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CALIBRATION OF SUGARCANE RESPONSE TO CALCIUM SILICATE ON FLORIDA HISTOSOLS

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□ *Silicon is considered a beneficial nutrient for sugarcane (*Saccharum *spp.) and yield responses to Si applications on Florida organic soils have been well documented. Growers need calibrated Si recommendations to be able to make cost-effective decisions regarding Si applications. The objective of this study was to develop a soil-test Si calibration based on yield responses to Ca silicate on Everglades Histosols. Twelve paired commercial field comparisons and three small-plot tests of Ca silicate application were conducted. Strong responses in t cane ha^{-1} and t sucrose ha^{-1} were determined with acetic acid-extractable soil Si <15 g m^{-3}, with some response to approximately 25 g m^{-3}. Recommendations were developed over this range with a maximum Ca silicate rate of 6.7 t ha^{-1}. Optimum leaf Si concentration was determined to be $\geq$ 6.0 g kg^{-1}, with 0.95 and 0.80 relative yield at 5.0 and 2.5 g kg^{-1}, respectively.*

Keywords: calcium silicate, calibration, Histosols, leaf analysis, nutrient management, rice, silicon, slag, sugarcane

INTRODUCTION

Silicon (Si) is not classified as an essential plant nutrient, but is considered a beneficial nutrient for sugarcane (*Saccharum* spp.) and rice (*Oryza sativa* L.) (Ma and Takahashi, 2002; Savant et al., 1999). Yields of each of these crops are increased with application of Ca silicate slag to soils low in soluble Si (Anderson et al., 1991; Elawad et al., 1982a, 1982b; Fox et al., 1967; Snyder et al., 1986). Raid et al. (1992) measured sugarcane yield increases averaging 20% for two crop years and five cultivars following calcium (Ca) silicate application at 6.7 t ha^{-1}. Studies in South Africa showed sugarcane responses ranging from 9 to 24 t cane ha^{-1} (TCH) to Ca silicate application in areas with insufficient soil and leaf Si concentrations (Meyer

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and Keeping, 2000). Calcium silicate application can benefit both crops of a rice-sugarcane rotation when applied prior to planting rice (Anderson et al., 1987). Mechanisms responsible for increased yield may include resistance to lodging through increased mechanical strength of cells, resistance to disease and insect damage, reduction in water loss through evapotranspiration, improved phosphorus (P) metabolism, and reduction of accumulation of toxic concentrations of heavy metals (Datnoff et al., 1997; Savant et al., 1999; Snyder et al., 1986).

Sugarcane responses to silicon fertilization have been reported in many areas of the world, particularly on weathered tropical and subtropical soils such as Oxisols, Ultisols, Entisols, and Histosols (Korndorfer and Lepsch, 2001). Sugarcane is grown on 157,000 ha in the Everglades Agricultural Area (EAA) of Florida. Approximately 80% of this total is grown on organic soils (Rice et al., 2009). Organic soils in the EAA that are near Lake Okeechobee tend to have relatively higher mineral content and soluble Si because of historic lake overflows. This includes the Torry muck soil series which has $>$350 g mineral content kg^{-1}, with the mineral content being predominately clay (McCollum et al., 1978). These organic soils with higher clay content should not require Si fertilization (Morgan et al., 2009). Histosols further from Lake Okeechobee may contain very low levels of total and soluble Si and so sugarcane on these soils can have strong yield responses to calcium silicate application (Gascho and Andreis, 1974).

Since Ca silicate application requires a substantial grower investment, consideration of cost/benefit is very important (Alvarez et al., 2009). Leaf analysis can be a useful indicator of Si status, with optimum growth requiring a suggested minimum of 6.0 g Si kg^{-1} (McCray et al., 2010). Berthelsen et al. (2003) determined a critical value of 5.3 g Si kg^{-1} at which 95% relative yield was reached in Australia. These values are lower than the previously suggested critical value of 10 g Si kg^{-1} by Anderson and Bowen (1990). A recent survey of Florida sugarcane fields determined that an estimated 25% of surveyed fields on organic soils had production losses $>$10% due to insufficient leaf Si (McCray et al., 2010).

Although there are recommendations for Ca silicate application to rice on Florida Histosols based on a soil test using 0.5 *N* acetic acid-extractable Si (Korndorfer et al., 2001), there is no soil-test Si calibration for sugarcane on these soils. The objective of this study was to relate soil and leaf Si concentrations to sugarcane yield and to calibrate soil-test Si with yield responses to Ca silicate on Florida organic soils.

MATERIALS AND METHODS

Experimental Design

Paired commercial sugarcane fields were compared in a study of yield response to Ca silicate application. Fields were selected so that each paired comparison had fields of similar size with the same soil type, sugarcane cultivar, previous fertilization, and other cultural practices. Seven and five paired comparisons were established in fall 1993 and fall 1994, respectively. The field study followed eleven comparisons through plant, first ratoon, and second ratoon, with one comparison being conducted only through first ratoon. One comparison was on a Torry muck soil (euic, hyperthermic Typic Haplosaprist with mineral content >350 g kg^{-1} and with depth >1.3 m). Other comparisons were on other organic soils with mineral content <350 g kg^{-1}. Within each pair of fields, one was randomly assigned to receive a pre-plant broadcast application of Ca silicate at 6.72 t ha^{-1}. Calcium silicate was incorporated with a disk prior to planting. The Ca silicate used in the study was a by-product of electric furnace production of elemental P in Tennessee and had Si content of approximately 200 g Si kg^{-1}. Each field in the study received recommended fertilizer applications based on preplant soil tests (Rice et al., 2010).

Small-plot tests were conducted at three locations in the EAA. Test 1 was in a field with Okeelanta muck soil (sandy, siliceous, euic, hyperthermic Terric Haplosaprist) on the east end which transitioned to Pahokee muck soil (euic, hyperthermic Lithic Haplosaprist) on the west end. The experiment was a randomized complete block design with eight replications and six treatments: 1) no dolomite and no Ca silicate, 2) dolomite (6.72 t ha^{-1}) and no Ca silicate, 3) dolomite (13.44 t ha^{-1}) and no Ca silicate, 4) Ca silicate (6.72 t ha^{-1}) and no dolomite, 5) Ca silicate (13.44 t ha^{-1}) and no dolomite, and 6) dolomite (6.72 t ha^{-1}) and Ca silicate (6.72 t ha^{-1}). Sugarcane cultivar CP 73-1547 was planted on 9 December 1994. Plots were 13.2 m long with 1.5 m row spacing and four rows per plot. There were 4.6 m unplanted lengthwise alleys and 3.0 m unplanted cross-alleys between plots with 6.1 m cross-alleys between replications.

Test 2 of the small-plot study was on an Okeelanta muck soil (sandy, siliceous, euic, hyperthermic Terric Haplosaprist). The experiment was a randomized complete block design with six replications and five treatments: 1) no dolomite and no Ca silicate, 2) dolomite (4.48 t ha^{-1}) and no Ca silicate, 3) Ca silicate (3.36 t ha^{-1}) and no dolomite, 4) Ca silicate (6.72 t ha^{-1}) and no dolomite, and 5) dolomite (4.48 t ha^{-1}) and Ca silicate (6.72 t ha^{-1}). Sugarcane cultivar CP 89-2143 was planted on 23 November 2004. Plots were 13.2 m long with 1.5 m row spacing and six rows per plot. There were 3.0 m unplanted lengthwise alleys and 4.6 m unplanted cross-alleys between plots.

Test 3 of the small-plot study was on a Dania muck soil (euic, hyperthermic, shallow Lithic Haplosaprist). The experiment was a randomized complete block design with six replications and four rates of Ca silicate: 0, 2.24, 4.48, and 6.72 t ha^{-1}. Sugarcane cultivar ‘CP 88-1762’ was planted on 17 Nov. 2005. Plots were 13.2 m long with 1.5 m row spacing and six rows per plot. There were 3.0 m unplanted lengthwise alleys and 4.6 m unplanted cross-alleys between plots.

TABLE 1 Chemical analyses of Ca silicate slag used in the studies[a]

Element	g kg^{-1}	Method
P	5.4	AOAC 958.01
Ca	258.8	AOAC 965.09
Mg	2.9	AOAC 965.09
Si	198.0	AFPC IX.5

[a] Analyses by Thornton Laboratories, Tampa, FL.

Analyses of Ca silicate used in small-plot tests 2 and 3 are given in Table 1. All commercial and small-plot experiments in the study used Ca silicate from the same source. All amendments in small-plot tests were broadcast by hand and incorporated with a disk prior to planting. Tests were planted vegetatively by placing pairs of whole sugarcane stalks side-by-side in the furrows and chopping them into similar billet lengths to fill the plot length before closing the furrows. Plots within each test received uniform fertilizer applications based on preplant soil tests (Rice et al., 2010).

Leaf Sampling and Analyses

Leaf samples were collected each year in June-August from commercial fields and small-plots. For leaf sample collection in commercial fields, two locations in each field were sampled in a V-pattern between 30 and 120 m from the end of the field. Sixteen top visible dewlap (TVD) leaves were taken from each of the two locations and combined into a single sample consisting of 32 leaves. Thirty-two TVD leaves were collected at random from the four rows of each plot of four replications of small-plot test 1, and from the middle four rows of each plot in small-plot tests 2 and 3. Leaf midribs were separated from leaf blades and discarded before washing the blades in deionized water and drying at 60°C. The dried leaf material was ground to pass a 1 mm screen in a stainless steel Wiley mill. All ground samples were dried overnight at 65°C before weighing for digestions. Leaf samples for commercial field samples and samples from small-plot test 1 were digested with nitric acid (2 hours, 150°C) followed by hydrogen peroxide (1 hour, 150°C) on an aluminum digestion block. Leaf samples from small-plot tests 2 and 3 were digested by dry ashing at 500°C and dissolving in hydrochloric acid (HCl). Leaf P and magnesium (Mg) concentrations were determined for each of these digests by inductively coupled plasma (ICP) spectroscopy. Leaf Si digestions for all leaf samples were performed with autoclave-induced digestion (Elliott and Snyder, 1991). Leaf Si concentrations were determined by ICP spectroscopy for commercial fields and small-plot test 1, and colorimetrically for small-plot tests 2 and 3.

Soil Sampling and Analyses

Composite soil samples were taken (0–30 cm) in commercial test fields after harvest each year. These samples were taken in a V-pattern through the field with no soil cores being taken within 30 m of field ends and 10 m of field ditches. Soil samples were taken after each harvest (0–30 cm) in each plot of four replications of small-plot test 1. Soil samples were taken after each harvest at depths of 0–15 and 15–30 cm in each plot of five replications of small-plot test 2. Soil samples were taken after each harvest at depths of 0–15 and 15–30 cm in each plot of small-plot test 3.

Soil samples were placed in aluminum drying pans, air-dried in a forced-air drying oven or drying room at 31°C, and sieved through a 2-mm screen before analysis. Soil-water pH was determined for all samples (15 cm^3 soil/30 mL water). Extractable Si for soil samples from commercial fields and small-plot test 1 was determined with a gravimetric extraction by placing 5 g air-dry soil into 25 mL 0.5 *N* acetic acid. Extractable Si for soil samples from small-plot tests 2 and 3 was determined volumetrically by placing 10 cm^3 air-dry soil into 25 mL 0.5 *N* acetic acid. In each of these extractions the soil/extractant mixtures were allowed to stand overnight (approximately 16 h) and then were shaken for 50 minutes before filtering for Si analysis. Silicon concentrations were determined by ICP spectroscopy for commercial fields and small-plot test 1, and colorimetrically for small-plot tests 2 and 3 (Elliot and Snyder, 1991). Gravimetric results from commercial fields and small-plot test 1 were converted to volumetric values by using an estimate of air-dried disturbed bulk density for specific organic matter content (Andreis and McCray, 1998).

Yield Measurements

Sugarcane production data was obtained in the commercial field study from mill harvest data. Biomass yield (TCH) was determined at harvest from net sugarcane railcar weights from a particular field divided by net sugarcane ha. Railcar sugarcane samples from each test field were used by the mill to estimate t sucrose ha^{-1} (TSH).

For small-plot test 1, sugarcane harvest weights were taken by cutting and weighing the middle two rows of each plot with a commercial harvester and a harvest wagon equipped with a load cell. These weights were used to calculate TCH. Previous to collecting harvest biomass weights, stalk samples (16 stalks/plot) were taken from the two middle rows of each plot of four replications for determination of kg sucrose t^{-1} (KST). Stalk samples were milled and the crusher juice analyzed for Brix and pol. Brix, which is a measure of percent soluble solids, was measured using a refractometer that automatically corrected for temperature. Pol, which is a unitless measure of the polarization of the sugar solution, was measured using a saccharimeter.

KST was determined according to the theoretical recoverable sugar method (Legendre, 1992). TSH was calculated as the product of TCH and KST (divided by 1000 to convert kg sucrose to metric tons). Harvest dates for small-plot test 1 were 19 January 1996 (plant cane) and 11–12 December 1996 (first ratoon).

For small-plot tests 2 and 3 harvest data were not determined by using commercial harvest weights as at small-plot test 1. Stalk counts and stalk weight measurements were used for harvest data determination at tests 2 and 3. Millable stalks were counted within two of the middle four rows of each plot in August–September each crop year. Selection of the two rows for counting was based on representative stand uniformity. A 40-stalk random sample was used to calculate sugarcane biomass yields. Plant fresh weights were used to determine individual stalk weight (kg stalk^{-1}), and TCH was calculated as the product of stalk number and stalk weight. To determine KST, a 10-stalk harvest random sample was milled and the crusher juice analyzed for Brix and pol using a NIR analyzer (Model 5000, Foss NIR Systems, Silver Spring, MD, USA) calibrated for sucrose measurement in sugarcane. The KST and TSH calculations were performed as described above.

Yield measurements were performed for small-plot test 2 on 3 and 5 January 2006 (plant cane) and 7 December 2006 (first ratoon). Yield measurements were performed for small-plot test 3 on 13 December 2006 (plant cane), 3 December 2007 (first ratoon), and 17 December 2008 (second ratoon). Remaining sugarcane in test 2 was commercially harvested on 8 February 2006 (plant cane) and 12 December 2006 (first ratoon). Remaining sugarcane in test 3 was commercially harvested on 11 March 2007 (plant cane), 22 February 2008 (first ratoon), and 12 February 2009 (second ratoon).

Relative sucrose ha^{-1} was determined for each commercial field comparison for each crop year (or combination of years) by dividing TSH by the highest TSH of the pair. Relative sucrose ha^{-1} was determined for each treatment for each crop year (or combination of years) of each small-plot test by dividing the TSH mean for that treatment by the highest TSH treatment mean. Relative sucrose ha^{-1} was used as a measure of relative yield that could be related to soil and leaf Si across multiple years and locations (Evans, 1987).

Statistical Analyses

Statistical analyses were performed with SAS Version 9.1 (SAS Institute, Cary, NC, USA). Comparisons of harvest data treatment effects in the commercial field study were made using paired t-tests conducted at probability levels of 0.05, 0.01, and 0.001. Analyses of variance for all measurements in small-plot tests were performed using the PROC GLM procedure for a randomized complete block design. F-tests and preplanned contrasts were used to determine probabilities of significant differences between treatments for small-plot experiments and were conducted at probability levels of 0.05, 0.01, and 0.001. Nonlinear relationships were determined with SAS (PROC NLIN) by determining best fit for each dataset by maximizing coefficient of determination (r^2) and minimizing residuals. Graphs were plotted using Sigmaplot Version 11.0 (Systat Software, Inc., San Jose, CA, USA).

RESULTS

Yield Responses

There were significant responses in TCH and TSH to Ca silicate application at 6.7 t ha^{-1} each year, comparing treatment means for all commercial field locations (Table 2). Fields receiving Ca silicate application had a cumulative average increase over 3 years of 3.8 TSH compared to fields not receiving the amendment. For individual paired comparisons this cumulative increase with Ca silicate application ranged from −0.76 to 7.01 TSH.

Dolomite was included in small-plot tests 1 and 2 to compare pH and Ca effects from limestone with the influence of Ca silicate so that the effect of Si could be determined. Dolomite was used instead of hi-cal lime because of potential magnesium (Mg) deficiencies (McCray et al., 2010). In test 1 there were no significant differences in TCH, KST, or TSH with dolomite application as compared to no amendments or when added in addition to Ca silicate (Table 3). There was a significant reduction in TSH with the 13.4 t ha^{-1} rate of dolomite compared to 6.7 t ha^{-1} in the first ratoon crop. Calcium silicate application significantly increased TCH each year of the test, and significantly increased TSH for the first ratoon crop and 2-year total. There were significant increases in TCH for the first ratoon crop and in TSH for each year and for 2-year total TSH with the 13.4 t ha^{-1} rate of Ca silicate compared to 6.7 t ha^{-1}. Ca silicate application did not significantly influence KST either crop year.

TABLE 2 Sugarcane production data for paired commercial field comparisons of preplant Ca silicate application on Florida organic soils

Ca silicate	TCH (t cane ha^{-1})			TSH (t sucrose ha^{-1})			
t ha^{-1}	Plant	R1[a]	R2	Plant	R1	R2	3 yr
0	106.9	92.6	68.0	11.96	9.95	7.50	28.47
6.72	120.8	99.5	76.1	13.98	10.98	8.40	32.30
t-test	***	**	**	***	**	**	***
N	12	12	11	12	11	11	11

, * Significant at $P = 0.01$ and 0.001, respectively, using a paired t-test.

[a] R1 and R2 are 1st and 2nd ratoon crops, respectively.

TABLE 3 Sugarcane production data for test 1 evaluating preplant dolomite and Ca silicate applications on Pahokee and Okeelanta organic soils

Treatment	Dolomite t ha^{-1}	Ca silicate t ha^{-1}	TCH (t cane ha^{-1}) Plant	TCH (t cane ha^{-1}) R1[a]	KST (kg sucrose t^{-1}) Plant	KST (kg sucrose t^{-1}) R1	TSH (t sucrose ha^{-1}) Plant	TSH (t sucrose ha^{-1}) R1	2 yr
1	0	0	110.8	82.4	99.0	102.2	10.91	8.52	19.43
2	6.72	0	104.0	87.1	98.1	104.5	10.58	9.54	20.11
3	13.44	0	114.5	82.9	101.5	103.9	11.50	7.87	19.37
4	0	6.72	120.6	98.1	101.6	104.0	11.09	9.61	20.71
5	0	13.44	126.3	113.7	105.8	107.9	12.76	11.50	24.26
6	6.72	6.72	121.4	97.5	104.1	104.2	12.16	9.85	22.01
F-test			**	***	NS	NS	*	**	**
Contrasts									
1 vs 2, 3			NS[b]	NS	NS	NS	NS	NS	NS
1 vs 4, 5			*	***	NS	NS	NS	**	*
2 vs 3			NS	NS	NS	NS	NS	*	NS
4 vs 5			NS	*	NS	NS	*	*	*
4 vs 6			NS	NS	NS	NS	NS	NS	NS

*, **, ***Significant at $P = 0.05$, 0.01, and 0.001, respectively.

[a] R1 is the first ratoon crop.

[b] NS, not significant at $P = 0.05$.

There were no significant differences in TCH, KST, or TSH with dolomite application as compared to no amendments or when added in addition to Ca silicate in small-plot test 2 (Table 4). Application of Ca silicate significantly increased TCH and TSH in the plant cane crop, and 2-year TSH. Although similar trends were observed in the second ratoon crop, variability in soil

TABLE 4 Sugarcane production data for test 2 evaluating preplant dolomite and Ca silicate applications on an Okeelanta organic soil

Treatment	Dolomite t ha^{-1}	Ca silicate t ha^{-1}	TCH (t cane ha^{-1}) Plant	TCH (t cane ha^{-1}) R1[a]	KST (kg sucrose t^{-1}) Plant	KST (kg sucrose t^{-1}) R1	TSH (t sucrose ha^{-1}) Plant	TSH (t sucrose ha^{-1}) R1	2 yr
1	0	0	93.4	66.0	112.2	126.8	10.48	8.38	19.17
2	4.48	0	102.5	56.2	113.2	126.8	11.63	7.12	18.95
3	0	3.36	115.5	74.1	114.8	129.6	13.28	9.68	23.30
4	0	6.72	116.4	76.4	112.5	129.8	13.10	10.01	23.45
5	4.48	6.72	114.3	82.2	116.3	133.7	13.28	10.95	24.10
F-test			***	NS[b]	NS	NS	***	NS	**
Contrasts									
1 vs 2			NS	NS	NS	NS	NS	NS	NS
4 vs 5			NS	NS	NS	NS	NS	NS	NS
1 vs 3, 4			***	NS	NS	NS	***	NS	*
3 vs 4			NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P = 0.05$, 0.01, and 0.001, respectively.

[a] R1 is the first ratoon crop.

[b] NS, not significant at $P = 0.05$.

TABLE 5 Sugarcane production data for test 3 evaluating preplant applications of Ca silicate on a Dania organic soil

Ca silicate	TCH (t cane ha^{-1})			KST (kg sucrose t^{-1})			TSH (t sucrose ha^{-1})			
t ha^{-1}	Plant	R1[a]	R2	Plant	R1	R2	Plant	R1	R2	3 yr
0	153.8	125.2	76.3	111.8	121.8	126.6	17.18	15.12	9.61	41.91
2.24	158.8	123.1	75.7	111.4	121.7	127.6	17.70	15.01	9.63	42.34
4.48	170.4	125.2	86.2	109.8	120.6	126.8	18.75	15.16	10.91	44.82
6.72	160.3	123.1	80.3	114.0	122.1	126.5	18.28	15.08	10.10	43.46
F-test	NS[b]	NS	NS	NS	NS	NS	NS	NS	NS	NS
Contrasts										
0 vs. others	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
2.24 vs. 4.48	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
4.48 vs. 6.72	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] R1, R2, and R3 are 1st, 2nd, and 3rd ratoon crops, respectively.

[b] NS, not significant at $P = 0.05$.

wetness at this location probably was a factor in the lack of significant differences in the second year. There were no significant differences in TCH or TSH between the 3.4 and 6.7 t ha^{-1} rates of Ca silicate. There were also no significant differences in KST with Ca silicate application.

In small-plot test 3 there were no significant differences in TCH, KST, or TSH among Ca silicate rates for any crop year or for cumulative TSH (Table 5). There was an appreciable increase in TCH in the plant cane crop with Ca silicate application (no Ca silicate versus other rates: $P = 0.059$), but there was not a well-defined response to Ca silicate at this location.

Leaf and Soil Si

Leaf Si concentration was significantly increased with Ca silicate application and increased with increasing Ca silicate rate in small-plot tests 1 and 2 (Tables 6 and 7). An increase in leaf Si concentration was not determined with increasing Ca silicate rate in the plant cane crop in test 3, but was evident in the first ratoon crop (Table 8). Leaf Si concentration was generally lower for the first ratoon crop of small-plot tests 1 and 2 compared to plant cane. Leaf Si concentration was substantially lower in tests 1 and 2 with no Ca silicate application (1.8–2.8 g Si kg^{-1}) compared to test 3 (4.4–6.8 g Si kg^{-1}). The only significant change in leaf Si determined with dolomite application was an increase in leaf Si concentration with dolomite and Ca silicate in test 1 as compared to Ca silicate alone (Table 6; 1st ratoon, treatment 4 versus 6). This suggests that in that location there may have been a limitation of Mg in addition to Si, but this did not translate into a significant increase in TCH or TSH when dolomite and Ca silicate were combined (Table 3). There were significant increases in leaf Mg concentration with dolomite application in

TABLE 6 Selected soil and leaf values for test 1 evaluating preplant dolomite and Ca silicate applications on Pahokee and Okeelanta organic soils

Treatment	Dolomite t ha^{-1}	Ca silicate t ha^{-1}	pH	Ext Soil Si (g m^{-3})[a]		Leaf P (g kg^{-1})		Leaf Mg (g kg^{-1})		Leaf Si (g kg^{-1})	
			Plant	Plant	R1[b]	Plant	R1	Plant	R1	Plant	R1
1	0	0	5.7	4.6	2.0	2.3	1.6	1.9	1.3	2.8	1.8
2	6.72	0	5.5	5.6	2.0	2.2	1.7	2.2	1.5	2.5	1.9
3	13.44	0	5.7	15.3	3.6	2.2	1.7	2.3	1.7	3.1	2.1
4	0	6.72	5.6	69.3	28.5	2.2	1.7	2.0	1.4	6.0	3.2
5	0	13.44	5.8	174.5	91.6	2.2	1.7	1.8	1.4	10.2	4.3
6	6.72	6.72	5.7	79.5	48.0	2.3	1.6	2.0	1.8	6.1	4.2
F-test			NS[c]	***	**	NS	NS	*	NS	***	***
Contrasts											
1 vs. 2, 3			NS	NS	NS	NS	NS	*	NS	NS	NS
1 vs. 4, 5			NS	***	**	NS	NS	NS	NS	***	***
2 vs. 3			NS	NS	NS	NS	NS	NS	NS	NS	NS
4 vs. 5			NS	**	*	NS	NS	NS	NS	***	**
4 vs. 6			NS	NS	NS	NS	NS	NS	*	NS	**

*, **, ***Significant at $P = 0.05$, 0.01, and 0.001, respectively.

[a] Extraction with 0.5 N acetic acid. Soil samples (0–30 cm) collected after harvest each year.

[b] R1 is the first ratoon crop.

[c] NS, not significant at $P = 0.05$.

TABLE 7 Selected soil and leaf values for test 2 evaluating preplant dolomite and Ca silicate applications on an Okeelanta organic soil

Treatment	Dolomite t ha^{-1}	Ca silicate t ha^{-1}	pH		Ext Soil Si[a] (g m^{-3})				Leaf P (g kg^{-1})		Leaf Mg (g kg^{-1})		Leaf Si (g kg^{-1})	
			Plant		Plant		R1[b]		Plant	R1	Plant	R1	Plant	R1
			15	30	15	30	15	30						
1	0	0	4.9	5.2	3.0	2.6	3.0	3.0	2.7	2.3	1.6	1.4	2.8	2.0
2	4.48	0	5.0	5.2	4.6	2.8	7.0	3.0	2.7	2.3	1.7	1.4	2.7	2.0
3	0	3.36	4.9	5.2	12.4	6.4	11.2	9.4	2.8	2.4	1.6	1.4	5.1	3.4
4	0	6.72	5.1	5.5	33.6	10.2	29.8	9.2	2.6	2.4	1.5	1.3	7.2	4.7
5	4.48	6.72	5.2	5.4	25.8	7.8	41.3	17.3	2.7	2.3	1.6	1.4	6.8	5.1
F-test			***	NS[c]	***	NS	***	NS	NS	NS	*	NS	***	***
Contrasts														
1 vs. 2			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
4 vs. 5			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
1 vs. 3, 4			NS	NS	***	NS	NS	NS	NS	NS	NS	NS	***	***
3 vs. 4			**	NS	***	NS	*	NS	*	NS	NS	NS	***	**

*, **, ***Significant at $P = 0.05$, 0.01, and 0.001, respectively.

[a] Extraction with 0.5 N acetic acid. Soil samples (15: 0–15 cm and 30: 15–30 cm) collected after harvest each year.

[b] R1 is the first ratoon crop.

[c] NS, not significant at $P = 0.05$.

TABLE 8 Selected soil and leaf values for test 3 evaluating preplant Ca silicate applications on a Dania organic soil

Ca silicate	pH Plant		Ext Soil Si (g m^{-3})[a]				Leaf P (g kg^{-1})			Leaf Si (g kg^{-1})		
			Plant		R1[b]		Plant	R1	R2	Plant	R1	R2
t ha^{-1}	15	30	15	30	15	30						
0	6.1	6.3	17.3	12.3	16.3	13.7	2.5	2.6	2.8	6.8	4.4	5.5
2.24	6.1	6.2	70.7	14.5	55.5	13.7	2.5	2.6	2.7	5.5	5.6	5.2
4.48	6.2	6.3	119.5	24.7	89.7	16.8	2.5	2.6	2.7	5.9	6.7	5.9
6.72	6.3	6.3	141.0	26.0	116.0	19.7	2.4	2.6	2.7	6.3	7.3	6.8
F-test	**	NS[c]	***	**	***	*	NS	NS	NS	NS	***	**
Contrasts												
0 vs others	NS	NS	***	*	***	NS	NS	NS	*	NS	***	NS
2.24 vs. 4.48	NS	NS	***	*	***	NS	NS	NS	NS	NS	***	NS
4.48 vs. 6.72	*	NS	*	NS	***	NS	NS	NS	NS	NS	**	*

*, **, *** Significant at $P = 0.05$, 0.01, and 0.001, respectively.

[a] Extraction with 0.5 *N* acetic acid. Soil samples (15: 0–15 cm and 30: 15–30 cm) collected after harvest each year.

[b] R1 and R2 are 1st and 2nd ratoon crops, respectively.

[c] NS, not significant at $P = 0.05$.

test 1 (Table 6), but not in test 2 (Table 7). The only significant treatment effects on leaf P were a slight decrease in leaf P concentration with the high rate of Ca silicate in the plant cane crop of test 2 and a slight decrease in leaf P concentration with all Ca silicate rates in the second ratoon crop of test 3. Leaf P concentration was below the critical value of 1.9 g P kg^{-1} (Anderson and Bowen, 1990) for all treatments in the first ratoon crop of test 1 which may have reduced overall yields and limited the yield response to amendments.

There was a very strong relationship between leaf Si concentration and relative sucrose ha^{-1} across all commercial and small-plot locations in the study (Figure 1). Relative sucrose ha^{-1} was $\geq$0.95 with leaf Si concentration $\geq$6.0 g kg^{-1} (combined means of plant and first ratoon for sucrose ha^{-1} and leaf Si). The regression curve in Figure 1 indicates that 0.95 and 0.80 relative sucrose ha^{-1} corresponded to approximate leaf Si concentrations of 5.0 and 2.5 g kg^{-1}.

Acetic acid-extractable soil Si was significantly increased by Ca silicate application and by rate of application at all small-plot locations (Tables 6–8). Extractable Si concentration was substantially greater at the 0–15 cm depth compared to the 15–30 cm depth after Ca silicate application (Tables 7 and 8). This difference was not as pronounced in soils not receiving a Ca silicate application. Where Ca silicate was applied, extractable Si was often lower for the first ratoon crop than for plant cane, indicating that crop uptake and leaching losses were reducing Si availability over time, although this effect was not evident in test 2. Soil pH was not increased significantly by dolomite

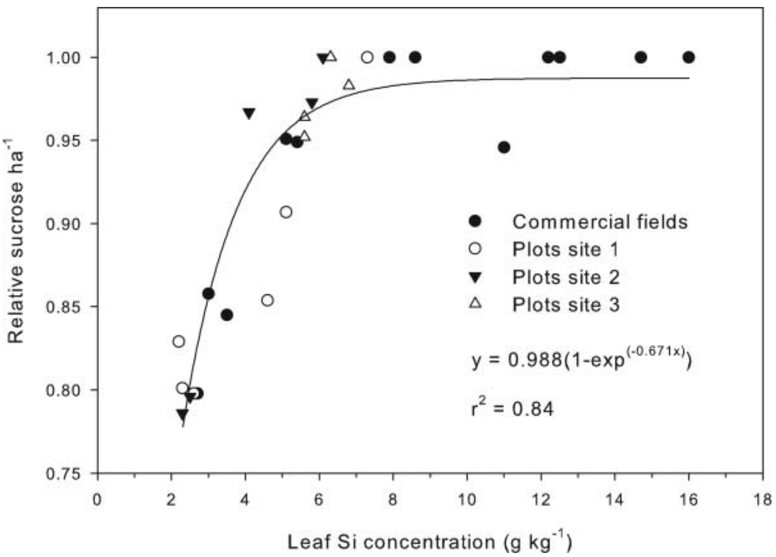

FIGURE 1 Relationship between relative sucrose ha^{-1} and leaf Si concentration for 2-yr means of plant and first ratoon crops of commercial field comparisons and small-plot tests of Ca silicate application. Only 6 of 12 commercial field comparisons could be used because of missing leaf data for some years.

or Ca silicate treatments in test 1, but was significantly increased by higher Ca silicate rates at the 0–15 cm depth in tests 2 and 3.

Acetic acid-extractable Si in soil samples collected after plant cane harvest was strongly related to relative sucrose ha^{-1} means of plant and first ratoon crops (Figure 2). Relative yield of 0.95 was reached on the regression curve at acetic acid-extractable Si of approximately 32 g m^{-3} (0–30 cm). There was a negative correlation ($P = 0.045$) of TCH response yr^{-1} (plant cane and first ratoon) with acetic acid-extractable Si (0–30 cm) without Ca silicate application for comparisons of 6.7 versus 0 t Ca silicate ha^{-1} (Figure 3). The single point with 218 g Si m^{-3} corresponds to a commercial field comparison on Torry muck soil with unamended leaf Si concentration >10 and no evidence of response to Ca silicate application. Primary yield responses were determined with acetic acid-extractable Si $\leq$21 (0–30 cm). Though there was a range of crop response, minimum yield response at a given soil test Si value generally was reduced as soil Si values increased to approximately 50 g m^{-3}. An economic break-even line for a 3-year crop at 5.1 TCH yr^{-1} (Figure 3) assumes that a standard t cane has a value of $US 28.07 and that Ca silicate costs $US 61.71 t^{-1} with application cost of $US 12.35 ha^{-1} (Roka et al., 2009). The break-even line in Figure 3 also assumes that the observed crop responses would be continued through the second ratoon crop since second ratoon data was not available for all comparisons. For soil test Si values $\leq$21 (0–30 cm) there were 9 of 11 locations with positive economic returns from a 6.7 t ha^{-1} application of Ca silicate.

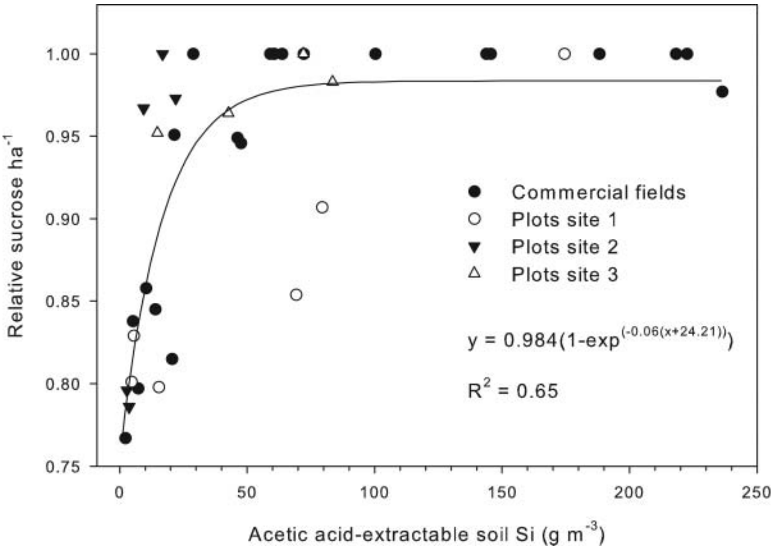

FIGURE 2 Relationship between relative sucrose ha^{-1} (2-yr means of plant and first ratoon) and acetic acid-extractable soil Si (sampled after plant cane) for commercial field comparisons and small-plot tests of Ca silicate application.

The relationship between acetic acid-extractable Si (after plant cane) and leaf Si concentration (means of plant cane and first ratoon) was defined reasonably well by the regression line of Figure 4 at soil Si <30 g m^{-3}, but was widely scattered at higher soil Si values. Acetic acid-extractable Si values

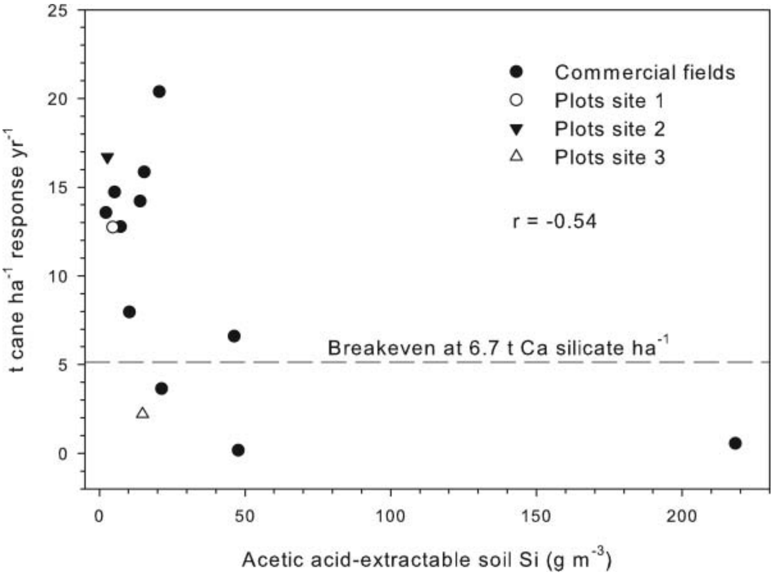

FIGURE 3 Relationship between TCH response yr^{-1} (plant and first ratoon) and unamended acetic acid-extractable soil Si for commercial fields and small-plots receiving 6.7 t Ca silicate ha^{-1} compared to the control (no Ca silicate).

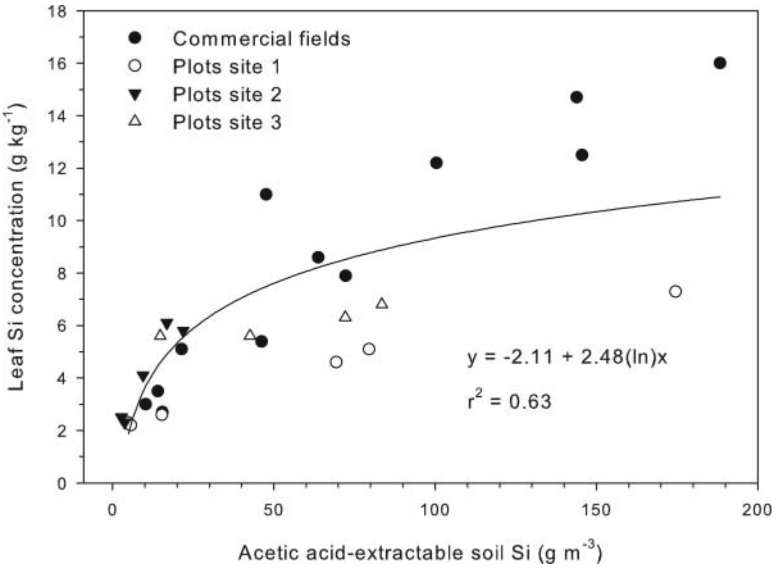

FIGURE 4 Relationship between leaf Si concentration (2-yr means of plant and first ratoon) and acetic acid-extractable soil Si (sampled after plant cane) for commercial fields and small-plot tests of Ca silicate application. Only 6 of 12 commercial field comparisons could be used because of missing leaf data for some years.

corresponding to previously noted leaf Si concentrations (Figure 1) of 6.0, 5.0, and 2.5 g kg^{-1} were 26, 18, and 5 g Si m^{-3} (0–30 cm).

DISCUSSION

As with previous studies with sugarcane in Florida (Anderson et al., 1991; Gascho and Andreis, 1974), there were strong responses in TCH and TSH to Ca silicate application. There was not a similar response to dolomite at two test locations, indicating that the responses are attributable to applied Si and not pH increase or applied Ca. Also, leaf P concentration was not increased by Ca silicate application, and so there was no indication of increased availability of P with slag application. Our findings agree with those of Elawad et al. (1982b) who determined that leaf P was directly related to the amount of P contained in the slag material. Phosphorus content in the Ca silicate applied in our study was relatively low (5.4 g P kg^{-1}). There was no evidence supporting previous suggestions (Matichenkov and Calvert, 2002; Matichenkov et al., 2002) that Ca silicate increases plant-available P.

Sugarcane yield responses to Ca silicate application ranged from 0 to 20 TCH yr^{-1} (Figure 3), with relative yield losses up to 23% without application (Figure 2). There was some variability in level of yield response, but responses of 12 to 15 TCH yr^{-1} were determined at several locations in the study with low initial soil-test Si. Some range in measured response may be expected due to sample and field variability, but there may also be variation in response to Si application depending on site-specific factors such as disease or insect pressure that increased plant Si may help alleviate (Kvedaras et al., 2007; Raid et al., 1992). Our study confirms the well-established role of Si as a beneficial nutrient in sugarcane (Savant et al., 1999) and emphasizes the need to maintain adequate soil Si availability for optimum growth (McCray et al., 2010).

Differences in leaf Si concentration among sugarcane cultivars have been reported (Deren et al., 1993), suggesting that there are differences in Si accumulation among genotypes. Although there were no specific comparisons among cultivars in this study, the response to applied Si was consistent across the cultivars included, and leaf and soil Si concentrations required for optimum yield were applicable across cultivars.

Leaf Si concentration was shown to relate strongly to relative sucrose ha^{-1} (Figure 1). Sucrose yield was optimal with leaf concentration $\geq$ 6.0 g Si kg^{-1}, and 0.95 and 0.80 relative yield levels corresponded to leaf concentrations of approximately 5.0 and 2.5 g Si kg^{-1}, respectively. This indicates the leaf Si critical level (0.95 relative yield) is 5.0 g kg^{-1} which is similar to the value of 5.3 g kg^{-1} at which 0.95 relative sugarcane yield was determined in Australia (Berthelsen et al., 2003). These leaf Si values are in close agreement with those previously suggested using survey data from Florida (McCray et al., 2010), but are substantially lower than the suggested critical value of 10 g Si kg^{-1} suggested by Anderson and Bowen (1990).

Relative sucrose ha^{-1} related strongly to acetic acid-extractable soil Si, with relative yield of 0.95 reached in a regression model at 32 g Si m^{-3} (0–30 cm) for samples taken after the plant cane crop and including soils with and without Ca silicate amendment (Figure 2). Acetic acid-extractable Si of approximately 26 g m^{-3} corresponded to a leaf Si concentration of 6.0 g kg^{-1}, the lower value required for optimum TSH (Figure 4). The primary response to Ca silicate was determined with unamended acetic acid-extractable Si $\leq$ 21 g m^{-3} (0–30 cm) (Figures 2 and 3). However, at one of the small-plot test locations there was no significant TCH or TSH response with unamended acetic-acid extractable Si of 15 and 17 g m^{-3} for 0–30 and 0–15 cm sample depths, respectively. Acetic acid-extractable Si tended to be substantially higher in the 0–15 cm depth than the 15–30 cm depth for soils receiving Ca silicate application (Tables 7 and 8). There was less difference in soil-test Si between the two soil depths for soils not amended with Ca silicate, with values being an average of 12% higher for a 0–15 cm sample compared to a 0–30 cm sample.

Alvarez et al. (2009) determined that application of Ca silicate to responsive soils could improve economic returns for Florida sugarcane growers. Predicting potential response in relation to soil-test Si levels is critical to making cost/benefit decisions, given the expense of Ca silicate application (Roka et al., 2009). A proposed soil-test Si calibration using acetic acid is

TABLE 9 Proposed Ca silicate recommendations for sugarcane grown on Florida organic soils.

Acetic acid-extractable Soil Si g m^{-3} (0–15 cm)	Ca silicate recommendation t ha^{-1}
0-5	6.7
6-10	5.6
11-15	4.5
16-20[a]	3.4
21-25[a]	2.2

[a] Maintenance application only for fields with a previous response to calcium silicate. Leaf Si concentrations will be useful for confirming the need for Si application (optimum: >6.0 g Si kg^{-1}, critical: 5.0 g Si kg^{-1}).

shown in Table 9. This calibration was developed using Ca silicate with approximately 200 g Si kg^{-1}. In the proposed calibration, 4.5 to 6.7 t Ca silicate ha^{-1} are recommended for soil-test Si values ≤ 15 g m^{-3}. The high rate of 6.7 t ha^{-1} was effective in this and previous studies in providing adequate Si in soils with low Si availability (Raid et al., 1992). Lower Ca silicate rates are recommended as maintenance applications for soils with acetic acid extractable Si in the range of 16–25 g m^{-3}. It is possible that there could be an economic response to a first-time Si application within the soil-test Si range of 16–25, but leaf Si concentration should be used in addition to soil-test Si to determine potential response. Soils that have previously responded to Si application that have soil-test Si >15 are expected to decrease in available Si over time, hence the maintenance recommendation up to 25 g Si m^{-3}. The range of primary yield response to Si is included with initial acetic acid extractable Si $\leq$ 25 for the 0–15 cm depth and so this calibration should provide for effective economic yield responses. The proposed calibration uses a similar range of acetic acid-extractable Si as the Si calibration for rice in Florida (Korndorfer et al., 2001).

CONCLUSIONS

Strong responses in TCH and TSH to Ca silicate application on organic soils were determined with acetic acid-extractable soil Si <15 g m^{-3}, with some response to approximately 25 g m^{-3}. Recommendations were developed over this range with a maximum Ca silicate rate of 6.7 t ha^{-1} with soil-test Si $\leq$ 5 g m^{-3}. First time applications of Ca silicate are only recommended based on soil-test values ≤ 15 g Si m^{-3}, with maintenance applications recommended up to 25 g Si m^{-3}. Leaf analysis should be used to complement soil-test Si values to ensure that crop Si levels are adequate and that Si applications are cost-effective. Optimum leaf Si concentration was determined to be $\geq$ 6.0 g kg^{-1}, with 0.95 (critical value) and 0.80 relative yield at 5.0 and 2.5 g Si kg^{-1}, respectively.

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