REVIEW OF RESEARCH INTO THE ROLE OF SILICON FOR SUGARCANE PRODUCTION

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Abstract

Although silicon (Si) is one of the most abundant elements found in the earth's crust, it is mostly inert and only slightly soluble and available to plants. With the exception of potassium, sugarcane is known to take up more Si than any other mineral nutrient, with the potential to accumulate up to 400 kg ha^{-1} of Si, in a 12-month old irrigated crop. This paper documents some of the more important studies and outcomes of research into the Si requirement of sugarcane in countries such as Florida, Hawaii, Puerto Rico, Australia, Mauritius and South Africa. Early field studies conducted in South Africa have shown that four out of five field trials produced significant responses to the application of calcium silicate and these varied from 9 to 24 tc/ha. Current research in South Africa is focussed on the association between Si assimilation and host-plant resistance to the stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae) and conducting surveys of the silicon status of cane based on leaf and soil sample analysis.

Although the reasons for sugarcane responding to Si on certain soils at the global level are not fully understood, there is evidence which suggests that yield responses to Si may be attributed to a number of factors including, prevention of Al and Mn toxicities, protection from pest and fungal disease, better water use efficiency, improved P nutrition, reduced lodging, and improved photosynthesis through the more effective use of sunlight. Recent evidence suggests that Si may reinforce plant pest and disease resistance by stimulating the expression of natural defence reactions through the production of low-molecular weight metabolites, which include flavonoid phytoalexins.

Keywords: Silicon, silicic acid, calcium silicate, sugarcane, soil acidity, genotypic differences, stalk borer.

Introduction

For many years Si deficiency in crops was relatively unknown and this element was widely regarded as non-essential for plant growth, despite the fact that it is often present in the highest concentration amongst inorganic constituents. Members of the grass family such as sugar cane (*Saccharum officinarum* L.) and rice (*Oryza sativa* L.), accumulate large amounts of Si in the form of silica gel ($SiO_2.nH_2O$) that is localised in specific cell types. Sugarcane is known to absorb more Si than any other nutrient from the soil. In Puerto Rico, the above ground parts of a 12-month crop contained 379 kg ha^{-1} of Si, compared with 362 kg ha^{-1} of K and 140 kg ha^{-1} of N (Samuels 1969).

Despite the prominence of Si in the composition of sugarcane and rice, the plant physiological literature is nearly devoid of publications dealing with this element. The reason for this marked discrepancy is the conclusion that Si is not an "essential" element because most plants can grow in nutrient solutions lacking Si in their formulation. The essentiality of Si as a nutrient for higher plants is very difficult to prove because of its abundance in the biosphere. Even highly purified water contains about 20 nM Si (Werner and Roth, 1983) and correspondingly, the leaves of Si accumulator plants that were subjected to a so-called no-silicon treatment usually contain between 0.5 - 1.9 mg Si g^{-1} leaf dry weight. Epstein (1994) reported that such Si-deprived plants are experimental artifacts. They may differ from Si-replete plants in (i) chemical composition; (ii) structural features; (iii) mechanical strength; (iv) various aspects of growth including yield; (v) enzyme activities; (vi) surface characteristics; (vii) disease resistance; (viii) pest resistance; (ix) metal toxicity resistance; (x) salt tolerance; (xi) water relations; (xii) cold hardiness. Because of these largely functional differences, there is now a greater consensus amongst scientists to classify Si as a "functional" plant nutrient.

Worldwide, since 1960, a considerable amount of research has been conducted on the potential agronomic benefits of Si in sugarcane. Significant responses to silicon treatment in both cane and sugar yields, have been reported in several countries including Hawaii, Mauritius, South Africa, Puerto Rico, Florida and Australia (Fox *et al*., 1967; Wong You Cheong and Halais, 1970; Du Preez, 1970; Samuels, 1969; Elaward *et al*., 1982, Haysom and Chapman, 1975). Savant *et al* (1999) have recently extensively reviewed the literature concerning the Si nutrition of sugarcane but only scant reference was made to important studies conducted in South Africa, Mauritius and Australia. The objective of this paper is to assess outcomes of past and present research in sugarcane with special reference to studies conducted in the South African sugar industry.

The discovery of silicon deficiency in sugarcane

The discovery that applications of silica may benefit cane growth was made indirectly in Mauritius in 1947, by D'Hotman De Villiers. He found that applying finely crushed basalt could rejuvenate highly weathered sugarcane soils. In carefully conducted trials, cumulative yield responses of between 30 to 60 tc/ha were obtained over five crops to crushed basalt applied at rates varying from 200 to 400 t/ha. Subsequent studies based on soil and leaf analysis confirmed that it was the soluble silica in the basalt that caused the favourable yield increases (Halais and Parish 1963).

Under a warm sub-tropical climate, soils are subject to chemical weathering whereby Si and bases are removed through hydrolysis, carbonation, oxidation, hydration and reduction. The process is commonly referred to as desilicification of Si and is normally accompanied by an accumulation of Fe and Al oxides. Although Si is slowly released by the weathering of primary silica (Si) minerals (quartz) and alumino-silicate feldspar minerals, part is lost through leaching and in drainage. Of interest is that in a climate characterised by frequent wetting and drying, the potential for leaching of Si is greater than in a climate that is continuously moist (Baker and Scrivner, 1985). The rate of desilication in soils has been classified according to clay mineralogical systems that can be ranked with respect to Si-content and Si-solubility, as follows: 2:1 clays > 1:1 clays > Al and Fe oxides (Fox *et al*., 1967). In general, Si concentration in solution of highly weathered acid Oxisols soils is several times less than in less weathered soils neutral to alkaline vertisols (Foy, 1992).

For plant growth the important soluble forms of soil Si are monosilicic acid $(Si(OH)_4)_n$, various polymers and silica gels, Si adsorbed onto sesquioxidic colloidal surfaces, and slowly available forms released from both crystalline and amorphous minerals. The availability of Si in the soil is governed by a number of factors which include soil moisture, temperature, soil pH, organic complexes, particle size distribution, the presence of aluminium, iron and phosphate ions,as well as various exchange/dissolution reactions (Beckwith and Reeve, 1964, Jones and Handreck, 1963, 1965).

Role of silicon in overcoming soil mineral toxicities

Hawaain research

The first direct use of Si in the USA for improving sugarcane growth took place in Hawaii. In 1960-61, researchers from the University of Hawaii, used a low-phosphate silica slag, to improve the fertility of certain aluminous humic ferruginous latosols. Shortly afterwards, Clements(1965a), investigated a disorder called leaf freckling, comprising small rust-colored or brownish spots on the leaves of cane. In severe cases, it was found that affected lower leaves died prematurely and cane yield was reduced. In a series of field experiments leaf freckling was corrected with applications of TVA calcium silicate slag as well as obtaining significant increases in cane and sucrose tonnage (Clements 1965b). Subsequent analysis of sugar cane leaves and roots from the various treatments indicated that yield increases from silica were associated with an increased uptake of Si and a drastic reduction in the ratio of manganese to Si in the TVD leaf. The response to Si application was greatest when the soluble silica supply of the soil was low or when soluble levels of toxic manganese depressed the silicon levels in the plant. In addition to serving as a source of calcium when needed, applications of calcium silicate suppressed the uptake of Al and B, when they were present in toxic levels, by raising the pH of the soil. Clements concluded that calcium silicate eliminated, through precipitation, toxic levels of Al and Mn that were injurious to the roots and tops of cane. Calcium carbonate helped to improve soil conditions, but calcium silicate appeared to be more suitable for a more permanent correction (Clements *et al* 1974).

Ayres (1966) obtained responses to Si ranging from 9 to 18% in cane yield and 11 to 22% in sucrose yield for plant cane, following the application of 6.2 t ha^{-1} of electric furnace slag to aluminous humic ferruginous latosols in Hawaii. The beneficial effect of the slag on low Si soils lasted for four years, and the first ratoon crop produced about 20 % more cane and sugar (see Table 1). Ayres acknowledged Clement's reason for Si depressing Al and Mn toxicity in certain soils but he pointed out that in his trials, that these elements were not toxic. Instead, soluble Si was found to be low in both the soil and the plant and Ayres expressed the view that there was a level of extractable or available soil silicon below which there would not be satisfactory growth of sugar cane regardless of the supply of other available nutrients.

Table1. Summary of response to calcium silicate treatment in various early trials (percent increase over control).

Calcium silicate [t/ha]	Hawaii[Clements 1965] Plant crop only	Hawaii [Ayres 1966] Average two crops Plant &1R	Puerto Rico [Samuels 1969] Average two crops Plant &1R
2.5	-	13	-
4	10	22	19
6	-	-	24
8	16	-	36
10	-	-	-
12	14	25	38
16	17	-	29
18	-	-	10

Samuels and Alexander (1969) performed an interesting nutrient culture pot trial with quartz sand as the inert medium and showed that Mn uptake of the cane plant was suppressd as its Si supply was increased. As the Mn content of the plant declined, the Si content increased.

However, the converse did not apply as when the cane plant was faced with an excessive supply of Mn, it attempted to compensate by increasing its Si uptake.

Fox *et al* (1967) obtained highly significant correlations between several soil extractants for total Si and soluble silicon extracted from sugar cane leaf sheaths [R ranged from 0,92 to 0,97]. From these data tentative calibration ranges were proposed for classifying sugarcane into probable, questionable and unlikely Si deficiency (see Table 2).

In Mauritius, following the early discovery by D'Hotman DeVilliers (1947) that large increases in sugarcane yields were obtained from massive applications of finely ground basalt, Vlamis and Williams (1957) first suggested the possible role of controlling Mn toxicity, while Halais and Parish (1963) concluded that cane yield was inversely related to the Mn/SiO2 ratio in the cane sheath. Controlled solution culture investigations by Wong *et al* (1973) showed that maximum cane and sucrose yields occurred between 50 and 75 ppm Si applied as silicic acid. Leaf freckling symptoms only occurred in the zero Si control plots and once they appeared, they increased in intensity particularly in the older leaves, covering as much as

Table 2. Critical soil and leaf sheath Si values for sugar cane [After Fox *et al* 1967].

Silicon status	Water ppm	Soil extracts			Sheath Si	
		$Ca[H_2PO_4]_2$	HOAc	H_2SO_4	TCA soluble ppm fresh	Total %Ovendry
Deficiency probable	<0. 9	**<50**	**<20**	**<40**	<30	<0.5
Deficiency questionable	0.9 to 2.0	**50 to 150**	**20 to 40**	**40 to 100**	30 to 40	0.5 to 0.7
Deficiency unlikely	> 2.0	**> 150**	**> 40**	**> 100**	> 40	>0.7

5% of the total leaf area (Table 3). Ross *et al*. (1974) observed marked residual effects on sugarcane yield over a 6-year crop cycle from applications of calcium silicate, applied at a rate of 7 t ha^{-1} to Si deficient soils (less than 77 mg dm^{-3} Si extractable with modified Truog's extractant). The application of calcium silicate was profitable when the total Si level in the third leaf lamina was below 0.67 % of Si or if the acid-soluble soil Si was below 77 mg dm^{-3} Si.

Table 3. Effect of silic acid on sugar cane biomass and Si content at harvest [After Wong You Cheong *et al* 1973].

Silicon rate ppm.	Stalk fresh g	Sucrose %	Sucrose Yield g	Root fresh g	TVD Si%
0	383	8.2	31.4	355	0.03
50	516	10.6	54.7	298	0.52
100	532	12.1	64.4	255	0.96
200	575	10.8	62.1	320	1.24
LSD [p=0.05]	**122**	**2.3**	**16.6**	**127**	**0.22**

In the late seventies the focus of silicon research in sugarcane shifted back to the USA but this time to Florida. Gascho and Andreis (1974) concluded from a 3 year study that Si was beneficial and probably essential for sugarcane grown on organic and quartz sand soils of Florida. The authors obtained significant positive responses to slag treatments ranging from 13 to 32% on the muck trial sites and two out of four sand sites. In follow up investigations, yields of five varieties of sugarcane were increased on average by 17 % and 21 % during 1989 and 1990 respectively following the addition of 6.7 t ha^{-1} calcium silicate slag (Raid *et al*. 1992). Florida is well known for its rice-sugarcane rotation, which has been shown to be both economically and agronomically beneficial (Alvarez and Snyder, 1984). Subsequently Anderson *et al* (1991) observed that an application of 20t ha^{-1} of slag increased cumulative cane yield by as much as 39 % and sugar yield as much as 50 % over three crop years. In all the studies conducted in Florida, no evidence could be found for any mineral toxicity causing the response to Si, nor an improvement in P uptake. Available evidence based on leaf analysis and a soil survey conducted by Gascho, indicated that the benefits from Si treatment were linked to a direct Si deficiency (Gascho 1976). Under field conditions at least 1% Si in the TVD leaf was considered necessary for optimal cane yields while a Si content as low as 0,25% will result a yield decline of a least 50% of the yield potential (Anderson *et al*, 1991). Very recent studies have focussed on genotypic differences between cane varieties as better Si acccumulating varieties may have the advantage of needing less frequent Si fertilization (Deren *et al* 1993 and Korndorfer *et al* 1998) .

Studies conducted in Australia have highlighted the fact that Si is an important component of the production system and should not be ignored when attempting to find reasons for below optimum production.

There are several reports of increases in yield and sugar attributed to silicate based materials and mill wastes (Hurney1973; Haysom and Chapman, 1975; Rudd and Berthelsen, 1998). During the eighties, in some areas cement was used commercially as a source of silicon and applied to cane where the soil Si content was below the critical value of 20ppm (using 0. 02N $CaCl_2$), or 100 ppm (using 0. 01N $H_2 SO_4$) based on the Truog method of extraction. In recent years cement has become uneconomical to use and cheaper sources such as fly ash and filter cake from the mill are increasingly being applied as a substitute (Kingston, 1999). Recently the Yield Decline Joint Venture has focussed some of its activities on studies of soil Si . The construction of a soil Si map for the Tully/Innisfail area, comprising 34 000 ha , has clearly demonstrated that substantial areas of the wet coast have inherently low (67%) to marginal levels (28%) of soil Si for sugarcane production. Of interest is that the occurrence of the condition known as Northern Poor Root Syndrome (NPRS) as outlined by Egan *et al.* (1984) and more recently referred to as 'yield decline', could in part be related to sub-optimal levels of soil Si found in many north Queensland sugarcane soils. The areas where NPRS was first recorded as a major problem are those now mapped as being low in soil silica status (Berthelsen and Noble 1999).

It was concluded that continual sugarcane production has undoubtedly lowered the Si levels to the extent where cane yields are being substantially affected. Paired site analysis of virgin and associated cultivated soils has also shown that many more soils are becoming deficient under long-term sugarcane monoculture. Conversely, analysis of rotation sites has shown that breaking the monoculture with a cover crop can increase the availability of Si. Garside *et al.* (1999) have demonstrated substantial yield improvement following breaks compared with continuous sugarcane. It has also been suggested that observed genotypic differences in the Si status of varieties may be because more recent selections have been made under declining levels of soil silicon and that "the effects of degraded soil conditions may conceivably be masked by genetic manipulation" (Berthelsen and Noble 1999). Apart from the foregoing research outcomes, there have been a few reports from other countries dealing with the agronomic benefits of silicate applications such as Malaysia (Pan, 1979), Taiwan (Shiue,1973), Brazil (Casagrande, 1981), and Indonesia (Allorerung, 1989)

Past South African research investigations

For many years, Si deficiency was relatively unknown in the South African sugar industry but in 1967, aluminium toxicity together with silicon deficiency, were first identified as potential growth limiting factors in the highly weathered oxisol soils of the newly developed cane areas of the Natal Midlands (Bishop1967). Further evidence that silicon was potentially a growth-limiting factor in these soils was one of the outcomes from the wattle brush ash investigation that was initiated in 1969 (Meyer 1970). Sugarcane planted in fields where wattle trees had previously been grown frequently exhibited a very marked 'tramline effect'. The superior growth of cane along these lines was associated with the windrows of wattle brush, which are burnt prior to land preparation. Analyses of soils containing wattle ash showed highly significant reductions in acidity and labile Al, and increases in the amounts of exchangeable Ca, Mg, P, Si and K. Examination of the associated sugarcane third leaf analytical data showed similar increases in nutrient levels, particularly in regard to P, K, Ca and Si.

Glasshouse investigations

Results of a follow up pot experiment using a humic oxisol clay loam (Balgowan form) showed that the greatest responses in cane growth were obtained from the addition of wattle ash, lime and the Si treatment (see Table 4). A heavy application of an Al salt caused a marked depression in yield and induced severe phosphorus deficiency symptoms. This negative response was more marked in the Balgowan soil series, which inherently contained large amounts of exchangeable Al. The main reason for yield improvement following application of either wattle brush ash appeared to have been due to a reduction in the amount of exchangeable Al, and better utilization of P and Si at the higher soil pH values. Further investigations on soils from fields under wattle, and from adjoining areas not under wattle, indicated that continued wattle production had a strong acidifying effect on the soil. This effect caused a loss of plant available Ca, Mg, K and Si from the soil and raised the exchangeable Al index from a level considered to be well below the critical value for sugarcane to levels that were dangerously high (Meyer 1970).

Table 4. Cane yield in relation to selected treatments.

Soil	Selected treatments	Code	Yield tops + stalk (g)	% Diff relative to c	Root yield (g)
BALGOWAN (B)	Control (N & K)	A	8,1	- 36	1,7
	Supers (single)	C	12,8	0	2,5
	Sterilisation	D	8,2	- 36	1,2
	Ash	I	19,2	+ 48	4,2
	Lime	H	15,2	+ 19	2,9
	Aluminium	O	4,2	- 66	0,4
	Al and Ash	M	11,5	- 10	1,2
	Silicon	L	15,0	+ 17	3,1
	LSD (P = 9,05)		1,06	-	1,3

(after Meyer JH, 1970)

A second pot trial with sugarcane that followed the exploratory wattle brush trial, focussed on comparing the relative efficiencies of limestone and various sources of Si on acid soils from the Natal Midlands (Du Preez, 1970).

Some of the outcomes of the trial may be summarised as follows:

- All sources of silica except sodium silicate gave significant yield responses as indicated in Figure 1.
- The highest yields were obtained with cement at 9 metric tons per hectare and Amcor slag at 18 metric tons per hectare. Both these yields were significantly better than the highest yield obtained from the addition of calcium carbonate.
- The greater effectiveness of the Si treatments was associated with an increase in the Si concentration in the plant, which was not observed with the lime treatments[see Fig2].
- All treatments caused a substantial reduction in exchangeable Al in the soil by raising pH values, the exchangeable Al being strongly pH-dependent.
- A depression in yield was observed at the highest level of calcium carbonate application on all three soils.
- There were no significant treatment differences in the concentrations of Fe, Cu, Zn and B in the plants, which indicated that none of them were deficient and that they were therefore not responsible for the yield differences.
- Calcium metasilicate at all levels increased the uptake of P by the plant. However, the addition of calcium carbonate reduced the amount of P taken up by the plant.
- All treatments caused a marked reduction in the Mn to silica ratio in the leaf. This was greater in the Si than in the calcium carbonate treatments, the Si treatments reducing the Mn concentration while increasing the Si concentration. However, the calcium carbonate treatments reduced both the Mn and Si concentrations.

Du Preez (1970) concluded that the main factors probably responsible for the yield increases were decreased levels of Al and Mn, and increased levels of silicon in the soil. He considered that the increased yields could not only be due only to the elimination of toxic amounts of Al and Mn, but that there was a level of soil Si below which optimum yields could not be obtained. Silicate slag appeared to be superior to lime because it gave higher yields and because the consequences of over-application were less harmful. The results of this trial closely

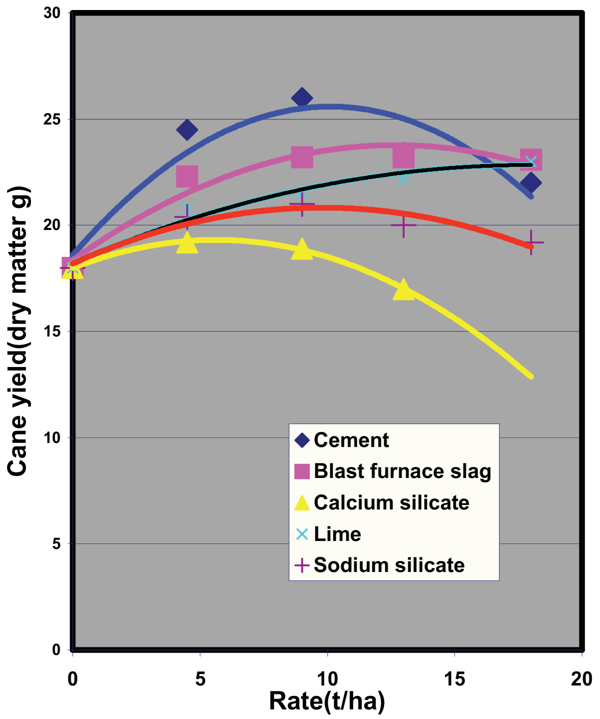

Figure 1. Effect of different Si sources on cane yield.

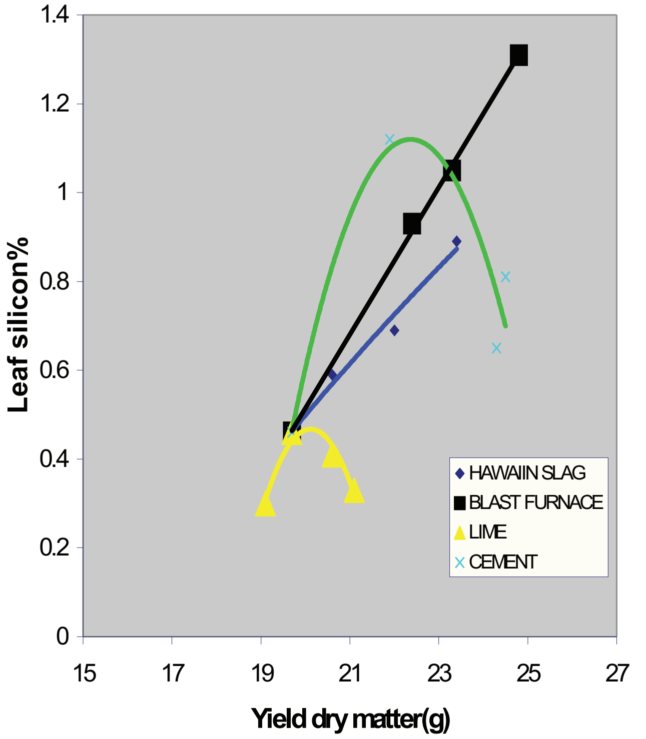

Figure 2. Relationship between leaf Si content and yield for various treatments.

supported the findings of Ayres (1966) that slag was more beneficial than coral stone (calcium carbonate) even though both neutralized soil acidity and diminished the solubility of Mn. Of the various Si carriers, cement proved to be the most effective in terms of yield but not on a cost basis. An important finding of Du Preez's investigation was the negative effect that overliming had in reducing Si uptake. An induced Si deficiency could explain why N12 is sensitive to overliming in soils such as the Inanda form which has an inherently low Si status.

Past field experiments

In South Africa a total of 14 crops from six trials were harvested to compare the effectiveness of various forms calcium silicate slag with lime. Results of some of these experiments have been reported by Moberly and Meyer (1975) and additional results have since become available. Some of the sites on which the trials were conducted were previously under wattle while the other sites had a history of moderate to poor cane yields. Apart from dolomitic and agricultural lime, other materials such as Slagsil [SiO_2 35%], Hulsar lime [SiO_2 <2%], Amcor slag [SiO_2 37%] and Hawaiian calcium metasilicate [SiO_2 49%,] were used in a number of experiments.

The responses obtained to the various sources of Si and lime, expressed as the percentage increase in tons cane/ha over the yield obtained in the unameliorated control treatment, are summarized in Table 5.

- Of the 14 crops harvested, responses to Si treatment were significant (p=0.05) in nine instances compared with the five responses that were significant with lime treatment.
- Significant responses to calcium silicate were obtained in the plant crop in four trials (sites 1,2,3 and 4) and at three sites, the residual effects to the Si treatment were also significant in either the the 1 st and /or 2nd ratoon crops (sites 1, 2 and 4).
- In general Si based treatments were generally superior to lime treatments but the advantage was not significant. The one exception was in the Seven Oaks trial at site 4 where the Si treatment was consistently superior to lime. In this trial slagsil and lime were both applied to a depth of approximately 65cm and the Si based treatment increased yield significantly in all five crops (plant and four rations), whereas the response to lime reached significance in only the last three ratoon crops (see Table 6). The superiority of Slagsil over lime was approximately 11%.
- There was no statistical evidence that Hawaiian silicate was superior to the local product Slagment
- The imported Brazilian variety CB36/14 and the Natal variety NCo376 were included in the experiments at sites 3 and 4. Results from the plant crop indicated that CB36/14 was slightly more sensitive than NCo376 to treatment with slagsil and lime. These results are shown in Table7.
- In general, the pH of treated soils tended to increase gradually with time. The effect of the various ameliorating materials on soil pH was a function of fineness and purity. The slagsil and imported Hawaiian slag generally performed as well as the standard lime treatments in raising pH. However, the coarser Amcor silica slag material did not perform as well as the standard liming materials.

Role of silicon in alleviating biotic stress

Increasing resistance to pests

There is increasing evidence from the literature that nutrients such as N and Si play important roles in the susceptibility and resistance of a range of crops to stalk borer damage. Studies

Table 5. A summary of mean yield responses obtained to the application of calcium silicate and agricultural lime in various field experiments.

Site No.	Locality	Soil form	Pre-treatment soil analysis (0-25 cm)				% change in sucrose yield compared with contol			
			pH water	Ca Ppm	EAI meq %	% Clay	Carrier	Plant	1st ratoon	2nd ratoon
1	Townhill	Clovelly	4,8	104	2,15	53	Hawaii slag 6t/ha Dolm lime 6t/ha	+27** +26**	+16** +18*	+35** +29**
2	Mowbray	Griffin	4,6	10	2,60	19	Slagsil 1t/ha IF Hulsar lime 6t/ha	+16* +16*	+6 +7	+16* +8
3	Seven Oaks	Clovelly	4,2	120	2,57	61	Hawaii slag 6t/ha Agric lime 6t/ha	+13* +4	- -	- -
4	Seven Oaks	Clovelly	4,6	270	1,93	45	Slagsil 20t/ha/60cm Dolm lime 20t/ha/60cm	+15* +6	+32** +16	+53** +47**
5	Upper Tongaat	Inanda	4,8	360	0,33	22	Hawaii slag 6t/ha Dolm lime 6t/ha	+1 Nil	- -	- -
6	Kranskop	Hutton	5, 0	207	2,30	45	Calcium silicate 2t/ha Dolm lime 2t/ha	+7 +1	+8,5 +2	7,6 +4

**Statistically significant, P<0,01; *Statistically significant, P<0,05

conducted in Nigeria on the maize borer *Sesamia calamistis* have shown that increasing N doses significantly increased larval survival from 18 to 37% while increasing silica supply reduced larval survival from 26 to 4% (Setamou *et al* 1993). It has been demonstrated that the mandibles of larvae of the rice stem borer are damaged when the Si content of rice plants is high (Jones and Handreck, 1967)

One of the earliest reports linking Si nutrition with borer damage in cane is credited to Indian researchers (Rao 1967). Sugarcane varieties that were tolerant to a shoot borer showed the highest number of Si cells per unit area in the leaf sheath. In Taiwan, it was shown that the incidence of borer damage in Si treated cane was less than in untreated sugarcane (Pan *et al.* 1979). In 1982, Atkinson and Nuss confirmed that excessive N usage increased the incidence of a stalk borer *Eldana saccharina* in sugar cane. Recommendations for N were subsequently reduced by 20kg N/ha where this stalk borer was considered to be a risk to cane production. Increased application of N fertilisers also increased the incidence of *E. saccharina,* in Mali (Coulibaly, 1990), and that of another borer (*Chilo auricilius*) in India (Sukhija *et al*., 1994).

Table 6. Residual effectiveness of Slagsil (20t/ha) versus limestone(20t/ha) incorporated to a depth of 60 cm on cane yield(tc/ha).

Crop stage	Control	Extra P	Lime	Slagsil
Plant	116	128	123	133**
1 st Ratoon	97	113	113	128**
2 nd Ratoon	47	70**	69**	72**
3 rd Ratoon	97	113	115*	114*
4 th Ratoon	46	59*	60*	59*
Average	81	97	96	101

**Statistically significant, P<0,01; *Statistically significant, P<0,05

Table 7. Varietal sucrose yield response to lime and slagsil as % increase over unlimed control on Griffin and Clovelly form soils.

	Variety	Lime	Slagsil	Mean
Site 1	Nco376	-6	+2	-2
	CB36/14	+9	+16	+13
Site 2	Nco376	+13	-	+13
	CB36/14	+17	-	+17

In Florida, Elawad *et al*. (1985) observed that with improved Si nutrition there was a marked increase in the resistance of sugarcane to stem borer (*Diatraea saccharalis*). Freshly hatched *D. saccharalis* larvae feed on epidermal tissue of the sheath, leaves and new internodes in the immature top of the plants. Increased Si uptake from Na_2SiO_3 treated plants apparently acted as a deterrent to the borers. An interesting outcome from their trial was that leaf Si contents were negatively related to shoot borer incidence (see Table 8).

Table 8. Effect of Si treatment on sugarcane resistance to stem borer (*Diatraea saccharalis*), yield and Si content in the TVD leaf.

Na_2SiO_3 g plot^{-1} (40 L)	Numbers plants attacked	Percent of total	Dry Weight g plant^{-1}	Si Leaf %
0	44	73	450	0.29
68	12	20	482	1.39
136	4	7	505	2.39

Source: Adapted from Elawad et al., 1985

In South Africa, recent studies have focussed on the association between Si assimilation and host-plant resistance to *Eldana saccharina*. Evidence from a large scale pot trial in which sugarcane was treated with calcium silicate and artificially infested with *E. saccharina* at 9.5 months, showed significant reductions of 24% in borer damage and 20% in borer mass (Keeping and Meyer, this volume).

When resistant and susceptible varieties were combined in the analysis, the interaction between variety and Si treatment approached significance. The two susceptible varieties (N11 and N16) and intermediate resistance variety (N17) showed the greatest effect of resistance from Si treatment (Figure 3).

A subsequent assessment of the six varieties tested showed a positive response in Si uptake with Si treatment. On average the intermediate Si treatment more than tripled the stalk Si content from 0.08 to 0.28 %.

Increasing resistance to disease

A review of the literature shows that rice has received the most attention in researching the use of Si to reduce the need for most fungicides and enhance host plant resistance. In Florida, it was shown that Si was as effective as conventional fungicides in controlling diseases such as leaf scald (*Monographella albescens*), blast (*Magnaportha grisea)*, sheath blight (*Thanatephorus cucumeris)*, brown spot (*Cochliobolus miyabeanus*) and grain discoloration (species of *Fusarium, Bipolaris*) (Datnoff, 1992). Recent research has indicated that Si can enhance resistance of partially resistant cultivars to the same general level as completely resistant cultivars to both blast and sheet blight (Datnoff 1999). The same author also reported on the results of a factorial experiment in the glasshouse in which the effects of Si treatment on grayspot caused by *Pyricularia grisea* in St Augustine grass was investigated. Si significantly reduced the area of gray leaf spot infection by between 44 and 78% among the four grass cultivars.

In sugarcane, progress has been less spectacular. In Florida, Elawad *et al*. (1982) reported a significant decrease in leaf freckling of sugarcane following the application of 20 t ha^{-1} of TVA slag to muck soil. Raid *et al.* (1992) assessed the effect of cultivar and calcium silicate slag treatment on foliar disease development in a number sugarcane hybrids. They reported a significant reduction by an average of 67% in the severity of ringspot with the addition of the slag (*Leptosphaeria sacchari* Breda de Hann) across the five cultivars studied. However, the severity of sugarcane rust (*Puccinia melanocephala* H. Syd. and P. Syd) was not affected by application of silicate slag.

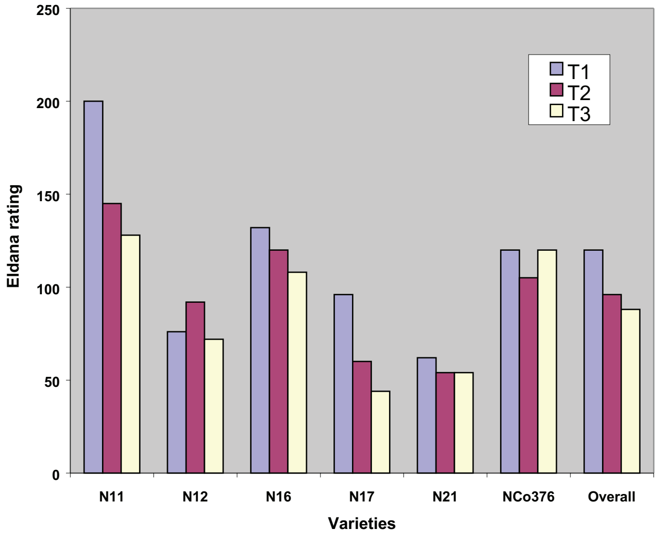

Figure 3. Effect of calcium silicate treatment in increasing resistance to eldana damage for six cane varieties.

Possible mechanisms for Si in alleviating biotic stress

Silica deposits, commonly called phytoliths, occur in cell walls, cell lumens or in intercellular spaces and external layers. Silicification also occurs in roots and the shoot including leaves, culms and, in grasses, most heavily in the inflorescence. Deposits occur in epidermal, strengthening, storage and vascular tissues (Sangster 1999). Silicification is reported in the Pteridophyta and the Spermatophyta, including gymnosperms and angiosperms. Among the monocotyledons, the Cyperaceae and Poaceae (Gramineae) are pre-eminent accumulators of Si although recent evidence indicates that certain Dicotyledon families such as Fabaceae, Cucurbitaceae and Asteraceae also contain significant amounts of Si. Biogenic silica structure is affected by ambient physico-chemical conditions mediated by tissue maturation, pH, ionic concentrations and cell wall structure. Silicon deposited in the epidermal tissue may have several functions including support and protection in the form of a mechanical barrier against pathogen and predator invasions (Takahashi, 1996). A earlier hypothesis proposes that the polymerized Si acids fill up apertures of cellulose micelle constituting cell walls and make up a Si cellulose membrane. This membrane is supposed to be mainly responsible for protecting the plant from some diseases and insects (Yoshida *et al*., 1969)

The increase of the borer's incidence may also be partly due to the formation of stronger stalks (Jones and Handreck, 1967; Lewin and Reimann, 1969) Plants like sugarcane and rice, with high Si contents, seem to interfere in the feeding of larvae, damaging their mandibles. The presence of Si crystals in these tissues hinders the feeding of the insect, which in the early stage has rather fragile mandibles.

Furthermore, Si physiologically promotes ammonium assimilation and restrains the increase in soluble nitrogen compounds, including amino acids and amide, which are instrumental for the propagation of hyphae (Takahashi, 1996). Recent evidence suggests that Si may also reinforce plant disease resistance by stimulating the expression of natural defense reactions through the production of low-molecular weight metabolites which include flavonoid phytoalexins (Belanger *et al* 1999). Previous research at SASEX has emphasised the role of stalk bud scale flavonoids in *Eldana saccharina* resistance (Rutherford *et al* 1993) and it is possible that Si similarly stimulates the expression of these flavonoids. This mechanism could explain the significant reduction in borer damage and in borer mass that was obtained in the most recent SASEX investigation (Keeping and Meyer, this volume.

Role of silcon in reducing moisture stress

The composition and distribution of Si within the plant is determined by the transpiration rate and pathway of transpiration flow in the apoplast (Jones and Handreck, 1967). Most of the Si is deposited in the outer walls of the epidermal cells on both surfaces of the leaves after water evaporation at the end of the transpiration stream (Hodson and Sangster, 1989). The Si deposit occurs either as amorphous opal (SiO_2. hH_2O,) or as opal phytoliths with distinct three-dimensional shapes (Parry and Smithson, 1964).

When Si becomes deficient in soils, there is evidence from a number of studies that the rate of transpiration increases and may become excessive. Studies by Okuda and Takahashi (1965) showed that the rate of transpiration of Si-deficient barley increased by about 10% over the rate in control plants. Lewin and Reimann (1969), obtained even more dramatic results and found that the difference between Si-deficient and control plants could be as high as 30%. Solution culture studies in Japan with rice have shown that Si strongly influences water loss in plants by reducing cuticular transpiration. In one particular study, an application of 45ppm Si in the nutrient solution decreased the transpiration rate from 5.1 to 3.6ml/g biomass/24 hour period (Okuda and Takahashi, 1965). According to Wong You Cheong *et al* (1973), improved Si nutrition may reduce excessive leaf transpiration in sugarcane. Jayabad and Chockalingam (1990), obseved increased yields in sugar cane treated with a foliar spray of sodium silicate following a period of prolonged moisture stress. They attributed the effect to Si reducing the rate of transpiration and thereby protecting the plant from excessive moisture loss.

These findings suggest a role for Si in the water economy of the plant. The rate of transpiration is controlled by the amount of silica gel associated with the cellulose in the cell walls of epidermal cells This mechanism could explain why wilting may occur under conditions of low humidity. A thickened layer of silica gel will help to reduce water loss, while the epidermal cell wall with less silica gel will allow water to escape at an accelerated rate. By increasing the Si content of plants, it may be possible to reduce their internal water stress and in this way increase their tolerance to salt stress. Yoshida (1965) showed that rice plants without a Si supply could not grow in a culture solution, which contained salt equivalent to an osmotic pressure of 5 atm, whereas plants with a Si supply grew well in the same nutrient solution.

Role of silicon in sucrose inversion

Apart from its role in improving the resistance of sugarcane to pest and disease infestation as well as in the depression of toxic levels of Al and Mn and other elements, Si has been assigned roles as an enzyme regulator in sugar synthesis, storage and retention in the cane plant. As early as 1968, Alexander *et al* concluded that within the plant, Si appears to assume the role of an equilibrium protector, acting as a buffer of enzyme activity as it attempts to help the plant maintain normal enzyme activity against factors which may act to disrupt it .In this role, it has been shown to: protect photosynthetic activity, by preserving green foliar tissue against the action of desiccants; inhibit phosphatases, which may destroy organic phosphates directly involved in sugar formation; suppress amylase activity, preventing starch accumulation and subsequent competition for reserves of organic phosphates; and inhibit invertase activity and prevent excessive sucrose inversion in pre-harvest and post-harvest stages.

Alexander (1969) found that sucrose inversion in sugarcane juice samples was delayed for several days by adding sodium metasilicate immediately after milling. Invertase and amylase were totally inactivated in the range of 3 to 9 micromoles of Si. This effect was verified by paper chromatography. At low levels, metasilicate forms a complex with sucrose, which then blocks invertase from combining with its substrate. Even after sucrose is inverted, the fructose-silicate configuration is preserved, in this way preventing fructose from being metabolised by microorganisms. Fructose appears to be the preferred carbon source for microbial growth. Preservation of fructose by silicates may constitute a bacterial repression operating in addition to the invertase-inhibitory action.

Role of silicon in improving photosynthesis

Alexander and Montalvo (1970 and 1971), first showed a relationship between Si and photosynthesis in investigating enzyme-silicon reactions with gibberellic-acid-treated sugar cane during the post-growth-stimulatory phase. In another study, Lau *et al* (1978) proposed that under normal light, silica deposited in silica cells and stomatal guard cells could serve as 'windows' allowing more light to pass through the epidermal to the photosynthetic mesophyll tissue, thus enabling higher rates of photosynthesis and more tillers per plant. However, no attempt was made to link these hypotheses with the phenomenon of leaf freckling. Freckled plants are considered to be less photosynthetically efficient because freckling reduces the active leaf area for photosynthesis. In Florida, Elawad *et al.* (1982) obtained a significant decrease in percent freckling in the plant crop as well as the ratoon crop with application of 20 t ha^{-1} of TVA slag to muck soil. Clements *et al.* (1974) proposed a protective action for Si in photosynthesis by distributing toxic levels of Mn, Fe and Al more evenly throughout the leaf, thus preventing freckling or necrotic areas of localised mineral accumulation while simultaneously increasing photosynthetic leaf area.

At one stage it was considered feasible that leaf freckling may be caused by the harmful short wavelength portion of solar UV radiation, which intensifies with the gradual depletion of ozone in the stratosphere. However, an elaborate greenhouse trial conducted by Elawad *et al* (1985), in which sugarcane was grown inside a glasshouse under enhanced UV B irradiation at low, medium and high levels of Si fertilisation, strongly suggested that UV B radiation was not involved in freckling, unless smaller wavelengths (280 to 290 nm) radiation at peak midday irradiation are involved. Of interest is that UV B irradiance damage which causes chlorosis and bronzing, has been reported for crops such as cotton (Carns et al 1977) and soybean (Allen *et al* 1978).

Other reported benefits

Reports in the literature indicate that Si also helps with increasing resistance in plants to lodging. Lee *et al* 1965, discovered that Si fertilisation reduced lodging in lowland rice that was caused by an excessive application of N. Liang *et al* 1994 found practically no lodging in rice fields fertilised with calcium silicate and more than 66% lodging in untreated control fields. In dense stands of sugarcane, Si can stimulate growth by improving leaf erectness, which will assist in reducing mutual shading thereby increasing light interception and hence photosynthesis. The effect of Si on leaf erectness is mainly due to Si depositions in the epidermal layers of the leaf panicle (Takahashi *et al,* 1982).

In China, it has been demonstrated that Zoysia grass *(Zoysia japonica L.*) has a naturally high Si status and it is widely used in sports turf and golf courses because of its excellent functional qualities, including rigidity, elasticity, resiliency, and disease tolerance.This turf grass contains considerable silica deposited in the cell wall and micrometer-sized intercellular spaces of leaf epidermal cells. Si deposition increased the mechanical strength of the plant cell wall, and Si acted as a compression-resistant element. This in turn improved the ability of grass to resist traffic and lodging (Lijun *et al,* 1999). Apart from increasing resistance to lodging, there is the added potential benefit of Si in sugarcane reducing stool damage from heavy infield compaction.

Brief mention should be made of past reports dealing with the potential role of Si in increasing the resistance of cane to freeze damage. In Florida, it was observed that there is an increased tolerance to freeze damage of commercial sugarcane in areas treated with calcium silicate (Ulloa and Anderson, 1991). Strip test observations with silicates suggest only mild freeze effects on sugarcane compared with badly damaged controls (Rozeff, 1992). These limited observations of Si-induced cold tolerance in sugarcane, may have important implications for Midlands growers and warrant additional field studies.

Possible reasons for increased silicon deficiency in the South African sugar industry

The nutrient information retrieval system, based on historical soil analyses undertaken by the Fertiliser Advisory Service of the Experiment Station (Meyer *et al* 1998), indicated that soil acidification has greatly increased in the coastal cane areas. This has come about mainly through shorter cane cycles during the past two decades (1979-99),which has had the effect of increasing the intensity of cropping and N usage compared with the previous two decades (1959-79). Under increasing levels of soil acidification, Si availability and uptake by the plant may be impaired and it is possible that a lack of Si will reduce stalk hardness and increase susceptibility to borer. In a recent assessment of 230 leaf samples from 12 regional variety trials, covering 15 cane varieties, both ash and Si content of TVD leaf samples were negatively correlated with *E. saccharina* resistance ratings (R= -0.61 and -0.63).

Under a system of continuous cane monocropping without rotation, sugarcane has the potential to remove substantial amounts of Si from the soil. A 100 t/ha crop of cane can remove up to 300 kg/ha of Si, while an excess of 500 kg/ha silicon can be removed under very high yielding conditions (Anderson *et al* 1991). Monosilicic acid is rapidly utilised by sugarcane and, unless it is replenished, plant available Si will become depleted. The visual symptoms of Si deficiency in sugarcane appear as minute white circular spots on older leaves. Leaves may senesce prematurely and tillering may be poor (Wong You Cheong *et al* 1972).

Methods of soil and leaf analysis used at the Experiment Station

In the South African sugar industry, 0.5N ammonium acetate extractant adjusted to pH 4.8 (Ayres1966) was used in early investigations (Bishop 1967), but in recent years the modified Truog 0.02N sulphuric acid (Fox 1967) has been found to correlate better with leaf Si analyses. In a previous survey of the Si status of soils in the sugar industry, it was found that Si extracted from soils by the modified Truog method, were moderately well correlated with clay content (Figure 5). In general, the results tend to suggest that Si can build up in soils with more than 30% clay. Mollisol and Vertisol soils containing 2:1 lattice clays, have the best supply of Si, usually in excess of 50 ppm extractable Si (Fox *et al* 1967).

Foliar diagnosis has been used to great advantage in determining the nutrient status of sugarcane and is widely accepted as a means of improving the effectiveness of fertiliser use. With the introduction of X-ray fluorescence and near infrared reflectance (Wood *et al*,1985), leaf analysis has become more accessible as a diagnostic tool. It compares favourably with soil analysis in correlating with fertilizer responses and provides a useful check on the uptake of fertilisers already applied. For diagnostic purposes a threshold value of 0.50% has been adopted for leaf Si. Investigations using the Diagnosis and Recommendation Integrated System (DRIS) (Meyer, 1981), in which nutrient indices are derived from ratios between nutrients, rather than nutrient percentages in the leaf, indicate that this system can help to expedite corrective fertiliser treatment of the crop that has been sampled. Since nutrient ratios vary less than nutrient percentages as the crop ages, diagnosis on irrigated cane can be made at two months, compared with four months using the conventional approach. Of interest is that ratios containing Si as a nutrient show the best correlation with cane yield. The K:Si ratio is especially significant in identifying high yielding cane.

Conclusions and future research

This review has highlighted Si as an important component of the sugarcane production system. A considerable amount of research has been conducted worldwide into the Si requirement of sugarcane and the evidence suggests that a multi functional role may be assigned to Si in alleviating stress in sugarcane. Sugarcane yield responses to Si may be associated with alleviating abiotic stresses such as Al and Mn toxicity, moisture stress during drought, reduced lodging, increased resistance to freezing as well as the potential for relieving biotic stress caused by certain diseases and pests. In the South Afican Sugar industry, previous studies indicate that silicate slags are more effective than limestone in overcoming Al toxicity problems in the highly weathered oxisols occurring in the Kwa -ZuluNatal Midlands. Based on promising results that have already been obtained, future research on the association between Si assimilation and host-plant resistance to stalk borer is warranted and needs to be accelerated.

Further studies into some of the other aspects of the Si nutrition of cane are also warranted and could include the following:

- Comparing the efficacy of locally available Si sources such as filter cake, flyash, siliceous slags and liming materials.
- Determining whether Si has a role in increasing resistance to diseases such as smut and mosaic as well as pests such as white grub and nematodes.
- Conducting periodic surveys of the Si status of sugarcane through the analysis of soil and leaf samples in the main extension areas of the sugar industry
- Investigating genotypic differences between cane varieties. Better Si-accumulating varieties may have the advantage of requiring lower rates of Si fertiliser or less frequent applications.
- Quantifying the effects of alleviating moisture stress in sugarcane using the rain shelter facility. Several researchers have shown that improved Si nutrition may reduce excessive leaf transpiration in rice and other crops.
- Determining the role that Si plays in the synthesis, storage and retention of sucrose in the sugarcane plant. Since the pioneering work by Alexander, very little follow up research has been carried out.

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