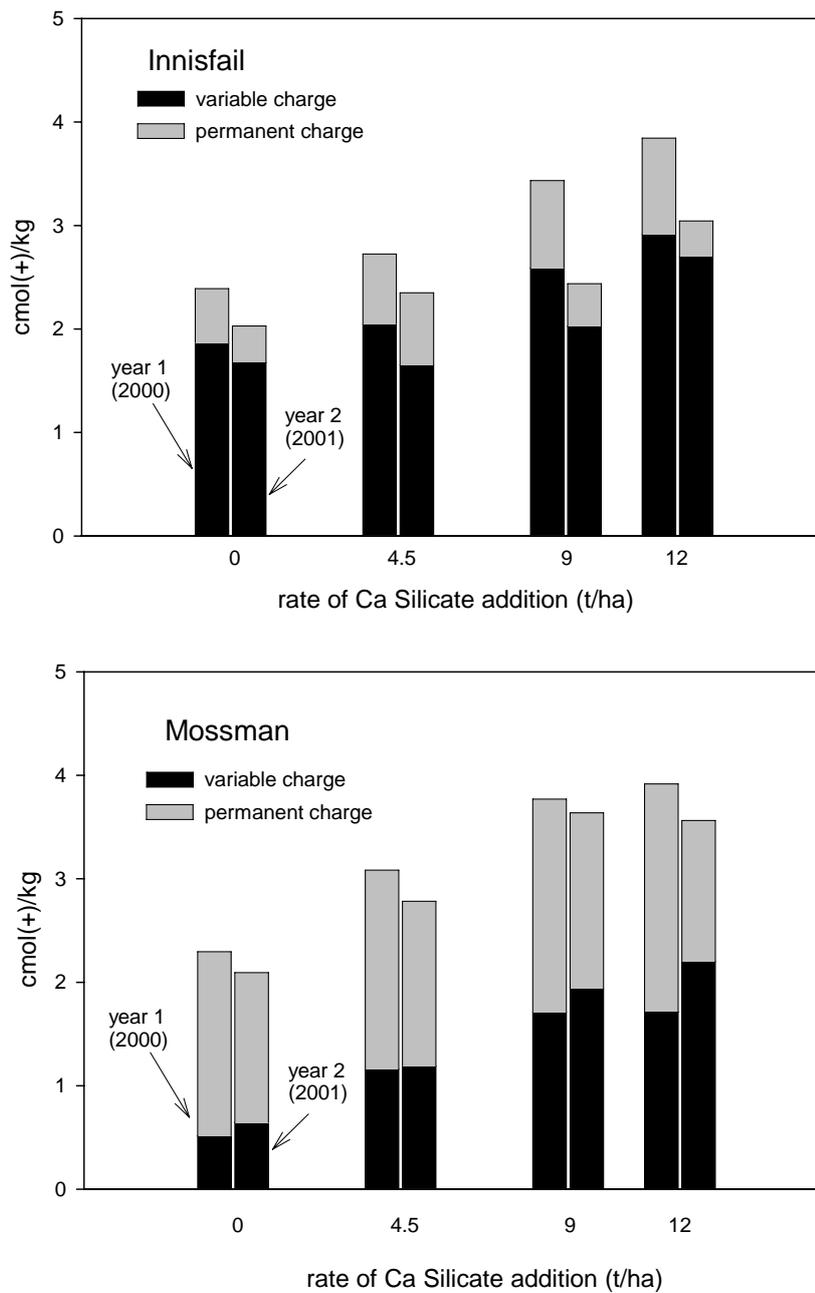


Figure 8.8. Changes in the 'variable' and 'permanent' charge components of the CEC generated in the surface 0-10cm following additions of Ca-silicate, at Innisfail and Mossman, measured after the plant crop (2000) and after the first ratoon (2001).

At Innisfail, it can be seen that although the addition of 2.5 t/ha “Blend 3” resulted in a significant increase in pH in the control plots in the first year, this pH increase has not had any effect on increasing CEC. At Mossman, where there was no extra addition of a liming material at the initiation of the trial, the control plots show neither a change in soil pH or CEC in the first year. Thus, increases in CEC are only associated with additions of calcium silicate. The readily soluble fraction of the calcium silicate has had some effect on soil pH and soil Ca and Si concentrations. An acid/base balance (Table 8.12) indicates there is a large amount of excess alkalinity which cannot be accounted for by that needed to increase soil pH, pH buffer capacity or crop removal. It is suggested that this alkalinity is “residual alkalinity” and represents the slowly soluble fraction of the calcium silicate, which in itself is contributing to increased surface charge.

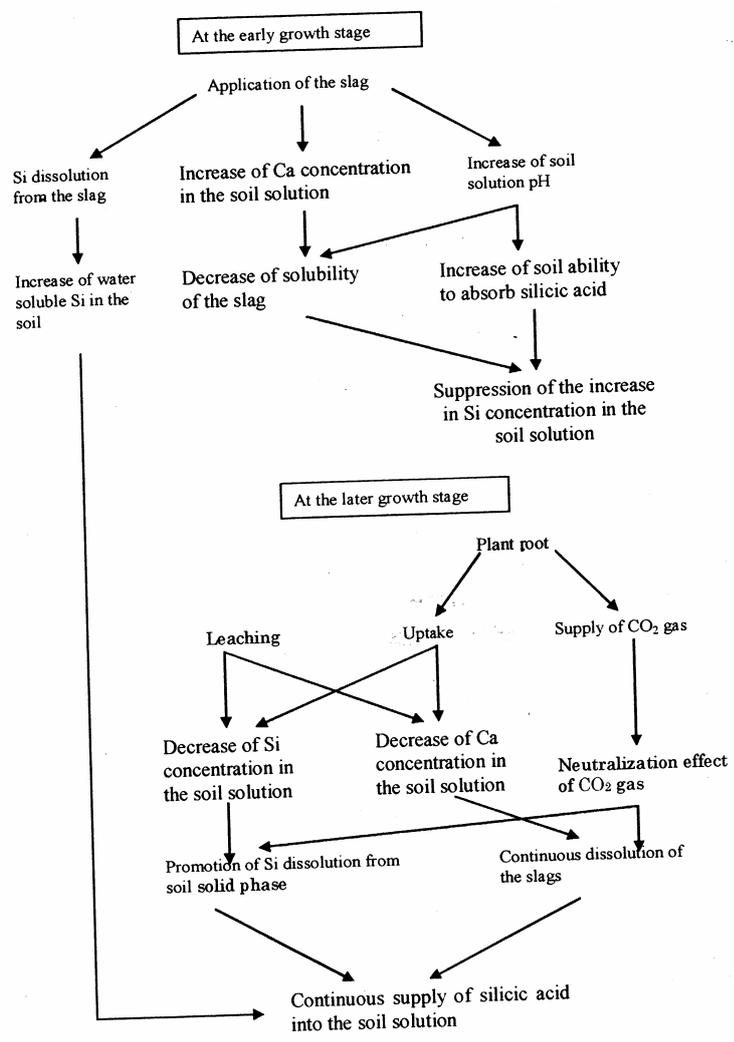
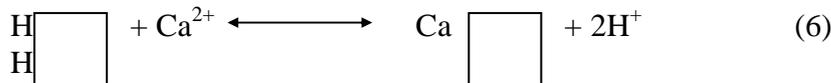
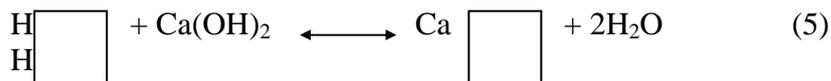
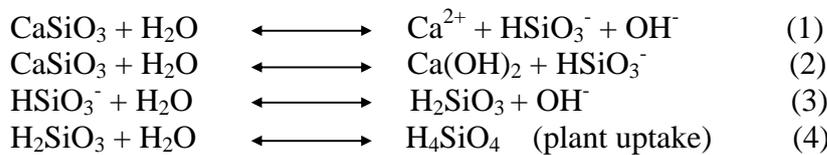


Figure 8.9. Possible reactions occurring in the soil following additions of calcium silicate slag (from Kato and Owa, 1997a).

It is generally accepted that calcium silicate slag contains a readily released fraction and a slowly released fraction (Kato and Owa, 1997a). Figure 8.9 illustrates the possible soil reactions following slag application. The initial increase in pH and Ca concentration in the soil solution may depress the continuous dissolution of the slag. Consequently the excess alkalinity (Table 8.12) attributed to the input of calcium silicate is not in reality immediately available.

As the calcium silicate slowly reacts to produce mono silicic acid (H₄SiO₄) for plant uptake (reactions 1 to 4), the Ca²⁺ and Ca(OH)₂ resulting from the reaction will be continuously absorbed onto the soil colloids (reactions 5 and 6). The hydroxylated surfaces present in the soil will release protons, gradually making the system more acid. As the soil pH decreases from these reactions Si dissolution from the slag in the soil is enhanced (Figure 8.9).



It is suggested that the increase in CEC observed is due to a combination of factors. Firstly, the introduction of the Si anion has directly provided more negative charge onto the colloid surface, resulting in a decrease in pH; secondly, as soil pH increases the magnitude of the net surface charge increases, as demonstrated by the “pH – pHo” values (Table 8.11); and thirdly, the slowly soluble forms of calcium silicate (as represented by the ‘excess alkalinity’ (Table 8.12)) are directly providing charge, as they forming amorphous structures and gels. As described by Drees *et al.* (1989), carbonates or metal hydroxides (Mg, Fe, Al, Mn) may act as templates or catalysts to initiate condensation reactions of Si polymers, which may then act as reactive sites for further Si precipitation (Figure 8.10 and 8.11). These reactions result in the formation of negatively charged, open-frame-work Si polymers. The difference between precipitates and the stable crystalline gels is the degree of strength of packing in the aggregates (Mitchell, 1975).

Table 8.11. Changes in pH₀ and the difference between pH₀ and soil pH as a result of Ca-silicate additions at the Innisfail and Mossman sites, after one (year 2000) and two (year 2001) years

| Rate t/ha | Innisfail 2000 | | | Innisfail 2001 | | |
|-----------|-----------------|---------|----------------------|-----------------|---------|----------------------|
| | pH ₀ | soil pH | pH - pH ₀ | pH ₀ | soil pH | pH - pH ₀ |
| 0 | 4.45 | 4.98 | 0.53 | 4.58 | 4.83 | 0.25 |
| 4.5 | 4.42 | 5.41 | 0.99 | 4.5 | 5.33 | 0.83 |
| 9 | 4.24 | 5.83 | 1.59 | 4.37 | 5.55 | 1.18 |
| 12 | 4.24 | 6.01 | 1.77 | 4.24 | 5.85 | 1.61 |

| Rate t/ha | Mossman 2000 | | | Mossman 2001 | | |
|-----------|-----------------|---------|----------------------|-----------------|---------|----------------------|
| | pH ₀ | soil pH | pH - pH ₀ | pH ₀ | soil pH | pH - pH ₀ |
| 0 | 3.91 | 5.01 | 1.1 | 3.97 | 4.93 | 0.96 |
| 4.5 | < 3.91 | 5.38 | 1.54* | < 3.97 | 5.31 | 1.45* |
| 9 | < 3.91 | 5.72 | 1.95* | < 3.97 | 5.65 | 1.9* |
| 12 | < 3.91 | 6.02 | 2.32* | < 3.97 | 5.82 | 2.18* |

* value for (pH - pH₀) determined assuming that the change in pH₀ with increasing rates of Ca-Silicate additions for the Mossman soils decreased at the same rate as for the Innisfail soils

As CEC is not a fixed quantity but varies with soil pH, it is probably more meaningful to compare treatments at one pH, rather than soil pH, to determine if any observed increase in charge is a real effect due to amendment addition or merely a consequence of changes in pH. At pH of 5.5, Al³⁺ should be effectively eliminated from the exchange complex, and any change in CEC should not be influenced by the percent of acid saturation of the exchange complex in soils that have a high reserve acidity (Menzies and Gillman, 1997). Therefore, using a nominal pH of 5.5, at Innisfail, the CEC increased by 1.45 cmol_c/kg with the application of 12 t/ha Ca-silicate compared to the control in the first year, and by 1.01 cmol_c/kg in the second year. The corresponding increases in CEC at Mossman were 1.62 and 1.47 cmol_c/kg respectively. Over the 24 month period the charge generation associated with the highest Ca-silicate application was in the order of 1.0-1.62 cmol_c/kg. Assuming that the bulk density of the soil is 1200 kg/m³ this would equate to approximately 240-380 kg of Ca²⁺, 144-184 kg of Mg²⁺ or 470-750 kg of K⁺ that potentially could be retained on the exchange complex.

It is evident that at the higher rates of amendment addition not all of the calcium silicate has reacted with the soil exchange complex. A plot of the sum of bases (Ca+Mg+K+Na) with respect to the independently measured CEC_B (Figures 8.12 and 8.13) shows a divergence from the 1:1 line, particularly at the rates of 9 and 12 t/ha. However, by plotting CEC values of the charge fingerprint at pH 5.5 against the rate of Ca-silicate application, it was estimated that for every tonne of Ca-silicate applied, CEC increased by approximately 0.15 cmol_c/kg (Figure 8.14). This charge generation could contribute significantly to the overall nutrient holding capacity of the soil and therefore productivity. Although the responses in yield to silicate amelioration are

predominantly ascribed to enhanced Si availability, the enhanced shift in CEC would influence these responses in a positive manner.

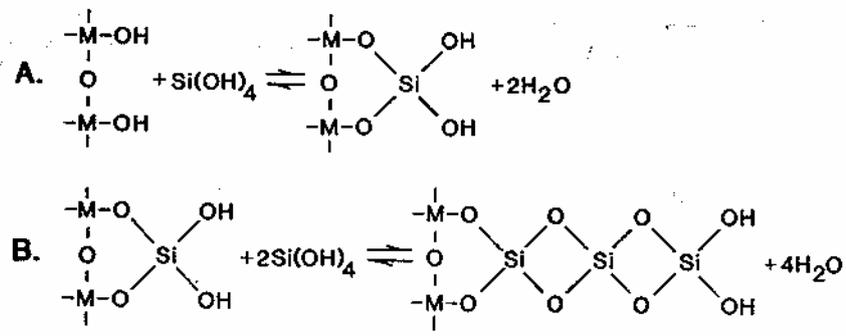


Figure 8.10. Condensation and precipitation reactions of Si polymers (Drees *et al.*, 1989)

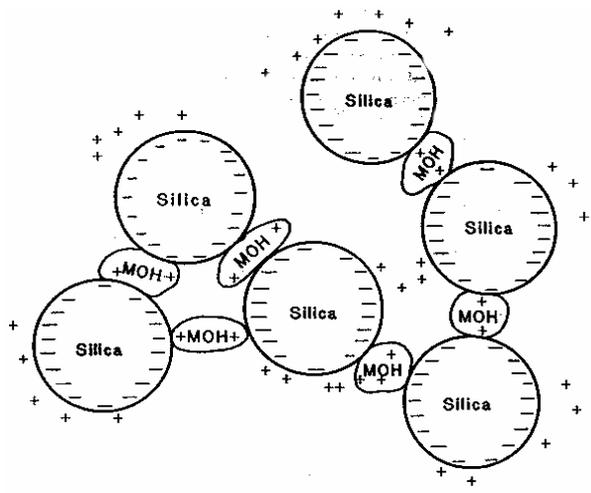


Figure 8.11. Flocculation of Si polymorphs by formation of positively charged metal hydroxide ions (MOH+) (Drees *et al.*, 1989).

Table 8.12. The 'excess alkalinity' and CEC (cmol/kg) measured with the charge fingerprint and through an independent assessment at the initiation of the experiment and at the end of the plant crop in 2000 for the Innisfail and Mossman sites.

| Site | Treatment | cmol (-)/kg | cmol(+)/kg | | | 1999 | | 2000 | | |
|-----------|-----------|--|---------------------------------------|--------------------------------------|---------------------------------------|---------|------------|---------|------------|---------------------------|
| | | "Reserve" alkalinity from calcium silicate additions | CEC _B (charge fingerprint) | Variable charge (charge fingerprint) | Permanent charge (charge fingerprint) | soil pH | cmol(+)/kg | soil pH | cmol(+)/kg | |
| | | | | | | | soil CEC | | soil CEC | sum cations (extractable) |
| Innisfail | control | 0.00 | 1.33 | 0.81 | 0.52 | 4.89 | 1.33 | 5.45 | 1.36 | 1.41 |
| 2000 | 4.5t/ha | 1.48 | 2.54 | 1.86 | 0.67 | 4.89 | 1.33 | 5.62 | 2.45 | 2.63 |
| | 9t/ha | 2.46 | 4.13 | 3.28 | 0.85 | 4.89 | 1.33 | 6.01 | 3.96 | 4.82 |
| | 12t/ha | 3.18 | 5.13 | 4.21 | 0.93 | 4.89 | 1.33 | 6.23 | 4.69 | 5.55 |
| Mossman | control | 0.00 | 1.54 | -0.24 | 1.78 | 5.14 | 1.88 | 5.00 | 1.58 | 0.91 |
| 2000 | 4.5t/ha | 0.69 | 2.90 | 0.97 | 1.92 | 5.14 | 1.88 | 5.81 | 3.06 | 3.30 |
| | 9t/ha | 2.79 | 4.12 | 2.06 | 2.06 | 5.14 | 1.88 | 5.66 | 4.20 | 5.20 |
| | 12t/ha | 3.54 | 4.60 | 2.40 | 2.20 | 5.14 | 1.88 | 5.99 | 4.53 | 5.80 |

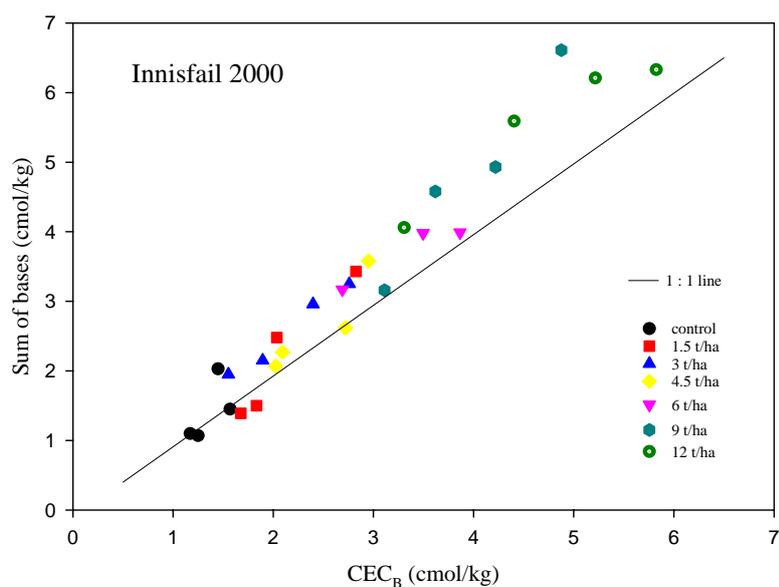


Figure 8.12. Relationship between CEC_B (cmol/kg) and sum of bases (cmol/kg) in the surface 0-10cm following additions of Ca-silicate, at Innisfail, measured after the plant crop (2000). The line represents the 1:1 line for the plot.

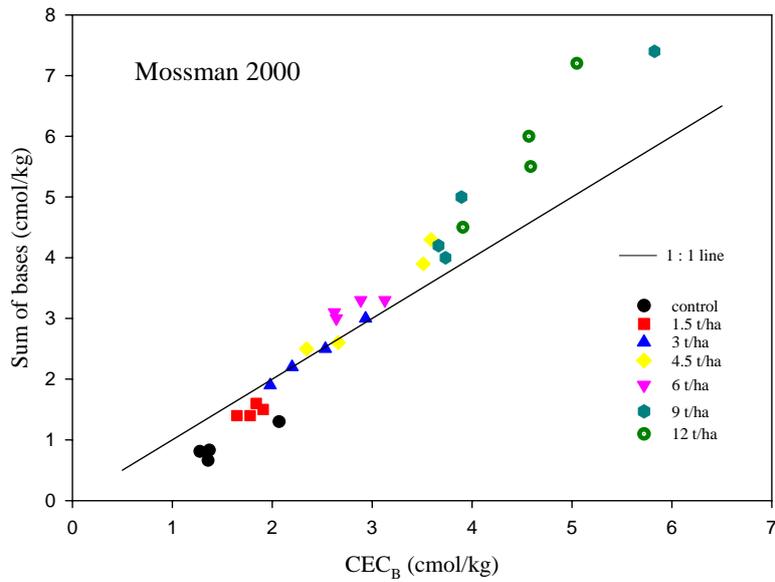


Figure 8.13. Relationship between CEC_B (cmol/kg) and sum of bases (cmol/kg) in the surface 0-10cm following additions of Ca-silicate, at Mossman, measured after the plant crop (2000). The line represents the 1:1 line for the plot.

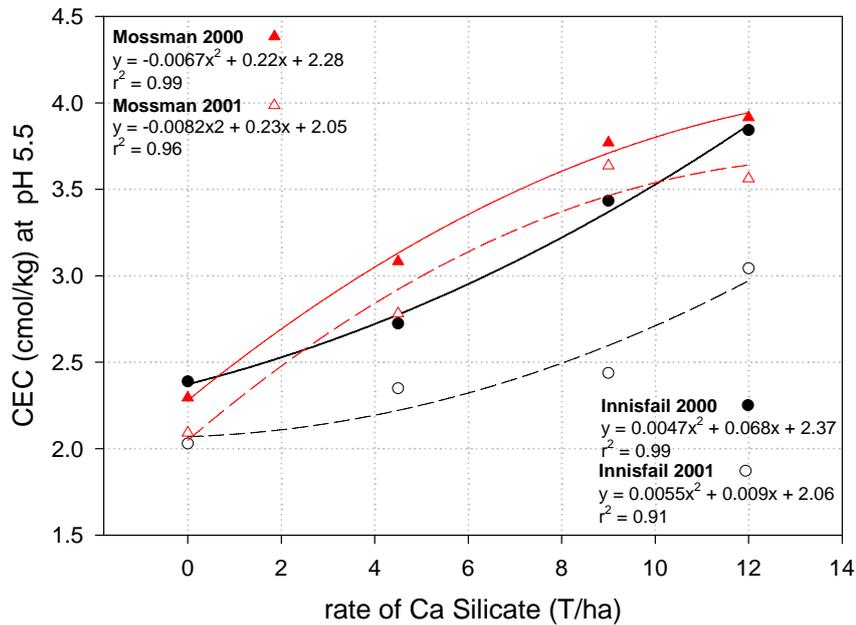


Figure 8.14. CEC generated in the surface 0-10cm following additions of Ca-silicate, at Innisfail and Mossman, measured after the plant crop (2000) and after the first ratoon (2001).

9. Silicate products used in agricultural production – Silicon product trials

Introduction

Initial research into silicon (Si) nutrition of sugarcane in Queensland was undertaken in the central region and on the wet tropical coast of north Queensland during the 1970's (Haysom and Chapman, 1975; Hurney, 1973). In most of these early studies cement was used as the Si source. It is of interest to note that observations of past liming trials have found that cement was generally a more reliable liming product than limestone (Ridge *et al.*, 1980). Kingston *et al.* (1996) reviewed past liming experiments across north and south Queensland, and concluded that from an economic perspective, maximum return was achieved by the cement treatments in 60 percent of the north Queensland sites. As cements can contain up to 20 percent Si, it has been suggested that as well as its high neutralising value, its magnesium content, and its effect on phosphorus availability, the silicate content was possibly a contributing factor.

Most products used for Si fertilization world-wide are by-products of various manufacturing processes. Generally, the high processing temperatures encountered in the processing release Si from tightly bound states resulting in increased solubility of the Si (Gascho, 2001). Silicon compounds in the ore react with limestone, leading to separation of calcium silicate, and Fe and other metals in the ore are reduced and separated (Ma and Takahashi, 2002). Calcium silicate slag, a by-product from the production of elemental P by reduction of phosphate rock with coke in electric arc furnaces is the major silicate slag fertilizer used in the rice and sugarcane industries in the USA, while by-product slags derived from the iron and alloy industries are used extensively for rice production in Japan. Slags can be variable in composition, and although have high concentrations of total Si, generally only a small proportion is easily solubilized (Gascho, 2001; Ma and Takahashi, 2002).

Although various by-product silicate slags dominate agricultural markets in many countries, and the benefits resulting from their application are well documented, availability and transport logistics mean that they are not necessarily the most economical source for use in all agricultural areas. Many other silicate sources such as Portland cement and lime kiln dust have been used effectively, but are often considered too expensive for wide-spread use. Soluble silicates such as sodium silicate and potassium silicates are effective for foliar applications and are used routinely in the greenhouse industry, but are generally uneconomical to use for the rates needed for soil application. Wollastonite, a naturally occurring calcium silicate mineral, has produced satisfactory research results, but its use is limited as there are few deposits found world-wide, while naturally occurring magnesium silicates are generally considered unsuitable due to their low solubility. Many other products have been researched, for example, mill furnace ashes, volcanic cinders, mini-granulated calcium silicate (produced by mixing cement with coral sand and binding with sodium oxide) and calcium silicate hydrate (a waste by-product of the building industry produced from quick lime, quartz and cement). Thermo-phosphate, made from a mixture of rock phosphate and magnesium silicate is used for phosphorus fertilization in Brazil is being trailed as a silicate source, as although its total Si content is

relatively low compared to basic- and calcium silicate slags, the soluble proportion is high (Gascho, 2001). Plant residues, particularly those emanating from high Si accumulating crops like sugarcane (bagasse and mill ash) and rice (hulls) are obvious silicate sources, but the application rates needed are very high.

Before any source can be considered useful for agricultural applications it must meet a number of criteria, such as solubility, availability, suitable physical properties and be free of, or have acceptably low levels of contaminants (Gascho, 2001). One of the most important criteria, and often the most difficult to achieve is solubility, as many natural sources are always combined with other elements and are largely insoluble. From a cost:benefit aspect, it is also important that the product is available at a reasonable distance from where it is required as generally large quantities of material are needed. Finding a silicate source that takes all these criteria into account demonstrates the difficulty of selecting a material suitable for agricultural purposes.

Ca-silicate slag, a by-product phosphorus furnace slag obtained from Rhodia Inc., was used as a 'control' silicate material in all the field trials established as part of this project, and used for the 3 major 'Rate' trials established at Mossman, Innisfail and Bundaberg. It was recognized from the out-set of the project, that positive and significant responses to cane yield as a result of these calcium silicate additions would necessitate the recommendation of readily available and economical sources of silicate material that preferably were available locally. In the 'Product' trials a number of different sources of Si were evaluated. These studies focused on easily accessible products that were available at the time. The products used included mill ash, mud ash, cement, cement building board by-product, rock dust, and two imported Ca-silicate slags (products A from Rhodia Inc, and Product B from Calcium Silicate Corp.).

As the project progressed, and other potential silicate materials were identified, additional "Add-on Product trials" were established in the Tully and Bundaberg districts. These trials included a wide range of silicate materials including acidulated olivine ('Silvine'), partially acidulated serpentine ('Dunnite'), various diatomaceous earths, lime kiln dust and thermo phosphate (Cal Phos). In addition, some of these additional trials examined product placement (broadcast versus banding).

Results and Discussion

Product Trials

Details of the trial design, soil and plant sampling techniques and soil chemical methodology are detailed in the Methodology section, but are briefly described here for convenience. In the 3 major "product trials" established at Mossman, Innisfail and Bundaberg in 1999, the rates of application were 0, 3 and 6 t/ha except for mill and mud ash. With these products, 25 and 50 t/ha (dry weight) of both the mill ash and mud ash were applied at Bundaberg, while rates of 30 and 60 t/ha (dry weight) of mill ash were used at Mossman. All treatments were broadcast and incorporated into the top 10 - 20 cm using an off-set disc plough or rotary hoe.

Soil samples were collected prior to the imposition of treatments from all control plots to a depth of 90 cm. Initial soil chemical properties for each of the trial sites prior to

the implementation of treatments are presented in Table 4.1. At the end of the first growing season soil samples were collected from all treatments for chemical analysis. Leaf samples were collected from the top visible dewlap (TVD) from all treatments approximately 7 months after the establishment of the trials. An interim yield sample was undertaken 8 months after planting at all sites. In addition to the interim yield assessment at 8 months, final harvest yields were undertaken at all sites using a weighing machine. The Innisfail trial was only sampled in the first year due to poor growth in the ratoon crop resulting from severe cane grub infestation, while further harvests were undertaken in the ratoon crop at both Mossman and Bundaberg.

Prior to the initiation of the field trials, samples from selected sources of Si were compared using total elemental analysis (using X-ray fluorescent analysis (XRF)). The results showed a range of Si contents (Table 9.1). In this respect cement contained 10% Si whilst mill ash had approximately 40%, with most of the other products being intermediate between these two. The Ca-silicate slags and cement contained between 30% to 45% calcium (Ca^{2+}), while the other products contained less than 10%. Crushed basalt had higher levels of magnesium (Mg^{2+}) and potassium (K^+) compared to all the other products. These results represent the total quantities of elements present and do not necessarily reflect the amounts available for plant uptake.

Table 9.1. Analytical data of the Si concentration from a range of products using different extraction methods.

| Source | XRF | UFL | Citric acid | Method 1 | Method 2 | Method 3 |
|-----------------------------------|-------|------|-------------|----------|----------|----------|
| | % | % | % | mg/kg | mg/kg | mg/kg |
| Calcium silicate slag (Product B) | 20.97 | 3.29 | 5.13 | 241 | 294 | 210 |
| Cement | 9.78 | 2.31 | 5.62 | 43 | 37 | 276 |
| CalPhos | 13.28 | 0.7 | 4.15 | 636 | 92 | 89 |
| Mill Ash | 42.63 | 0.15 | 0.34 | 1054 | 924 | 727 |
| Mud/ash heap | 27.87 | 0.2 | 0.19 | 208 | 195 | 172 |
| Mud/ash mill | 39.09 | 0.14 | 0.16 | 230 | 267 | 223 |
| Hi-Yield (building by-product) | 30.55 | 0.79 | 3.42 | 377 | 516 | 834 |
| Gypsum silicate | 7.48 | 0.2 | 0.09 | 295 | 377 | 341 |
| Concrete wash CSR | 31.88 | 0.72 | 3.14 | 219 | 25 | 517 |
| Concrete wash Pioneer | 34.05 | 0.79 | 2.74 | 136 | 17 | 432 |
| Pink gypsum | 12.93 | 0.16 | 0.06 | 60 | 120 | 93 |
| Min-Plus (crushed basalt) | 21.14 | 0.14 | 2.49 | 174 | 107 | 231 |

Methods:

1. Shaking samples in a 0.01 M CaCl_2 matrix for 24 hour;
2. Continual infusion (in 0.01 M CaCl_2 matrix) over a 72 hour period with periodic sampling at 4,11,22,48 and 72 hours
3. Sequential infusion, with the solution (0.01 M CaCl_2) being replaced after each sampling at 4,20,40,and 72 hours

Table 9.2. Millable stalks harvested (t/ha) from the ‘product assessment’ trials at Mossman, Innisfail and Bundaberg, 8 months after establishment and at final harvest.

| Product | Interim harvest at 8 months | | | Final harvest | | |
|--|-------------------------------|------|------|---------------|------|------|
| | Rate (t/ha) | | | Rate (t/ha) | | |
| | 0 | 3 | 6 | 0 | 3 | 6 |
| <i>Mossman</i> | Millable stalks (t/ha) | | | | | |
| 1. Untreated control | 42.4 | | | 43.3 | | |
| 2. Calcium silicate slag(A) | | 65.7 | 63.8 | | 63.2 | 60.5 |
| 3. Calcium silicate slag (B) | | 55.0 | 50.4 | | 53.7 | 47.6 |
| 4. Cement | | 64.0 | 66.7 | | 56.5 | 57.6 |
| 5. By-product from cement building board manufacture | | 53.1 | 51.3 | | 41.1 | 50.2 |
| 6. crushed basalt | | 39.2 | 48.8 | | 42.5 | 44.0 |
| 7. Mill ash* | | 60.5 | 64.5 | | 45.3 | 53.8 |
| LSD_(0.05) | 14.7 | | | 7.9 | | |
| <i>Innisfail</i> | | | | | | |
| 1. Untreated control | 63.5 | | | 60.1 | | |
| 2. Calcium silicate slag (A) | | 78.5 | 75.7 | | 71.4 | 76.7 |
| 3. Calcium silicate slag (B) | | 74.3 | 74.8 | | 73.7 | 69.3 |
| 4. Cement | | 67.3 | 77.0 | | 63.6 | 68.2 |
| 5. By-product from cement building board manufacture | | 75.2 | 74.2 | | 66.7 | 60.4 |
| 6. Crushed basalt | | 70.6 | 69.2 | | 62.7 | 61.1 |
| LSD_(0.05) | ns | | | ns | | |
| <i>Bundaberg</i> | | | | | | |
| 1. Untreated control | 73.3 | | | 83.9 | | |
| 2. Calcium silicate slag (A) | | 86 | 73.2 | | 87.6 | 88.5 |
| 3. Calcium silicate slag (B) | | 79.4 | 83.9 | | 89.9 | 88.3 |
| 4. Cement | | 82.7 | 88.9 | | 88.9 | 92.8 |
| 5. By-product from cement building board manufacture | | 83.3 | 78.1 | | 86.8 | 88.4 |
| 6. Mill ash* | | 78.2 | 99.5 | | 78.6 | 87.8 |
| 7. Mud/ash* | | 95.7 | 97 | | 91.6 | 97.4 |
| LSD_(0.05) | ns | | | ns | | |

* Applied at 30 and 60 t/ha (dry weight) at Mossman, and at 25 and 50 t/ha (dry weight) at Bundaberg.

Samples were sent to the University of Florida (UFL) for further assessment using a continuous leaching method established at their laboratory for determining availability of Si for plant uptake (Snyder, 2001). The samples were also assessed at Davies Laboratory, Townsville, using ‘shaking and ‘infusion’ tests to determine the relative solubility of Si in each of the products (Table 9.1). The results generally

indicated that the Ca-silicate slags, cement, and to a lesser extent, the cement building board by-product (Hi-Yield) had the highest levels of soluble Si. However, these early tests highlighted a problem that is discussed in more detail in this report, that most laboratory chemical extraction methods show little commonality with respect to the amounts of Si extracted.

Table 9.3. Readily soluble and acid extractable soil Si concentrations (mg/kg) at Mossman, Innisfail and Bundaberg following the application of various Si products.

| Silicate Product | Rate (t/ha) | Mossman | | Innisfail | | Bundaberg | |
|-------------------------|-------------|--------------------|----------------------|--------------------|----------------------|--------------------|----------------------|
| | | soluble Si (mg/kg) | acid ext. Si (mg/kg) | soluble Si (mg/kg) | acid ext. Si (mg/kg) | soluble Si (mg/kg) | acid ext. Si (mg/kg) |
| Control | 0 | 2.5 | 17 | 7.3 | 60 | 7.9 | 54 |
| Ca-silicate slag (A) | 3 | 3.1 | 42 | 13.1 | 102 | 15.4 | 123 |
| | 6 | 4.6 | 39 | 16.7 | 112 | 20.8 | 213 |
| Ca-silicate slag (B) | 3 | 3.8 | 26 | 10.6 | 91 | 8.2 | 63 |
| | 6 | 3.6 | 69 | 15.0 | 124 | 8.3 | 74 |
| Cement | 3 | 3.2 | 19 | 11.7 | 97 | 13.6 | 126 |
| | 6 | 4.6 | 50 | 15.4 | 185 | 15.6 | 151 |
| Cement board by-product | 3 | 2.1 | 26 | 9.3 | 79 | 9.3 | 81 |
| | 6 | 3.6 | 40 | 10.8 | 79 | 12.1 | 93 |
| Crushed basalt | 3 | 3.8 | 23 | 8.3 | 102 | n.a. | n.a. |
| | 6 | 2.9 | 75 | 10.4 | 130 | n.a. | n.a. |
| Millash | 25 | 2.5 | 27 | n.a. | n.a. | 8.2 | 89 |
| | 50 | 4.9 | 44 | n.a. | n.a. | 6 | 73 |
| Mud/ash | 25 | n.a. | n.a. | n.a. | n.a. | 9.3 | 72 |
| | 50 | n.a. | n.a. | n.a. | n.a. | 10.6 | 90 |
| CalPhos | 300 kg/ha | n.a. | n.a. | n.a. | n.a. | 5.4 | 55 |
| | 600 kg/ha | n.a. | n.a. | n.a. | n.a. | 9.5 | 60 |
| LSD(0.05) | | 1.4 | 37.0 | 3.5 | 38 | 3.7 | 72 |

At the interim harvest, significant increases in millable stalks yields were recorded with several Si products at the Mossman site (Table 9.2). Highly significant responses were obtained with both rates (3 and 6 t/ha) of Ca-silicate slag (A), cement and millash. The cane yield increases for these three treatments were on average 23 t/ha greater than the control treatment, equating to approximately a 53% increase in yield. Ground basalt dust was the exception, having no effect on yield at 6 t/ha and a slight decrease at 3 t/ha. Measurements made at 8 months indicated that significant differences in both plant height and stalk weight were responsible for yield increases at Mossman. The early positive responses to various silicate amendments at Mossman were continued through to harvest where highly significant increases in both cane and sugar yield were recorded (Table 9.2).

Although the responses at Innisfail and Bundaberg were not significant, the yield trends observed between products at Mossman were also evident at these two sites (Table 9.2). The products trial at Bundaberg had moderate to severe orange rust disease and the Innisfail site was affected by cane grub damage, these undoubtedly influenced final yields. Despite this, yield increases were still substantial and probably of economic significance. At Innisfail the Ca-silicate and cement treatments yielded approximately 12 t/ha more than the control, equating to a 20% increase in cane yield. While at Bundaberg the increases in cane yield were 11, 16 and 27 t/ha for the Ca-silicate, cement and millash treatments, equating to a 15, 22 and 37% increase compared to the control treatment, respectively.

Table 9.4. Soil pH (water) and exchangeable soil Ca concentrations (mg/kg) at Mossman, Innisfail and Bundaberg following the application of various Si products.

| Silicate Product | Rate (t/ha) | Mossman | | Innisfail | | Bundaberg | |
|-------------------------|-------------|------------|-------------------------|------------|-------------------------|------------|-------------------------|
| | | pH (water) | exchangeable Ca (mg/kg) | pH (water) | exchangeable Ca (mg/kg) | pH (water) | exchangeable Ca (mg/kg) |
| Control | 0 | 5.43 | 1.10 | 5.05 | 0.65 | 6.79 | 1.94 |
| Ca-silicate slag (A) | 3 | 5.42 | 2.22 | 5.26 | 1.18 | 7.51 | 2.87 |
| | 6 | 5.96 | 3.70 | 5.31 | 1.97 | 8.09 | 3.96 |
| Ca-silicate slag (B) | 3 | 5.53 | 1.95 | 5.09 | 0.96 | 6.80 | 2.10 |
| | 6 | 5.69 | 2.49 | 5.37 | 1.81 | 7.20 | 2.48 |
| Cement | 3 | 5.84 | 3.30 | 5.62 | 2.23 | 8.31 | 4.45 |
| | 6 | 5.88 | 5.02 | 5.85 | 3.98 | 8.59 | 5.50 |
| Cement board by-product | 3 | 5.48 | 1.16 | 5.18 | 0.98 | 7.39 | 3.12 |
| | 6 | 5.45 | 1.71 | 5.12 | 0.80 | 7.46 | 2.62 |
| Crushed basalt | 3 | 5.3 | 1.18 | 5.13 | 0.75 | n.a. | n.a. |
| | 6 | 5.45 | 1.20 | 5.18 | 0.75 | n.a. | n.a. |
| Millash | 25 | 5.62 | 1.12 | n.a. | n.a. | 6.84 | 1.78 |
| | 50 | 5.74 | 1.12 | n.a. | n.a. | 6.84 | 1.82 |
| Mud/ash | 25 | n.a. | n.a. | n.a. | n.a. | 6.83 | 2.32 |
| | 50 | n.a. | n.a. | n.a. | n.a. | 6.93 | 2.41 |
| CalPhos | 300 kg/ha | n.a. | n.a. | n.a. | n.a. | 6.56 | 1.59 |
| | 600 kg/ha | n.a. | n.a. | n.a. | n.a. | 7.07 | 2.51 |
| LSD(0.05) | | 0.42 | 0.66 | 0.28 | 0.99 | 0.45 | 0.76 |

Chemical analysis of the soils collected at harvest of the plant crop tended to reflect the chemical composition and Si solubility of the various products, as generally there was a significant increase in both 0.01 M CaCl₂ (soluble Si) and acid extractable Si in the Ca-silicate slags and cement treatments when compared to the control (Table 9.3). The results clearly demonstrate the interaction of soil type in determining the final concentration of available soil Si. Regardless of product type or rate of application, the sandy soil at Mossman had much lower levels of available and extractable Si compared to Innisfail and Bundaberg. The difference in soil reaction between the two calcium silicate slags is also noteworthy as both are by-product furnace slags from the production of elemental P, but differ due to the original source of rock phosphate used in the production process. The Ca-silicate slags, cement and cement building board by-product also significantly increased the exchangeable Ca²⁺ levels and soil pH (Table 9.4), whereas crushed basalt and mill ash increased the concentration of

exchangeable Mg^{2+} and K^+ (data not shown). Although the cement treatment was the most comparable treatment to the two slag treatments, in providing available Si, Ca and adjusting pH, its higher reactivity compared to the slags suggest that lower rates of application would be more applicable.

Plant analysis of the TVD leaf sampled at approximately 7 months (Table 9.5) demonstrated that most of the products resulted in an increase in Si uptake by the plant, particularly at the higher application rate of 6 t/ha. At Mossman the Si concentration in the TVD leaf was significantly greater in both slag treatments, and also at the higher application rate of mill ash. At both Innisfail and Bundaberg, the two Ca-silicate slag treatments and the cement resulted in significantly higher concentrations of Si compared to the control. A comprehensive elemental analysis of the TVD leaf from the highest application rate (6 t/ha) of each treatment at Mossman, Innisfail and Bundaberg trials are presented in Table 9.6, 9.7 and 9.8 respectively. Although the various treatments had an effect on the chemical status of the soil, in particular Ca, Mg and K, this was not evident in uptake levels in the plant. In general, there was no significant effect on any other nutrient except Si as a result of the treatments. In addition, with the exception of phosphorus (P) and sulfur (S), which had concentrations slightly below the recommended critical levels at the Mossman site only (Reuter and Robinson, 1997), all other nutrient elements were present at adequate concentrations. It is interesting to observe that in this first year, the Mossman trial was the only trial that exhibited significant crop responses to the various silicate products despite the soil and plant concentrations resulting from the treatment additions being considerably lower than at the other two sites.

Table 9.5. Concentration of Si (%) in the top visible dewlap (TVD) leaf, at approximately 7 months in response to varying rates of silicate products in trials at Mossman, Innisfail and Bundaberg

| Silicate Product | | % Si TVD leaf | | |
|-----------------------------|----------|---------------|-----------|-----------|
| | | Mossman | Innisfail | Bundaberg |
| Control | | 0.19 | 0.40 | 0.41 |
| Ca-silicate slag (A) | 3 t/ha | 0.39 | 0.63 | 0.58 |
| | 6 t/ha | 0.52 | 0.70 | 0.66 |
| Ca-silicate slag (B) | 3 t/ha | 0.42 | 0.54 | 0.50 |
| | 6 t/ha | 0.60 | 0.63 | 0.61 |
| Cement | 3 t/ha | 0.18 | 0.57 | 0.47 |
| | 6 t/ha | 0.26 | 0.59 | 0.53 |
| Cement board by-product | 3 t/ha | 0.26 | 0.43 | 0.49 |
| | 6 t/ha | 0.36 | 0.48 | 0.42 |
| Crushed basalt | 3 t/ha | 0.26 | 0.51 | na |
| | 6 t/ha | 0.36 | 0.45 | na |
| Millash | 25 t/ha* | 0.34 | na | 0.38 |
| | 50 t/ha* | 0.53 | na | 0.45 |
| Mud/ash | 25 t/ha | na | na | 0.44 |
| | 50 t/ha | na | na | 0.51 |
| LSD_(0.05) | | 0.14 | 0.15 | 0.11 |

* Applied at 30 and 60 t/ha (dry weight) at Mossman, and at 25 and 50 t/ha (dry weight) at Bundaberg.

Table 9.6. Concentration of plant nutrients (TVD leaf), determined using XRF, sampled at approximately 7 months, in response to various products in the 'product assessment' trial at Mossman.

| Plant nutrient (TVD leaf, 7 months) | Silicate product (6 t/ha) | | | | | | | LSD _(0.05) | Critical level* |
|---|---------------------------|-----------------------------|-----------------------------|--------|--|-------------------|---------------|-----------------------|--------------------|
| | Control | Ca- silicate slag (A) | Ca- silicate slag (B) | Cement | Cement building board by- product | Crushed basalt | Mill ash** | | |
| Si % | 0.19 | 0.52 | 0.60 | 0.26 | 0.36 | 0.36 | 0.53 | 0.17 | 0.80 |
| Ca % | 0.24 | 0.29 | 0.33 | 0.24 | 0.37 | 0.21 | 0.25 | 0.09 | 0.15 |
| Mg % | 0.10 | 0.08 | 0.08 | 0.08 | 0.08 | 0.12 | 0.11 | 0.01 | 0.08 |
| K % | 1.26 | 1.19 | 1.25 | 1.27 | 1.28 | 1.19 | 1.30 | 0.07 | 1.10 |
| P % | 0.19 | 0.17 | 0.18 | 0.18 | 0.18 | 0.18 | 0.19 | n.s. | 0.19 |
| S % | 0.11 | 0.10 | 0.11 | 0.10 | 0.11 | 0.10 | 0.11 | n.s. | 0.13 |
| Cu mg/kg | 6.1 | 8.0 | 6.3 | 5.5 | 6.0 | 9.2 | 7.5 | n.s. | 3.0 |
| Zn mg/kg | 22.7 | 20.0 | 19.9 | 20.4 | 21.6 | 22.2 | 21.5 | n.s. | 14.0 |
| Mn mg/kg | 21.4 | 23.1 | 29.3 | 19.3 | 23.6 | 26.4 | 32.5 | n.s. | 15.0 |
| Fe mg/kg | 154 | 109 | 121 | 91 | 106 | 132 | 104 | n.s. | 50 |

* The critical level recorded for each nutrient is reported in Reuter and Robinson (1997).

** Mill ash applied at 60 t/ha (dry weight)

Table 9.7. Concentration of plant nutrients (TVD leaf), determined using XRF, sampled at approximately 7 months, in response to various products in the 'product assessment' trial at Innisfail

| Plant nutrient (TVD leaf, 7 months) | Silicate product (6 t/ha) | | | | | | | Critical level* |
|---|---------------------------|-----------------------------|-----------------------------|--------|--|-------------------|-----------------------|--------------------|
| | Control | Ca- silicate slag (A) | Ca- silicate slag (B) | Cement | Cement building board by- product | Crushed basalt | LSD _(0.05) | |
| Si % | 0.41 | 0.70 | 0.63 | 0.59 | 0.48 | 0.45 | 0.14 | 0.80 |
| Ca % | 0.36 | 0.37 | 0.41 | 0.47 | 0.35 | 0.37 | 0.06 | 0.15 |
| Mg % | 0.16 | 0.16 | 0.15 | 0.14 | 0.15 | 0.17 | n.s. | 0.08 |
| K % | 1.46 | 1.50 | 1.48 | 1.48 | 1.50 | 1.49 | n.s. | 1.10 |
| P % | 0.22 | 0.22 | 0.23 | 0.22 | 0.23 | 0.23 | n.s. | 0.19 |
| S % | 0.17 | 0.18 | 0.17 | 0.18 | 0.17 | 0.17 | n.s. | 0.13 |
| Cu mg/kg | 6.4 | 6.3 | 6.9 | 6.9 | 12.6 | 7.5 | n.s. | 3.0 |
| Zn mg/kg | 30 | 25 | 26 | 29 | 30 | 32 | n.s. | 14.0 |
| Mn mg/kg | 176 | 153 | 179 | 139 | 200 | 162 | n.s. | 15.0 |
| Fe mg/kg | 220 | 173 | 225 | 258 | 185 | 146 | n.s. | 50 |

* The critical level recorded for each nutrient is reported in Reuter and Robinson (1997).

Table 9.8. Concentration of plant nutrients (TVD leaf), determined using XRF, sampled at approximately 7 months, in response to various products in the 'product assessment' trial at Bundaberg.

| Plant nutrient (TVD leaf, 7 months) | Silicate product (6 t/ha) | | | | | | | LSD _(0.05) | Critical level* |
|---|---------------------------|----------------------|----------------------|--------|----------------------------------|------------|----------------|-----------------------|-----------------|
| | Control | Ca-silicate slag (A) | Ca-silicate slag (B) | Cement | Cement building board by-product | Mill ash** | Mud/mill ash** | | |
| Si % | 0.41 | 0.66 | 0.61 | 0.53 | 0.42 | 0.45 | 0.51 | 0.13 | 0.80 |
| Ca % | 0.37 | 0.36 | 0.36 | 0.38 | 0.36 | 0.37 | 0.38 | n.s. | 0.15 |
| Mg % | 0.19 | 0.18 | 0.19 | 0.18 | 0.20 | 0.19 | 0.20 | n.s. | 0.08 |
| K % | 1.34 | 1.51 | 1.52 | 1.54 | 1.39 | 1.46 | 1.51 | n.s. | 1.10 |
| P % | 0.25 | 0.26 | 0.27 | 0.25 | 0.25 | 0.25 | 0.27 | n.s. | 0.19 |
| S % | 0.18 | 0.19 | 0.19 | 0.19 | 0.19 | 0.18 | 0.18 | n.s. | 0.13 |
| Cu mg/kg | 6.1 | 10.2 | 7.6 | 9.9 | 10.0 | 8.6 | 10.6 | n.s. | 3.0 |
| Zn mg/kg | 20 | 24 | 21 | 23 | 24 | 24 | 23 | n.s. | 14.0 |
| Mn mg/kg | 39 | 40 | 36 | 44 | 36 | 51 | 42 | 8.1 | 15.0 |
| Fe mg/kg | 168 | 213 | 265 | 384 | 235 | 402 | 311 | n.s. | 50 |

* The critical level recorded for each nutrient is reported in Reuter and Robinson (1997).

** Mill ash applied at 50 t/ha (dry weight)

In 2000, the first ratoon crop from each of the three trial sites were harvested again. The trials at both Mossman and Bundaberg demonstrated significant yield responses to silicate treatments, while there was still no response to any silicate additions at the Innisfail trial.

The Innisfail trial was infested with canegrubs in the plant crop. Growth was extremely variable in the young first ratoon crop and it was considered that the crop might have been too variable to be of any use. However, the crop improved with age and, although some variability was still apparent, it was decided to harvest the trial. It was harvested at 13 months of age using a weigh truck and the CV's obtained from the trial were quite acceptable under the circumstances. No difference between treatments was noted at any stage during the growth of the first ratoon crop, and although the ratoon crop did not demonstrate a significant response to any of the silicate products, a comparison of the yields obtained with the 3 and 6 t/ha treatments of Ca-silicate slag (B) for both the plant crop and the ratoon crop illustrate that similar yields were obtained for these treatments as in the adjacent Rate trial (Table 9.9).

Table 9.9. Cane yield (t/ha) for the control and the 3 and 6 t/ha Ca-silicate slag treatments from the Product and adjacent Rate trial at Innisfail.

| Treatment | Cane yield (t/ha) | | | |
|-----------------------|-------------------|------------|----------------|------------|
| | plant crop | | ratoon crop | |
| | Product trial | Rate trial | Product trial* | Rate trial |
| Control | 64 | 64 | 77 | 64 |
| Ca-silicate (B) 3t/ha | 79 | 73 | 90 | 93 |
| Ca-silicate (B) 6t/ha | 76 | 77 | 79 | 91 |

* machine harvest

There was variable growth due to grub damage in both the rates trial and the products trial in the ratoon crop, and this, combined with the difference in yield due to the differences expected between hand and machine harvest, could help explain the greater variability in yield between the Product and Rate trial in the this crop (Table 9.9).

At Mossman, although there were no significant differences stalk number as observed in the plant crop, the first ratoon crop did demonstrate a significant response in average weight of millable stalks and cane yield (t/ha) (Table 9.10). Lowest stalk mass was observed in treatments receiving Minplus and this corresponded with the lowest yield. Applications of calcium silicate (product B), cement and mill ash at a rate of 6 t/ha were significantly greater than the control. The cumulative yield associated with the two consecutive harvests is presented in Figure 9.1. The best performing product is cement at a rate of 6 t/ha followed by the equivalent rate of calcium silicate (Figure 9.1). Crushed basalt (Minplus) had no effect on yield at both rates of application, this possibly being due to the low solubility of this material. The overall increase in yield of the best performing treatment from the control is equivalent to 49 t/ha.

Table 9.10. Yield data from first ratoon silicate products trial, Mossman.

| Product | Rate applied (t/ha) | Stalk weight (kg) | Cane yield (t/ha) |
|----------------------|--------------------------------|------------------------------|------------------------------|
| Control | - | 0.96 | 52.1 |
| Calcium silicate (A) | 3 | 1.16 | 59.9 |
| Calcium silicate (A) | 6 | 1.17 | 71.4 |
| Calcium Silicate (B) | 3 | 0.98 | 59.3 |
| Calcium Silicate (B) | 6 | 0.98 | 64.5 |
| Cement | 3 | 1.04 | 65.4 |
| Cement | 6 | 1.20 | 76.7 |
| Hi Yield | 3 | 0.93 | 53.3 |
| Hi Yield | 6 | 0.93 | 56.5 |
| Minplus | 3 | 0.81 | 34.7 |
| Minplus | 6 | 0.91 | 53.7 |
| Mill ash | 30 | 1.08 | 62.6 |
| Mill ash | 60 | 1.13 | 70.2 |
| LSD 5% | | 0.19 | 17.7 |
| CV% | | 11.1 | 17.6 |

At Bundaberg, both the first ratoon and second crops demonstrated significant yield responses in all treatments consisting of a calcium silicate material, namely both calcium silicate slags and also cement (Table 9.11). Although there were no differences between the various products in the plant crop, it appears that the addition of calcium silicate has helped sustain yields in the following ratoon crops.

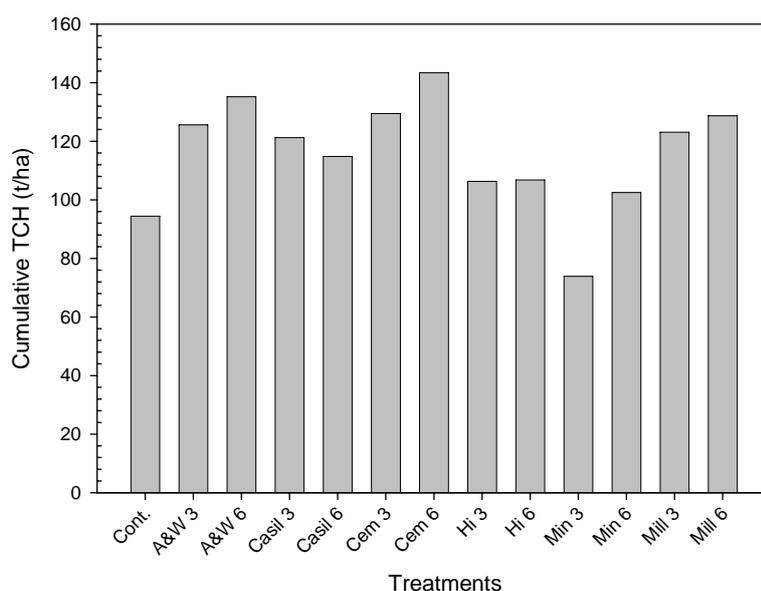


Figure 9.1. Cumulative yield of two consecutive crops at the Mossman products trial. LSD 5% level of significance is 21.1 t/ha.

Table 9.11. The cane yield (t/ha) from the Product Trial at Trebbin's, Bundaberg for the plant crop, ratoon 1 and ratoon 2 crops

| Product | Rate | Cane yield t/ha Plant crop 2000 | Cane yield t/ha Ratoon 1 2001 | Cane yield t/ha Ratoon 2 2002 |
|----------------------|--------------|--|--|--|
| Control | | 83.9 | 75.5 | 60.83 |
| Calcium Silicate (B) | 3 T/ha | 89.9 | 89.2 | 66.03 |
| Calcium Silicate (B) | 6 T/ha | 88.3 | 95.2 | 72.7 |
| Calcium Silicate (A) | 3 T/ha | 87.6 | 82.7 | 63.3 |
| Calcium Silicate (A) | 6 T/ha | 88.5 | 85.8 | 74.7 |
| Cement | 3 T/ha | 88.9 | 76.3 | 66.2 |
| Cement | 6 T/ha | 92.8 | 76.0 | 75.0 |
| Hi Yield | 3 T/ha | 86.8 | 76.0 | 56.7 |
| Hi Yield | 6 T/ha | 88.4 | 81.0 | 63.2 |
| Mill Ash | 25 T/ha | 78.6 | 74.7 | 58.9 |
| Mill Ash | 50 T/ha | 87.8 | 81.9 | 60.7 |
| Mud Ash | 25 T/ha | 91.6 | 75.6 | 59.6 |
| Mud Ash | 50 T/ha | 97.4 | 73.0 | 57.4 |
| Cal Phos | 300 kg/ha | 80.7 | 71.1 | 58.2 |
| Cal Phos | 600 kg/ha | 88.0 | 70.9 | 59.5 |
| Isd 5% | | n.s. | 7.78 | 12.4 |

Add-on Product trials

The initial set of product trials were restricted to commercially available products that were available at the time the trials were being established. As the project progressed many other potential sources of silicated materials were identified. Among these sources, two acidulated magnesium silicates supplied by Growforce (“Silvine’) and Incitec (‘Dunnite’) were considered to have significant potential, as results from preliminary laboratory based dissolution studies indicated that these materials were significantly more soluble with respect to Si than the current range of products being evaluated, and had the potential to be used as high analysis fertilizers supplying both Si and basic cations (Mg^{2+} and Ca^{2+}). Consequently, further trials were established to examine the potential use of these acidulated materials applied to a crop, at lower rates and using banded as against broadcast applications.

Northern Trials:

A trial was established at Feluga in the Tully area in 2000, where the two acidulated magnesium silicates were applied to the row at 250, 500 and 1000 kg/ha. In addition calcium silicate (product B) was broadcast and incorporated at 4 t/ha, and cement banded at 500 kg/ha. Germination was slow and adversely affected in some plots by wet conditions following planting. Product application in the row was delayed initially because of the late arrival of the acidulated materials. This was further compounded by the extremely wet conditions experienced during the October – November period in 2000 resulting in materials being applied much later than originally planned. It is considered that crop growth was adversely affected by the wet conditions during the developmental phases, and this was reflected by low stalk populations and cane yield. The addition of silica to the soil, either broadcast or row application, had no beneficial effect on any growth or yield parameter. The results may have been influenced by site variability exacerbated by the wet conditions. It is possible late application combined with the wet conditions may have minimized the opportunity to obtain a response to the row treatments. However, it is difficult to accept this as the reason for the lack of response to broadcast Ca–silicate slag.

Soil data (Table 9.12) suggested that this site should respond to silicate application as the Si level is below the tentative critical value of 10 mg Si/kg in $CaCl_2$ extract. However, a response could possibly be unexpected based on the tentative critical value of 100 mg Si/kg in H_2SO_4 extract. Also the citric acid value for Si is much higher than the sulphuric acid value whereas normally they are similar. Perhaps this indicates a high level of slowly available Si, which would limit responses to Si amelioration. This result indicates further work is still required to clearly define responsiveness to Si.

Table 9.12. Soluble and extractable soil Si concentrations (mg/kg) from the acidulated olivine trial, Feluga

| Depth (cm) | Si | | |
|---------------|-------------------|--------------------------------|---------|
| | CaCl ₂ | H ₂ SO ₄ | Citric |
| | (mg/kg) | (mg/kg) | (mg/kg) |
| 0-10 | 6 | 98 | 155 |
| 10-20 | 7 | 98 | 148 |
| 20-30 | 8 | 111 | 107 |
| 30-50 | 13 | 116 | 190 |
| 50-70 | 11 | 119 | 189 |

Although there were no yield responses in the plant crop, top visible dewlap leaf samples collected at 7 months showed significant increases in Si concentration in the broadcast Ca-silicate slag and the highest rate of Dunnite treatments. These measured Si concentrations were well below the critical value of 0.7 % commonly quoted for sugarcane. Soils sampled at the end of the plant crop demonstrated significant differences in soluble (CaCl₂ extractable), but these differences were not large (Table 9.13)

Table 9.13. Concentration (mg/kg) of Si (soluble and extractable) and Mg in the soil, at 0 – 10 cm, sampled at the end of the plant crop; and concentration (%) of selected plant nutrients (Si and Mg) from the top visible dewlap leaf, sampled at approximately 7 months from the Plant and Ratoon 1 crop.

| Treatment | Concentration of soil nutrients (mg/kg) at harvest plant crop (2001) | | | Concentration of plant nutrients (%) from TVD leaf at 7 months | | |
|----------------------|---|-------------------|--------------------|--|----------------|-----------------|
| | Soluble Si | Extractable Si | Exchangeable Mg | Si | Si | Mg |
| | | | | Plant crop | Ratoon 1 crop | |
| Control | 5.5 | 74 | 0.29 | 0.28 | 0.40 | 0.080 |
| Calcium silicate | 5.8 | 83 | 0.39 | 0.46 | 0.52 | 0.083 |
| Cement | 5.3 | 74 | 0.32 | 0.35 | 0.43 | 0.093 |
| Silvine 250kg/ha | 6.1 | 93 | 0.44 | 0.31 | 0.41 | 0.093 |
| Silvine 500kg/ha | 6.2 | 99 | 0.4 | 0.34 | 0.47 | 0.087 |
| Silvine 1000kg/ha | 6.7 | 99 | 0.54 | 0.33 | 0.47 | 0.103 |
| Dunnite 250kg/ha | 5.9 | 97 | 0.47 | 0.32 | 0.49 | 0.087 |
| Dunnite 500kg/ha | 6.5 | 101 | 0.33 | 0.37 | 0.51 | 0.083 |
| Dunnite 1000kg/ha | 7.8 | 96 | 0.48 | 0.37 | 0.50 | 0.090 |
| Lsd 5% | 1.6 | n.s. (28) | 0.17 | 0.08 | n.s. (0.15) | n.s. (0.017) |

It is interesting to note that although soil analysis at the end of the plant crop indicated that the magnesium silicate products (Silvine and Dunnite) has a greater effect on increasing soil Si levels, plant analysis of the TVD leaf sampled from the plant crop at approximately 7 months recorded the highest plant % Si for the calcium silicate treatment. The Si % for the acidulate olivine treatments were not as high as the calcium silicate treatment, but were, at the higher rates of application, still significantly higher than the control. The plant concentrations of Si from the ratoon crop followed the same trend as for the plant crop, but the differences between treatments were no longer significant. Acidulated olivines are also a source of magnesium. The olivine products significantly increased exchangeable soil Mg levels compared to the control, however, this was not reflected in plant Mg levels. It is possible the original soil levels of Mg were adequate and a response to applied Mg would not normally be expected.

The cane yield (t/ha) and ccs of the first ratoon crop are shown in Table 9.14. Although there is a clear trend for the olivine treatments to have higher yields, the high level of site variability meant that these differences were not significant. Despite this it can be seen that the highest rate of dunnite resulted in an increase of 25 t/ha, equivalent to a 23% yield increase compared to the control.

Table 9.14. The cane yield (t/ha) and ccs from the Add-on Olivine Trial at Feluga for the ratoon crop.

| Treatment | Cane yield (t/ha) ratoon crop (2002) | ccs |
|-------------------|---|-------------|
| Control | 107 | 13.6 |
| Calcium silicate | 115 | 12.8 |
| Cement | 117 | 13.2 |
| Silvine 250kg/ha | 111 | 12.4 |
| Silvine 500kg/ha | 128 | 12.5 |
| Silvine 1000kg/ha | 119 | 13.8 |
| Dunnite 250kg/ha | 121 | 13.3 |
| Dunnite 500kg/ha | 125 | 13.4 |
| Dunnite 1000kg/ha | 132 | 13.3 |
| Lsd 5% | n.s. (28) | n.s. (1.14) |

Table 9.15. Selected elemental analysis, showing the mean values and standard deviation for the trial site at Feluga, and the published 'critical' and 'adequate' ranges as detailed in Reuter, D.J. and Robinson, J.B. (1997)

| Plant nutrient | Trial mean value (%) (\pm std. dev.) | Plant analysis ranges for sugarcane* | |
|-----------------------|--|---|-----------------|
| | | critical - marginal | adequate |
| Si | 0.47 (\pm 0.047) | 0.31 – 0.53 | 0.68 – 0.76 |
| Mg | 0.09 (\pm 0.007) | 0.08 | 0.12 – 0.18 |
| Ca | 0.34 (\pm 0.03) | 0.15 – 0.20 | > 0.16 |
| K | 1.41 (\pm 0.03) | 0.90 – 1.30 | 1.3 – 2.0 |
| P | 0.13 (\pm 0.01) | 0.15 – 0.23 | 0.21 – 0.30 |

* suggested 'critical' and 'adequate' levels from Reuter, D.J. and Robinson, J.B. (1997)

Plant analysis of the TVD leaf collected from the first ratoon crop (Table 9.15) demonstrated no significant treatment response for any element tested. When compared to suggested 'critical' and 'adequate' ranges, it is clear that the plant levels of Ca and K are adequate, while the levels of Si, Mg and P are marginal. However, when cane yield (t/ha) is regressed against the plant concentration of these elements, it is only the % Si that is positively and significantly correlated against yield (r values of 0.77, -0.13, and -0.32 for Si, Mg and K respectively) (Figure 9.2). Although the olivine treatments supplied Mg and Si, and Si additions are reputed to assist in the plant uptake of P, the results from this trial suggest that plant uptake of Si, is an important driver in determining yield.

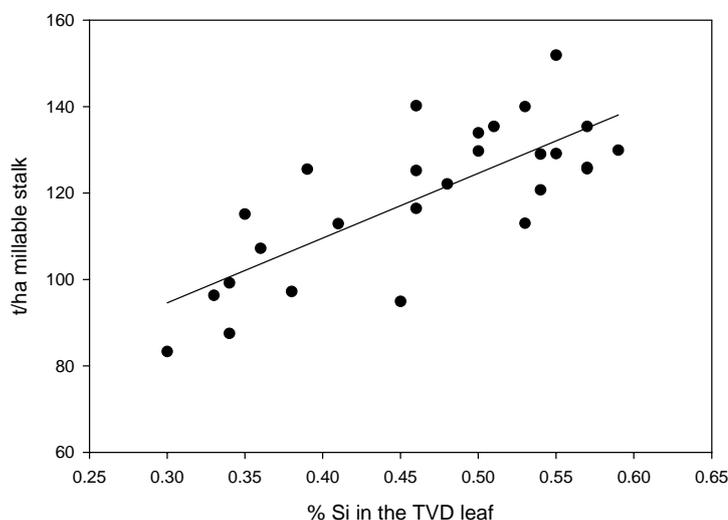


Figure 9.2. Correlation of cane yield (t/ha) of the first ratoon crop, against the concentration of Si (%) in the TVD leaf collected at approximately 7 months.

Southern Trials:

In 2000, a similar trial to the Feluga acidulated magnesium trial was established in the Bundaberg district. In contrast to the Feluga trial, in the plant crop the Silvine treatments did result in marginally higher yields compared to the control and other treatments, although these differences were not significant. Plant analysis on selected treatments showed the average % Si in the control treatments to be 0.61% while the calcium silicate slag treatment was 1.24%. In contrast, the average concentrations for the three increasing rates of Silvine were 0.37, 0.35 and 0.38% Si. Consequently it seems unlikely that any marginal response in yield to the Silvine treatments in the plant crop was due to Si.

A second Add-on trial was established at Bundaberg (the Schulte experiment), where, in addition to calcium silicate slag, cement and acidulated magnesium (Silvine), other potential sources of Si, including lime-kiln dust (LKD) and diatomaceous earth, were tested. This experiment was affected by drought conditions and un-even distribution

of water from a travelling irrigator. Replicates were aligned to account for the latter effect, but conditions were so dry that this technique was only partly successful. There was a large range in cane yield in this experiment (Table 9.16), but there was no significant treatment effect ($P=0.58$). However it was of interest that calcium silicate treatments applied at 2 and 4 t/ha were among the highest yields. TVD silicon data reflect higher values in the first ratoon crop for harvest in 2003 than in the plant crop, and that significant improvement in leaf silicon status above the control was associated with calcium silicate (2 and 4 t/ha) and cement at 4 t/ha.

Table 9.16. Cane yield (t/ha) associated with broadcast and row application of silicate products in Q151 plant (2002) cane on Schulte's farm at Bundaberg.

| Treatment | t/ha |
|------------------------------------|-------------|
| Control 1 | 88.1 |
| Control 2 | 98.6 |
| Calcium silicate 0.5t row | 88.3 |
| Calcium silicate 1.0t row | 96.8 |
| Calcium silicate 2.0t b'cast | 100.2 |
| Calcium silicate 4.0t b'cast | 104.3 |
| Cement 0.5t row | 97.5 |
| Cement 1.0t row | 83.8 |
| Cement 4.0t b'cast | 97.2 |
| Lime kiln dust 0.5t row | 100.5 |
| Lime kiln dust 1.0t row | 94.1 |
| Lime kiln dust 4.0t b'cast | 96.7 |
| Diatom. Earth (A) 0.5 row | 90.9 |
| Diatom. Earth (A) 4.0 b'cast | 92.1 |
| Diatom. Earth (B) 2.0 row | 94.0 |
| Diatom. Earth (B) 2.0 row + "bugs" | 91.7 |
| Acidulated olivine 0.1t row | 96.1 |
| Acidulated olivine 0.2t row | 98.8 |
| Acidulated olivine 0.4t row | 88.3 |
| LSD | NS |

Similar treatments were imposed on a third trial site, at Maryborough (Morris's farm). Again the treatments consisted of calcium silicate slag, cement, lime kiln dust, diatomaceous earth (Siliconite) and acidulated olivine (Silvine) in various combinations of broadcast and row applications. There was visual evidence of yield response in the plant crop on the Morris farm at Maryborough, but yield data were not obtained through the un-cooperative action of the harvest contractor who would not stop to empty the elevator between plots as this caused cane loss from the elevator boot. This site was furrow irrigated and did not suffer from the 2002 drought. TVD Si data from this experiment (Table 9.17) reinforce the value of calcium silicate and cement as sources of plant available Si, with significant responses associated with calcium silicate (4 and 8 t/ha) and cement 4 t/ha in both plant and first ratoon crops. The high rate of calcium silicate was included in this experiment because of experience with yield increases above 4 t/ha in the rates experiments. Leaf analysis in the first year (2002) showed an increase in % Si due to the calcium silicate slag (0.55

and 0.75% Si for the 4 and 8 t/ha rates respectively) and cement (0.50 % Si) treatments compared to the control (0.36 % Si). As demonstrated in the first trial established at Bundaberg, the Silvine (acidulated magnesium) had no effect on increasing plant Si levels in this trial. The three rates of Silvine (0.1, 0.2 and 0.4 t/ha) resulted in 0.39, 0.38 and 0.38% Si which was very similar to the control treatment.

Table 9.17. Effect of broadcast and row application of silicated products on TVD silicon in Q124 plant (2002) and first ratoon (2003) crops the Morris farm at Maryborough.

| Treatment | Si% TVD 2002 | Si% TVD 2003 |
|---------------------------------------|--------------|--------------|
| Control 1 | 0.38 | 0.29 |
| Control 2 | 0.36 | 0.23 |
| Blast slag 4t b'cast | 0.40 | 0.28 |
| Calcium silicate 4.0t b'cast | 0.55 | 0.36 |
| Calcium silicate 8.0t b'cast | 0.75 | 0.47 |
| Cement 4.0t b'cast | 0.50 | 0.40 |
| Lime kiln dust 0.5t row | 0.39 | 0.25 |
| Lime kiln dust 1.0t row | 0.36 | 0.26 |
| Lime kiln dust 4.0t b'cast | 0.37 | 0.29 |
| Diatom. Earth (A) 3.34t b'cast | 0.37 | 0.22 |
| Earth Life Minerals Plus 2.69t b'cast | 0.31 | 0.27 |
| Acidulated olivine 0.1t row | 0.39 | 0.26 |
| Acidulated olivine 0.2t row | 0.38 | 0.26 |
| Acidulated olivine 0.4t row | 0.38 | 0.28 |
| LSD (p<0.05) | 0.13 | 0.08 |

nn = significantly greater than average of controls

A fourth Add-on trial was established at Mackay (the Franetovich experiment). This site was considered interesting, as the acid extractable Si was extremely low (24 mg Si/kg), while the CaCl₂ extractable Si (13 mg Si/kg), although low, was considered marginal, and possibly not responsive. This trial design did not include acidulated olivine products, but concentrated on comparing other potential Si products, namely lime kiln dust and diatomaceous earth to the standard calcium silicate slag and cement treatments. This experiment received supplementary irrigation but was also affected by the dry conditions in 2002, as there was a major moisture gradient across the trial (perpendicular to the replications).

The harvest results demonstrated no significant responses to any of the treatments, most probably because of the seasonal conditions. There was little variation between treatments and the average yield over the entire site was 81 t/ha. As shown in the other trials, the treatments that resulted in an increase in leaf Si % were the calcium silicate and cement treatments. Compared to a concentration of 0.30% Si in the control, there was a linear increase in % Si in the leaf (0.40, 0.45, 0.52 and 0.67% Si) with increasing rates of calcium silicate additions. The cement treatments showed a similar trend, with the leaf % Si increasing from 0.36, 0.36, 0.43 and 0.50 % for the four rates of application. While the highest rate (4 t/ha) of lime kiln dust also resulted

in increased uptake of plant Si (0.48% Si), none of the other treatments differed from the control (Table 9.18).

There was a significant ($p < 0.05$) residual response in soil Si status (12 months after application) to some of the broadcast materials at the Franetovich site (Table 9.19). Only calcium silicate and cement at 4t/ha provided a significant response in $Si_{(sol)}$, whereas these treatments plus calcium silicate at 2 t/ha gave a significant residual response in $Si_{(ext)}$. Lime kiln dust at 4 t/ha just failed to achieve significant residual value over the control for both estimates of soil silicon status. Diatomaceous Earth had no impact on soil Si status.

Table 9.18. Effect of broadcast and row applications of silicate products on TVD silicon and cane yield of Q135 plant cane (2002) on the Franetovich farm at Mackay.

| Treatment | Si% TVD 2002 | Cane yield (t/ha) |
|-------------------------------|--------------|-------------------|
| Control | 0.30 | 81.6 |
| Calcium silicate 0.5t row | 0.40 | 84.2 |
| Calcium silicate 1.0t row | 0.45 | 79.5 |
| Calcium silicate 2.0t b'cast | 0.53 | 85.1 |
| Calcium silicate 4.0t b'cast | 0.67 | 85.3 |
| Cement 0.25t row | 0.36 | 79.7 |
| Cement 0.5t row | 0.36 | 84.8 |
| Cement 1.0t row | 0.43 | 73.5 |
| Cement 4.0t b'cast | 0.50 | 88.0 |
| Lime kiln dust 0.25t row | 0.30 | 87.8 |
| Lime kiln dust 0.5t row | 0.38 | 79.3 |
| Lime kiln dust 1.0t row | 0.27 | 81.2 |
| Lime kiln dust 4.0t b'cast | 0.41 | 72.2 |
| Diatom. Earth (A) 0.5t row | 0.34 | 78.5 |
| Diatom. Earth (A) 4.0t b'cast | 0.34 | 77.4 |
| Soft rock 1.0t row | 0.34 | 79.0 |
| LSD ($p < 0.05$) | 0.10 | NS |

nn = significantly greater than control

Table 9.19. Effect of broadcast applications of silicated products on soil silicon status after harvest of the Q135 plant crop (2002) on the Franetovich farm at Mackay (soil samples not taken from treatments with row applications).

| Treatment | $Si_{(sol)}$ (mg/kg) | $Si_{(ext)}$ (mg/kg) |
|-------------------------------|----------------------|----------------------|
| Control | 8.0 | 86.0 |
| Diatom. Earth (A) 4.0t b'cast | 8.3 | 85.7 |
| Lime kiln dust 4.0t b'cast | 9.3 | 92.0 |
| Calcium silicate 2.0t b'cast | 9.3 | 95.0 |
| Calcium silicate 4.0t b'cast | 10.7 | 96.3 |
| Cement 4.0t b'cast | 10.7 | 100.3 |
| LSD ($p < 0.05$) | 1.8 | 7.9 |

nn = significantly greater than control

TVD Si data from these additional products trials in Mackay and South Queensland are summarised in Tables 9.20, 9.21, 9.22 and 9.23. These data support earlier conclusions from soil analysis about the efficacy of silicate products in releasing plant available silicon. TVD Si% values in these tables show significant responses in TVD Si% above untreated soil to the broadcast application of calcium silicate, cement, lime kiln dust, mud/ash and to row dressings of CalPhos. Diatomaceous Earth has had no significant impact on TVD Si status.

Table 9.20. Effect of broadcast and row applications of silicated products on TVD silicon in Q151 plant (2002) and first ratoon crops on Schulte's farm at Bundaberg. "Bugs" = biological solution supplied by agents.

| Treatment | Si% TVD 2002 | Si% TVD 2003 |
|------------------------------------|--------------|--------------|
| Control 1 | 0.42 | 0.56 |
| Control 2 | 0.40 | 0.57 |
| Calcium silicate 0.5t row | 0.44 | 0.58 |
| Calcium silicate 1.0t row | 0.43 | 0.60 |
| Calcium silicate 2.0t b'cast | 0.42 | 0.73 |
| Calcium silicate 4.0t b'cast | 0.56 | 0.73 |
| Cement 0.5t row | 0.44 | 0.56 |
| Cement 1.0t row | 0.45 | 0.57 |
| Cement 4.0t b'cast | 0.49 | 0.64 |
| Lime kiln dust 0.5t row | 0.43 | 0.59 |
| Lime kiln dust 1.0t row | 0.36 | 0.57 |
| Lime kiln dust 4.0t b'cast | 0.45 | 0.61 |
| Diatom. Earth (A) 0.5 row | 0.41 | 0.56 |
| Diatom. Earth (A) 4.0 b'cast | 0.43 | 0.53 |
| Diatom. Earth (B) 2.0 row | 0.29 | 0.55 |
| Diatom. Earth (B) 2.0 row + "bugs" | 0.43 | 0.52 |
| Acidulated olivine 0.1t row | 0.42 | 0.55 |
| Acidulated olivine 0.2t row | 0.40 | 0.55 |
| Acidulated olivine 0.4t row | 0.41 | 0.54 |
| LSD (p<0.05) | 0.08 | 0.07 |

mn = significantly greater than control

Table 9.21. Effect of broadcast and row applications of silicated products on TVD silicon in Q124 plant (2002) and first ratoon (2003) crops the Morris farm at Maryborough.

| Treatment | Si% TVD 2002 | Si% TVD 2003 |
|---------------------------------------|--------------|--------------|
| Control 1 | 0.38 | 0.29 |
| Control 2 | 0.36 | 0.23 |
| Blast slag 4t b'cast | 0.40 | 0.28 |
| Calcium silicate 4.0t b'cast | 0.55 | 0.36 |
| Calcium silicate 8.0t b'cast | 0.75 | 0.47 |
| Cement 4.0t b'cast | 0.50 | 0.40 |
| Lime kiln dust 0.5t row | 0.39 | 0.25 |
| Lime kiln dust 1.0t row | 0.36 | 0.26 |
| Lime kiln dust 4.0t b'cast | 0.37 | 0.29 |
| Diatom. Earth (A) 3.34t b'cast | 0.37 | 0.22 |
| Earth Life Minerals Plus 2.69t b'cast | 0.31 | 0.27 |
| Acidulated olivine 0.1t row | 0.39 | 0.26 |
| Acidulated olivine 0.2t row | 0.38 | 0.26 |
| Acidulated olivine 0.4t row | 0.38 | 0.28 |
| LSD (p<0.05) | 0.13 | 0.08 |

nn = significantly greater than average of controls

Table 9.22. Effect of broadcast silicated products on TVD silicon in Q136 plant cane (2001) in block 18 on McCarthy's farm at Isis.

| Treatment | Si% TVD 2001 |
|-------------------------------|--------------|
| Control | 0.31 |
| Calcium silicate 4t b'cast | 0.80 |
| CalPhos 0.15t row | 0.37 |
| CalPhos 0.30t row | 0.45 |
| CalPhos 0.60t row | 0.48 |
| Diatom. Earth (A) 0.5t row | 0.35 |
| Diatom. Earth (A) 1.0t row | 0.39 |
| Diatom. Earth (A) 2.0t b'cast | 0.38 |
| Diatom. Earth (A) 6.0t b'cast | 0.33 |
| Potassium silicate 0.15t row | 0.33 |
| Potassium silicate 0.30t row | 0.34 |
| Potassium silicate 0.60t row | 0.33 |
| LSD (P<0.10) | 0.08 |

nn = significantly greater than control

Table 9.23. Effect of broadcast silicated products on TVD silicon in Q138 first ratoon (2001) in block 10 on McCarthy's farm at Isis. Products were applied prior to planting in 1999.

| Treatment | Si% TVD 2001 |
|------------------------|--------------|
| Control | 0.25 |
| Calcium silicate 6t/ha | 0.33 |
| Cement 6t/ha | 0.41 |
| Mud Ash 45 dry t/ha | 0.34 |
| LSD (p<0.12) | 0.09 |

nn = significantly greater than control

We have not been able to obtain reliable yield data from trials that included diatomaceous earth (two sources), the TVD data consistently indicate this material does not supply plant available Si and the +12 month data from the Franetovich site suggests lack of impact on the indices of plant available Si in soil. Seasonal conditions also preclude definitive statements about Lime Kiln Dust, which has very similar properties to cement, but has only been associated with a significant improvement in TVD Si status at one site (Table 9.17).

Summary

While the results of these trials show that many of the products have some potential value as a silicate source, none tested compared favourably to the calcium silicate slag imported from the USA. The yield benefits observed in the 'Rate' trials support the suggestion that Si should be treated as an integral part of any fertilizer strategy associated with cane production, however the lack of a locally available and economical source of Si is an issue. This is a concern encountered in other parts of the world where Si fertilizers are used routinely, and on-going research and development into new silicate products is continually being undertaken (Gascho, 2001; Ma and Takahashi, 2002; Owa, 2002; Matichenkov et. al., 2002; Yao et. al., 2002; Yoshida et. al., 2002).

Although it is difficult from the current trials to make a firm recommendation based on any of the products tested, a lot of progress has been made within the project in better identifying potential silicate sources. Of the products tested, and one that is available locally, cement has probably proved the most effective. At present, the economics of using cement are likely to preclude its wide-spread use. However, this does identify the need for more research into field placement methods (banding versus broadcast). In addition, the impact of soil type and the soils reactions with various products depending on their chemical composition, suggests that in many cases different fertilizers strategies may be necessary. It may be more beneficial for some soil types to receive large tonnages of a broadcast applied, slow release product like calcium silicate slag, applied every few years to the plant crop; while others may require lower application rates of a more soluble Si source, strategically placed and applied on an annual basis. In this respect, more research work needs to be carried out with acidulated metal silicates or other soluble sources of Si.

New potential sources of Si are continually being identified. Since concluding the 'Product' trials undertaken within this project, a wollastonite deposit situated in north Queensland has been identified. This material contains 21% Si, 33% Ca and has a neutralizing value of 62%, and may prove to be an easily accessible and economical source of a silicate/liming material. However, before recommendations can be made on any products, comprehensive field testing needs to be undertaken on a range of soils showing sub-optimal Si levels. The need to identify suitable locally available products is an important issue as the importation of calcium silicate slag on a commercial basis at present is likely to be uneconomic.

It is also worth commenting on the yield benefits arising from the use of sugarcane mill by-products. Plant Si-recycling should be considered as an important option for supplying Si to sugarcane. The significant results obtained from Product trials in both the Mossman and Bundaberg districts provide strong evidence that when mill by-products such as ash and filtermud are returned to the field there is a yield benefit of which Si input from the product is an important component. However, another large and significant input of potentially recyclable plant material is the leaf trash deposited during crop growth and at harvest. The question becomes 'how available is the Si returned as trash to the next crop of cane'.

When trash decays, Si is returned to the soil surface as cellular structural material and opal phytoliths, which can be released basically unaltered into the soil. They are relatively insoluble and are usually concentrated in the surface horizons of the soil. As sugarcane accumulates large quantities of Si in its tops, it is possible that large amounts of Si are returned to the soil surface in this relatively insoluble form. Si is also deposited in cell lumens, cell walls and intercellular spaces. The structure of the cell walls indicates that the Si is an integral part of the thickening of the cell wall and that it is deposited in intimate association with other constituents of the wall. Consequently, in addition to the slow dissolution rate of opal phytoliths, a significant proportion of polymerised Si in sugarcane trash is associated with non-easily decomposable polysaccharide fractions such as cellulose and hemicellulose.

While the change to green cane trash blanketing has many irrefutable benefits, recent evidence suggests that available soil Si levels are lower under a green cane trash system than under a burnt system (S. Berthelsen unpublished, and J. Klok pers. comm.). It can be hypothesised that the burning of trash may promote Si solubility by breaking down the associated cellulose material. Thus the change from a burnt to a green cane trash blanketing system is likely to reduce the amount of soluble Si being cycled in the sugarcane system, further exacerbating the gradual depletion of plant-available Si after long-term monoculture. Whilst, bioavailability of biogenic Si was not addressed in this project, it is clear that a significant amount of Si is returned with the leaf material, and our management of this trash may be an important issue to ensure maximum use is made of this source of Si.

10. Methods for testing available Si in silicate materials

Introduction

Although silicon is ubiquitous, it is not found free in nature, but always combined, usually as oxides or silicates. Therefore, while many materials have a high total Si content and may be seen to be potential sources of silicate fertilizer, their effectiveness as a silicate fertilizer is not dependent on the total Si content, but rather on its chemical reactivity. Before any source can be considered useful for agricultural applications it must meet a number of criteria, such as solubility, availability, suitable physical properties and be free or have acceptably low levels of contaminants (Gascho, 2001).

As a major objective of this project, a number of commercially available silicate materials were tested in field trials established in the Mossman, Innisfail and Bundaberg districts. In all cases, these products were tested against a 'control' silicate material, namely calcium silicate slag, a by-product from the production of elemental P. This product is the major silicate slag fertilizer used in the rice and sugarcane industries in the USA and came with a proven and well-documented record of beneficial crop response. Although this slag material was used as a 'control' silicate material in the trials, it was always considered that its importation costs would never make its wide spread use an economic possibility. Therefore identifying and testing locally available materials was an essential outcome of the project. During the course of the project, many local materials were identified and investigated in field trials. However, as it is not financially or practically possible to test the efficacy of all materials directly in the field, a laboratory measure of availability is an important first step in assessing the potential of any new material.

Unfortunately selecting a suitable silicate materials and assessing its efficacy is difficult, as there are no proven methods for adequately determining the availability of Si in the potential Si source. While a number of chemical extractant methods have been used to estimate both total and soluble Si in silicate materials, often the results obtained do not correlate well with plant uptake of Si, once the material is applied to the soil. In addition to the effect on particle size on solubility, other chemical characteristics of the material such as pH, molar ratio of CaO:SiO₂ have been shown to influence Si availability (Ma and Takahashi, 2002). Once a product is added to the soil, soil chemical reactions, eg. increase in soil pH due to the dissolution of Ca and Mg from the material can further influence the solubility and hence availability of Si (Ma and Takahashi, 2002). Consequently, it is possible that there is not a universal extractant that is suitable for determining available Si that will cover all types of materials, and for all soils and soil conditions (Gascho, 2001).

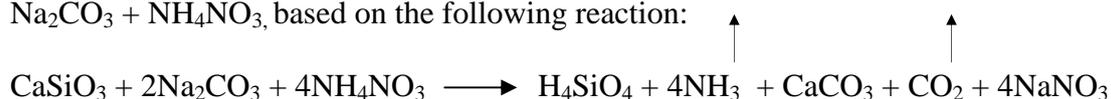
However a suitable chemical extractant may still be useful as a rapid test and provide the first estimate of the potential value of a silicate source. Therefore, an attempt was made to identify a chemical extractant method that may be used as a rapid test, to thus allow further glasshouse and field testing to concentrate on materials with the most potential. The effectiveness of a number of chemical extraction methods described in the literature were used to assess a range of potential silicate materials. These same materials were then compared through indirect chemical extraction after soil incubation. Finally, as a most reliable means of determining the solubility and

chemical reactivity of a silicate material is by determining plant uptake after a short-term bioassay (Savant *et al.*, 1999), a selection of these materials were compared by undertaking extensive plant and soil analysis following glasshouse pot studies.

Results and Discussion

Direct chemical Extraction

A number of different chemical extractants for estimating available Si in silicate materials have been used to varying success (Table 10.1). Extraction with 0.5 M NH₄OAc or 0.5 M HCl are two of the earliest methods recorded, and at various stages were standard methods in Japan. However, these, plus many other acidic extractants commonly used, including citric acid and acetic acid have lost favour as they have generally shown poor correlation with crop uptake of Si. Simple water extractions of calcium silicate slags have also been used, however, as it was found that dissolution of the calcium silicate resulted in increases in pH and Ca in solution, both of which repressed further dissolution of the product, this method was modified to include a weakly acidic cation exchange resin in the water to both moderate pH and adsorb Ca (Kato and Owa, 1997b). More recently, Pereira *et al.* (2002) proposed an extraction method that they stated would quantify the Si potentially available to plants by using an alkaline extractor (using different extraction ratios and extraction/resting times) of Na₂CO₃ + NH₄NO₃, based on the following reaction:



As various forms of calcium silicate materials are the most widely used Si fertilizer, most proposed methods are based on estimating available Si from this source. Other silicate materials may possibly behave quite differently. Whatever method is used, it is important to keep a wide product to solution ratio, to keep the concentration of monosilicic acid low and prevent polymerization from occurring. In addition, as generally Si availability increases with decreasing particle size, it is important to define and standardize particle size when attempting to determine their reactivity and Si availability.

To test the efficacy of some of these methods, a wide range of silicate materials were compared with the extraction procedures outlined in Table 10.1. In addition to the extraction techniques sourced from literature (methods 1, 2, 3, 4, and 5), simple dissolution procedures using 0.01 M CaCl₂ (method 6), and adding the product to a soil and equilibrating at a 1:5 soil to solution ratio (method 7) were undertaken. All samples were ground to pass through a 500 micron sieve prior to analysis. Total elemental composition was also determined of a selection of samples. The results are presented in Table 10.2.

The various products tested show little commonality in the ranking of the values obtained with the different extractants, and poor relationship to the total amount of Si as determined by XRF. The influence of pH is evident by examining the values obtained for cement. While it has one of the highest extractable values when extracted with an acidic extractant (methods 1, 2 and 3 in particular), very little Si was extracted when cement was added to the soil and allowed to equilibrate in a 1:5 soil:water medium for 40 hours. Although the extract pH was not measured during

this analysis, the cement addition used in this method was very high (approximately equivalent to 20 t/ha) and this would have resulted in a very high soil pH. Although some products are generally ranked amongst the highest in extractable Si in all tests, for example calcium silicate slag, cement, wollastonite and the Dow Corning filtercake, the variability between different methods, and ranking of products within methods would make it hard to predict the potential of any product to adequately supply plant-available Si based on any of the extractants used.

Table 10.1. Chemical extraction procedures used for assessing Si sources for plant-available Si.

| Method No. | Chemical Procedure | Reference |
|------------|---|--|
| 1 | 1 g Si source + 150 ml 0.5 M NH ₄ OAc (pH 4.0), end-over-end shake @ 17 rpm for 1 hour | Hagihara (1981); Bair (1966); Barbosa Filho <i>et al.</i> (1996) |
| 2 | 1 g Si source + 150 ml 0.5 M HCl, end-over-end shake @ 17 rpm for 1 hour | Barbosa Filho <i>et al.</i> (1996) |
| 3 | 0.5 g Si source + 1 g H-resin Amberlite (IRC-50) + 500 ml water, bottle roll @ 4 rpm for 16 hour | Kato and Owa (1997b) |
| 4 | 1 g Si source + 50 ml 0.3 M Na ₂ CO ₃ + 50 ml 0.4 M NH ₄ NO ₃ , end-over-end shake @ 17 rpm for 3 hour, rest for 8 hours | Pereira <i>et al.</i> (2003) |
| 5 | 1 g Si source + 50 ml 0.1 M Na ₂ CO ₃ + 50 ml 0.2 M NH ₄ NO ₃ , end-over-end shake @ 17 rpm for 1 hour, rest for 5 days, reshake 10 minutes | Pereira <i>et al.</i> (2003) |
| 6 | 0.5 g Si source + 500 ml 0.01 M CaCl ₂ , bottle roll @ 4rpm for 16 hour | |
| 7 | 1 gm Si source + 100 g soil + 500 ml water, bottle roll @ 4rpm for 16 hour, sit 8 hours, bottle roll @ 4rpm for 16 hour | |
| 8 | Elemental analysis using X-ray fluorescent spectrophotometry | |

Indirect Chemical Extraction after soil incubation

A sub-set of products was tested further by extracting the available soil Si present following a period of incubation. The silicate products were thoroughly mixed into 500 gm soil (sandy loam soil, classified as a acidic stratic Rudosol according to the new Australian soil classification), at a rate equivalent to 12 t/ha (2.86 g/500 g soil), and transferred to a PVC tube (5 cm diameter x 15 cm in height). The bottom of the tubes were covered with 50 micron nylon mesh, the soil was watered regularly and allowed to drain freely.

After 16 weeks, the soil solution was extracted from the moist, but fully drained soils, by centrifuging for 30 minutes at 2000 rpm (859 rcf). The solution collected was

Table 10.2. Total elemental analysis (%) from a range of silicate materials and their corresponding extractable Si content (mg Si/kg product) using a number of different extraction procedures

| Product | Chemical extraction methods (mg Si / kg product) | | | | | | | XRF (%) | | | | | |
|---|--|----------|----------|----------|----------|----------|----------|------------------|--------------------------------|--------------------------------|------|-------|-------------------|
| | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 | Method 6 | Method 7 | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | MgO | CaO | Na ₂ O |
| Calcium silicate slag | 13876 | 20970 | 26187 | 100.75 | 71.89 | 2140 | 8.99 | 46 | 2.94 | 1.9 | 0.6 | 44.07 | 0.79 |
| filtercake (scrubber waste) | 697 | 31259 | 1962 | 31.05 | 33.23 | 11609 | 2.22 | 27.4 | 0.43 | 0.48 | 1.03 | 24.07 | -0.06 |
| cement | 10616 | 51117 | 27338 | 57.75 | 50.61 | 3616 | 0.09 | 20.9 | 4.40 | 3.24 | 1.82 | 62.83 | 0.00 |
| concrete | 282 | 4239 | 2418 | 0.32 | 1.79 | 448 | 7.77 | 64.4 | 9.57 | 2.17 | 0.45 | 8.23 | 3.81 |
| olivine (natural magnesium silicate) | 766 | 2710 | 1662 | | | 1163 | 16.32 | | | | | | |
| wollastonite (natural calcium silicate) | 1752 | 33783 | 4587 | 3.83 | 24.05 | 1100 | 16.04 | 54.2 | 6.91 | 2.33 | 1.44 | 29.80 | 1.45 |
| acidulated olivine | 1091 | 12200 | 11693 | | | 9045 | 22.24 | | | | | | |
| acidulated serpentine | 181 | 1425 | 1826 | | | 173 | 8.66 | | | | | | |
| CaSO ₄ | 163 | 380 | 166 | | | 96 | 4.28 | | | | | | |
| Dow Corning BP060 gels | 1562 | 4815 | 2186 | 4.29 | 8.37 | 3635 | 13.45 | 33.2 | 0.70 | 0.15 | 0.94 | 6.83 | 0.00 |
| Dow Corning BP065 filtercake | 3843 | 14946 | 8128 | 31.35 | 21.71 | 3596 | 6.20 | 17.6 | 1.40 | 0.73 | 3.39 | 17.04 | 0.00 |
| alumina red mud | 379 | 44259 | 21158 | 0.00 | 0.00 | 630 | 47.80 | 17.8 | 19.20 | 32.05 | 0.50 | 2.52 | 7.90 |
| alumina red mud (neutralised with salt water) | 689 | 45145 | 25321 | 0.00 | 0.00 | 1020 | 66.35 | 20.3 | 20.64 | 26.14 | 0.70 | 1.18 | 12.93 |
| alumina red mud (neutralised with CaOH) | 100 | 44658 | 1101 | | | 844 | 0.91 | 11.95 | 19.73 | 14.67 | 0.38 | 25.77 | 4.59 |
| Stanwell flyash | 498 | 4978 | 2342 | 2.24 | 2.14 | 2365 | 13.82 | 54.0 | 23.60 | 9.20 | 1.22 | 4.58 | 0.36 |
| lime kiln dust | 2269 | 11698 | 4002 | 1.05 | 1.38 | 2165 | 6.44 | 12.7 | 8.48 | 0.97 | 0.68 | 42.91 | 0.53 |
| diatomaceous earth | 152 | 750 | 287 | 6.01 | 5.44 | 252 | 4.70 | 68.2 | 16.30 | 4.08 | 0.57 | 0.93 | 0.07 |
| Na bentonite | 71 | 429 | 390 | | | 101 | 3.88 | | | | | | |
| Colloidal clay soft rock P | 46 | 5172 | 1805 | | | 77 | 3.13 | | | | | | |
| Nutri-Phos soft rock | 45 | 4467 | 1788 | | | 82 | 3.52 | | | | | | |
| B'kin Lime Co soft rock P | 55 | 4970 | 2129 | | | 143 | 3.04 | | | | | | |
| Guano gold | 104 | 2263 | 593 | | | 57 | 3.66 | | | | | | |
| Oaky kaolonite | 55 | 493 | 254 | | | 108 | 3.54 | | | | | | |
| sugar cane mill ash | 1156 | 3029 | 1690 | | | 806 | 13.74 | 91.19 | 2.22 | 2.54 | 0.62 | 0.55 | 0.06 |

Table 10.3. Chemical characteristics of the soil and the soil solution following 16 weeks incubation of the soil with various silicate sources.

| Treatment (applied at 12t/ha) | Soil extraction | | | | | | | | | Soil solution | |
|---|-----------------|---------------|----------------------------------|------------|------|------|-------|----------------|-------|---------------|------------------------------|
| | pH | EC (uS/cm) | CaCl ₂ Si mg/kg | Ca | Mg | K | Na | sum cations | CEC | pH | Si (mg Si/ kg AD soil) |
| | | | | cmol(+)/kg | | | | | | | |
| control | 5.50 | 40 | 8.20 | 0.69 | 0.15 | 0.1 | 0.059 | 1.00 | 1.69 | 4.81 | 0.51 |
| Calcium silicate slag | 8.13 | 124 | 60.00 | 11.49 | 0.12 | 0.11 | 0.14 | 11.86 | 10.37 | 7.5 | 1.59 |
| filtercake (scrubber waste) | 7.52 | 132 | 12.60 | 6.75 | 0.18 | 0.14 | 0.15 | 7.21 | 6.19 | 6.69 | 0.33 |
| CaSO ₄ | 4.64 | 1139 | 8.30 | 4.09 | 0.04 | 0.13 | 0.07 | 4.34 | 1.90 | 4.29 | 0.74 |
| cement | 9.21 | 208 | 22.80 | 11.76 | 0.07 | 0.15 | 0.08 | 12.06 | 7.40 | 8.4 | 0.31 |
| concrete | 6.82 | 74 | 16.60 | 3.12 | 0.18 | 0.16 | 0.08 | 3.54 | 3.80 | 6.29 | 0.87 |
| olivine (natural magnesium silicate) | 6.12 | 101 | 14.70 | 0.73 | 1.49 | 0.14 | 0.07 | 2.42 | 2.64 | 5.4 | 0.97 |
| acidulated olivine | 6.06 | 280 | 15.50 | 1.23 | 1.86 | 0.15 | 0.09 | 3.33 | 2.88 | 5.23 | 1.05 |
| acidulated serpentine | 4.76 | 276 | 13.20 | 0.29 | 1.08 | 0.12 | 0.06 | 1.54 | 1.56 | 4.29 | 1.03 |
| wollastonite (natural calcium silicate) | 7.47 | 117 | 62.40 | 6.87 | 0.52 | 0.13 | 0.08 | 7.59 | 6.81 | 6.79 | 1.61 |

Table 10.4. Comparison of the 0.01M CaCl₂ extractable soil Si and soil solution Si to the concentration of extractable Si from the various silicate materials used in the incubation study.

| Treatment (applied at 12t/ha) | CaCl ₂ ext. soil Si mg/kg | Soil solution Si (mg Si/ kg AD soil) | Chemical extraction methods (mg Si / kg product) | | | | | | |
|---|--|---|--|-------------|-------------|-------------|-------------|-------------|-------------|
| | | | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 | Method 6 | Method 7 |
| control | 8.20 | 0.51 | | | | | | | |
| Calcium silicate slag | 60.00 | 1.59 | 13876 | 20970 | 26187 | 100.75 | 71.89 | 2140 | 8.99 |
| filtercake (scrubber waste) | 12.60 | 0.33 | 697 | 31259 | 1962 | 31.05 | 33.23 | 11609 | 2.22 |
| CaSO ₄ | 8.30 | 0.74 | 163 | 380 | 166 | | | 96 | 4.28 |
| cement | 22.80 | 0.31 | 10616 | 51117 | 27338 | 57.75 | 50.61 | 3616 | 0.09 |
| concrete | 16.60 | 0.87 | 282 | 4239 | 2418 | 0.32 | 1.79 | 448 | 7.77 |
| olivine (natural magnesium silicate) | 14.70 | 0.97 | 766 | 2710 | 1662 | | | 1163 | 16.32 |
| acidulated olivine | 15.50 | 1.05 | 1091 | 12200 | 11693 | | | 9045 | 22.24 |
| acidulated serpentine | 13.20 | 1.03 | 181 | 1425 | 1826 | | | 173 | 8.66 |
| wollastonite (natural calcium silicate) | 62.40 | 1.61 | 1752 | 33783 | 4587 | 3.83 | 24.05 | 1100 | 16.04 |

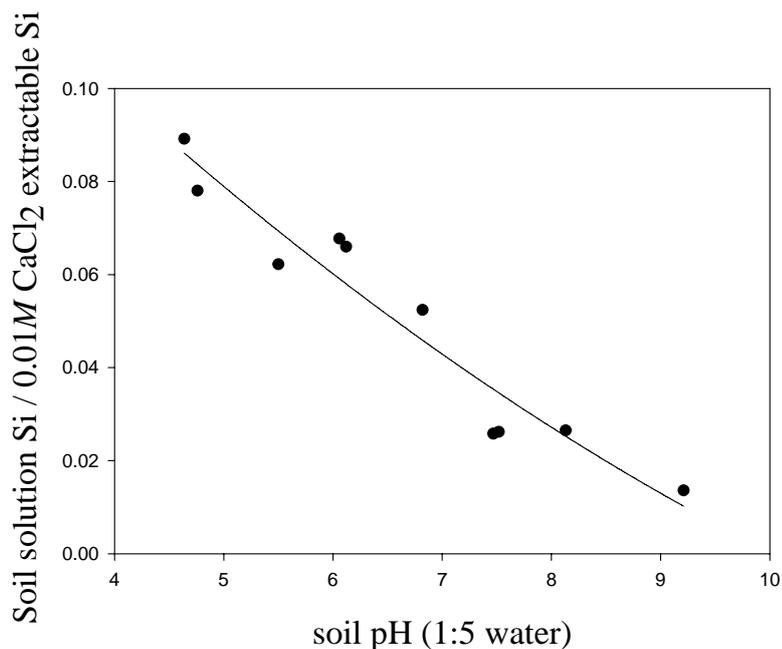


Figure 10.1. The relationship of 0.01M CaCl₂ extractable soil Si and soil solution Si to soil pH

passed through a 0.45 micron filter prior to analysis for pH and soluble Si. The wet weight of the soil, and the volume of soil solution extracted were recorded, and the % soil moisture calculated to allow solution concentration of Si to be expressed as mg Si /kg AD soil. The remaining soil was air dried, sieved through a 2 mm sieve and analysed for pH, electrical conductivity, 0.01M CaCl₂ extractable soil Si, exchangeable cations and cation exchange capacity (Table 10.3). The relationship between 0.01M CaCl₂ extractable soil Si and soil solution Si was significantly correlated at 5% level of significance ($r^2 = 0.60$). For most of the products the value of extractable Si was approximately 15 times that of the soil solution (magnitude difference partly due to differences in extraction ratios). Four outliers, calcium silicate slag, filtercake scrubber waste, wollastonite and cement had concentrations of 38, 38, 39 and 74 times greater than the soil solution concentration respectively (Table 10.1). The reason for this becomes clear when the ratio of soil solution Si / extractable Si is plotted against soil pH (Table 10.1). This produces a highly significant relationship ($r^2 = 0.94$) and demonstrates the effect of a high soil pH on reducing the solubility of Si (Table 10.1).

Comparing the chemical extraction results for the various products, to the extractable soil Si or the soil solution Si indicates poor relationships with the exception of method 7, which was significantly correlated at 5% level of significance, to the soil solution Si. The results suggest that a technique to estimate the available Si as described for method 7, may provide a reasonably rapid means of assessing the potential of a product. In addition, adaptation of the method to include a series of product addition rates more in keeping with field application rates, and using a representative selection of soil types, may also assist in developing semi-quantitative recommendations for field application.

Biological Extraction

In order to relate chemical extraction data determined from a range of silicate materials (Table 10.2), to changes in soil chemical composition and plant uptake of Si, a greenhouse incubation study was undertaken. The soil used was a sandy loam (classified as an acidic dystrophic Kandosol by the new Australian soil classification) and known to have low available soil Si concentration. The treatments (Table 10.5) were thoroughly mixed throughout the soil and placed in free draining pots. Pots were watered for 2 months allowing leaching to occur. The trial was replicated 3 times. At the end of this equilibration period soils were air-dried and a sub-sample collected for chemical analysis. The pots were then established to rice and two crops were grown successively. The plant material was combined for chemical analysis.

Table 10.5. Materials and rates of application made to soil for the incubation study.

| Source material | Rates of application (t/ha) |
|--|-----------------------------|
| Control | 0 |
| Calcium silicate slag | 4, 8, 12 |
| Filtercake (scrubber waste) | 4, 8, 12 |
| Cement | 4, 8, 12 |
| Concrete | 4, 8, 12 |
| Wollastonite | 4, 8, 12 |
| Dow Corning BP060 gels | 4, 8, 12 |
| Dow Corning BP065 filtercake | 4, 8, 12 |
| Alumina red mud | 4, 8, 12 |
| Alumina red mud (neutralized with sea water) | 4, 8, 12 |
| Stanwell fly ash | 40, 80, 120 |
| Lime kiln dust | 4, 8, 12 |
| Diatomaceous earth | 4, 8, 12 |

Significant interactions between rate and source were observed for extractable Si using 0.01 M CaCl₂, exchangeable cations, pH and CEC. All sources other than the diatomaceous earth had a significant effect on soil pH (Table 10.6). The greatest increase in pH was observed in those treatments receiving cement, Stanwell fly ash and lime kiln dust. Exchangeable Ca increased with increasing additions of materials, other than for the bauxite red mud, which had no significant effect on this attribute. Cement, lime kiln dust and calcium silicate slag had the greatest effect on exchangeable Ca. Most sources had little effect on exchangeable Mg and in some cases reduced the amount on the exchange complex with increasing rates. The Stanwell fly ash significantly increased exchangeable Mg. Exchangeable K was largely unaffected by source or rate of application. However, cement and lime kiln dust increased the exchangeable K content. The two red mud materials resulted in significant increases in the exchangeable Na content of the soils. Most other treatments tended to reduce the Na content with increased application rates. The cation exchange capacity increased in all cases from the control, with cement resulting in the largest increase followed by lime kiln dust, and the diatomaceous earth causing the smallest increase in CEC followed by the Dow Corning and red mud products.

Extractable Si levels after 2 months incubation are presented in Table 10.6. Products varied significantly with respect to the amount of Si extracted with 0.01 M CaCl₂ with

Wollastonite, the red muds, calcium silicate slag and cement having greater amounts of extractable Si. The filtercake (scrubber waste), concrete, lime kiln dust, diatomaceous earth and Dow Corning BP060 gels had little effect on extractable Si.

There was a significant response to both rate and amendment on the growth of rice (Table 10.6). The best performing amendments were calcium silicate slag, wollastonite and the Stanwell flyash (Table 10.6). Although the Stanwell flyash treatment yielded well, and there was an increase in both soil and plant concentrations of Si, it would be difficult to attribute the response in this treatment to enhanced Si, as this treatment also had a significant impact on soil Mg levels. The diatomaceous earth and Dow Corning BP060 gels had no significant affect on yield whilst the un-neutralized red mud had a negative impact on the growth of rice. In the latter case it is assumed this is associated with the elevated Na levels in this product.

The influence of elevated soil pH on the concentration of extractable soil Si is again demonstrated clearly by comparing the soil Si values obtained with the three 'calcium silicate' products, namely calcium silicate slag, cement and wollastonite (Figure 10.2). Extractable Si levels were depressed at pH's greater than approximately 7.5 (calcium silicate slag at 12 t/ha, and cement at both 8 and 12 t/ha).

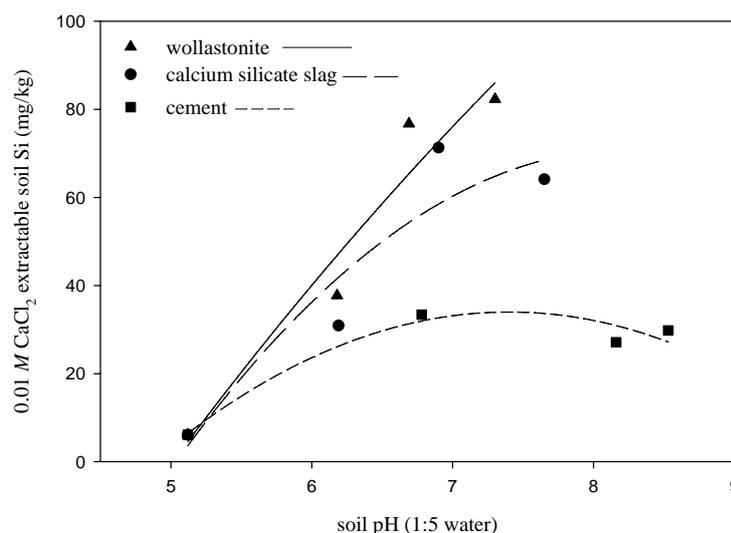


Figure 10.2. The effect of increased soil pH on concentration of extractable soil Si

Despite the confounding influences of soil pH, or other nutrient imbalances due to the differing chemical characteristics of the silicate materials, plant Si uptake and plant Si % were significantly correlated with the extractable soil Si levels (Table 10.6). At the higher product application rates, soil and plant Si concentrations tend to plateau, or in some cases decline, due to soil factors associated with the amendment, or simply due to polymerization of soluble Si because of the higher levels of monosilicic acid present. For these reasons, only the soil and plant data obtained from the lowest application rate (4 t/ha) was considered and compared to the values of Si extracted from the various silicate materials (Table 10.5), using the chemical extraction techniques described in Table 10.1. It is clear that products that have result in high levels of soil and plant Si generally have relatively higher levels of extractable Si in

Table 10.6. Changes in soil pH, extractable soil Si, plant weight and plant uptake of Si as a result of the various silicate amendments

| Product | Soil pH | | | | Extractable soil Si (mg/kg) | | | | Plant wt. (g/pot) | | | | Total plant uptake (mg Si/pot) | | | |
|---|---------|--------|--------|---------|-----------------------------|--------|--------|---------|-------------------|--------|--------|---------|--------------------------------|--------|--------|---------|
| | 0 t/ha | 4 t/ha | 8 t/ha | 12 t/ha | 0 t/ha | 4 t/ha | 8 t/ha | 12 t/ha | 0 t/ha | 4 t/ha | 8 t/ha | 12 t/ha | 0 t/ha | 4 t/ha | 8 t/ha | 12 t/ha |
| Control soil | 5.12 | | | | 6.1 | | | | 3.1 | | | | 13 | | | |
| Calcium silicate slag | | 6.19 | 6.90 | 7.65 | | 30.9 | 66.0 | 64.1 | | 4.7 | 5.2 | 4.8 | | 46 | 90 | 74 |
| filtercake (scrubber waste) | | 6.15 | 6.48 | 7.03 | | 4.9 | 7.1 | 6.7 | | 4.1 | 5.1 | 5.1 | | 15 | 20 | 24 |
| cement | | 6.78 | 8.16 | 8.55 | | 33.4 | 27.1 | 29.8 | | 4.4 | 4.3 | 4.0 | | 43 | 45 | 41 |
| concrete | | 5.55 | 5.77 | 6.01 | | 8.9 | 11.1 | 15.6 | | 3.8 | 4.5 | 4.9 | | 21 | 24 | 26 |
| wollastonite (natural calcium silicate) | | 6.18 | 6.70 | 7.30 | | 37.7 | 76.7 | 82.3 | | 4.7 | 5.1 | 5.2 | | 54 | 98 | 117 |
| Dow Corning BP060 gels | | 5.89 | 6.13 | 6.47 | | 6.4 | 7.5 | 9.5 | | 3.8 | 3.7 | 3.9 | | 17 | 19 | 24 |
| Dow Corning BP065 filtercake | | 6.78 | 7.36 | 7.93 | | 13.2 | 14.9 | 19.7 | | 4.9 | 4.8 | 2.9 | | 26 | 31 | 26 |
| alumina red mud | | 6.31 | 6.68 | 7.15 | | 26.1 | 44.3 | 68.2 | | 3.2 | 2.1 | 0.8 | | 45 | 61 | 34 |
| alumina red mud (neutralised with salt water) | | 6.11 | 6.50 | 6.83 | | 20.9 | 30.0 | 44.3 | | 3.7 | 3.9 | 4.3 | | 35 | 56 | 72 |
| Stanwell flyash | | 6.71 | 7.32 | 8.10 | | 13.1 | 17.3 | 16.9 | | 5.5 | 5.3 | 5.2 | | 32 | 40 | 38 |
| lime kiln dust | | 6.48 | 7.54 | 8.08 | | 8.5 | 7.1 | 9.4 | | 5.1 | 4.6 | 4.0 | | 15 | 19 | 21 |
| diatomaceous earth | | 5.14 | 5.17 | 5.16 | | 6.9 | 7.2 | 9.3 | | 3.2 | 3.1 | 3.0 | | 13 | 13 | 14 |
| Isd 5% | 0.07 | | | | 3.2 | | | | 0.7 | | | | 14 | | | |

the product, regardless of the methods used. However, conversely, there are a number of products that also have high levels of extractable Si, for example, the lime kiln dust (all methods) and filter cake-scrubber waste (Methods 2 and 6) (Table 10.2), but have caused very marginal changes in extractable soil Si or plant uptake of Si (Table 10.6). Therefore, in most cases, care should be taken when using these product extractant methods as a predictive tool for assessing the potential of a material to supply plant-available Si.

However, for the range of silicate materials used in this incubation/bioassay experiment, extraction Method 3 (water + resin) did prove to be well correlated with both soil and plant Si concentrations, with the exception of wollastonite (Figure 10.3). This may be due to wollastonite having a lower solubility and a longer extraction time may improve this relationship. The method described by Kato and Owa (1997b), used 0.2 g product + 0.5 g resin in 400 ml distilled water and was placed on a reciprocal shaker for 96 hours. This is a more vigorous shake and a longer equilibration time than used in these experiments. Adopting similar methodology as described by Kato and Owa (1997b) may further improve the efficacy of this method.

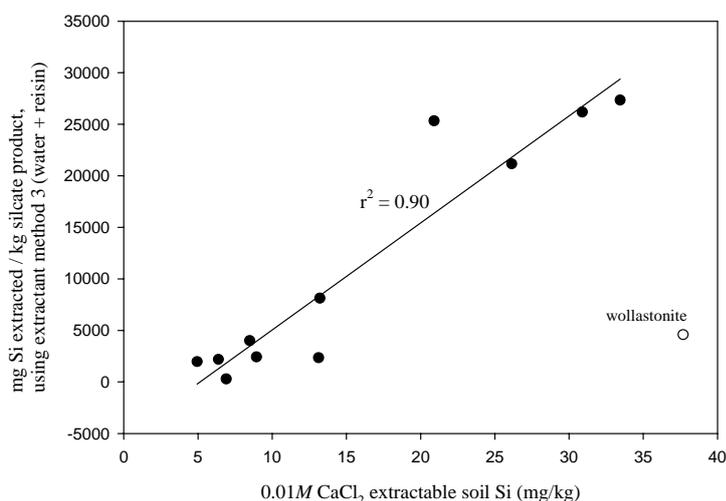


Figure 10.3. The relationship of 0.01 M CaCl₂ extractable soil Si (mg/kg), to the level of extractable Si in the various silicate materials, using Extraction Method 3 (resin + water).

Summary

This series of experiments indicate that there no proven or reliable method for assessing the availability of Si in potential Si sources. However, of the methods tested the extraction method developed by Kato and Owa (1990), using the addition of a weakly acidic cation exchange resin in the H⁺ form (Amberlite IRC-50) to the extraction medium, appears to be the most successful. Recent work by Pereira *et al.* (2003), comparing a similar range of extraction methods as used in these experiments, and testing them against 12 different sources of Si material, also found the highest correlation with Si content and Si uptake in rice was obtained with the ‘resin’ method.

Based on these results, of the methods presently available, the 'Resin' method is recommended as the first estimate of plant-available Si in potential sources of silicate materials. In addition, it is considered that further refinement of the soil-based equilibration method (Method 7, Table 10.1), to include a series of product addition rates more in keeping with field application rates, and using a representative selection of soil types, may also assist in developing semi-quantitative recommendations for field application.

11. Extension and Publications

From the initiation of the project, the importance of establishing awareness within the Industry of the role of Si in cane production was recognised. To this end, extension and communication of results has been a high priority by all researchers involved in the project. In addition, BSES extension staff were included from the out-set of the project to be responsible for extension and technology transfer. This role was initially filled by Peter Lawrence, BSES, Innisfail, and later by David Calcino, BSES, Meringa.

Growers have been continually informed of progress with respect to the studies on a one-to-one basis and have taken a keen interest in outcomes. Posters have been provided and displayed at BSES Field days at Bundaberg, Mackay, Ingham, Meringa and Tully

In addition, at various times, presentations have been made to Grower groups. Trial sites at Bundaberg were visited by the BSES Board, Cane Talk discussion groups and Grower Services Officers. During 2000, Graham Kingston made presentations at the Southern Region Cane Protection & Productivity Boards conference in Maryborough, to an ASMC breakfast meeting, to the Elliott River "Cane Talk" group and to INCITEC and southern region extension staff. Suzanne Berthelsen, Graham Kingston and Alan Hurney were invited to give a presentation of project results at the Fertilizer Recommendation Advisory Committee meeting held in Townsville in June 2000. In 2001, Alan Rudd and Suzanne Berthelsen attended the Mossman Productivity meeting at Port Douglas to present outcomes of the project.

During the course of the project there have been a large number of media releases including newspaper and farming magazine articles and radio and television interviews. Many of these articles have attracted the attention of a significant international audience resulting in requests for contributions to several on-line sugar journals.

Outcomes from the project have been disseminated through a number of Conference presentations, including a presentation at ASSCT Conference in Townsville in 1999, two presentations at the ASSCT Conference in Mackay in 2001, and presentations made at two international "Si in Agriculture" Conferences held at Fort Lauderdale, Florida in 1999 and at Tsuruoka, Japan in 2002. Poster presentations were also included at all of these conferences. Papers arising from these presentations have been published.

Conference Presentations:

Paper presentation at the ASSCT Conference held at Townsville in April 1999, entitled "An assessment of soil and plant silicon levels in north Queensland", presented by Suzanne Berthelsen.

Poster presentation at the ASSCT Conference held at Townsville in April 1999, entitled "Soil analysis for predicting sugarcane response to silicon", presented by Graham Kingston and Mike Haysom.

Keynote address at the Silicon in Agriculture Conference held at Fort Lauderdale, Florida in September 1999, entitled “Silicon Research Down Under: Past, Present and Future”, presented by Suzanne Berthelsen.

Poster presentation at the Silicon in Agriculture Conference held at Fort Lauderdale, Florida in September 1999, entitled “Silicon is involved in cane yield response to sugar mill waste products”, presented by Graham Kingston.

Paper presentations at the ASSCT Conference held at Mackay in May 2001, entitled “An assessment of current silicon status of sugarcane production soils from Tully to Mossman” and “Plant cane responses to silicated products in the Mossman, Innisfail and Bundaberg districts”, presented by Suzanne Berthelsen.

Paper presentation at the Second Silicon in Agriculture Conference held in Tsuruoka, Japan in August 2002, entitled “Effect of calcium silicate amendments on soil chemical properties under a sugarcane cropping system”, presented by Suzanne Berthelsen.

Poster presentations at the Second Silicon in Agriculture Conference held in Tsuruoka, Japan in August 2002, entitled “Increased co-accumulation of iron and silicon may be responsible for greener leaves in sugarcane treated with silicated amendments” and “Yield response of sugarcane from uptake of applied silicon in Australia.” presented by Graham Kingston.

Keynote address, presented by Andrew Noble, entitled “Quantification of chemical degradation and its remediation in tropical Australia, China and Thailand” presented at the International Symposium on Sustainable Land Management in the Tropics: Planning and Action in June 2002 in Haikou, Hainan, China, highlighted results from this project with particular reference to charge generation associated with Ca-silicated materials

Published Papers

Berthelsen, S., Noble, A. D and Garside, A L. (1999), An assessment of soil and plant silicon levels in north Queensland. *Proc. Aust. Soc. Sugar Cane Technol.* 21: 92-100

Berthelsen, S., Noble, A. D and Garside, A L. (2001), Silicon research down under: Past, present and future. In ‘Silicon in Agriculture’, Datnoff, L. E., Snyder, G.H. and Korndorfer, G. H. (Editors), Elsevier Science B. V. Amsterdam, the Netherlands.

Berthelsen, S., Hurney, A.H., Noble, A. D., Rudd, A., Garside, A. and Henderson, A. (2001), An assessment of current silicon status of sugarcane production soils from Tully to Mossman. *Proc. Aust. Soc. Sugar Cane Technol.* 23: 289-296

Berthelsen, S., Hurney, A. H., Kingston, G., Rudd, A., Garside, A. and Noble, A. D. (2001), Plant cane responses to silicated products in the Mossman, Innisfail and Bundaberg districts. *Proc. Aust. Soc. Sugar Cane Technol.* 23: 297-303

Noble, A. D., Moody, P., Guodao, L., Ruaysoongnern, S., Zhiping, Qi and Berthelsen, S. (2003), Quantification and remediation of soil chemical degradation in tropical Australia, China and Thailand. *Pedosphere* 13(1):31-39

Berthelsen, S., Noble, A., Kingston, G., Hurney, A and Rudd A. Effect of Ca-silicate amendments on soil chemical properties under a sugarcane cropping system. (in preparation for publication)

Posters

The series of posters have been used over the term of the project at BSES field days have been updated when necessary to reflected current results, including:

“Impact of silicon on sugarcane productivity”

“Increased yield from silicon additions to a Mossman plant crop”

“An assessment of silicate-based products and their potential use in the sugarcane industry”

“Silicon: an important nutrient in sugarcane production in the tropics”

“An assessment of current silicon status of sugarcane production soils from Tully to Mossman”

“Silicon deficiency–risk maps of the Tully – Innisfail areas”

Media Releases

CSIRO Media release in October 1998, entitled “Silicon implant, sugar? Soil maps show the way” resulted in a number of radio news reports, newspaper and magazine articles, including:

- The Proserpine Guardian, October 22, 1998, p 28 “Silicon implant for sugar...Soil maps show the way”
- The Herbert River Express, October 22, 1998, p 9 “Silicon boosts growth”
- The Land, October 22, 1998, p 45 “Silicon sugarcane”
- Queensland Country Life, November 5, 1998, “Silicon boosts cane yields”
- Canegrower magazine, October 26, 1998, p 25 “Cane shows liking for silicon”
- Farming Ahead magazine, No. 83, November, 1998, p 30 “Silicon proves vital for sugarcane”
- Australian Sugarcane magazine, October-November 1998, p15 “Silicon: gives sugarcane a much needed boost as well” and p 18 “Increases in cane and sugar yields from Mossman silicon trials”
- ABC Regional Radio Mackay – radio news October 21, 1998
- Toowoomba 4QS – radio news October 21, 1998

CSIRO Media release in October 2000, entitled ‘Silicon ‘implant’ to bolster sugar industry” ” resulted in a number of radio news reports, newspaper and magazine articles, including

- Rockhampton WIN TV News
- Townsville WIN TV News
- Toowoomba WIN TV News
- ABC NSW Regional Radio
- ABC National Regional Radio
- ABC Qld Regional Radio
- ABC Radio National Earth Beat

- Herbert River Express (Ingham).
- Australian Cane Grower magazine, November 6, 2000 “Researchers find 70% yield increase on silicon-treated soil”
- Queensland Country Life, July 19, 2001, p 25 “Silicon boost lifts cane yields”
- On-line journal Alchemist ‘Sweeter Yields from Silicon Fields’ www.chemweb.com/alcem/2000/news/nw_001102_silicon.html
- Queensland Country Life, Sept 6, 2001, p 28 “Silicon delivers at Bundy” and p 29 “Big response to silicon injection”
- Farming Ahead magazine, 2001 “Silicon trials show dramatic boost in sugar production”
- Land and Water Link, “Silicon boosts sugar production”

12. General discussion and Conclusion

The majority of agricultural soils of the wet tropical coast of north Queensland have been cropped to sugarcane for approximately 50 to 100 years. Under the high temperature, rainfall and leaching conditions of these environments, soils undergo significant weathering, resulting in the base stripping from the exchange complex and a decline in surface charge capacity. The consequences of these weathering processes, combined with accelerated chemical and physical degradation due to soil perturbation and crop removal, are increased soil acidification and dissolution of the alumino-silicate clay minerals (de-silication). This results in both a loss of plant available Si through leaching and a decline in cation exchange capacity and hence an inability to retain essential plant.

The current project has highlighted that large areas of cane-growing soils in North Queensland have sub-optimal levels of plant-available Si. The sites selected for the survey represented the dominant soil series present within the major soil types found in these areas. Based on the current soil test, some 85% of soils that were evaluated in the six mill areas on the wet tropical coast have sub-optimal to marginal levels of available Si. Hence the implications of silicon deficiency for substantial areas under sugarcane production, and therefore the potential yield benefit from prophylactic applications of silicate materials are enormous.

A major objective of this project was to quantify responses in cane yield and CCS to Si application. To address this objective, six major field trials were established in Bundaberg, Innisfail and Mossman. These trials included (a) Si rate trials, which used a range of application rates of calcium silicate slag (0, 1.5, 3, 4.5, 6, 9 and 12 t/ha), and (b) trials designed to evaluate the efficacy of various sources of Si. The Si rate trials demonstrated substantial yield increases to applied calcium silicate slag. At Innisfail, over the 2 years of the trial, there was a 32% increase in total yield at a rate of 9t/ha Ca-silicate (189 t/ha) when compared to the control treatment (128 t/ha). At Mossman, a rate of 12 t/ha gave a 35% total yield increase (161 t/ha) compared to the control (105 t/ha) over the same time period. While at Bundaberg, over a crop cycle of 3 years, the 12 t/ha rate of Ca-silicate resulted in a 23 % increase (278 t/ha) compared to the control (213 t/ha). Contrary to indications from the literature that Si may have a positive effect on sugar accumulation, these trials did not demonstrate an increase in CCS following silicate application. However, the fact that CCS was not depressed at final harvest by silicate application could be considered a positive result, as generally CCS tends to decline as yields increase. The results clearly indicate that silicon should be treated as an integral part of any fertilizer strategy associated with cane production.

In addition, detailed study of the soil chemical response on the contrasting soil types at the Mossman (sand) and Innisfail (basaltic clay loam) demonstrated significant increases in pH, pH buffer capacity, exchangeable Ca, cation exchange capacity (CEC), readily soluble Si_(sol), extractable Si_(ext) and P in all treatments receiving Ca-silicate additions. The effect of differing soil chemical characteristics on the ability of silicate additions to increase plant available soil Si levels was clearly demonstrated, with the Innisfail soil exhibiting large and sustained increases in available Si compared to the Mossman site. The results obtained from Innisfail may indicate the importance of amorphous alumino-silicate surfaces on the sesquioxides in supplying

soluble Si. In contrast, it appears that the soil properties of the Mossman site are such that the levels of $\text{Si}_{(\text{sol})}$ in the soil solution are more dependent on the dissolution of applied Ca-silicate, and that by the second year the solubility of this source had declined significantly. Most of the increase in CEC is associated with the variable charged surfaces, likely to be due to the development of amorphous aluminosilicate surfaces in the Innisfail soil, and possibly the formation of Al-Si gels/coatings on quartz surfaces at Mossman. Over the 24 month period the charge generation associated with the highest Ca-silicate application was in the order of 1.0-1.62 cmol_c/kg . Assuming that the bulk density of the soil is 1200 kg/m^3 this would equate to approximately 240-380 kg of Ca^{2+} , 144-184 kg of Mg^{2+} or 470-750 kg of K^+ that potentially could be retained on the exchange complex. Therefore, in addition to improved Si nutrition, the results suggest that the increase in CEC due to the application of Ca-silicate slag may contribute to the observed yield increases of sugarcane on these degraded and Si deficient soils.

The soil survey study and the field rate trials have clearly demonstrated a significant correlation between soil silicon levels and top visible dewlap (TVD) tissue levels and as such provides the basis of a useful diagnostic tool. The yield response observed in the Si rate trials demonstrated a strong and significant relationship exists between relative cane yield and TVD Si status ($r^2 = 0.73$). The asymptotic function provided by the regression analysis predicts that 95% of Y_{max} will be achieved with a TVD of 0.55% Si.

One focus of the project has been in developing reliable laboratory soil tests to adequately determine sub-optimality in soil Si levels, and also responsiveness to silicate amendments. The results indicate that the current soil tests used to determine Si status of the soil is effective when estimating the yield response to silicate additions, particularly for the light textured soils. Using 95% of Y_{max} as the response threshold, the rate trial data supports the current recommendations of 10 mgSi/kg soil in 0.01 M CaCl_2 extract and 100 mgSi/kg in 0.005 M H_2SO_4 extract. However, interpretation of soil and plant data for soils with a higher clay content and high sorptive ability due to significant quantities of Al and Fe oxides and hydroxides and still needs more understanding. In this case, because of the importance of clay in supplying soils with plant available silicon and the role that AEC from sesquioxide surfaces plays in retention of silicate and phosphate anions, normalising the soil data using a factor based on the (AEC / 100g clay) indicated that the 0.005 M H_2SO_4 extraction may be the most useful technique for providing management information about the critical part of the response curve when determining relative yield response to applied Si.

Grower and industry interest is evident as a number of commercial laboratories are now offering soil Si testing as part of their routine soil tests. However, it is felt that more work still needs to be done to define responsive soils, as, although some soils clearly have sub-optimal levels of soil Si, other properties associated with the soil can minimize the response to Si additions. Future work needs to further refine these soil-testing techniques to enable not only the prediction of 'sub-optimality', but importantly 'responsiveness' to silicate additions. Results from the soil survey have shown that the method of extraction is important for determining the level of available silicon in the soil and that caution should be taken when assessing results obtained solely with 0.005 M H_2SO_4 . While dilute salt solutions such as 0.01 M CaCl_2 provide

a measure of the readily available Si, stronger extractants like 0.005 M H₂SO₄ will solubilize the slightly available and more insoluble amorphous forms of Si. Although this may provide an indication of the total capacity of the soil Si pool, it may not be related to the concentration of soluble Si in the soil solution, as this tends to be controlled by the solubility of the most soluble silicate mineral, regardless of the amount present. Although these two tests, depending on the laboratory, are currently being used to predict 'sub-optimality', neither test on its own may be a reliable test to assess the 'responsiveness' of soils to applications of Si-based amendments. From results obtained in the survey, it was hypothesised that a combination of both tests may be a better indication of 'responsiveness'.

Developing a reliable laboratory test to provide the first estimate of the potential value of silicate sources has been another important focus. Considerable progress has been made using laboratory tests combined with soil incubation experiments to predict both the potential and possible application rates necessary for field applications. Progress was made in identifying locally available potential silicate materials, although none of the silicate materials tested within the scope of this project compared in efficacy with the calcium silicate slag imported from the USA. Identifying and testing further potential products is on-going, and before recommendations can be made on any products, comprehensive field testing needs to be undertaken on a range of soils showing sub-optimal Si levels. The need to identify suitable locally available products is an important issue as the importation of calcium silicate slag on a commercial basis at present is likely to be uneconomic.

Overall the project has been very successful in establishing awareness within the Industry of the role of Si in cane production, and has clearly demonstrated the potential yield benefits that can be obtained from the application of silicate materials. Extension and communication of results has been a high priority by all researchers involved in the project. Growers have been continually informed of progress with respect to the studies on a one-to-one basis and have taken a keen interest in outcomes. Outcomes from the project have been disseminated through published papers, Conference presentations, poster displays at BSES Field days, presentations to Grower and Industry groups, and via a large number of media releases including newspaper and farming magazine articles and radio and television interviews.

13. References

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Outputs

1. The soil survey results indicate substantial areas of sugarcane growing soils may benefit from prophylactic applications of Si. Results illustrate that plant available Si levels on the majority of soils on the coastal plain are low. Greater than 50% of all sites sampled had sub-optimal soil Si levels (< 10 mg/kg), and in excess of 85% of all sites had Si levels that have the potential to limit production (< 20 mg/kg).
2. The demonstrated significant correlation between soil Si levels and top visible dewlap tissue levels provides the basis for useful diagnostic tools. This current project has established reliable analytical methodology for determining plant-available soil Si. Many commercial laboratories now offer a soil Si tests for sugarcane soils based on both extraction with 0.05 M CaCl₂ and extraction with 0.005 M H₂SO₄, using a critical values of <10 and <100mg/kg respectively, as indicative of sub-optimal levels.
3. Demonstrated significant yield responses have been recorded to additions to Ca-silicate, which are still evident in the first and second ratoon crops. At Innisfail, over the 2 years of the trial, there was a 32% increase in total yield at a rate of 9t/ha Ca-silicate (189 t/ha) when compared to the control treatment (128 t/ha). At Mossman, a rate of 12 t/ha gave a 35% total yield increase (161 t/ha) compared to the control (105 t/ha) over the same time period. While at Bundaberg, over a crop cycle of 3 years, the 12 t/ha rate of Ca-silicate resulted in a 23 % increase (278 t/ha) compared to the control (213 t/ha).
4. Demonstration that calcium silicates improve the cation exchange capacity (CEC) of soils, thus improving the retention of essential nutrients and fertility of the soil. It was estimated that for every tonne of calcium silicate applied, CEC increased by approximately 0.15 cmol_c/kg.
5. Identification of appropriate methodology for determining available Si in various silicate products.
7. Growers have been continually informed of progress with respect to the studies. Posters have been provided and displayed at BSES Field days. Presentations have been made to Grower and Industry groups. During the course of the project there have been a large number of media releases including newspaper and farming magazine articles and radio and television interviews. Outcomes from the project have been disseminated through a number of Conference presentations. To date a total of 5 papers arising from the results have been published. Details are outlined in Chapter 11 (“Extension and Publications”).

Expected Outcomes

1. Improved awareness from the farming community and the fertilizer industry of the importance and role of Si in sugarcane nutrition.
2. International recognition of the work being carried out in Australia, including cooperative work with researchers in USA, Brazil, Japan, Russia.
3. Adoption of Si fertilization within the industry as an integral part of any fertilizer strategy associated with cane production. This will require the identification of a suitable local source of material that provides a cost effective supply of available Si.
4. Overall improved soil health and nutrient retention as a result of including silicate materials into the routine fertilizer strategy.
5. Improved cane yields, and therefore increased profitability and viability for growers and the industry in areas where plant-available soil Si levels are sub-optimal or marginal. Assuming 85% of North Queensland showed a 10% increase in yield due to application of Si-fertilizer, this would translate to an additional 70,000 tons of sugar, worth \$20 million per annum, in this area alone. The cost of Si-fertilizer to achieve this is currently unknown.

Recommendations and Future Research Needs

1. Reliable soil test/s for assessing responsiveness to applications of silicate materials

Although the two soil tests used in this project (0.01 M CaCl₂ and 0.005 M H₂SO₄) proved effective in predicting **sub-optimality** (and currently a number of commercial laboratories are offering both tests), neither test on its own may be a reliable test to assess the **responsiveness** of soils to applications of Si-based amendments. A combination of both tests may be a better indication of responsiveness. Some soils have a variable response to silicate additions for differing reasons, in part due to differing mineralogies. Soils will differ in their ability to adsorb added Si, predominantly due to the reactivity of the oxidic surfaces of Al and Fe oxides, and to a lesser extent silicated surface of the clay minerals

There needs to be a focus on refining soil-testing techniques, that will not only predict sub-optimality **but** also responsiveness to silicate additions. This could be based on a '2-test' approach for soil testing, changing the parameters that define the response quadrats if necessary, and determining if this an effective means to identify Si-responsive soils, and test a range of soils that fall into these different groups through both greenhouse and field based bio-assessment studies.

2. Understanding the conditions that influence the bioavailability of biogenic Si

Data from current field trials should enable an estimate to be made of the net export of Si in the cane harvest (stalk) and the net addition associated with trash retention (tops). This should demonstrate both the exploitative nature of sugarcane with respect to soil Si, and also give an indication of the amount returned as trash.

Initially, a study investigating Si release from trash vs burning (e.g. using leaching columns/ large pots, with additions of burnt trash, green trash, composted trash material etc.) needs to be undertaken. Assuming slow release from trash, the questions become 'how can we change the production system to enhance Si release' and/or 'how can we manipulate the trash input'.

System changes: Moving to a legume break suggests greater Si availability. There is a need to understand whether this due to changes in the C:N ratio, a break from cane allowing time for the soil to replenish available Si levels through natural dissolution, or changes in the microbial population that may enhance Si solubility.

Manipulation of trash: By decreasing the C:N ratio (eg. legume break crop input), preparation of trash compost by spreading harvest trash (and bagasse) in furrows, (adding N and P, cellulolytic fungal mixes, dunder) can we effect an increase in Si release from the trash.

3. Examine the impact of silicate additions on soil chemical properties and improved and sustained soil fertility

This could be achieved by a broad laboratory/greenhouse based study to include major soil types from representative sugarcane growing areas in north Queensland, and incubation experiments initiated using a selection of the most promising silicate amendments. In addition to using existing laboratory techniques for determining changes in soil Si, other innovative laboratory methods could be used to quantify levels of mono-, poly- and organo-silicic acids present in the soil and determine the role and significance of these different soil Si components on Si availability. In addition to these analytical methods, charge fingerprint analysis and soil tests which determine the 'Index of Si reactivity' and the 'Index of Si saturation', could be used to study the effects of the additions of various silicate materials on soil properties such as CEC, Si availability and other soil chemical and physical properties.

4. To continue to identify, develop and test sources of silicate materials that may prove beneficial for use as agricultural amendments

Before any source can be considered useful for agricultural applications it must meet a number of criteria, such as solubility, availability, suitable physical properties and be free or have acceptably low levels of contaminants. One of the most important criteria, and often the most difficult to achieve is solubility, as many natural sources are always combined with other elements and are largely insoluble. From a cost:benefit aspect, it is also important that the product is available at a reasonable distance from where it is required as generally large quantities of material are needed. Finding a silicate source that takes all these criteria into account demonstrates the difficulty of selecting a material suitable for agricultural purposes. Before recommendations can be made on any products, comprehensive field testing needs be undertaken on a range of soils showing sub-optimal Si levels.

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