

Silicon Nutrition and Sugarcane Production: A Review¹

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ABSTRACT

Silicon (Si) is one of the most abundant elements found in the earth's crust, but is mostly inert and only slightly soluble. Agriculture activity tends to remove large quantities of Si from soil. Sugarcane is known to absorb more Si than any other mineral nutrient, accumulating approximately 380 kg ha⁻¹ of Si, in a 12-month old crop. Sugarcane (plant growth and development) responses to silicon fertilization have been documented in some areas of the world, and applications on commercial fields are routine in certain areas. The reason for this plant response or yield increase is not fully understood, but several mechanisms have been proposed. Some studies indicate that sugarcane yield responses to silicon may be associated with induced resistance to biotic and abiotic stresses, such as disease and pest resistance, Al, Mn and Fe toxicity alleviation, increased P availability, reduced lodging, improved leaf and stalk erectness, freeze resistance, and improvement in plant water economy. This review covers the relationship of silicon to sugarcane crop production, including recommendations on how to best manage silicon in soils and plants, silicon interactions with others elements, and laboratory methodology for determining silicon in the soil, plant and fertilizer. In addition, a future research agenda for silicon in sugarcane is proposed.

INTRODUCTION

Integrated management of 13 physiologically essential nutrients, namely six macronutrients [nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg)] and seven micronutrients [iron (Fe), manganese (Mn), zinc (Zn), boron (B), copper (Cu), molybdenum (Mo), and chloride (Cl)] are generally considered by agronomists for increasing and sustaining crop yields. However, there are non-essential elements, that under certain agroclimatic conditions, enhance plant growth by promoting several physiological processes. Although not considered essential, these elements are said to be functional nutrients (Mengel and

Kirkby, 1982). At times they are so important that they can be regarded agronomically essential to sustainable crop production. As far as rice (*Oryza sativa* L.) and sugarcane (*Saccharum officinarum* L.) crops are concerned, Si is such an element.

Members of the grass family accumulate large amounts of Si in the form of silica gel (SiO₂.nH₂O) that is localized in specific cell types. The function of Si in plants has been proposed as i) support for cell walls (resistance to lodging); ii) deterrence to pest and pathogens; iii) reduction in water loss by evapotranspiration; iv) reduction in certain heavy metal toxicities, and v) an essential

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element for normal development in some species.

Several reports in the literature suggest that Si nutrition has a definite agronomic role in sugarcane crop cultivation, especially on weathered tropical soils such as Oxisols, Ultisols, Entisols and Histosols (organic soils). Sugarcane absorbs large amounts of Si from soil. According to Samuels (1969), at 12-months the above ground parts contained 379 kg ha⁻¹ of Si, compared with 362 kg ha⁻¹ of K and 140 kg ha⁻¹ of N. Ross et al. (1974) reported the removal of 408 kg ha⁻¹ of total Si from soil by a sugarcane crop (tops + millable cane) yielding of 74 t ha⁻¹. The removal of Si from soil could be more important in intensively cultivated areas. As a result of the Si export of this magnitude, a temporary depletion of bio-available Si in soils could also be a possible factor of declining yields of ratoon crops. In other words, there may be an apparent need for consideration of Si nutrient management in developing appropriate integrated nutrient management system for sustainable sugarcane production, especially in certain ecoregions having Si-deficient weathered soils and organic soils.

This paper intends to review available literature on Si nutrition of sugarcane and to summarize potential agro-economic benefits of Si management in sugarcane cultivation. Suggestions for research on soil and plant testing are discussed for determining the need for Si application in sugarcane farming so that sugar productivity could be increased and/or sustained over a long period of time in certain agroclimatic regions.

SILICON IN SOIL

Silicon, after oxygen, is the most abundant element in the earth's crust, with soils containing approximately 32% Si by weight (Lindsay, 1979). Because of its abundance in the biosphere, the essentiality

of Si as a micronutrient for higher plants is very difficult to prove. 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.

Literature on forms of Si and their reaction in soils has been reviewed by McKeague and Cline (1963ab); Jones and Handreck (1967); Mitchell (1975); Lindsay (1979); Hallmark et al. (1982); Drees et al. (1989); and Tan (1994).

With increasing rainfall and laterization in warm sub-humid and humid tropical ecoregions, the soils are characterized by a lowering of base saturation and Si content, accompanied by the accumulation of iron and aluminum oxides (dissilication) (FIGURE 1). Dissilication is a continuing process mitigated by Si recycling. Silicon is released by the weathering of minerals, but only part is lost by drainage or in a crop ecosystem that is regularly harvested or burned. Inversely, soluble Si may be introduced by runoff, capillary ascension from the water table, or by aeolian, alluvial or any other deposition of silicate material at the soil surface.

According to Baker and Scrivner (1985), the potential leaching losses of Si in the Menfro soil series (fine-silt, mesic Typic Hapludalfs) were approximately 54.2 kg ha⁻¹ yr⁻¹, which is approximately 200 times greater than the estimated losses for Al, 0.27 kg ha⁻¹ yr⁻¹.

Leaching of Si from the soil and plant uptake are also important in determining Si concentrations in soils (Kittrick, 1969). The concentration of soluble Si in soils is undoubtedly dynamic, where equilibrium conditions are the exception rather than the rule. Changes in moisture content related to alternating wetting-drying cycles in the soil may

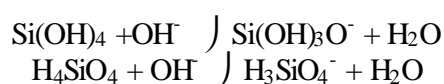
influence Si concentration in solution more readily than the other processes. Quartz is lost from soils upon weathering; consequently, perturbations of the Si equilibrium must occur, and these reduce the soluble Si concentrations. In soils, quartz is generally concentrated in sand and silt fractions, with secondary quantities in the clay fraction. The parent material of the soil generally dictates which size fraction will have the maximum quartz content. The quartz content of the clay fraction generally ranges from 0 to 250 g kg⁻¹, depending on the parent material and degree of weathering (Tedrow, 1954; Borchardt et al., 1968; Le Roux, 1973); although it may be as high as 750 to 850 g kg⁻¹. Generally, the most highly weathered soils have the lowest content of quartz (Jackson and Sherman, 1993).

A summary of the main reactions/transformations influencing Si concentration in soil solution is shown in FIGURE 2.

The solid-phase of Si occurs in various discrete and associated forms in soils in well-ordered (quartz) and disordered polymorphs (e.g. opal), and clay-mineral lattice structures. The solubility of disordered or amorphous Si polymorphs in soils at an ambient temperature and neutral pH is approximately 50 to 60 mg Si L⁻¹; whereas that of quartz is much lower, commonly 3 to 7 mg Si L⁻¹ (Alexander et al., 1954; Krauskopf, 1959; Blatt, 1979; Dapples, 1979; Hallmark et al., 1982). The liquid-phase of Si in soil is more complex, but agronomically important. It includes Si in soil solution mainly as monosilicic or orthosilicic acid [H₄SiO₄ or Si(OH)₄] and may range from 1 to 40 mg Si L⁻¹ (McKeague and Cline, 1963a; Beckwith and Reeve, 1964; Jones and Handreck, 1963, 1967; Crook, 1968; Elgawhary and Lindsay, 1972), with 16 to 20 mg Si L⁻¹ most common in soils near field capacity (Hallmark et al., 1982).

According to Elgawhary and Lindsay (1972), a solid-phase that is less soluble than amorphous Si but more soluble than quartz controls Si in soil solution. Others have suggested that amorphous Si coatings formed due to dehydration (McKeague and Cline, 1963c), kaolinite and montmorillonite (Kittrick, 1969), a surface aluminosilicate component (R) of variable composition (Weaver and Bloom, 1977), and/or opal (Wilding et al., 1979) might regulate the amount of Si in the soil solution. As monosilicic acid loses water, it forms so-called silica gel until the proper moisture content is reached. When the dissolved Si in soil solution exceeds 65 mg Si L⁻¹, polymerization of Si usually occurs and a mixture of monomers and polymers of Si(OH)₄ and Si-organic compounds may be found in soil solution at a given time (Tan, 1994; Matichenkov and Ammosova, 1996).

The solubility of Si (both crystalline and amorphous) is essentially constant between the pH limits of 2 and 8.5, but increases rapidly above 9. The rapid rise in solubility above 9 is due to ionization of monosilicic acid, as illustrated below:



The relationship observed by Ayres (1966) between Si in the sugarcane leaf and soil Si extracted by 0.5 N ammonium acetate (pH 4.0), implies that the plant uptake of Si is governed by the concentration of Si in the soil solution. If the concentration of monosilicic acid, although varying in soils of same pH, is being maintained at a steady level by soil reserves, the highly weathered soils are bound to become severely depleted in Si if continuously cropped with sugarcane.

The concentration of Si in soil solution seems to be controlled more by chemical kinetics than by thermodynamics (Hallmark et al., 1982), and apparently has

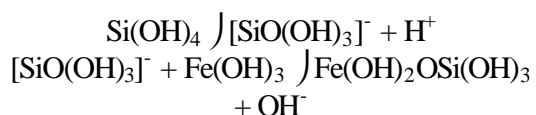
no relationship to the total in the soil (FIGURE 3). However, where Si in solution is higher (soluble Si), the plant content of this element generally is greater (Korndörfer et al., 1999a). According to Drees et al. (1989) the dissolution kinetics of soil Si are influenced not only by nature of Si polymorphs but also by a myriad of soil factors such as organic matter, redox potential, metallic ions, phyllo-silicates, sesqui-oxides, surface area, surface coatings, and overall soil solution dynamics. Organic compounds such as alginic acid, ATP, and amino acids may enhance the dissolution of soil Si (Evans, 1965). Crook (1968) as is demonstrated by the high rates of dissolution of soil Si, including quartz, to leachates containing organic matter, with the Si going into solution as complexes Si-organic molecules. However, Douglas et al., (1984) did not find a correlation between the large concentrations of soluble organic carbon and monosilicic acid movement in the leachate. Sadzawka and Aomine (1977) reported that humus protected soil Si from dissolution and at the same time prevented Si from adsorption by soils. These observations suggest that the role of soil organic matter in Si dissolution is rather complex and needs further clarification. As particle size decreases or surface area of particles increases, the dissolution rate of Si minerals increase (Iler, 1955; Huang and Vogler, 1972; Lidstrom, 1968). Chemi-sorption of metallic cations (Al, Fe, etc.) to SiO_2 reduces its dissolution rate, probably due to the formation of relatively insoluble coatings (Jones and Handreck, 1963; Beckwith and Reeve, 1964; Lidstrom, 1968). Soil moisture dynamics seem to play an important role in determining the concentration of Si in soil solution. Evaporation of soil water may result in deposition of amorphous Si coatings that may later be involved in Si dissolution (McKeague and Cline, 1963b).

Silicon sorption in soils is pH-dependent. Low pH results in less sorption, and greater sorption occurs at higher pH (McKeague and Cline, 1963b). A highly significant correlation ($r=0.989^{**}$) was obtained by Wong You Cheong et al. (1968) using 4 different great soil groups, between extractable Si and pH. Many researchers believe that sesqui-oxides, especially Al oxides, are largely responsible for much of the capacity of soils to sorb soluble Si, with the maximum capacity between pH 8 and 10 (Beckwith and Reeve, 1964; Drees et al., 1989). Adsorption studies of monomeric Si by volcanic ash soils suggest that the pH effect was primarily related to the total number of sites available for Si sorption at a given pH (Wada and Inoue, 1974). Gibson (1994) has determined the kinetics of Si release from soils. He observed relatively rapid removal of Si from soil during the first hour of extraction with 0.01 M CaCl_2 , which continued steady for 144 hours. Si sorption by soil appears to be controlled by a second order reaction kinetics (Brown and Mahler, 1987). Jones and Handreck (1963) also showed that iron oxides and especially aluminum oxides were very effective in sorbing monosilicic acid. Therefore, the solubility of Si in soils of the same pH was influenced by the free sesqui-oxides present.

Although the Si sorption process was found to depend on soil pH and sesquioxides, it appears that the equilibrium Si concentration was controlled by amorphous Si deposited at the surfaces of soil particles (Brown and Mahler, 1987). Lopes (1977), working with six soils from different regions of Brazil concluded that, in general, an increase in pH increased Si adsorption and that the adsorption of Si by the soils decreased P adsorption, especially around pH 7.

In general, the pH-dependent sorption-desorption of Si by sesqui-oxides and clays can result in faster equilibrium between solid and liquid phases of Si in soil

than dissolution-precipitation phenomenon (McKeague and Cline, 1963a; Beckwith and Reeve, 1964; Jones and Handreck, 1963). A typical pH-dependent adsorption of Si(OH)_4 by sesqui-oxides can be illustrated by the following reaction:

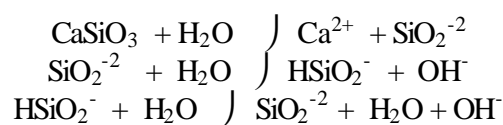


The primary processes of chemical weathering of soil silicate are hydration, solution and carbonation; hydrolysis; chelation; oxidation and reduction (Sticher and Bach, 1966). In intensive weathering in sub-humid and humid tropical region, soil Si is lost through leaching. In a climate characterized by wetting and drying, leaching of Si would be greater than in a climate that is continuously moist (Baker and Scrivner, 1985). Based on a mathematical model, potential leaching losses of Si from Hapludalf (Menfro series) could be approximately $54 \text{ kg ha}^{-1} \text{ yr}^{-1}$. As a result of desilication, soils have distinct 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 b). Saturation extracts of Oxisols of Puerto Rico generally contained less Si (2.4 mg dm^{-3} Si in solution) than that of Ultisols (5.8 mg dm^{-3} Si in solution) (Fox, 1982). Soluble Si in red, gray upland, gray lowland and dark red soils of Okinawa, Japan, under sugarcane cultivation, ranged from 0.9 to $46 \text{ mg Si } 100 \text{ g}^{-1}$ and was positively related to soil pH (Oya et al., 1989; Oya and Kina, 1989). In general, Si concentration in solution of highly weathered soils such as Ultisols and Oxisols is several times less than those soils in temperate regions (McKeague and Cline, 1963c; Juo and Sanchez, 1986; Foy, 1992). This may be a possible factor of lower productivity of sugarcane on tropical soils.

TABLE 1 presents the variation found in extractable Si in several soils with accompanying determinations of total Si content of leaves growing of these soils. A sample of sandy soil from near Ocala contained approximately twenty times as much soluble Si as did a sample of Terra Ceia from Oklawaha. Among the organic soils, the highest sample contained eight times as much soluble Si as the lowest. Okeechobee muck from Pahokee carries 3.7 times as much extractable Si as the sample of Everglades peat from Belle Glade (Bair, 1966).

Application of silicates increased the water-soluble P as the rate of application increased, despite the fact that the pH of the soil also increased. The result suggests that the Si effect is not to reduce the formation of insoluble calcium phosphates, but rather to reduce the adsorption of P by the freshly precipitated Fe and Al hydroxides. McKeague and Cline (1963bc) reported that freshly precipitated hydroxides of polyvalent metals such as Al and Fe are highly effective in Si sorption.

Calcium silicate may neutralize the soil acidity (see equations below) with the formation of silicic acid and could thus diminish the solubility of such elements as Mn, Fe and Al.



The addition of CaCO_3 to soil reduced Si solubility, mostly because of a change in pH of the soil (more alkaline pH). The effect of soil pH is shown by Ayres (1966), who found that liming a soil decreased the uptake of Si by various plants including sugarcane.

Amounts of opal phytoliths in soils commonly range from < 1 to 30 mg kg^{-1} on a total soil basis. As much as $500 \text{ to } 750 \text{ g kg}^{-1}$ of the total contributed to soils by many

grass and forest species is in the <5 μm size fractions (Jones and Beavers, 1964; Wilding and Drees, 1971). Coarser opaline constituents are more stable and easier to fractionate from soils, but finer ones are often more valuable for plant taxonomic purposes.

Several interrelated factors govern concentrations of biogenic opal, which may vary by several orders of magnitude from one geographical area to the next. These include plant species, soil factors (pH, soluble Si, reactive Fe and Al sesqui-oxides, hydrology, etc.), climate, geo-morphology, and opal stability (Jones and Handreck, 1967; Wilding and Drees, 1971).

Quantities of biogenic opal in soils commonly decrease with depth. The maximum concentration usually occurs in the surface or subjacent horizon, whereas a minimum occurs 50 to 100 cm below the surface unless a buried paleosol is present (Wilding and Drees, 1971; Jones and Beavers, 1964).

SILICON IN WATER

Irrigation water could be a potential source of Si for sugarcane, because the following forms of Si may occur in natural waters: ionic and molecular Si, aggregate Si (as colloid, solid and/or gel), Si adsorbed onto sesqui-oxides, organic-Si complexes (humites), metal-Si complexes and in living organisms, plankton, detritus, etc. (Mitchell, 1975; Tan, 1994). The monomeric form of Si (H_4SiO_4) has been recognized to be the main form. However, the overall composition of forms of Si is influenced by several factors such as pH, temperature, degree of super saturation, and the presence of other substances.

Rain water contained less than 0.2 mg dm^{-3} Si and was considered not enough to be of agronomic importance (Whitehead and Feth, 1964; Fox et al., 1967a and b). In Hawaii, mountain water at about 300 m

contained only 2.5 mg dm^{-3} Si whereas irrigation water pumped from wells near sea level contained 30 mg dm^{-3} Si (Fox et al., 1967a). Well water from Kerala state (India) having weathered soils, contained less Si (2.4 to 3.2 mg dm^{-3} Si) than irrigation water from dam (5.6 mg dm^{-3} Si) (Nair and Ayer, 1968). Kobayashi (1960) observed for Japanese rivers that the average dissolved Si in those flowing through regions of sedimentary rocks was 4.7 mg dm^{-3} Si whereas it was 21 mg dm^{-3} Si for those in the neighborhood of volcanic rocks. Sadzawka and Aomine (1977) have reported similar observation in river waters from the volcanic ash area of central Chile. Silicon contents of 23 to 28 mg dm^{-3} Si have been reported for deep ground water (Dapples, 1959).

SILICON NUTRITION IN SUGARCANE

There is ample evidence that different species uptake greatly different amounts of Si. Legumes and other dicotyledons have much lower levels than monocotyledons, for example, the Gramineae. Sugarcane is a Si accumulator plant, which strongly responds to Si supply. The Si form that which sugarcane usually absorbs has no electric charge (H_4SiO_4) and is not very mobile in the plant. Because the uptake of undissociated H_4SiO_4 may be nonselective and energetically passive, and its transport from root to shoot is in the transpiration stream in the xylem, the assumption has sometimes been made that the movement of Si follows that of water (Jones and Handreck, 1965). The silicic acid is deposited mainly in the walls of epidermal cells, where it is integrated firmly into the structural matter and contributes substantially to the strength of the stem.

The distribution of Si within the shoot and shoot parts is determined by the transpiration rate of the part (Jones and

Handreck, 1967). Most of the Si remains in the apoplasm mainly in the outer walls of the epidermal cells on both surfaces of the leaves as well as in the inflorescence bracts of graminaceous species and is deposited after water evaporation at the end of the transpiration stream, (Hodson and Sangster, 1989). Silicon is deposited either as amorphous b ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$, 'opal') or as so-called opal phytoliths with distinct three-dimensional shapes (Parry and Smithson, 1964). The preferential deposition of Si in the apoplasm of epidermal cells and trichomes is reflected in similarities between surface features of leaf and structure of Si deposits (Lanning and Eleuterius, 1989). The epidermal cell walls are impregnated with a firm layer of Si and become effective barriers against both fungal infections and water loss by cuticular transpiration. Despite that, there is increasing evidence for the necessity to modify the traditional view of Si deposition in the cell walls as a purely physical process leading to mechanical stabilization (rigidity) of the tissue and acting as a mechanical barrier to pathogens.

Silicon may be involved in cell elongation and/or cell division. In a field study, plant crop height was quadratically related to the rate of Si applied, while plant crop stem diameter was linearly related (Elawad et al., 1982a). Gascho (1978) reported that application of TVA slag and Na silicate to greenhouse grown sugarcane increased plant height. Phickett (1971) indicated that some of the effects of Si on sugarcane were longer stalks with larger diameters and increased number of suckers. These observations on cane and observations for other crops suggest a possible role of Si in cell elongation and/or cell division (Elawad et al., 1982ab).

Ayres (1966) determined that only 15% of the total plant Si are present in sugarcane stalks at 14 months. The leaf sheaths on the best cane-growing soils contained about 2.5 percent Si. Using the

sixth leaf sheath, Halais (1967) suggested critical levels of 1.25 percent of Si and 125 mg dm^{-3} of Mn. If the Si level was below this value, Si responses could be expected. Under field conditions, in Florida, Anderson (1991) suggested that at least 1% Si (~2.1 % SiO_2 in the leaf dry matter) is required for optimal cane yield. At 0.25% Si the yield drops to about 50%. According to Rodrigues (1997), increasing Si rate from 0 to 924 kg ha^{-1} using Wollastonite, resulted in substantial increase of the Si content in the leaves from 0.7 to 1.93 % and Si in the soil from 14 to 46 mg dm^{-3} (TABLE 2).

Better Si-accumulating cultivars may have the advantage of requiring lower rates of Si fertilizer or less frequent applications. A relatively narrow base of sugarcane germplasm demonstrated significant variability for Si content in leaf tissue (Deren et al., 1993). Korndörfer et al. (1998a) also found that sugarcane cultivars have different capacities to accumulate Si in the leaves. The Si levels in the leaf were of 0.76, 1.04 and 1.14% respectively for the cultivars: RB72454, SP79-1011 and SP71-6163.

POTENTIAL BENEFITS OF SILICON MANAGEMENT

Increased Yields

Research work demonstrating the use of silicate slag as a source of Si for sugarcane has been largely conducted in Hawaii, Mauritius, and Florida. Yield responses are great enough that sugarcane grown in the Everglades (South Florida) is routinely fertilized with calcium silicate when soil tests indicate the need. However, Si fertilization requires large quantities of slag (generally 5 Mg ha^{-1}), making it quite costly (Alvarez et al., 1988). Yields of cane and sugar in Hawaii have been increased 10-50% on soils low in Si, and many sugar plantations regularly apply calcium silicate

in responsive fields (Ayres, 1966; Clements, 1965a; Fox et al., 1967b). Increased yields of sugarcane in fields have been reported in Mauritius (Ross, 1974) and Puerto Rico (Samuels, 1969); while in South Africa (Preez, 1970) and Brazil (Gascho and Korndörfer, 1998), several sources of silicate increased sugarcane yields in pots.

In 1961, D'Hotman reported large increases in sugarcane yields from massive applications of finely ground basalt to soils in Mauritius. In similar work, Halais and Parish (1964) found increased Si in leaf sheaths and increased yields of sugarcane with the application of basalt dust. Ayres (1966) found that the Si of calcium silicate slag acts as a growth stimulant for sugarcane on low Si soils in Hawaii.

The benefits of Si fertilization are generally observed in sugarcane grown on Si-deficient soils such as weathered tropical soils and Histosols. Ayres (1966) obtained increases in tonnage of sugarcane amounting to 18% in cane and 22% in sugar for plant cane crop 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 lasted on low Si soils for four years, and the first ratoon crop produced about 20 % more cane and sugar. In Mauritius, calcium silicate slag applied at 7.1 t ha⁻¹ to low Si soils (less than 77 mg dm⁻³ Si extractable with modified Truog's extractant) at planting gave annual cane increases that were economically profitable over a 6-year cycle. A net return from the application of calcium silicate could be expected if 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 (Ross et al., 1974) (TABLE 3 and 5).

Based on the results of a 3-year study, Gascho and Andreis (1974) concluded that Si is beneficial and probably essential for sugarcane grown on organic and quartz sand soils of Florida. For TVA calcium silicate slag applied at 4.9 to 11.6 t

ha⁻¹ to muck and soils, Gascho (1979) observed significant positive response at all seven muck locations and two out of four sand locations. The economic analysis of the results of these field tests showed profitability of Si management under the given field conditions (Alvarez and Gascho, 1979). With the addition of calcium silicate slag (obtained from El SIGLO Corporation, Columbia, Tennessee) at 6.7 t ha⁻¹, yields of five inter-specific hybrids of sugarcane were increased by an averages of 17.2 % and 21.8 % during 1989 and 1990 respectively (Raid et al. 1992). In Mauritius, Ross et al. (1974) observed that there was marked increase in sugarcane yield with calcium silicate applications throughout the cycle (TABLE 4).

In Brazil, only a few experiments have been done on the effect of Si on sugarcane yield. Casagrande (1981) observed little effect on yield when 4 t ha⁻¹ of cement was applied (TABLE 5). The same results are observed for the amount of sucrose (Pol).

Rice and sugarcane are grown in rotation in the Everglades Agriculture Area, Florida. From this rice-sugarcane rotation, both economic and agronomic benefits have been observed (Alvarez and Snyder, 1984; Snyder et al. 1986). Anderson et al. (1986 and 1987) observed that a single application of silicate slag to Terra Ceia muck prior to planting of rice increased production of rice and sugarcane in rotation, but to a lesser extent than the slag applied prior to cane planting. In an investigation to determine multi-year response of sugarcane (cv. CP72-1020), the application of 20 t ha⁻¹ of slag (100% passing through 40 mesh screen) increased cumulative cane yield as much as 39 % and sugar yield as much as 50 % over three crop years (Anderson, 1991).

Since Si plays the role of a beneficial nutrient in sugarcane, it improves cane plant growth. Application of TVA and Florida calcium silicate slag (up to 20 t ha⁻¹) to

sugarcane (cv. CP 63-588) grown in a Pahokee muck soil increased plant height, stem diameter, number of millable stalks, and cane and sugar yields in both plant and ratoon crops (Elawad et al., 1982a). This suggested that Si improved the photosynthetic efficiency of individual plants as well as of the whole stand. They observed application of 15 t ha⁻¹ of slag increasing cane and sugar yields by 68% and 79% in plant crop, and by 125% and 129% in the ratoon crop, respectively. Similar results have been reported in Taiwan (Shiue, 1973), Australia (Hurney, 1973) and Puerto Rico (Samuels, 1969). In most of the above reports, the increases in cane and sugar yields associated with the application of silicate materials have been attributed to the increased number of millable stalks and increased plant size, and not to Pol reading.

A few reports on agronomic benefit in sugarcane from silicate application in Indonesia, Malaysia and South Africa are seen in the literature.

In field trials at two non-irrigated sites in South Africa conducted during 1983-1985 on fine-textured acid soil (pH 4.5), steel slag from Japan was applied at a rate of 1-3 t ha⁻¹ before planting cane. The results of the trials indicated increase in cane and sugar yields in the plant and ratoon crop (Allorerung, 1989). Preez (1970) has reported positive yield responses of sugarcane to applied silicate materials to South African soils.

Recycling of nutrients in bagasse furnace ash (BFA) may have some agronomic value as a source of Si. Pan et al. (1979) incorporated BFA containing 28 % Si at rates of 12, 24, 36, and 48 t ha⁻¹ into Malaysia soils before planting. They observed the highest cane yields of 119 and 127 metric t ha⁻¹ at 36 and 48 t BFA ha⁻¹; 13 and 20% more than the control respectively, and also sugar yields 15 and 20% more than the control, respectively. Lee et al. (1965) reported similar increases in plant cane and

the succeeding ratoon canes from massive application of BFA to Taiwanese soils. Further field investigations into recycling of Si for developing a practice using reduced rates of BFA would be rewarding.

Induced Resistance to Stress

Under field conditions, crop yields are adversely affected by biotic stresses such as pests and plant diseases, and abiotic stresses such as soil water shortage, cold temperature, UV-B radiation, Fe, Al and Mn toxicities, etc. Appropriate Si management of crops may offer some practical solutions to these stress problems (Savant et al., 1997).

a) Disease Control

In sugarcane, small rust-colored or brownish spots on the leaves of cane growing on highly weathered soils characterize a leaf disorder called freckling. In severe cases, affected lower leaves may die prematurely and can affect cane yield. Freckled plants are less efficient in performing photosynthesis not only because they have less leaf but also because many leaves are freckled. This leaf disorder was corrected by application of silicate materials (Clements, 1965b). Ayres (1966), Fox et al. (1967b), and Wong You Cheong et al. (1972) have also noticed that leaf freckling symptoms in sugarcane were gone following Si treatments.

Elawad et al. (1982a) observed 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. The mechanism for the disappearance of leaf freckling in sugarcane following Si application is still not well understood. Clements et al. (1974) attributed leaf freckling mainly to the presence of toxic levels of Fe, Al, Mn and Zn in the soil solution. However, Gascho (1978) stated

that the development of freckled leaves is an expression of the plant's need for Si.

Silicon deposited in the epidermal tissue mechanically deters hyphae invasion (Takahashi, 1996). 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).

Recently, Raid et al. (1992) investigated the influence of cultivar and soil amendment with calcium silicate slag on foliar disease development in sugarcane hybrids (TABLE 6). Severity of sugarcane rust (*Puccinia melanocephala* H. Syd. and P. Syd) was not affected by application of silicate slag. However, they noticed significant reduction in severity of ringspot with the addition of the slag (*Leptosphaeria sacchari* Breda de Hann) by an average of 67% across the five cultivars studied. Silicon is known to be deposited at the external surface of cell walls of plants, thus forming a mechanical barrier to penetration of the pathogen causing ringspot but not to that of rust in sugarcane (Kunoh, 1990; Raid et al., 1992). A hypothesis has been presented 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)

b) Pest Control

While studying the influence of UV-B radiation and soluble Si on growth of sugarcane, Elawad et al. (1985) additionally observed increased resistance of sugarcane to stem borer (*Diatraea saccharalis* F.) with improved Si nutrition. Newly hatched *D. saccharalis* larvae, when starting their attacks on sugarcane plants, do so by feeding on epidermal tissue of the sheath,

leaves and developing internodes in the immature top of the plants. The presence of Si crystals in these tissues should hinder the feeding of the insect, which in this phase has rather fragile mandibles. Plants like sugarcane and rice, with high Si contents, seem to interfere in the feeding of larvae, damaging their mandibles. It is possible that plants with higher Si contents in their tissue would have a higher level of resistance to the infections by such pests.

The high Si levels in Na₂SiO₃ treated plants may have served as a deterrent to the borers (TABLE 7). A significant negative relation was observed between leaf Si content and shoot borer incidence. Sugarcane varieties with a higher number of Si cells per unit area in the leaf sheath portion 5 to 7 cm from the base were found resistant to the shoot borer (Rao, 1967). The percentage of the incidence of borer damage was less in sugarcane (var. GPB 5) treated with bagasse furnace ash and silicate slag than in untreated sugarcane (Pan et al. 1979). It is interesting to note that increased application of N fertilizers alone increased the incidence of sugarcane stalk borer (*Eldana saccharina*, Walker) in Mali (Coulibaly, 1990), and that of another borer (*Chilo auricilius* Dudgeon) in India (Sukhija et al., 1994). The increase of the borer's incidence may be partly due to the formation of softer stalks resulting from the lower than adequate levels of plant Si required for strengthening of the stalk cells (Jones and Handreck, 1967; Lewin and Reimann, 1969). In other words, the borer incidence could have been prevented by application of Si together with N fertilizers (Maxwell et al., 1972).

c) Toxicities Alleviation

According to Clements (1965b), there is a positive effect of applying soluble silicates in areas where sugarcane absorbs excess amounts of certain elements such as Mn, and where the plant is unable to absorb

Si to maintain a sheath level at or beyond 0.7% Si (dry weight). The most important negative factor was the Mn/SiO₂ ratio, i.e., the lower the ratio, the better plants grow. The two dominant factors affecting yield of sugar were Ca and Si, the latter being outstanding. The level of Si which appears adequate is about 0.7%, and the best ratio is in the 30 to 50 range.

The main effect of the Si on alleviating manganese toxicity was to distribute the Mn more evenly through the leaves, thereby preventing it from collecting into localized areas which become necrotic (Jones and Handreck, 1965; Jones and Handreck, 1967; Vlamis and Williams, 1967).

d) Freezing Alleviation

Freeze damage during the winter in the sub-tropical areas in the continental United States (including Florida, Louisiana, and Texas) and south of Brazil is one of the major constraints in sugarcane production (Irvine, 1963 and 1968; Tai and Miller, 1986). Cultivation and cold tolerant varieties can reduce freeze damage to leaves and stalks and the failure of the ratoon crop. In Florida, it has been noted that there is an increased tolerance to freeze damage of commercial sugarcane in areas treated with calcium silicate (Ulloa and Anderson, 1991). Results of strip tests with silicates suggest that applications of silicates have ameliorated mild freeze effects on sugarcane (Rozeff, 1992abc). According to Ulloa (quoted from Rozeff, 1992abc), silicate slag-treated cane resisted deterioration caused by a deeper freeze in Florida. These limited observations on Si-induced cold tolerance in sugarcane, however, warrant additional field studies.

e) Water Economy

Water stress under field conditions is common and affects cane yields. Improved Si nutrition may reduce excessive leaf

transpiration (Wong You Cheong et al., 1972).

One of the symptoms associated with Si deficiency is the excessive rate of transpiration. The rate of transpiration of Si-deficient plants increased by about 30% over the rate of control plants (Lewin and Reimann, 1969) (rates were measured as grams of water lost through transpiration per gram of dry weight per day). Okuda and Takahashi (1965) obtained a similar result, but found that in barley the effect was small (less than a 10% difference between Si-deficient and control plants). This observation suggests a role for Si in the water economy of the plant. An increased rate of transpiration in Si-deficient plants could explain the wilting that may occur, particularly under conditions of low humidity, and could also help to explain the increased accumulation of Mn and other mineral nutrients in the aerial parts of Si-deficient plants. The rate of transpiration is presumably influenced by the amount of silica gel associated with the cellulose in the cell walls of epidermal cells. Hence, a well-thickened layer of silica gel should help to retard water loss, while epidermal cell wall with less silica gel will allow water to escape at an accelerated rate.

Since this role of Si nutrition may result in water economy and may be important in water management, field research on this potential beneficial has merit.

f) Reducing Lodging and Improving Erectness

One other effect of increased plant Si content, which has been reported in literature, is the increased mechanical strength of plant tissue, which results in reduced lodging.

Under field conditions, particularly in dense stands of sugarcane, Si can stimulate growth and yield by decreasing mutual shading by improving leaf erectness,

which decreases susceptibility to lodging. Leaf erectness is an important factor affecting light interception in dense plant population and, hence, photosynthesis. In rice, Si supply increased the photo-assimilation of carbon, especially after heading, and promoted the translocation of assimilated carbon to the leaves. This effect of Si on leaf erectness is mainly a function of the Si depositions in the epidermal layers of the leaf panicle (Takahashi and Miyake, 1982).

Sucrose Inversion

Few investigations of the role of Si in sugarcane have considered the mechanism by which it affects sugarcane tonnage production. However, Alexander et al. (1971) has undertaken the task of finding the role that Si plays in the synthesis, storage and retention of sucrose in the sugarcane plant. He found that sucrose inversion in sugarcane juice samples was delayed for several days by adding sodium metasilicate immediately after milling. Chromatographic evidence suggests that at low levels metasilicate forms a physical complex with sucrose which prevents the union of invertase with its substrate. The hypothetical fructose-silicate configuration is retained even after sucrose is inverted, thereby preventing fructose from being metabolized by microorganisms. Fructose appears to be the preferential hexose for microbial growth, i.e. most suitable carbon source. The effective preservation of fructose by silicates may constitute a bacterial repression operating in addition to the invertase-inhibitory action.

Next to K, Si is the most extensive constituent of ash in sugarcane juice. It is the highest component of millable stalks ash and represents an even greater percentage in leaves. However, silicates in cane are believed to be one of the major contributors to mill roll wear.

SILICON MANAGEMENT

Agronomic practices for Si management mainly include Si fertilization and plant Si recycling.

Silicon Fertilization

Research work on Si nutrition has been reported in Australia, South Africa, Brazil, Taiwan, India, Mauritius, Puerto Rico, the United States and other countries. Si fertilization has been practiced in Hawaii and Florida in the United States, and in Mauritius. For effective use of Si fertilizers, it is essential to have adequate knowledge of physical and chemical characteristics of Si sources, and when, and at what rate and how (methodology) to apply them.

a) Silicon Sources

The usual carrier for Si is calcium silicate and this material can also supply Ca to a Ca-deficient soil. The Hawaiian Cement Corp. first manufactured calcium silicate in August 1965.

Gascho and Korndörfer (1998) working with four different soils groups from Brazil and several Si sources (Wollastonite, thermal-phosphate, calcium silicate and basic slag) concluded that thermal-phosphate was the most effective source to supply both Si and P to the rice plant (TABLE 8 and FIGURE 4).

In several studies, no attempt was made to maintain constant Ca levels with increasing calcium silicate applications. It is important to separate Si from Ca effects. Ayres (1966) reasoned that since both calcium silicate and calcium carbonate treatments had increased yields, the calcium supply probably was not the factor causing higher yields in their studies. Teranishi (1968) concluded that yield increases from calcium silicate applications could not be attributed to Ca supply in his experiment

since plant Ca was above the critical level for sugarcane and also since calcium carbonate had been added to the zero Si plots to maintain pH and supply adequate Ca.

According to Ross et al. (1974), calcium silicate applied to low Si soils at planting increase annual cane yield over a 6 year cycle (TABLE 4) and well demonstrated the residual effect from this source.

For research purposes, many different Si sources have been tested: Wollastonite (CaSiO_3), cement kiln fired (fused) calcium silicate, Portland cement (9 to 23 % Si), di-calcium ortho-silicate (Ca_2SiO_4), calcium metasilicate, mini-granulated calcium metasilicate, electric furnace slag (by-product of furnace production of elemental P), blast furnace slag, basic slag, Thomas slag, mill furnace ashes, crushed basalt, volcanic cinder, and others (Rozeff, 1992abc) (TABLE 9).

Since 1970, Hawaiian Sugar Planter Assoc. researchers have tested several silicate materials and their findings can be summarized as follows:

- a) Based on extractable Si, siliceous materials can be grouped as: low level (18 to 250 mg dm^{-3} Si) materials such as mill furnace ash, rock dust and steel slag; intermediate level (2200 to 9800 mg dm^{-3} Si) materials such as blast furnace slag and coarse calcium silicate; and high level (30750 to 91500 mg dm^{-3} Si) materials such as Portland cement, fine calcium silicate and Hawaiian cement calcium silicate (HSPA, 1979).
- b) The degree of Si solubility from siliceous materials was dependent on particle size and chemical composition (HSPA, 1979).
- c) Extractable Si levels were higher in the finer silicate particles (HSPA, 1980).
- d) A long-term comprehensive approach to study residual silicates from application of siliceous materials to soils is required.

- e) Calcium metasilicate was generally much more soluble and readily available to sugarcane than calcium ortho-silicate. Mini-granules of calcium metasilicate, which were small, spherical (50 to 150 mesh) made from fine (100 to 200 mesh) material using 2% sodium oxide as a binder, were agronomically equivalent to fine ungranulated calcium metasilicate (HSPA, 1982). According to Datnoff et al. (1992), a fine grade of Si fertilizer was best for increasing Si content and grain yield. Rice yields increased relative to the control by 20-26%, 18%, and 4-11% for the fine, standard, and pelletized forms, respectively in 1990/1991. Agronomic feasibility of mini-granulation of CaSiO_3 has been confirmed by the results of Medina-Gonzales et al. (1988). When containing high amounts of Si, both granular and powdered slag are equally efficient (Schaffer and Henze, 1962). These are useful findings because they offer potential the option of mini-granulation of fine silicate sources for solving their handling problem (Jakeway, 1983).

Working on three acid soils, Preez (1970) tested various Si-containing materials on cane growth, and showed that, with the exception of metasilicate slag (soil B; Balgowan - 63% clay) and cement, all the silicate treatments showed increase yield with increasing Si concentration in the plant. The CaCO_3 had the opposite effect (FIGURE 5 and TABLE 10).

In addition to the solubility of Si in silicate sources, reactions of applied Si with organic and inorganic colloid might influence their bio-availability. Therefore, the soil-silicate reactions may need consideration for developing Si management for a given eco-region (Bair, 1966; Medina-Gonzales et al., 1988).

Since slag is a by-product of industry, in addition to containing Ca and Si, it may contain various other elements or

contaminants, some of which may under certain conditions have favorable and/or unfavorable effects on sugarcane growth. Although calcium silicate slag contains trace amounts of non-recovered P, significant amounts of P (up to 67 kg ha⁻¹) could be added to soil using commercial rates of slag (up to 6 to 7 t ha⁻¹). However, Anderson et al. (1992) have reported that P applied through slag was biologically not available to sugarcane, probably due to its low solubility.

In short, by using information on the chemical and physical nature of a Si source, it should be managed to fully realize its agronomic potential benefits, and assure that adverse effects on soil and human health, if not eliminated, are reduced to a minimum.

b) Rate of Application

Silicon application rates are mainly influenced by the chemical makeup of the Si source, Si levels in the soil, and in the plant. In Hawaii, the first silicate recommendation for plant cane was made in 1962 for 7.5 tons ha⁻¹ of TVA (Tennessee Valley Authority) slag. In 1970, 4.94 t ha⁻¹ of Hawaiian Cement corporation calcium metasilicate (CaSiO₃) was recommended. The reduction in the rate was due to the greater reactivity of CaSiO₃ as compared with TVA slag. Subsequently, in 1971 a tentative recommendation of 1.2 to 2.5 t ha⁻¹ of CaSiO₃ was made for ratoon cane, if the soil Si level was between 64 to 78 kg ha⁻¹. Based on the economic evaluation of field trials conducted on McBryde and Lihue plantations during 1976 to 1982, the following CaSiO₃ recommendations for sugarcane in Hawaii have been revised based on soil and plant Si indexes:

(1) For fields not fertilized with CaSiO₃ for two or more consecutive crops, apply 4.48 t ha⁻¹ CaSiO₃ to the current crop if soil Si levels are at or below the critical level of 112 kg ha⁻¹.

(2) For fields to which CaSiO₃ was applied to one or both of the preceding crops (plant cane and ratoon), apply 2.24 t ha⁻¹ CaSiO₃ to the current crop if the soil Si levels are at or below the critical level of 78 kg ha⁻¹. Thereafter, apply 2.5 t ha⁻¹ to each succeeding crop if soil Si levels fall below 78 kg ha⁻¹.

(3) The critical levels for the "Crop log" sheath Si (0.7 %) and the Mn/SiO₂ ratio = 75 established by Clements (1965a) remain the same; if sheath Si levels of "Crop Log" samples are less than 0.7% or the sheath Mn/SiO₂ ratios are above 75, apply 2.5 t ha⁻¹ of CaSiO₃ to the current crop (Hagihara and Bosshart, 1984).

In Florida, a rate of 7 to 9 t ha⁻¹ of TVA slag or other similar finely ground slag has been recommended under the following specified conditions (Kidder and Gascho, 1977):

- a) The land in question must be located more than five km from Lake Okeechobee.
- b) Soil pH must be less than 8.
- c) Leaves of sugarcane grown on the soil in question must have shown heavy freckling symptoms.
- d) Calcium silicate slag used as the soil amendment must be ground finer than 60 mesh.
- e) Slag must be applied broadcast and disked into the soil prior to planting the cane. When the slag is applied to sandy soils with Mg test levels below 120 (according to Everglades Research and Education Center, laboratory test), concurrent Mg fertilization at the rate of 40 kg Mg ha⁻¹ at planting is suggested as a precaution (Kidder and Gascho, 1977).

c) Timing and Frequency of Application

Generally, all Si is applied to soil before planting. In Florida, if response to the applied Si is obtained in the first year of

application, no further applications of slag are needed for at least four years (Kidder and Gascho, 1977). Florida farmers grow sugarcane in rotation with rice. Silicate slag applications prior to a sugarcane crop and prior to a rice crop in rotation with sugarcane have shown positive agronomic response. These two timing applications of slag were agroeconomically evaluated in the three crop production systems: before rice, before sugarcane and before rice-sugarcane rotation. Results of the evaluation indicated that, under the costs and prices assumed, it was more profitable to apply the slag prior to the rice crop in the rice-sugarcane rotation (Alvarez et al., 1988).

d) Method of Application

In order to apply Si to sugarcane, calcium silicate is broadcast and then incorporated into the soil before planting. The silicate material should be used in the same manner as limestone in liming sugarcane soils. Big cane plantations employ two types of mechanical spreaders, "E-Z Flow" spreader and a centrifugal broadcast spreader, a so-called spin spreader (Jakeway, 1983). Broadcasting of the slag using the E-Z Flow spreader is more uniform but has a narrow zone of coverage (26 to 46m). Its rotating parts such as bearings wear prematurely because silicate slag is abrasive. Trafficking many times for uniform coverage contributes to soil compaction. Broadcast (spin) spreaders deliver wider coverage for every pass, but broadcasting is less uniform than the E-Z Flow spreader. Plantations have reported handling and application problems in fields under windy conditions.

Generally, slag materials are incorporated into the soil as soon as possible after broadcasting to avoid caking on the ground surface. This is usually performed with a disc harrow, which is followed by complete land preparation (Jakeway, 1983).

The particle size of the Si fertilizer is important in increasing Si content of leaves and subsequent disease control (Datnoff et al., 1992). Particle size is associated with increased surface area; consequently, the distribution and dissolution of smaller Si particles mixed in the soil is enhanced and the probability of root particle contact is increased. Combining fine particles into pellets probably results in less Si-soil contact, leading to reduce Si availability to the crop, although some particle degradation could occur during soil incorporation. The particle should be of a size and well mixed with the soil. If very fine, Si sources create dusty conditions and can adversely affect material handling and application performance in the field. Special precautions are necessary for avoiding exposure of workers to the dust. This dust problem may limit the use of silicate slag for sugarcane in developing countries where it will be mainly applied manually. Mini-granulation of fine calcium silicate materials seems to a potential alternative for addressing the dust problem. Small particle size increases the effectiveness of silicate materials. Harada (1965) called attention to the superiority of finely ground TVA slag compared with coarsely ground, 16 mesh (<1.6 mm) material.

Plant Silicon Recycling

Plant Si recycling is another option available for supplying Si to sugarcane. It should be considered for developing region-specific integrated nutrient management systems that are essential for sustainable sugarcane production.

In several reports, positive effects on the growth and yield of sugarcane have been reported for the application of trash (dried leaves left in field after harvesting cane), bagasse, bagasse furnace ash, and filter-press cake. However, plant materials generally are applied as sources of organic

carbon (organic matter) and their positive effects are normally attributed to increase in availability of N, P, and K in soil and, at times, to the improvement in soil chemical and/or physical properties of soil (King, 1955; Yang, 1958; Story, 1963; Pao, 1973; Eavis and Chase, 1973; Prasad, 1976 a and b; Medina, 1979; Cooper and Abu Idris, 1980; Shinde, et al., 1990, 1993; Jonathan et al., 1991; Orlando Filho et al., 1991; Kathiresan, 1991). It is possible that some of the effects observed could be also due to Si supplied through these plant materials.

In spite of the potential value of plant material as a source of Si, its proper recycling is not common among sugarcane farmers. Some of the probable reasons for this could be bulkiness of the material, additional labor cost of recycling practices, and low cost:benefit ratios. Moreover, polymerized Si in the plant is largely associated with non-easily decomposable polysaccharide fractions such as cellulose, hemicellulose, etc. The rate of their decomposition is also slowed down because of their wide C:N ratio (nearly 120:1). For rapid decomposition of trash in soil or during composting, the use of cellulolytic fungi together with reduction of its C:N ratio appears to a practical solution. Mixed culture of fungi, namely *Aspergillus flavipes*, *Penicillium chrysogenum*, *Cochliobolus spicifer*, *Rhizopus oryzae* and *Trichoderma viride* have produced good results in the preparation of trash compost and when applied onto the trash spread in furrows. Shinde et al., (1990 and 1993) have used the mixed fungi (1 kg culture t⁻¹) for enhancing decomposition of chopped and non-chopped trash applied (2.5, 5.0, 7.5 t ha⁻¹) in furrows before planting cane and those of ratoon cane. The trash was supplemented with 8 kg of urea and 10 kg ha⁻¹ of a single super phosphate. They observed improved plant growth and increased yield of plant as well as ratoon cane. Bagasse is used as mill fuel and as such plays a valuable part in the

sugar-mill economy. In this process, a large amount of bagasse furnace ash is produced during each grinding season. This product has been regarded as a waste material, and piles of it accumulate in the factory compound. However, it might have a function in Si soil amelioration. As the main constituent of bagasse furnace ash is silica (as high as 28% Si), it might also have some effect in increasing sugarcane yield. In practice, the cost of transportation must be taken in account. Pan et al. (1979) showed a 20% increase in cane yield as a result of bagasse application. However, there was decline in sucrose content with increasing application of bagasse furnace ash. Pan et al. (1979) reported increased cane yields (GPB 5 cultivar) due to the incorporation of bagasse furnace ash (28% Si).

TESTING OF SOIL, PLANT AND SILICON SOURCES

Under certain agroclimatic conditions, sugarcane responds positively to soil application of Si sources. There is, however, a need to test soil, plant and silicate materials used as Si sources for making Si management in sugarcane efficient and affordable for farmers.

Analysis of Si by atomic absorption spectrometry (AAS) or colorimetric techniques requires that Si be in solution. When analysis of soluble or extractable forms of Si is performed, this requirement is easily met; however, when total Si analysis is desired, dissolution is made difficult by the presence of silicates and aluminates.

Soil Testing

Since plants absorb Si from soil, it is important to understand its forms and reactions in soils. Silicon forms may be defined in terms of total, extractable, and soluble. As the name implies, total Si comprises all forms of Si that may be

present and can be solubilized by strong alkali fusion or acid-digestion bomb methods. Extractable Si represents those forms removed by less severe dissolution agents, such as sodium dithionite, ammonium oxalate, weak alkalis, and sodium pyrophosphate. These extractants remove Si of intermediate stability that are often found associated with crystalline or amorphous soil components. Soluble Si represents the most labile form in soils and consists primarily of monomeric silicic acid; soluble Si occurs in interstitial soil solutions when determination is desired.

Observations on a sugarcane field at the Everglades Research and Education Center (Florida), showed that the concentration of Si in sugarcane was 1.0 - 1.2% in leaves, 0.68 - 0.84% in nodes and 0.42 - 0.67% in internodes (dry weight). Based on these data and average sugarcane harvest data (80 t ha⁻¹ of fresh mass), it was determined that nearly 100 kg ha⁻¹ of Si are removed with each harvest. Data in 1992 at the Everglades Research and Education Center (Belle Glade, FL) showed that for each harvested crop between 50 to 450 kg ha⁻¹ of Si are removed every year. The total amount of plant available Si makes up not more than 45 kg ha⁻¹ of Si (sum of mobile and potentially soluble Si in the 0-10 cm layer) in Histosol and less than 6 kg ha⁻¹ of Si in Spodosol. Consequently, the total balance of Si on agricultural fields is negative in both soils.

Since the 1960s, sugarcane scientists in Hawaii, Mauritius and Florida have been working on soil testing to assess Si status of soils. Several chemical extractant procedures have been developed to determine plant-available Si status of sugarcane soils (TABLE 11).

Plant-available Si in soil seems to be influenced by several factors, such as pH, clay content, parent material and its weathering, and chemical procedure. Therefore, sugarcane scientists are faced

with a challenge to develop and adopt a simple-to-use, but dependable, soil testing procedure that is appropriate for a given agro-climate.

The most common chemical extractant used is 0.5 M ammonium acetate (NH₄OAc, pH 4.8) This use has produced encouraging results. In Florida, an agronomic response to silicate application can be obtained when Si extracted from air-dry soil with acetate buffer (pH 4.85) is greater than 100 mg dm⁻³ (Kidder and Gascho, 1977). The acetate buffer-extractable Si can be determined using a new colorimetric procedure that is superior to earlier methods in terms of color stability, and sensitivity (Yanai et al., 1996). Although 0.01 M CaCl₂ extractant mimics the ionic strength and pH of soil solution, it has been used for studying the chemical kinetics of Si release from soils and not for bio-available Si in soils (Gibson, 1994). The phosphate extractant with 3.5 pH adjusted with acetic acid (HAOc) may have some advantages because it seems to extract adsorbed Si (capacity factor) as well as water-soluble Si (intensity factor) from soil. (Fox et al., 1967a; Khalid et al., 1978). Korndörfer et al. (1999b) working with upland rice and four different soils concluded that among the extractants tested, the acetic acid 0.5 M gave the best estimate for the available Si in the soil.

Shaking time and temperature can affect Si extracted from soil. Most of soluble Si seems to be released within the first hour of shaking (Gibson, 1994). Therefore, a 4-hour shaking period used by many workers should be adequate for routine soil testing. The use of wider soil:extractant ratios of 1:5 or 1:10 is common, perhaps to minimize desorption of Si by soil.

Plant uptake of Si was most closely related to Si in the soil where a 1:10 (soil: NH₄OAc.) extractant was used. The "r" value for the water extraction method increased as soil pH decreased, indicating

the Si solubility and Si uptake from applied silicates increased as pH decreased (Medina-Gonzales et al., 1988).

Recently, Matichenkov and Snyder (1996) have used a 1:5 soil to water ratio for extraction of so-called mobile forms of Si from south Florida soils. According to them, it is possible to determine monosilicic acids, polysilicic acids and organo-Si compounds in the water extract. However, the practical significance of these fractions in sugarcane nutrition is not clear.

Other factors such as soil sampling, storage time and extent of drying could also affect Si status of soil samples. The process of soil drying in field and/or laboratory may increase aggregate stability and resistance to dispersion (Jersak et al., 1992); and therefore can affect the extractability of soil Si. Usually various extractions from dry soil samples are used for research of mobile forms of soil Si substances (Barsykova and Rochiev, 1979; Nonaka and Takahashi, 1986). Results of dry soil extractions do not reflect actual contents of mobile Si forms. Drying of soil samples leads to essential change in the equilibrium between soluble and solid Si substances. The soluble Si compounds (monosilicic, polysilicic acids and organo-Si substances) are adsorbed on soil particles, being dehydrated in the process. To restore the natural equilibrium between various Si substances, it is necessary to immerse the soil sample in water for about one month (Sadzawka and Aomine, 1977). In addition, by using only dry soil extraction it is impossible to determine the distribution among monosilicic acids, polysilicic acids and organo-Si substances, which play very different roles in various soil biogeochemical processes (Matichenkov and Animosova, 1996). Therefore, it is necessary to develop new, highly informative methods of investigating mobile Si compounds in soil.

Plant Testing

Plant testing for Si status mainly consists of leaf tissue sampling and its chemical analysis. Since analytical errors are relatively small, perhaps more attention should be given to proper leaf tissue sampling and preparation.

Halais et al. (1969) described details of leaf tissue sampling and its preparation. According to them, leaves from primary stalks should be sampled when there has been no water stress during the fortnight preceding the sampling and no wind damage resulting in shredding of leaves. Workers on Mauritius have sampled third to sixth leaf sheaths of plant and ratoon crops generally at boom stage (Halais, 1966, 1967, and 1969; Wong You Cheong and Halais, 1970). However, Ross et al. (1974) sampled the middle section (10 cm) of the third leaf lamina free of midrib in the peak growth stage of ratoons.

Fox et al. (1969) used the system of numbering tissue for plant samplings for securing crop log samples. Leaves were designated in numerical order counting the spindle cluster as number 1. The spindle cluster was defined so that the sheath of leaf 3 was well elongated. The internodes were given the same number of the leaf sheath attached at the upper end of the node. The entire blade was used for the leaf blade sample. Total Si was determined by ashing ground plant tissue in a nickel crucible. Soluble Si was estimated in 5 to 10 fresh plant samples using 2% tri-chloro-acetic acid (TCA). They found that soluble Si in plant tissue gave more useful information about the Si-status of the plant, but the fraction was found unstable with time. A good relation of TCA-soluble Si in the sheath to water-soluble Si in soils was observed (Fox et al., 1967b).

In Florida, sampling of randomly selected 10 to 20 top-visible dewlap (TVD) leaves (youngest fully expanded leaves)

with midribs has been a common practice (Elawad et al., 1982b; Anderson et al., 1987; Anderson, 1991; Raid et al., 1992). Response to silicate application is probable in Florida soils if total Si of TVD leaves is less than 1.0% (Kidder and Gascho, 1977).

For the determination of total Si in plant tissue, a rapid gravimetric procedure developed by Elliott et al. (1988) or an autoclave-induced digestion procedure for colorimetric determination of Si in rice plant tissue (Elliott and Snyder, 1991) may be used with necessary modifications.

Silicon Source Testing

In general, calcium silicate has been used as a Si source for sugarcane. Unfortunately, there are no proven methods for assessing the availability of Si in potential Si sources. Effectiveness of silicate material as a Si source for crops depends mainly on its particle size and chemical reactivity. In general, a finer Si source is more effective in supplying Si to sugarcane and rice (Datnoff, et al., 1992). Hagihara (1981) used 100-mesh silicate material for their evaluation studies in sugarcane. Medina-Gonzales et al. (1988) studied calcium silicate materials having two ranges: 0.25 to 0.84 mm (20 to 60 meshes) and 0.07 to 0.15 mm (100 to 200 meshes). They found, in general, decreased Si availability with increased particle size. These examples suggest that particle size of silicate materials must be defined when evaluating their chemical reactivity.

Chemical reactivity of silicate materials to be used as an Si source for sugarcane can be determined using three types of testing procedures (See also TABLE 12):

1) *Direct Chemical Extraction* - In this procedure, Si is directly extracted from silicate materials with chemical solution such as 0.5 M NH_4AOc .

2) *Indirect Chemical Extraction After Soil Incubation* - The silicon source to be evaluated is incubated with soil at near field capacity for varying periods and the chemical extractant is used to determine Si released in the soil from the Si source. Medina-Gonzales et al. (1988) used three extractants: shaking in water (soil:water ratio, 1:10) for four hours; displacing water from saturated soil in leaching tubes after equilibrating for two days; and shaking soil for one hour with 0.5 M NH_4AOc in a ratio 1:20.

3) *Biological Extraction* - Medina-Gonzales et al. (1988) used an adaptation of the method devised by Stanford and De Ment (1957) for short-term biological extraction of Si using a previously developed mat of sugarcane roots.

RESEARCH AGENDA

There are certain areas relevant to Si nutrition and its management that need to be investigated for making sugarcane production economically more viable and sustainable during the 21st century.

1. *Regional Si Status Surveys of Soils and Waters*: Due to desilication process, weathered soils (Alfisols, Inceptisols, Oxisols, Ultisols, etc.) of the sub-tropics and tropics (D'Hoore and Coulter, 1972) and problematic organic soils (Histosols) are most likely to be low or deficient in plant-available Si. They may not be able to support healthy and productive growth of crops that absorb relatively large amounts of Si from soil. In other soils, intensive cultivation of high yielding sugarcane cultivars having very short fallow periods, may show signs of temporary depletion of bio-available Si. Decreasing trends in yields of ratoon crops could be an example of the temporary depletion. In order to address these soil Si related issues, periodical Si status surveys of soils, plants and waters should be helpful for sustaining

sugarcane yields over a long time. The better understanding of soluble or plant-available Si in soil during crop growth may assist formulating efficient region-specific integrated nutrient management systems for sugarcane.

2. Development of Efficient Management Practices of Si Sources: Improved utilization of Si sources by plants through their proper management is essential for higher agronomic efficiency. Research should continue to develop efficient Si management practices for sugarcane for increasing value:cost ratios and eventually affordability of Si sources for small farmers of developing countries. Application of Si sources appropriately integrated with the use of different organic manure, and other conventional fertilizers, especially soluble P sources warrant consideration.

3. Development of Biotechnology for Si Management: There are research areas in which biotechnology for using Si sources could be rewarding in the future. Two areas of research are:

- use of cellulolytic fungi for enhancing decomposition of sugarcane trash and
- use of silicate-dissolving bacteria as a part of integrated nutrient management system.

At present, Si in trash is not effectively recycled. Generally, most of the trash is burned in the fields. For the trash that is placed for mulching in the furrows of the ratoon crop or that is composted, efficient microbial organisms, especially cellulolytic fungi, may speed up its decomposition and could help the recycling of plant Si. Yadav (1977), Shinde et al. (1990) and Shinde et al. (1993) have identified efficient cellulolytic fungi. Genetic engineering approaches for developing efficient microorganisms that can decompose trash at an accelerated rate should be considered.

Reports in the literature suggest that microorganisms are involved in Si cycle (transformations) in nature (Vintikova, 1956; Tsyurupa, 1964; Krumbein and Werner, 1983). Certain bacteria seem to possess an ability to decompose siliceous rocks and minerals (Vintikova, 1956), and aluminum-silicates and quartz sand (Kol'chugina et al., 1985). Webley et al. (1960) of the Macauley Institute of Soil Research, Aberdeen, observed decomposition of amorphous synthetic silicates, crystalline Wollastonite, apophyllite and olivine that were incorporated into molten agar by a species of *Pseudomonas*. According to Vintikova (1964), soil bacteria lacking a mucous coat were more effective than those of the mucous type were. Vintikova (1956) and Surman (1958) have studied some morphology and physiology of silicate bacteria. Several beneficial effects of silicate bacteria, so-called silico-bacterian are reported on maize (Vintikova, 1964); vegetables (Aleksandrov, 1958; Zak, 1964) and wheat (Aleksandrov, 1958). The beneficial effects of silicate-decomposing bacteria on Si-accumulating plants, such as sugarcane, are not seen in the literature, but if confirmed, would be very useful for crops like sugarcane. Biotechnology to identify and/or to develop new genetically engineered strains of bacteria having the ability to decompose insoluble silicates should be on the research agenda.

4. Foliar Application of Si - Is it effective?: Plants are known to absorb some nutrients through leaves. However, very little information is reported about Si absorption through sugarcane leaves (Alexander, 1968; Alexander, 1969). Foliar spraying of soluble Si as 0.1 to 0.2 mg L⁻¹ solution of Na₂SiO₃ (Okamoto, 1993) and 1% solution of sodium silicate (Hooda and Srivastava, 1996; Parvar and Hegde, 1979) on leaves of rice plants has been reported with favorable effect on plant growth.

Jayabhad and Chockalingam (1990) conducted field experiments to develop management practices for mitigating effects of drought on sugarcane. When drought was imposed by irrigating only once a week during summer (May and June), they observed increased yields of sugarcane (var. CO. 6304) due to spraying 2.5 % sodium metasilicate. The effect was attributed to a reduced rate of transpiration. If the observation that a foliar spray of soluble Si improves plant growth and yield in sugarcane is confirmed, an appropriate Si management practice for alleviating the effect of drought could be developed for sugarcane. According to Schnug and Franck (1985), under intensive systems of fertilization and plant protection, the possibilities of using the yield-promoting effect of Si are limited mainly to foliar application.

5. Genetic Research for Efficient Si-accumulating Sugarcane Cultivars: Genetics plays an important role in nutrient uptake by plants including that of Si. Genotype variability for Si content exists in sugarcane (Deren et al., 1993). Better Si-accumulating sugarcane cultivars may have the advantage of requiring lower rates of Si fertilizers or their less frequent applications. While using a genetic approach for development and/or screening of genotypes for certain desirable traits, consideration of a Si-accumulation trait will be rewarding.

6. Interaction Between Silicon Nutrition and UV-B Radiation: Ambient ultraviolet-B (UV-B) flux in the tropics, the major sugarcane growing area, is among the highest on the earth's surface because the stratospheric ozone layer is naturally thinner and because solar angles are higher near the equator than at the higher latitudes. With the depletion of stratospheric ozone caused by chloro-fluorocarbons, increased UV-B flux

may adversely affect sugarcane yields. Crop cultivars having differential ability to absorb Si from soil may also differ in sensitivity to UV-B, which could be detrimental to their growth. In rice, certain biochemical and physiological variables were more sensitive to UV-B than other variables and shoot dry weights were reduced by 21% and 23% for the most UV-B sensitive cultivars, namely IR45 and IR74 (IRRI, 1990). The workers at IRRI also noticed increased leaf Si in UV-B sensitive but not in tolerant rice cultivars. These observations may be applicable to sugarcane. Gascho (1978), Wong You Cheong et al. (1972) and Elawad et al. (1985) suggest that solar UV-B radiation may have caused leaf freckling in Si-deficient sugarcane grown under direct sunlight. Supporting this, Elawad et al. (1985) could not obtain this UV-B effect under greenhouse conditions. Therefore, research to enhanced UV-B radiation on selected sugarcane cultivars, having different abilities to absorb Si from soil, and screening of sugarcane germplasm for their responses to increased UV-B radiation, with and without a Si supply, may be initiated now to address probable UV-B radiation effects, a potential future environmental problem.

7. Tolerance to Salt Stress: Si influences water use by reducing cuticular transpiration (Jones and Handreck, 1967; Lewin and Reimann, 1969; Yoshida, 1975). Reports suggest that, by improving Si nutrition of plants, it may be possible to reduce their internal water stress and thereby make them withstand salt stress better (Yoshida, 1975; Matoh et al., 1986; Miyake, 1993). These results may be applicable to sugarcane and, if demonstrated, they could be used for making salt-affected sugarcane soils more productive.

GLOSSARY

abiotic	Non-living basic elements of the environment, such as rainfall, temperature, wind, and minerals.
adsorption	The attraction of ions or compounds to the surface of a solid. Soil colloids adsorb large amounts of ions and water.
adsorption complex	The group of organic and inorganic substances in soil capable of adsorbing ions and molecules.
aluminosilicates	Compounds containing aluminum, silicon, and oxygen as their main constituents. An example is microcline, KAlSi_3O_8 .
available nutrient	That portion of any element or compound in the soil that can be readily absorbed and assimilated by growing plants. ("Available" should not be confused with "exchangeable").
bagasse	The dry pulp remaining from sugar cane after extraction of the juice.
base saturation percentage	The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen and aluminum. It is expressed as a percentage of the total cation exchange capacity.
basic silicate	A by-product in the manufacture of steel, containing lime, phosphorus, and small amounts of other plant nutrients such as sulfur, Mn and iron.
broadcast	To scatter seed or fertilizer on the surface of the soil.
calcium metasilicate	A white powder, CaSiO_3 , insoluble in water, used as an antacid, and as a filter for paper.
calcium silicate	Any of the silicates of calcium: calcium metasilicate, dicalcium silicate, and tricalcium silicate.
cation	A positively charged ion; during electrolysis it is attracted to the negatively charged cathode.
cation exchange	The interchange between a cation in solution and another cation on the surface of any surface-active material, such as clay or organic matter.
cation exchange capacity	The sum total of exchangeable cations that a soil can adsorb. Sometimes called total-exchange capacity, base-exchange capacity, or cation adsorption capacity. Expressed in centimoles of charge per kilogram ($\text{cmol}_c \text{ kg}^{-1}$) of soil (or of other adsorbing material, such as clay).
clay	(1) A soil separate consisting of particles <0.002 mm in equivalent diameter. (2) A soil textural class containing $>40\%$ clay, $<45\%$ sand,

and <40% silt.

decomposition	Chemical breakdown of a compound (e.g., a mineral or organic compound) into simpler compounds, often accomplished with the aid of microorganisms.
desorption	The removal of sorbed material from surfaces.
diatomaceous earth	A geologic deposit of fine, grayish, siliceous material composed chiefly or wholly of the remains of diatoms. It may occur as a powder or as a porous, rigid material.
diatoms	Algae, having siliceous cell walls that persist as a skeleton after death; any of the microscopic unicellular or colonial algae constituting the class Bacillariaceae. They occur abundantly in fresh and salt waters and their remains are widely distributed in soils.
essential element	A chemical element required for the normal growth of plants.
evapotranspiration	The combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants.
exchange capacity	The total ionic charge of the adsorption complex active in the adsorption of ions. See also anion exchange capacity; cation exchange capacity.
fertilizer requirement	The quantity of certain plant nutrient elements needed, in addition to the amount supplied by the soil, to increase plant growth to a designated optimum.
fungi	Eukaryote microorganisms with a rigid cell wall. Some form long filament cells called hyphae that may grow together to form a visible body.
gibbsite	$Al(OH)_3$ - An aluminum trihydroxide mineral most common in highly weathered soils, such as oxisols.
goethite	$FeOOH$ - A yellow-brown iron oxide mineral that accounts for the brown color in many soils.
granulation	The process of producing granular materials. Commonly used to refer to the formation of soil structural granules, but also used to refer to the processing of powdery fertilizer materials into granules.
hematite	Fe_2O_3 - A red iron oxide mineral that contributes red color to many soils.
Histosol	Soils formed from materials high in organic matter. Histosols with

essentially no clay must have at least 20% organic matter by weight (about 78% by volume). This minimum organic matter content rises with increasing clay content to 30% (85% by volume) in soils with at least 60% clay.

hyphae	Filament of fungal cells. Actinomycetes also produce similar, but thinner, filaments of cells.
imogolite	A poorly crystalline aluminosilicate mineral with an approximate formula $\text{SiO}_2\text{Al}_2\text{O}_3 \cdot 2.5\text{H}_2\text{O}$; occurs mostly in soils formed from volcanic ash.
leaching	The removal of materials in solution from the soil by percolating waters.
lime (agriculture)	In strict chemical terms, calcium oxide. In practical terms, a material containing the carbonates, oxides and/or hydroxides of calcium and/or magnesium used to neutralize soil acidity.
lime requirement	The mass of agricultural limestone, or the equivalent of other specified liming material, required to raise the pH of the soil to a desired value under field conditions.
limestone	A sedimentary rock composed primarily of calcite (CaCO_3). If dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$) is present in appreciable quantities, it is called a dolomitic limestone.
lodging	Falling over of plants, either by uprooting or stem breakage.
micas	Primary aluminosilicate minerals in which two silica tetrahedral sheets alternate with one alumina/magnesia octahedral sheet with entrapped potassium atoms fitting between sheets. They separate readily into visible sheets or flakes.
muck	Highly decomposed organic material in which the original plant parts are not recognizable. Contains more mineral matter and is usually darker in color than peat. See also muck soil; peat.
muck soil	(1) A soil containing 20 to 50% organic matter. (2) An organic soil in which the organic matter is well-decomposed.
oxidation	The loss of electrons by a substance; therefore, a gain in positive valence charge and, in some cases, the chemical combination with oxygen gas.
Oxisols	Soils with residual accumulations of low-activity clays, free oxides, kaolin, and quartz. They are mostly in tropical climates.
particle size	The effective diameter of a particle measured by sedimentation, sieving,

or micrometric methods.

productivity (soil)	The capacity of a soil for producing a specified plant or sequence of plants under a specified system of management. Productivity emphasizes the capacity of soil to produce crops and should be expressed in terms of yields.
reaction (soil)	The degree of acidity or alkalinity of a soil, usually expressed as a pH value or by terms ranging from extremely acid for, pH values <4.5 to very strongly alkaline for pH values >9.0.
residual material	Unconsolidated and partly weathered mineral materials accumulated by disintegration of consolidated rock in place.
savannah	Grassland with scattered trees; often a transitional type between true grassland and forest.
silica	A white or colorless crystalline compound, SiO_2 , occurring as quartz, sand flint, agate, and many other minerals and used to make glass, and concrete. Also called silicon dioxide.
silica gel	A highly adsorbent gelatinous form of Si, used as drying and humidifying agent.
silica/alumina ratio	The molecules of silicon dioxide (SiO_2) per molecule of aluminum oxide (Al_2O_3) in clay minerals or in soils.
silica/sesquioxide ratio	The number of molecules of silicon dioxide (SiO_2) per molecule of aluminum oxide (Al_2O_3) plus ferric oxide (Fe_2O_3) in clay minerals or in soils.
silicate	Any of numerous compounds containing silicon, oxygen, and a metallic or organic radical, occurring in most rocks except limestone and dolomite.
siliceous	Containing, resembling, relating to, or consisting of Si. Growing in soil rich in Si.
silicic acid	A jellylike substance, $\text{SiO}_2 \cdot n\text{H}_2\text{O}$, produced when sodium silicate solution is acidified.
silicon	Symbol Si. A nonmetallic element occurring extensively in the earth's crust: used in glass, semiconducting devices, concrete, brick, refractories, pottery, and silicones.
silicone	Any of a group of semi-inorganic polymers based on the structural unit R_2SiO , where R is the organic group (extremely stable in high temperature, and water-repellent): used in adhesives, lubricants,

protective coatings, paints, and electrical insulation.

slag

A product of smelting, containing mostly silicates.

soil amendments

Any substance other than fertilizers, such as lime, sulfur, gypsum, and sawdust, used to alter the chemical or physical properties of a soil, generally to make it more productive.

tetrahedral sheet

Sheet of horizontally linked tetrahedron-shaped units that serve as one of the basic structural components of silicate (clay) minerals. Each unit consists of a central four-coordinated atom (e.g., Si, Al, Fe) surrounded by four oxygen atoms that, in turn, are linked with other nearby atoms (e.g., Si, Al, Fe), thereby serving as interunit linkages to hold the sheet together.

Ultisol

Soils that are low in bases and have subsurface horizons of alluvial clay accumulations. They are usually moist, but during the warm season of the year some are dry part of the time.

wilting point
(permanent wilting
point)

The moisture content of soil, on an oven-dry basis, at which plants wilt and fail to recover their turgidity when placed in a dark, humid atmosphere.

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TABLE 1. Soluble and total soil silicon compared with silicon content in sugarcane leaf.

Sample Location	Si in soil		Si Leaf
	Soluble*	Total	
	----- % -----		
Ocala. Rd. 315	0.0178	42.7	--
Fellsmere	0.0110	41.4	1.18
Pahoke	0.0071	4.7	1.00
Oklawaha	0.0042	12.2	1.56
Florahome	0.0042	4.3	0.46
Florahome	0.0037	4.3	1.06
Canal Point	0.0028	2.2	0.40
Fellsmere	0.0025	38.0	0.09
Belle Glade	0.0019	0.7	0.15
Oklawaha	0.0009	3.1	2.05

Source: adapted from Bair (1966).

TABLE 2. Effect of Wollastonite in an Oxisol on the Si content in the plant and soil and Si accumulation by the aerial part of the sugarcane plant.

Si applied kg ha ⁻¹	Si in the tissue %	Si accumulated g pot ⁻¹	Si in the soil mg dm ⁻³
0	0.70	0.36	14
116	0.89	0.43	17
231	1.41	0.68	19
462	1.77	0.74	30
924	1.93	1.03	46

Source: Adapted from Rodrigues, 1997.

TABLE 3. Average silicon content of 3rd leaf lamina (free of the midrib) collected in the peak growth stage (7.5 months after harvest).

	Si - Dry matter					Average
	1969	1970	1971	1972	1973	
	----- % -----					
Control	0.45	0.42	0.61	0.48	0.59	0.51
7.1 t - Calcium Silicate	0.71	0.56	0.93	0.60	0.85	0.73
14.2 t - Calcium Silicate	0.85	0.68	1.07	0.77	1.02	0.88

Source: Ross et al. (1974).

TABLE 4. Effects of calcium silicate on average cane yields of 2 cultivars.

Treatments	Plant Cane	Ratoon					Means
	1968	1969	1970	1971	1972	1973	
	----- t ha ⁻¹ -----						
Control	40.0	78.4	53.8	71.1	61.1	55.2	59.9
7.1 t Calcium Silicate	63.5	92.2	62.1	83.9	72.8	68.5	73.8
14.2 t Calcium Silicate	68.5	96.2	64.5	90.5	76.8	72.0	78.1

Source: adapted from Ross et al. (1974).

TABLE 5. Sugarcane yield, Pol ha⁻¹ and Pol % of cane obtained for cultivars NA56-79 and IAC48/65 (plant cane and ratoon) with cement application.

CULTIVARS		PLANT CANE			RATOON		
		----- Cement - t ha ⁻¹ -----					
		0	2	4	0	2	4
NA56-79	Cane t ha ⁻¹	108	112	114	97	88	96
	Pol *% cane	16.2	15.9	16.1	17.7	17.7	17.6
	Pol - t ha ⁻¹	17.5	17.8	18.3	17.2	15.3	16.9
IAC48/65	Cane t ha ⁻¹	119	124	128	94	96	96
	Pol % cane	14.7	15.3	15.1	17.1	16.9	17.0
	Pol - t ha ⁻¹	17.5	19.0	19.3	16.1	16.2	16.3

*Percentage of sucrose in the sugarcane juice or stalk.

Source: Casagrande et al. (1981).

TABLE 6. Effect of cultivar and soil amendment with calcium silicate slag on leaf silicon concentration, ringspot (*Leptosphaeria sacchari*) severity.

CULTIVAR	Slag Rates t ha ⁻¹	Si Tissue %	Ringspot Severity	
			Leaf 4 %	Leaf 5 %
CP72-1210	0	0.28	23.4	45.8
	6.7	0.67	7.3	17.8
CP74-2005	0	0.29	8.5	23.0
	6.7	0.59	3.1	7.6
CP80-1827	0	0.29	5.2	9.0
	6.7	0.55	1.7	3.1
CP70-1133	0	0.28	10.5	23.8
	6.7	0.54	4.2	11.0
CP72-2086	0	0.25	4.1	11.5
	6.7	0.73	0.9	2.0

Adapted from Raid et al. (1992).

TABLE 7. Influence of Si on plant resistance to stem borer (*Diatraea saccharalis*), Si in the TVD leaf and dry weight of sugarcane plants.

Na ₂ SiO 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.

TABLE 8. Total and citric acid soluble silicon in Si sources.

Source	Total Si (indicated by supplier)	Total Si	Si - soluble by citric acid 2%	Soluble Portion
		----- Si % -----		%
Calcium Silicate Slag*	---	21.1	14.8	70
Wollastonite - Calc. Silicate	24.2	23.1	Trace	0
Minas Liga - Basic Slag**	41.2	39.2	0.05	0
Magnesium Silicate - course	---	27.8	Trace	0
Magnesium Silicate - fine	---	27.7	Trace	0
Piau - Basic Slag**	---	8.5	6.9	82
Thermalphosphate Yoorin	---	10.8	10.4	96

* Elemental P Electric Furnace by-product (Monsanto/Calcium Silicate Corp.).

** Byproduct of iron manufacture.

Source: Gascho and Korndörfer (1998).

TABLE 9. Total and soluble Si content of some silicon fertilizers and location.

Material	Location	Si	
		Total	Soluble*
		----- % -----	
Slag - electric furnace	Alabama	18.2	3.960
Slag - open hearth (ground)	Alabama	6.9	1.720
Slag - open hearth	Alabama	2.0	1.660
Hi-cal silicate limestone (ground)	Kendrik	0.2	0.016
Hi-cal silicate limestone (ground)	Brooksville	3.4	0.026
Dolomite	Lebanon	0.4	0.023
Dolomite	Venice	4.5	0.023
Rock phosphate	Florida	3.6	0.025
Colloidal phosphate	Dunnellon	10.8	0.023
Fuller's earth	Georgia	35.1	0.023

* 2 g of fertilizer + 50 ml ammonium acetate 0.5 N, pH 4.8 (30 min agitation).

Source: adapted from Bair (1966).

TABLE 10. Yields, pH and nutrient uptake for the different soils and amendments.

Soil series	Amendments	Level t ha ⁻¹	Soil pH	Mn In tops G kg ⁻¹	Mn:Si X 100
(A) Balgowan (71% clay)	Control	0	4.67	360	79
	CaSiO ₃	4.5	4.7	278	47
	CaSiO ₃	9.0	4.8	283	41
	CaSiO ₃	18.0	5.0	223	25
	Blast Furnace Slag	4.5	5.1	363	39
	Blast Furnace Slag	9.0	5.3	283	27
	Blast Furnace Slag	18.0	5.6	170	13
	Cement	4.5	5.1	246	38
	Cement	9.0	5.4	163	20
	Cement	18.0	5.8	56	5
	Metasilicate Slag	4.5	5.0	270	38
	Metasilicate Slag	9.0	5.3	166	19
	Metasilicate Slag	18.0	5.6	69	6
	CaCO ₃	4.5	5.1	307	75
	CaCO ₃	9.0	5.4	197	59
	CaCO ₃	18.0	5.8	67	22
(B) Balgowan (63% clay)	Control	0	4.5	338	61
	Metasilicate Slag	4.5	5.0	230	24
	Metasilicate Slag	9.0	5.1	128	13
	Metasilicate Slag	18.0	5.4	57	4
	CaCO ₃	4.5	4.9	183	37
	CaCO ₃	9.0	5.1	117	33
	CaCO ₃	18.0	5.6	67	19
(C) Trevanian (24% clay)	Control	0	4.6	428	116
	Metasilicate Slag	4.5	5.6	93	12
	Metasilicate Slag	9.0	6.2	59	4
	Metasilicate Slag	18.0	7.2	46	3
	CaCO ₃	4.5	5.8	90	28
	CaCO ₃	9.0	6.7	85	26
	CaCO ₃	18.0	7.3	67	13

Source: adapted from Preez (1970).

TABLE 11. Chemical extraction procedures used for assessing plant-available Si in sugarcane and rice soils.

EXTRACTION PROCEDURE	MAIN Si FORM	REFERENCE
- 10g soil + 100 ml water. 4 h. shaking high centrifugation (24000 g) used for clarification	Ionic	Fox et al. (1967a) Khalid et al. (1978)
- 10 g soil + 100 ml of solution containing 500 ppm P as Ca(H ₂ PO ₄) ₂ and 0.1N (H, NH ₄) OAc., pH 3.5	Adsorbed and soluble	Fox et al. (1967a) Khalid et al. (1978)
- 1g soil + 100 ml of solution 0.02N H ₂ SO ₄ containing 3g (NH ₄) ₂ SO ₄ per liter, 30 min shaking.	Soluble	Fox et al. (1967a)
- 10g soil + 50 ml of 0.5M NH ₄ OAc (pH 4.8), 30 min shaking	Soluble	Bair (1966)
- 10g soil + 50 ml of 0.5M NH ₄ OAc (pH 4.8), 1h shaking	Soluble	Fox et al. (1967a)
- 10 g soil + 50 ml of 0.5M NH ₄ OAc (pH 4.85), 4 h shaking	Soluble	Kidder and Gascho (1977)
- 5 g soil + 100 ml of 0.5M NH ₄ OAc (pH 4.8), 4 h shaking	Soluble	Medina-Gonzales et al. (1988)
- 4 g soil + 50 ml of HC ₂ H ₃ O ₂ 0.5M.	Available	Barbosa Filho (1996)
- 10 g soil + 100 ml of HC ₂ H ₃ O ₂ 0.5M.	Available	Korndörfer et al. (1998b)

TABLE 12. Chemical extraction procedures used for assessing Si sources for plant-available Si.

CHEMICAL PROCEDURE	REFERENCE
- 2 g of Si source + 50 ml of 0.5 M NH ₄ OAc (pH 4.8), shaking for 30 min.	Bair (1966)
- Si source (100 mesh) + 0.5 M NH ₄ OAc. (pH 4.85), shaking for varying periods	Hagihara (1981)
- 10 g of Si source + 1g polyethylene. Leach with Tris buffer (pH 7) using a peristaltic pump for 56 hours	Barbosa Filho (1996)
- 0.2 grams Si source (65 mesh) + 0.5 g H-resin Ambertite (IRC-50, pK 6.1) + 400 ml water, shaking for 4 d (100 rpm) at 35 °C	Kato and Owa (1990)
- 1 g of Si source + 150 ml of 0.5 M HCl shaking for 1 h at 30 °C (commonly used in Japan)	Barbosa Filho (1996)
- 1 g of Si source + 150 ml of 0.5M NH ₄ OAc (pH4.0), shaking for 1 h at 30 °C. (NH ₄ OAc buffer prepared by diluting 49.2 ml acetic acid and 14.8 g anhydrous sodium acetate to 1L, pH adjusted to 4.0 with acetic acid or sodium acetate	Barbosa Filho (1996)

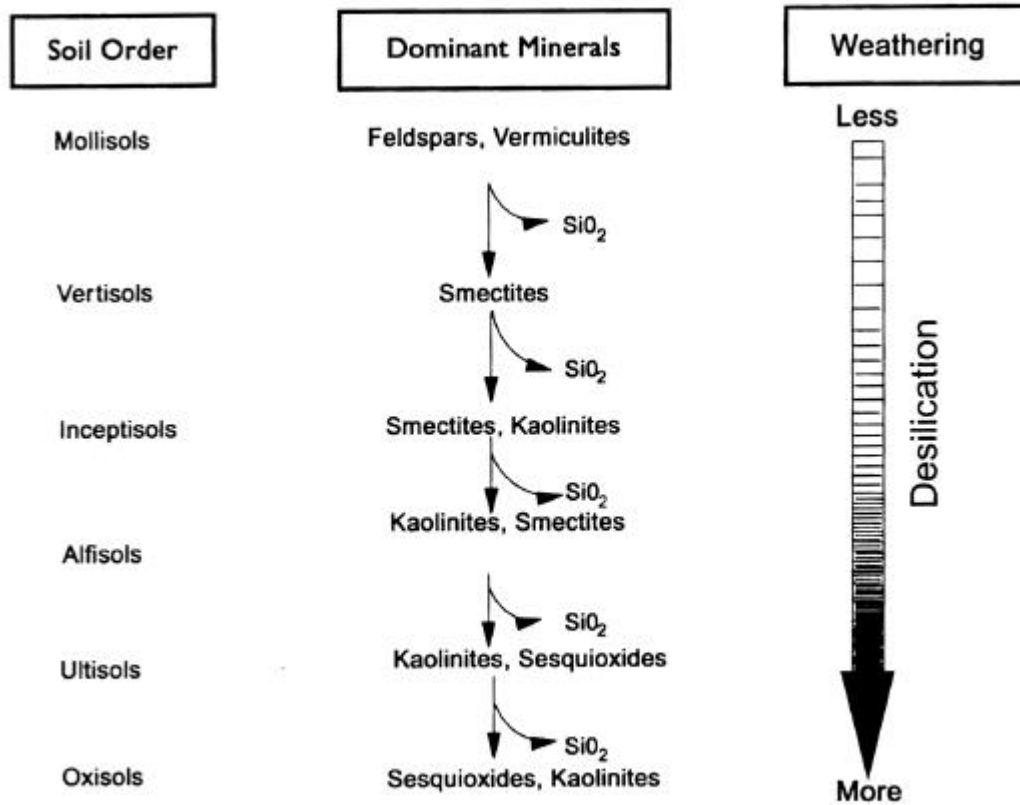
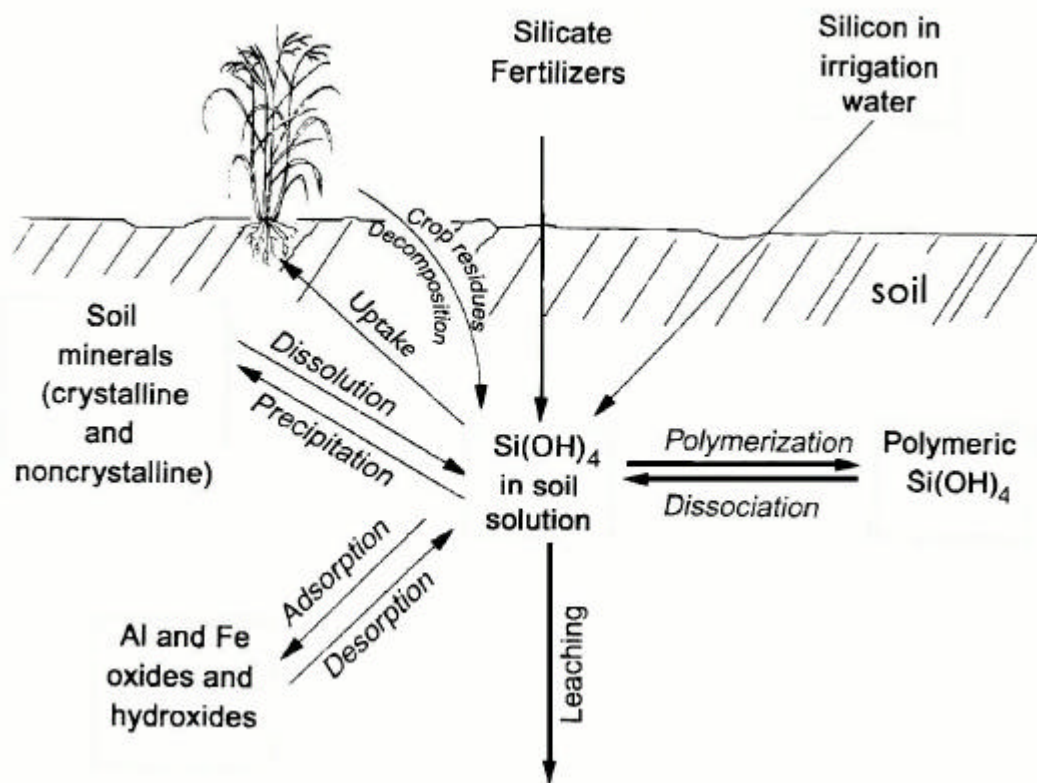


FIGURE 1. Simplified acid weathering sequence in soils (Friesen et al., 1994)



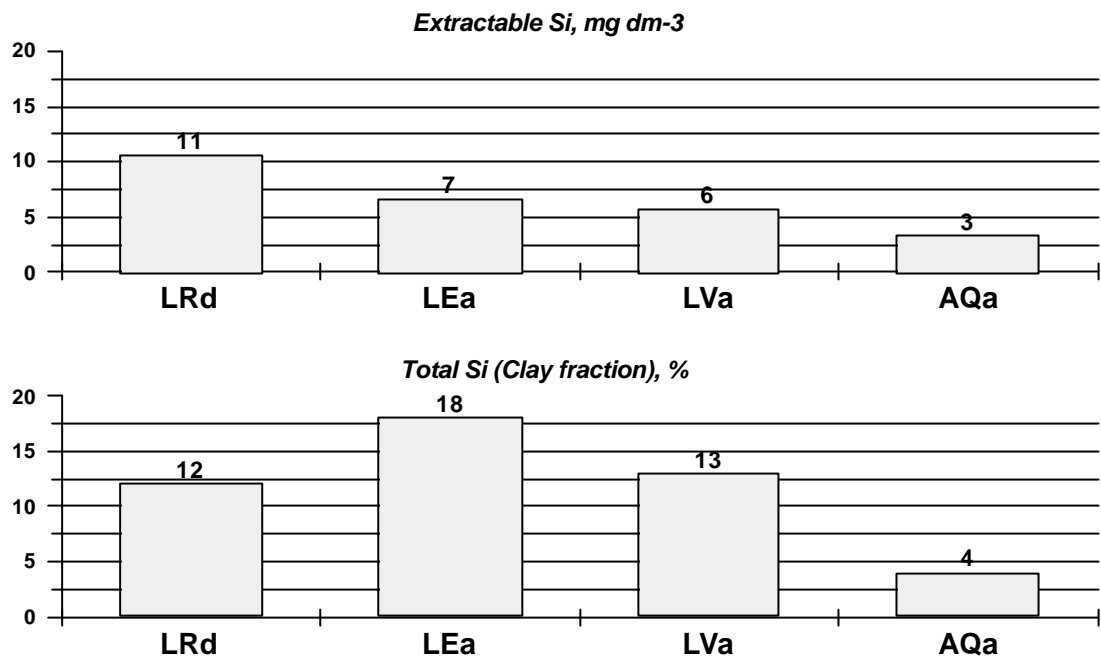


FIGURE 3. Total Si from clay fraction (sulfuric acid method) and available Si in the soil (without Si). Typic Acrustox (LEa), Typic Acrustox (LVa), Rhodic Acrustox (LRd) and Ustoxic Quartzipsammentic (AQa).

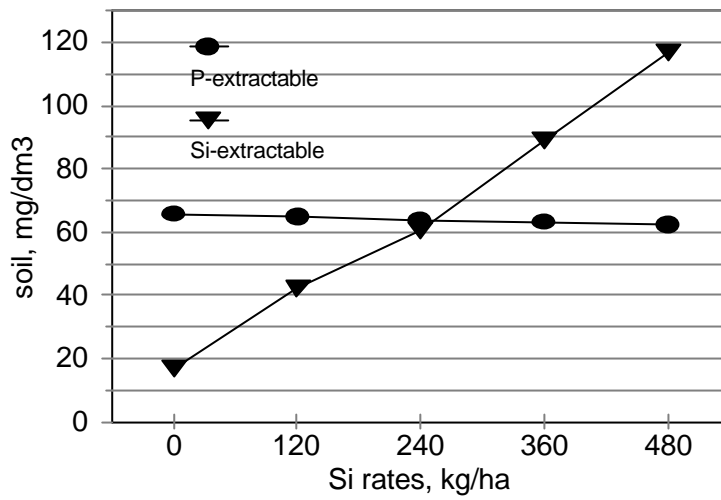


FIGURE 4. Phosphorus and silicon level in the soil after 18 months of thermal-phosphate application (Korndörfer, 1998a).

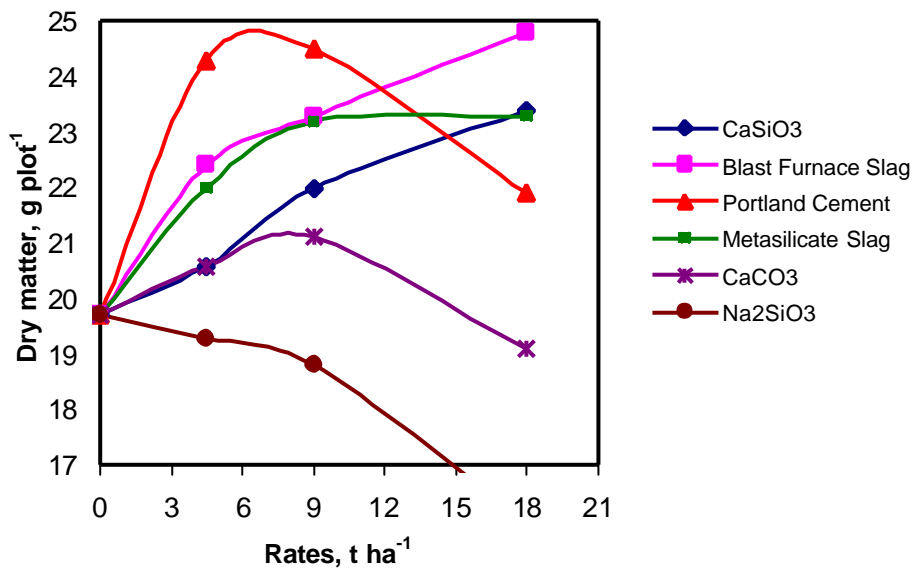


FIGURE 5. Effect of different Si sources on sugarcane dry matter