The Use of Soluble Silicates in Hawaiian Agriculture

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University of Queensland Papers
Department of Agriculture
Volume I Number 6
UNIVERSITY OF QUEENSLAND PRESS
St. Lucia
11 February 1972

PRINTED AND BOUND BY WATSON FERGUSON AND CO., BRISBANE, QUEENSLAND, AUSTRALIA

National Library of Australia card number and ISBN 0 7022 0604 0

THE USE OF SOLUBLE SILICATES IN HAWAIIAN AGRICULTURE

Summary

A sporadic but continuing interest in Hawaii in use of silicates for reducing phosphorus fixation and improving poor plant growth in leached infertile soils led in the late 1950's to significant yield responses by sudangrass to sodium silicate in pot and field experiments. In 1962 dramatic yield increases were obtained in sugarcane at Grove Farm Plantation on Kauai; these increases included gains in sugar (2.9 tons per acre) and in total cane (17 tons per acre). The striking success of this work has led to use of soluble silicates, especially calcium metasilicate slags, in commercial practice on Hawaiian sugar plantations, where sugar yield increases of over 50 percent have been recorded.

Great soil groups on which silicon responses have been obtained include: Humic Latosol, Hydrol Humic Latosol, Aluminous Ferruginous Latosol, and Humic Ferruginous Latosol. In one case a significant sugar yield increase was obtained on a Low Humic Latosol. These soils lie in belts of high rainfall on the windward sides of the major islands.

Presented, in part, as an invited paper to the Australian Society of Soil Science, Queensland Branch, on 29 May 1968 at CSIRO Cunningham Laboratory, St. Lucia, Brisbane.

A "freckling" disease of sugarcane leaves commonly observed in high rainfall, low-silicon soil areas, especially in winter, has been alleviated or corrected by silicate applications. To date only silicon has corrected the leaf freckle disease. Several growth characteristics of sugarcane with silicon treatment have been observed: larger stalk size and elongation, greater number of green and functioning leaves, increased dry matter yield, increased cane yield, and increased sugar yield.

It should be emphasized that no element other than silicon has produced the described yield and plant responses in sugarcane. It has been suggested that there is a level of soil silicon below which satisfactory growth of sugarcane cannot be obtained. Soil and plant analyses are valuable in predicting probable responses to silicate applications.

At present it would be difficult to determine the number of experiments on silicates in Hawaii, but it is safe to assume that all plantations possessing fields in the highly weathered soil zones are conducting silicate research.

Introduction

A number of recent review articles on silicon emphasizes renewed interest in this element. Krauss (1958) discussed the role of silicon in diatoms. McKeague and Cline (1963) reviewed silica in soils. Okuda and Takahashi (1964) reviewed the considerable literature on silicon effects in rice. Jones and Handreck (1967) surveyed the pathways of the "silica cycle" from soil, to plants, through animals and return to soil in plant and animal residues. Comhaire (1966) concluded silicon is beneficial to all crops. Clements (1965*b*) and Chan et al. (1968) reviewed crop responses to silicon and related these responses to those in sugarcane.

Bollard and Butler (1966) reviewed the role of minor elements in plant nutrition, including silicon effects in plants, and concluded that enzymatic or structural systems dependent upon silicon must have evolved in plants.

Historical background

Interest in use of silicates in Hawaiian agriculture goes back before the turn of the century when Maxwell (quoted by Moir, 1936) called attention to the low levels of silica in Hawaiian soils, a mean of about 28 percent in 1,300 samples. Just after the turn of the century, basic slag was applied to sugarcane grown on a Hydrol Humic Latosol at rates of 750 and 1,500 lbs per acre but sugar yields were not increased (Ayres, 1966). McGeorge (1924*b*) first proposed the use of soluble silicates in Hawaii to increase phosphorus availability and assimilation in sugarcane. In these and related studies (McGeorge, 1924*a*) he had noted that greater silica solubility accompanied an increased availability of phosphorus and greater phosphorus assimilation by sugarcane. Also, juices of cane grown on high silica soils contained higher concentrations of phosphorus.

Ayres (1930) found that silicon was absorbed by sugarcane in greater amounts than any other mineral element. In a 12-month crop the following analyses of above-ground tissues were obtained: SiO_2—725 lbs per acre; K_20—390 lbs per acre; N—125 lbs per acre; and P_20_5—40 lbs per acre. At the end of a 30-month crop $Si0_2$ totaled 2,250 lbs per acre.

Ballard (1940) quoted unpublished chemical data by Ayres which gave silica values, as percent dry weight, for the various fractions of the sugarcane crop: dead leaves—2.6 percent; green leaves—1.8 percent; non-millable top or growing point region—0.28 percent; green leaf cane—0.20 percent; and dry leaf cane—0.15 percent.

Borden (1940) in an attempt to study poor growth of sugarcane on 23 soils used an "A-Z" mixture of minor elements which included magnesium silicate as 25 percent of the mixture. The mixture significantly increased sugar yield in 5 soils, but no explanation was presented to account for the yield increase because of the complexity of the mixture used.

Despite this early interest in silica, no beneficial effect of silicate materials was demonstrated until the mid-1950's when the Agronomy and Soil Science Department, Hawaii Agricultural Experiment Station, turned its attention again to the problems of phosphorus fixation and to finding methods to make the infertile aluminous and ferruginous soils suitable for productive agriculture.

Sherman, Chu, and Sakamoto (1955) applied sodium silicate at rates of 0, 250, 500, 1,000 and 2,000 lbs per acre to two soils, Wahiawa and Honolua, in pot experiments with sudangrass as a test plant. No beneficial effects were obtained with applications to the Wahiawa soil, which is predominantly kaolin. In Honolua soil sudangrass yield was increased threefold and phosphorus deficiencies disappeared with 1,000 lbs per acre of sodium silicate.

Ikawa (1956) found phosphorus fixation capacity of a Humic Latosol was reduced by sodium silicate applications; also, sodium silicate increased plant growth and dry matter yield of maize grown in pots. In 1957 the Tennessee Valley Authority (TVA) provided a grant to Dr. G. Donald Sherman, Chairman of the University of Hawaii Department of Agronomy and Soil Science, to study phosphorus problems in tropical soils. This project had as one of its objectives the study of the effects in Hawaiian latosols of various phosphorus fertilizers manufactured by TVA.

Early efforts to reduce phosphorus fixation included study of sodium silicate applications in highly weathered tropical Latosols. Suehisa (1961) obtained the first field responses to soluble silicates in 1960 using sudangrass as the test plant. A later publication (Suehisa, Younge, and Sherman, 1963) reviewed these field and pot experiments in detail. About the same time Monteith (1961) and King (1962) obtained responses to silicates with sudangrass in pots. In this early work responses were considered due to increased phosphorus availability and decreased aluminum toxicity.

Following the field responses to silicates by sudangrass (Suehisa, 1961; Suehisa, Younge, and Sherman, 1963), and other sudangrass responses to silicate applications (Monteith, 1961; Monteith and Sherman, 1962, 1965; King, 1962), the Hawaiian Sugar Planters' Association Experiment Station and the Agronomy and Soil Science Department, Hawaii Agricultural Experiment Station, joined in a series of cooperative experiments using silicates in sugarcane. Co-leaders of this cooperative research programme were Dr. G. Donald Sherman and Dr. A. S. Ayres, with Dr. L. D. Baver as adviser and Mr. William Moragne, manager of Grove Farm, the plantation on the island of Kauai where the experiments were located.

The first sugarcane field experiments in which field responses to TVA slag were obtained were laid out in June 1960 at Grove Farm, Kauai, on an Aluminous Ferruginous Latosol. (For chemical analysis of TVA slag see Table 1.) In August 1960 Kilauea Sugar Company, Kauai, planted a field experiment on an Aluminous Ferruginous Latosol using sodium silicate. The Kilauea experiment was harvested on 6 June 1962 and the Grove Farm experiments were harvested on 21 and 27 June 1962.

In the Grove Farm experiments a yield increase of 5.1 tons of raw sugar in the combined plant and first ratoon crops was obtained with 5,000 lbs per acre of calcium silicate, while lime at 4,000 lbs per acre produced a slight depression in yield (Sherman, Dias, and Monteith, 1964). These authors considered calcium silicate as a liming material. In the Kilauea experiment a significant gain of 0.6 tons sugar was obtained in the plant crop with sodium silicate at 1,000 lbs per acre (Clements, 1965*b*), but the experiment was not followed into the ratoon because of the small response (Ayres, 1966).

TABLE 1

CHEMICAL COMPOSITION OF TVA SLAG

	%
SiO_2	39.5
CaO	36.9
P_2O_5	2.3
Al_2O_3	2.4
Fe_2O_3	1.6
MgO	0.45
Mn	0.070
B	0.018
Zn	0.005
Mo	$<$ 0.001

Because TVA slag produced such a marked improvement in sugar yield in the infertile wetlands at Grove Farm, the number of field experiments increased rapidly in 1962 and 1963 (Ayres, 1966; Clements, 1965*b*). Ayres (1966) reported the results of 9 field experiments throughout Hawaii, including an experiment laid out by the Hawaii Agricultural Experiment Station on Kauai (Younge and Plucknett, unpublished data; Fox et al., 1967*b*). This experiment was the first laid out using very high rates of phosphorus fertilizers (as much as 1,000 lbs phosphorus per acre), thus tending to nullify the argument that beneficial effects of silicate were due to better phosphorus nutrition, and suggesting a direct effect of silicon on yield. Clements (1965*b*) discussed crop log data from a series of experiments carried out in 1963 on the 9 plantations managed by C. Brewer and Company, but for which no yield data were available at the time of publication.

In 1964 Grove Farm Plantation, Kauai, applied 460 tons of calcium silicate to 700 acres of cane land, and in 1965 1,000 tons were purchased for field applications (Spillner, 1965). Kilauea Plantation Company, Kauai, also was an early leader in commercial use of silicates; in 1965 over 250 acres were treated with TVA slag ground to pass a 60 mesh screen (Harada, 1965).

In 1965 the Tennessee Valley Authority awarded another grant in silicate research to the Hawaii Agricultural Experiment Station, with Dr. R. L. Fox as leader. In 1967 the Hawaiian Cement Company presented a grant to Dr. Fox to further explore the silicate problem in Hawaii.

At present, application of soluble silicate is commercial practice on many sugar plantations on the following Great Soil Groups: Humic Latosol, Aluminous Ferruginous Latosol, Humic Ferruginous Latosol, and Hydrol Humic Latosol. In addition, research is being conducted into the effect of soluble silicates on other tropical crops.

Soils likely to respond to silicate applications

Silica is low in many Hawaiian soils for two major reasons—low silica in the parent basic basaltic rocks and silica removal through intense soil weathering (Ayres, 1943).

Degree of weathering largely determines the probability of obtaining a response to silicate materials, and weathering patterns closely follow rainfall. In general, the low silicon soils lie on upper elevation slopes in agricultural regions of the windward sides of the major islands. The moisture-laden northeast tradewinds which sweep in over the land are the dominant source of rainfall, bringing rain as the air ascends over the rather mountainous land mass.

The main Great Soil Groups in which responses to silicates have occurred in Hawaii have been the Hydrol Humic Latosols, Aluminous Ferruginous Latosols, Humic Ferruginous Latosols, and Humic Latosols (Table 2). Silica/sesquioxide ratios of these soils are very low, for example: Low Humic Latosol—1.5; Humic Ferruginous Latosol—0.7; Humic Latosol—0.5; and Hydrol Humic Latosol—0.4 (Matsusaka and Sherman, 1950). Only in one case to date has sugarcane responded to silicate on a Low Humic Latosol (Ayres, 1666). In Mauritius the Humic Ferruginous Latosols appear to be most likely to respond to silicates for sugarcane growth (Halais, 1967, 1968; Wong You Cheong et al., 1968). Workers in other countries have observed the association of poor sugarcane growth and low silica soils, e.g., South Africa (Bishop, 1967); Taiwan (Shiue, 1964); and Mauritius (Halais and Parish, 1964; Halais, 1968).

Fox et al. (1967*b*) found the general order of extractable silicon in Great Soil Groups of Hawaii was: Humic Ferruginous Latosol $<$ Humic Latosol $<$ Low Humic Latosol $<$ Dark Magnesium Clay. This was also the order of decreasing weathering as measured by total silica and type of secondary minerals present in these soils. Soil mineralogy was considered as an important guide to low silica for plant growth. In general, the hydrated aluminum and iron oxides and in some cases illite and kaolin predominate in "deficiency-probable" soils; kaolin is the major mineral in the intermediate or "deficiency-improbable" soils; and montmorillonite minerals predominate in "deficiency unlikely" soils.

The low silica soils contain little phosphorus and usually have very great phosphorus fixation potential (Chu and Sherman, 1952). Massive phosphorus applications to these soils have produced large yield responses, and residual benefits of such applications have been striking (Younge and Plucknett, 1966; Plucknett and Fox, 1965; Fox, Plucknett, and Whitney, 1968).

Active aluminum is very high in the soils in which responses to silicates have been obtained (Plucknett and Sherman, 1963), but judicious liming and phosphorus application can reduce extractable aluminum markedly (Plucknett and Sherman, 1963; Clements, 1963). Many of the early responses to silicates were attributed to a reduction in aluminum toxicity (Suehisa, Younge, and Sherman, 1963; Monteith and Sherman, 1965); however this view was not accepted by Ayres, Hagihara, and Stanford (1965).

Clements, Putman, and Wilson (1967) called attention to the "toxicity" of soils as a negative growth factor for sugarcane. They evaluated various unrelated chemicals with silicate materials in attempting to determine their effect on overcoming soil toxicities of such elements as aluminum, manganese, boron, and iron.

Recent research in sugarcane (Teranishi, 1968) indicates an interaction between soil pH, and phosphorus and silicon levels. As soil reaction was shifted from pH 5 to 7, sugarcane yield increased as available soil silicon and phosphorus increased. Sugar yields also followed the same trend as cane yields, but were not so marked.

As a result of the dramatic field responses of sugarcane to silicates on certain soils, research is under way or planned in other countries which grow sugarcane; for example, in Mauritius (Halais and Parish, 1964; Halais, 1968; Wong You Cheong et al. 1968; Wong You Cheong and Halais, 1970); Puerto Rico (Soto and Ramos, 1966; Alexander, 1968*a*, 1968*b*, 1968*c*; Samuels and Alexander, 1968); South Africa (Bishop, 1967); Taiwan (Shiue, 1964), and Australia.

TABLE 2

SOME GENERAL PROPERTIES OF GREAT SOIL GROUPS RESPONDING TO SILICATES IN HAWAII

Great soil group	Rainfall	pH	Elev.	Predominant clay minerals	SiO_2/ sesquioxide ratio	Extractable silicon (H_2SO_4)	Range of reported sugarcane plant crop yield responses to silicates
	inches		ft.			ppm	sugar, tons/acre
Low Humic Latosol	15–80	3.5–7.5	Sea level—1,500	mostly kaolin (60-80 percent), some free Fe oxides	1.2–1.8	50–90 irrigated with surface mountain water (2.5 ppm Si) 366–545 irrigated with well water (30 ppm Si)	0.7
Humic Latosol	50-150	4.4–6.6	Sea level—3,000	mainly hydrated Fe and Al oxides, 30–50 percent kaolin	0.5	12–42	0.3
Humic Ferruginous Latosol	35–150	4.0–6.5	Sea level—2,000	free oxides of Fe, Al, Ti	0.1–1.1	29	2.9–4.0
Aluminous Ferruginous Latosol	70–150	4.0–6.5	Sea level—2,000	free oxides of Fe and Al	0.1–1.1	12	0.6–4.2
Hydrol Humic Latosol	120–300	4.5–5.5	500–6,000	amorphous hydrated oxides of Fe and Al	0.4	340	0.2–2.3

Data from Chu and Sherman, 1952; Matsusaka and Sherman, 1950; Sherman, 1958; Fox et al., 1967*b*.

Silicon in irrigation and ground water

The silicon present in water sources may have important effects on levels of plant available silicon in the soil. Mink (1962) studied silicon levels in ground water from the aquifers of south central Oahu. In three wells he found mean concentrations of 16 ppm silicon in an unirrigated area, 25 ppm in the centre of an irrigated area, and 29 ppm in an area toward which ground water from irrigated areas moved. He concluded excessive irrigation of sugarcane lands was causing leaching of silicon from Low Humic Latosols which contain about 15-20 percent SiO_2.

Fox et al. (1967*a*, 1967*b*) conducted a transect study on Oahu of sugarcane freckling, soil and plant silicon, pH, and other factors. In the middle of the Low Humic Latosols an abrupt and significant increase in extractable silicon and pH was noted. On checking further the abrupt change was found due to a change in source of irrigation water, from mountain surface water (2.5 ppm silicon) to well water pumped from the Ghyben-Herzberg lens (30 ppm silicon). In areas where sugarcane is grown under rain-fed conditions, silicon in the water source was even lower, and silicon in rainwater appeared to be associated with raindrop size. Silicon levels in a heavy mist in Manoa Valley, Oahu, were measured at 0.2 ppm, while a heavy rain in Kailua, Oahu, measured 0.05 ppm.

It may be very difficult to obtain silicon-free water for experiments. For example, Ayres (1966) tells of a pot experiment in which an expected response was not obtained. Later 23 ppm silicon was found in the demineralized water used for irrigation.

Effects of silicate on sugarcane yields

In the first field experiments at Grove Farm Plantation Company, a yield increase of 5.1 tons of raw sugar per acre in the combined plant and first ratoon crops was obtained with 5,000 lbs of calcium silicate per acre (Sherman, Dias, and Monteith, 1964). Ayres (1966) reported results from nine field experiments throughout Hawaii in which plant crop yield responses to silicates ranged from 0.2 to 3.9 tons of sugar per acre. Ayres attributed these yield responses to obtaining adequate soil levels of silicon for good sugarcane growth.

TABLE 3

SUGARCANE YIELD WITH LIME, CALCIUM METASILICATE AND PHOSPHORUS TREATMENTS, KAUAI BRANCH STATION*

Treatments			Plant crop yields				First ratoon crop yields	
Lime	Calcium meta-silicate	Phos-phorus	Cane	Dry matter	Si in millable cane	Sugar (Pol)	Cane	Sugar (Pol)
lbs/a	lbs/a	lbs/a	tons/a	tons/a	lbs/a	tons/a	tons/a	tons/a
—	—	250	112.9	25.22	164	10.47	56.7	5.9
4,000	—	1,000	117.1	23.15	192	9.25	61.8	5.9
—	4,000	250	146.2	32.07	459	14.10	70.4	6.5
—	4,000	1,000	151.1	36.14	462	14.59	83.8	7.4

After Fox et al, 1967*b*; and Younge and Plucknett, unpublished data.

* Means enclosed by the same bracket are not statistically significant at the 0.05 level of probability (Duncan's multiple range test).

In 1964 the Hawaii Agricultural Experiment Station harvested an experiment at its Kauai Branch Station in which sugar yields were increased over 4 tons per acre in a 25-month plant crop (Table 3). This experiment included rates of phosphorus as high as 1,000 per acre. The high phosphorus rates produced an increased sugar yield of 0.8 tons per acre; however, 4,000 lbs of TVA calcium silicate slag plus 1,000 lbs phosphorus per acre increased yields 5.34 tons above the yield recorded for 4,000 lbs of lime plus 1,000 lbs phosphorus.

Yields of plant and ratoon crop cane with increasing rates of silicates on an Aluminous Ferruginous Latosol are reported in Table 4. In these experiments sugar yields were increased as high as 58 percent above normal practice.

TABLE 4

EFFECT OF CALCIUM METASILICATE ON SUGAR YIELDS, KILAUEA PLANTATION COMPANY, KAUAI

Lbs calcium metasilicate per acre	Plant crop yields		First ratoon	
	Field 13.1	Field 15.1	Field 13.1	Field 15.1
	Sugar (Pol), tons/acre			
0	12.45	11.15	9.9	9.65
4,000	14.65	15.60	10.5	10.90
8,000	15.55	15.25	10.8	12.15
12,000	16.10	15.05	11.5	11.60
16,000	16.70	15.45	13.9	13.25

Clements, Putman, and Wilson, 1967

Table 5 presents sugar yields with calcium silicate, volcanic cinder, and coralstone lime treatments on a Hydrol Humic Latosol. The striking yield differences between calcium silicate and coralstone are typical of many such experiments on soils which respond to silicates.

TABLE 5

SUGAR YIELD WITH CALCIUM METASILICATE, CINDER, AND CORALSTONE TREATMENTS, AKAKA FALLS, ISLAND OF HAWAII

Treatment	Sugar (Pol), tons/acre				
	Amendments applied, lbs/acre				
	0	4,000	8,000	12,000	16,000
TVA slag (calcium metasilicate)	14.4	15.7	16.3	16.9	16.7
Olivine cinder	14.4	14.0	14.8	14.0	13.6
Coralstone	14.4	14.6	14.8	14.4	13.9

Clements, Putman, and Wilson, 1967

In Mauritius calcium silicate applied in virgin (plant crop) sugarcane has produced yield increases in the order of 30-75 percent.*

*Wong You Cheong, 1968: personal communication.

Silicon and freckling of sugarcane

In addition to increased sugar yields, a major phenomenon in use of silicates in sugarcane is alleviation of the apparently physiological disease called "freckling". An example of freckling is shown in Fig. 1. This disease, described by Martin et al. (1961), appears in upper high rainfall areas especially during winter. Symptoms appear at about 5-6 months of age, especially on older leaves of the plant. From about 7 months of age, growth is inhibited by heavy freckling and "rusting" through the life of the crop, resulting in low yield at harvest (Harada, 1965). The appearance of the disease is marked by tiny clear spots or "flecks" on the lamina; such "flecks" are especially apparent when the leaf is held before sunlight. These clear spots gradually become necrotic and then coalesce to a point where the entire leaf is "fired" and green active tissue is at a minimum. The top third of many leaves is more affected than the rest of the leaf. Fields with severe freckling have a sparse, brown appearance due to the large number of necrotic leaves, and weed growth after close-in can become a problem (Fig. 2).

FIG. 1.—"Freckle" disease of sugarcane, common in low silicate soils in regions of high rainfall, especially in winter. At lower right a necrotic leaf can be seen. This sugarcane is from a zero-silicate plot at Kilauea Sugar Co. Ltd. The variety is 52-263.

(Photo by J. Silva)

With silicate application freckling diminishes or is completely corrected provided sufficient silicate is applied (Fig. 3). Fields treated with silicates can even be located from the air due to the dark green colour and dense, vigorous growth of the crop. Experimental plots treated with silicates can readily be located due to the striking vegetative response and alleviation of freckling.

FIG. 2.—Sugarcane, variety 52-263, without silicate treatment, at Kilauea Sugar Co. Note sparse, open growth and weed invasion. Most of the leaves are severely freckled and necrotic. (*Photo by J. Silva*)

FIG. 3.—Influence of calcium silicate slag (12,000 lbs of TVA slag/acre) on freckling and density of the crop, Kilauea Sugar Co. Ltd. Leaves are deep green and free of freckling; crop growth is dense and vigorous. The variety is 52-263. (*Photo by J. Silva*)

Fox et al. (1967*b*) rarely observed freckling under the following conditions (extractants used to measure extractable soil silicon are listed in parenthesis): when extractable soil silicon levels were greater than 2 ppm (H_2O), 150 ppm (PO_4), 40 ppm (acetate), 100 ppm (sulphate), or when sheath silicon reaches more than 40 ppm (TCA soluble) or 0.7 percent (total).

Clements (1965*a*, 1965*b*) has called attention to the similarity of freckling to a necrotic spotting of barley caused by an intense localization of manganese in areas of the leaves and which has been corrected by silicon (Williams and Vlamis, 1957). In barley leaves total manganese concentrations were equal in +Si and −Si plants, and beneficial effects of silicon were attributed to more even distribution of manganese (Williams and Vlamis, 1957). For this reason and because silicon does seem to decrease manganese uptake by sugarcane, Clements (1965*a*, 1965*b*) attributes alleviation of leaf freckle by silicates to reduction of the Mn/SiO_2 and B/SiO_2 ratios in the leaves. In this regard, Clements (1965*a*) proposed the ratio, Mn (ppm)/SiO_2 (percent), in sugarcane sheaths as best in the range 30 to 50. At one site of their transect to study the relations between soil silicon, plant silicon, and freckling of sugarcane, Fox et al. (1967*b*) found a Mn/SiO_2 ratio of 48, within the favourable range proposed, but still severe freckling was observed at this site. Teranishi (1968) reported freckling and Mn/SiO_2 ratios decreased with silicon application; also, highest cane yields were associated with lowest Mn/SiO_2 ratios.

Ayres (1966) discounted the theory that manganese toxicity was to blame for poor sugarcane growth; indeed, in one of his experiments on a low silicon soil he obtained a gain of 0.4 ton of sugar with Mn-100 lbs/acre, applied as $MnSO_4$. In addition, Ayres called attention to the fact that the silicate-responsive soils contain only a fraction of the available manganese present in the most productive sugarcane soils of the islands.

In recent studies Clements, Putman, and Wilson (1967) found that healthy sugarcane leaves grown in nutrient culture contained higher concentrations of "toxic" manganese, aluminum, and iron than severely freckled leaves. They attributed this apparent discrepancy in relating manganese to the freckling problem to an unexplained prevention of necrosis by the high silicon and calcium levels in healthy leaves. Samuels and Alexander (1968) reported decreased manganese in sugarcane grown with silicon in sand culture.

In spite of the efforts to discover either the cause of freckle or the basis of its correction, only silicon has corrected the condition in the field or glasshouse.

The main effects of silicon on the growth of sugarcane may be summarized as follows:

1. Correction of freckling disease (Younge and Plucknett, unpublished; Harada, 1965; Clements, 1965*a*, 1965*b*; Ayres, 1966; Fox et al., 1967*b*; Teranishi, 1968).
2. Greater growth index, expressed as green weight of leaf sheaths 3-6 (Clements, 1965*a*, 1965*b*; Fox et al., 1967*b*).
3. A gain in stalk size and elongation of 9.9 percent and 19.4 percent for 2 and 8 ton/acre application, respectively, at 8.3 months of age (Harada, 1965).
4. Larger stalks and longer sucker canes at harvest (Harada, 1965).
5. Increased number of green and functioning leaves (Harada, 1965; Clements, 1965*a*).
6. Greater yield of cane (Ayres, 1966; Clements, 1965*a*; Younge and Plucknett, unpublished; Fox et al., 1967*b*; Teranishi, 1968) and greater dry matter yield (Younge and Plucknett, unpublished).

7. Increased sugar yield (Sherman, Dias, and Monteith, 1964; Ayres, 1966; Clements, 1965*a*, 1965*b*; Fox et al., 1967*b*; Harada, 1965; Spillner, 1965; Younge and Plucknett, unpublished; Teranishi, 1968).

Soluble and total silicon in sugarcane tissues

Halais and Parish (1964) studied silicon levels in leaf sheaths 3-6 over a range of soils in Mauritius. Lowest values—less than 1 percent SiO_2 (0.47 percent silicon) on a dry weight basis—were found on coral sand Regosols. Similar values were obtained on Humic Ferruginous Latosols, increasing to almost 2.33 percent silicon on young or montmorillonitic soils. In Mauritius the highest yielding sugarcane soils produced leaf sheath silicon values of 1.16 percent or more and between 50-75 ppm manganese.

Clements (1965*b*) reported a range of 0.33 to 1.92 percent silica in leaf sheaths from seven Hawaiian plantations. Calcium silicate applications increased leaf sheath SiO_2 from 0.33 percent in untreated plots to 0.86 percent in plots where 8 tons of calcium silicate were applied.

Fox et al. (1968) and Teranishi (1968) found a 10-minute extraction with 2 percent TCA was satisfactory for determining soluble silicon in sugarcane plants. Soluble silicon was highest in young tissues, especially in the terminal portions of the plant. Total silicon was highest in leaves and sheaths. A complete analysis of leaves, sheaths, and stalks was conducted to study soluble and total silicon in the plant. Transpiration deposition did not appear to play a significant role in total silicon in younger or older leaves.

Fox et al. (1968) found sheaths or fully expanded internodes were more sensitive tissues for soluble silicon than leaves. For total silicon, stalks were most sensitive, while leaves and sheaths followed in that order. Total silicon was influenced more by silicate treatment than was soluble silicon. Total silicon of leaves 3-6 would be a suitable tissue measurement of silicon requirement, but soluble silicon is much easier to measure. Table 6 presents critical total and soluble silicon levels for determining potential silicon deficiency in sugarcane.

TABLE 6

SUGGESTED LEVELS OF SOIL AND SUGARCANE SHEATH SILICON IN RELATION TO ADEQUACY FOR SUGARCANE

	Extractable soil silicon				Sheath silicon	
	Water ppm (solution)	$Ca(H_2PO_4)$	$HOAc_2$	H_2SO_4	TCA soluble (ppm, fresh)	Total %, OD
		ppm soil				
Deficiency probable	0.9	50	20	40	30	0.5
Deficiency questionable	0.9–2.0	50–150	20–40	40–100	30-40	0.5–0.7
Deficiency unlikely	2.0	150	40	100	40	0.7

Fox et al., 1967*b*

Low sheath silicon values are often associated with low sugarcane yields; this is apparent in Table 7, where sheath silicon values closely followed yield responses to silicon applications. Clements (1965*b*) proposed 1.50 percent silica (0.70 percent silicon) in sugarcane sheaths as a value below which growth responses to silicate might be expected. Halais (1967) suggested above 1.25 percent SiO_2 (0.58 percent silicon) in sheath dry matter as a tentative optimum level. Halais (1967) measured percent silica in dry matter of leaf sheaths of six varieties at seven locations in Mauritius. Variety means ranged from 2.97 to 3.58 percent, while location means ranged from 1.92 to 5.07 percent. Halais then calculated SiO_2 percent correction factors for each of these varieties to aid in accurate interpretation of SiO_2 tissue analysis data.

TABLE 7

EFFECTS OF INCREASING CALCIUM SILICATE ON SUGARCANE SHEATH SILICA, CANE YIELD, AND SUGAR YIELD ON AN ALUMINIUM FERRUGINOUS LATOSOL

TVA slag lbs/acre	Sheath SiO_2 (% of dry weight)	Cane tons/acre	Sugar (Pol) tons/acre
0	0.68	104.0	12.3
4 000	1.37	124.8	15.2
8,000	1.48	125.3	15.2
12,000	1.63	128.8	15.6
16,000	1.84	134.3	16.2

After Harada, 1965

Many effects of silicon on sugarcane composition have been reported. Some of these are summarized in Table 8.

Benefits of silicates in crop production

According to Fox et al. (1967*a*) many benefits have been attributed to silicon in crop production: (1) greater solubility of soil phosphorus; (2) decreased fertilizer phosphorus fixation; (3) correction of calcium or magnesium deficiencies; (4) increased soil pH; (5) decreased phosphorus requirement within the plant; (6) prevention of the accumulation of toxic concentrations of manganese (or other elements) in the plant; (7) enhanced efficient use of water in the plant; (8) guarding of tissue against damage by insects and fungus disease; (9) strengthening of tissue, decreased lodging and promotion of more efficient use of sunlight; (10) benefiting of plants in some "essential" role.

Forms of silicate

Several silicate materials have been used in the Hawaiian experiments. In sugarcane, field responses have been obtained with sodium metasilicate (Clements, 1965*b*), various calcium metasilicate carriers such as TVA slag (Ayres, 1966; Fox et al., 1967*b*; Clements, 1965*b*; Younge and Plucknett, unpublished data; Clements, Putman, and Wilson, 1967), and Kau volcanic cinder (Clements, 1965*b*). With sudangrass, yield responses have been obtained with sodium metasilicate (Suehisa, 1961; Suehisa, Younge, and Sherman, 1963), and TVA calcium metasilicate (Monteith and Sherman, 1965; Dias, 1965; King, 1962; Mahilum, 1965). Clements, Putman, and Wilson (1967) obtained sudangrass yield responses to the following silicate minerals: pseudowallastonite ($CaSiO_3$), rankinite ($Ca_3Si_2O_7$), larnite Ca_2SiO_4), gehlenite ($Ca_2Al_2SiO_7$), TVA calcium metasilicate, and Hawaiian Cement Company calcium metasilicate. Pseudorankinite, rankinite, and larnite were especially active materials and increased silica in sudangrass markedly. Gehlenite was relatively less active than pseudorankinite, rankinite, or larnite. It is believed that TVA slag is mostly gehlenite but does include some pseudowallastonite (Clements, Putman, and Wilson, 1967).

TABLE 8

REPORTED EFFECTS OF SILICATE MATERIALS ON THE COMPOSITION OF SUGARCANE

Element or factor affected	Concentration in the plant			Total uptake		
	increased	decreased	author	increased	decreased	author
Silicon	in sheath		Clements, 1965*a*, 1965*b*; Ali, 1966	greatly in millable cane		Ayres, 1966; Spillner, 1965; Younge and Plucknett, unpublished
Calcium	yes		Clements, 1965*b*	yes		Ayres, 1966
Phosphorus	usually		Clements, 1965*b*	in millable cane		Ali, 1966; Ayres, 1966; Younge and Plucknett, unpublished
Magnesium		yes	Clements, 1965*a*, 1965*b*, Samuels and Alexander, 1968	slightly in millable cane		Ayres, 1966
Nitrogen		yes, in plants grown in nutrient solution yes, in leaves	Samuels and Alexander, 1968; Clements, 1965*a*, 1965*b*	in millable cane		Ayres, 1966
Potassium				slightly 4 months, and in millable cane		Ayres, 1966
Manganese		yes	Clements, 1965*a*, 1965*b*; Samuels and Alexander, 1968	in millable cane		Ayres, 1966
Sulfur		yes	Samuels and Alexander, 1968			
Mn/SiO_2 ratio		yes	Halais and Parish, 1964; Clements, 1965*a*			
Boron		yes	Clements, 1965*a*, 1965*b*			
B/SiO_2 ratio		yes	Clements, 1965*a*, 1965*b*			
Copper		in sheath	Clements, 1965*a*			
Zinc		yes	Clements, 1965*a*	slightly in 14-month crop, and in millable cane		Ayres, 1966
Moisture		in sheath	Clements, 1965*a*			

Fineness of the silicate material used is very important since solubility relates to mesh size after grinding. A coarsely ground TVA slag (16-35) failed to produce an expected response at Kilauea Plantation Company, Kauai (Clements, Putman, and Wilson, 1967). These authors stress the need for grinding to enable all material to pass a 60 mesh per inch screen. Harada (1965) first called attention to the superiority of finely ground (60 mesh) TVA slag over the more coarsely ground (16 mesh) material.

In Mauritius massive applications (over 200,000 lbs per acre) of finely ground basalt on highly weathered soils have produced increases in yield and sheath SiO_2 (%) coupled with decreased manganese in cane sheaths (Halais and Parish, 1964). As Clements (1965*b*) points out, however, massive applications of such materials could cause effects other than increased silica supply on weathered soils. Halais (1966) suggests the use of bagasse furnace ash which contains about 75 percent SiO_2 as a soil amendment on low silica soils.

Probably any silicate-bearing material ground to suitable fineness to obtain significant solubility would provide enough silica for silicate responsive soils. Further study is needed of various silicate-bearing minerals to determine most suitable types and local sources for use in commercial practice.

Methods of applying silicates

Most silicates have been applied on a broadcast basis, in a manner closely resembling lime applications. Lime spreaders are commonly used to spread the materials on the soil surface. Incorporation of these materials in the root zone is desirable, and rotovators or disc harrows are used in some instances to ensure thorough incorporation.

Harada (1965) compared furrow application versus broadcast application in sugarcane. Crop growth indicated broadcast application was superior to furrow application.

Younge and Plucknett (unpublished data) obtained some correction of freckling by broadcasting TVA slag in the interrow following harvest of plant-crop sugarcane and rototilling the interrows to 4-6 inch depth.

In placement studies in a pot experiment, Manuelpillai (1967) obtained highest yields of maize and kikuyugrass (*Pennisetum clandestinum*) when silicon and phosphorus were mixed in a 1 cm layer of soil placed 2 cm below the surface.

Residual effects of silicates

Residual effects of silicate materials must be determined, but little is known at this time of the potential fate or life of these materials in deficient soils. Residual effects will depend on several factors including: the rate and solubility of silicates applied; the silica status of the soil concerned; leaching and movement in the soil solution; and fixation or complexing in the soil.

In the original sugarcane experiment at Grove Farm, residual silicon was sufficient to produce ratoon yields only slightly lower than in the plant crop (Ayres, 1966); however, at Kauai Branch Station, where large responses were obtained in the plant crop, ratoon yields were only 0.6 to 1.5 tons sugar per acre higher than in minus-silicon plots, although some correction of freckling was still evident (Table 3).

Clements, Putman, and Wilson (1967) reported plant and ratoon crop yields at Kilauea at silicate rates of 0, 4,000, 8,000, 12,000, and 16,000 lbs TVA slag per acre (Table 4). As in the plant crop, ratoon sugar yields increased with increasing silicon. In relation to the control treatment, the 16,000 lbs/acre rate increased sugar yields by the same order of magnitude, about 4 tons sugar per acre, as in the plant crop. It is probable that, initially, high rates of silicate may be necessary to satisfy the various fixation or complexing sites of the soil in order to provide sufficient soluble silicon for plant growth. This situation holds true for phosphorus in these soils (Younge and Plucknett, 1966) and, if this is the case, after the initially high requirement of the soil is reached, small annual or biennial silicate dressings may provide satisfactory residual silicon for crop production.

Silicate research in other crops

Several crops are grown in the silicate-responsive soils; these include: banana, papaya (Adlan, 1969), maize (Tamimi and Hunter, 1970), vegetables, pineapple, and pastures. Research is under way to determine effects of silicate on these crops.

Pasture legume seed pelleted with TVA slag and using methyl ethyl cellulose as an adhesive has proved successful for aerial sowing in the infertile wetlands. Motooka et al. (1967) conducted an integrated study of land clearing and pasture establishment in infertile wetlands using aircraft in applying herbicides, seed, and fertilizers. Seven legumes — *Centrosema pubescens, Glycine wightii* (Tinaroo, Clarence, Cooper, and Yatesco varieties), *Phaseolus atropurpureus, Stylosanthes guianensis, Lotononis bainesii, Trifolium repens* (mother white, P.P. Certified white, and Ladino), and *Desmodium intortum*—were innoculated and pelleted with TVA slag on a 1:1, seed/TVA slag basis. Pelleted seed was mixed with treble superphosphate just prior to aerial sowing. Excellent establishment and growth were obtained with stylo, *D. intortum*, siratro, and white clover. Grazing commenced 13 months after seeding.

A later opportunity to study effects of TVA slag pelleting was presented in 1967 when an area of about 2,500 acres of forest reserve wetlands at Hanalei, Kauai, was burned accidentally. Seeding with a pasture grass (green panic) and legumes (Stylo and *Lotononis*) was recommended and approved. The Hawaii State Division of Forestry, the Soil Conservation Service-U.S.D.A., the University of Hawaii College of Tropical Agriculture and Murrayair joined together in a cooperative project to reseed and fertilize the burned-over lands. The legumes were pelleted with methyl ethyl cellulose and TVA slag, mixed with the green panic seed, and aerially sown in December 1967. Fertilizers were later applied by air.

Growth of both Stylo and *Lotononis* has so far been satisfactory under conditions of very high rainfall and in soils of low fertility (Plucknett, Daehler, and Smithhisler, unpublished data, 1968).

The beneficial effects of TVA slag in pelleting are not fully understood. From a physical standpoint, such pellets are easily formed and resist mechanical injury. Norris (1967) has pointed out the need for a near-neutral reaction material for pelleting.

As far as the plant is concerned, a mildly alkaline calcium silicate would supply calcium in the micro-environment of the seed, a factor of importance in leached, acid wetland soils. In the soils of these experiments, however, silica would also be low and the question of a possible beneficial effect of silicates must be considered. Research is needed on the nutritional aspects of calcium silicate seed pelleting as well as on longevity of seed and inoculum during storage in pelleted form.

A word of caution must be given at this point. All calcium silicate materials may not be suitable for pelleting. A sample of Hawaiian Cement Company calcium silicate slag proved very toxic to *Rhizobia* and inhibited germination of *Desmodium intortum* seed; later this slag proved to have a highly alkaline reaction, almost pH 12.0.* In selecting coating materials for pelleting, pH measurements of potential materials should be made prior to use. Calcium metasilicate has a pH of about 8.3, while the pH of TVA slag is 8.8.

An intriguing situation exists on Princeville Ranch, Kauai, which might relate to animal performance and behaviour on low silicon soils. In 1966 Mr. John Midkiff, Manager of Princeville Ranch, called my attention to an apparently eroded section of an old rock-based military road built through the ranch during World War II. In certain sections, rocks at the edge of the road were missing; these rocks were being loosened and carried away by cattle which were chewing and feeding on them (Figs. 4, 5). Mr. Midkiff informed me he had seen cattle with rocks in their mouths, as well as bottles, and that the cattle made their way to exposed rocks at the roadside immediately upon being returned to the paddock in the rotational grazing system. He then prepared some of the rock by grinding and fed it to the cattle free-choice in mineral boxes; they ate it immediately. He also fed TVA slag in mineral boxes.

FIG. 4.—Cattle feeding on saprolitic basalt rock on the edge of an old military roadway on Princeville Ranch, Kauai.

The rock of the old military road is a saprolitic basalt from a quarry on Kilauea Sugar Company. Apparently it has been softened by weathering, but has not undergone extensive base and silica removal. A sample of the rock was analysed at the University of Hawaii Department of Agronomy and Soil Science and the partial analysis is shown in Table 9.

The cattle in this paddock were provided with free-choice mineral supplement containing calcium, phosphorus, and trace elements, but still the animals spend much of their time feeding on the rock of the roadway.

*D. Norris, 1968: personal communication.

FIG. 5.—Close-up view of the rock on which the cattle feed. Note the light-coloured areas of the rock where fresh feeding and chewing have occurred. Parts of the road edges have been removed in a semi-circular pattern by the action of the cattle.

TABLE 9

PARTIAL CHEMICAL ANALYSIS OF SAPROLITIC BASALT ROCK EATEN BY CATTLE, PRINCEVILLE RANCH, KAUAI

Element	%
SiO_2	39.90
Al_2O_3	5.03
Fe_2O_3	7.03
MgO	12.21
CaO	8.81
TiO_2	1.12
H_2O	9.60
Loss on ignition	12.77

(P and trace element analyses not completed)

There the matter lies. The rock is high in silicon, and apparently the only other element not provided by the mineral mixture but which is present in the rock in quantity is magnesium. There is no evidence of magnesium deficiency. The following question could well be raised, however; since cattle probably did not evolve on low silicon soils, what effect would pasture and forage species grown on such soils have on animal production and health? Study of animal performance on the low-silicon soils of Hawaii could assist in finding some answers to this question.

Acknowledgments

The author wishes to express thanks to those who have made this review possible, particularly Professor E. J. Britten and the Department of Agriculture for the opportunity of spending the year 1968 on sabbatic leave at the University of Queensland, during which the manuscript was initiated and prepared; my colleagues at the University of Hawaii College of Tropical Agriculture, Hawaii Sugar Planters' Experiment Station, and the Hawaii sugar plantations, who have had so much to do with silicate research; Dr. G. Donald Sherman, Dr. O. R. Younge, Dr. H. F. Clements, Dr. R. L. Fox, and Dr. J. A. Silva, all of the University of Hawaii; Dr. A. S. Ayres and Dr. Robert Cushing of the H.S.P.A. Experiment Station; Mr. William Moragne; Eric Spillner and Masao Ono, Grove Farm Plantation Company, Ernest Smith and K. Harada of Kilauea Sugar Company; also the postgraduate students of the University of Hawaii who have studied the problem in detail; Mr. John Midkiff and Princeville Ranch, Murrayair Limited, Hawaii Fruit Packers, and other Hawaii sugar plantations for providing services or land for silicate research.

Financial support from the Tennessee Valley Authority (TVA) and Hawaiian Cement Company is gratefully acknowledged. Several postgraduate students were financed by East-West Center study grants. Other student support was provided by the Sudan government and research funds of the Hawaii Agricultural Experiment Station.

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