Soil and leaf nutrient interactions following application of calcium silicate slag to sugarcane

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Received 27 September 1990; accepted in revised form 28 June 1991

Key words: Calcium silicate slag, cane, Everglades Agricultural Area, Florida, Histosols, leaf Si, magnesium, nutrient antagonism, organic soils, Saccharum, silicon, soil testing, stubble production, sugar, tissue testing

Abstract

In certain areas of the Everglades Agricultural Area, plant and ratoon sugarcane (Saccharum L.) yields are increased by application of Si from calcium silicate slag. The greatest yield responses are obtained in the plant crop the first year after application of slag and when plant uptake of Si is increased. Magnesium deficiencies have been reported after slag application. The objective of this study was to quantify interactions of soil and leaf nutrients on sugarcane grown on a Terra Ceia muck (Euic, hyperthermic Typic Medisaprists) that had previously received calcium silicate slag. Slag was applied at five rates, and yields were evaluated from plant, first-ratoon, and second-ratoon (stubble) crops at two locations. Soil and leaf from each crop were sampled for nutrient analysis and the results were used to interpret the yield data. Although slag increased cane yield by as much as 39% and sugar yield by 50%, for each 100 mg L\(^{-1}\) drop in extractable soil Mg, cane yields declined by 5.3 Mg ha\(^{-1}\) and sugar yields by 0.9 Mg ha\(^{-1}\). At leaf Si concentrations exceeding 10 g kg\(^{-1}\), optimum cane and sugar yields were observed, while leaf Mg concentrations approached critical leaf concentrations below 1.5 g kg\(^{-1}\). Estimates of total leaf nutrient uptake during each crop indicated that uptake of Mg did not meet nutrient demands at high biomass production. Nutrient antagonism between Si and Mg is suggested. Low soil Mg may contribute to the marked crop responses to slag and for the decline in stubble production. Application of a magnesium fertilizer may be necessary to maintain high nutrient availability.

Introduction

Magnesium, an essential plant nutrient, is involved in plant metabolism, protein synthesis, enzyme activation, and as a component of chlorophyll is involved in photosynthesis [Marschner 1986]. Low plant Mg has been shown to limit sugarcane yields in Hawaii, Philippines, Puerto Rico, and Taiwan [Chao & Li 1949; Clements 1981; Hagihara 1972; Landraw & Samuels 1956; Manopla & Nartea 1981]. Soils reported in these areas were characterized by low pH (<6.0), low cation exchange capacity and base saturation, high leaching conditions, high rates of K or N fertilization, and low extractable soil Mg.

Kidder and Gascho [1977] noted that Mg deficiencies could be induced when calcium silicate slag is applied on low Mg content Histosols (<88 mg L\(^{-1}\) soil) in the Everglades. Although yield declines associated with low extractable soil Mg have not been shown under Florida condi-
tions, Kidder and Gascho [1977] recommended that 40 kg Mg ha$^{-1}$ should be applied once at planting when using slag. These recommendations were made neither with supporting data nor recognizing the ranges of extractable soil Mg impacting yield. Soil Mg was implicated with possible sugarcane yield losses in long-term cropping responses studies with calcium silicate slag [Anderson et al. 1991]. Calcium silicate slag was shown to increase crop longevity, but the question that remains whether other nutrients contribute to the decline of sugarcane ratoon production under these conditions. The purpose of this study was to delineate and assess the influence of available Mg and other nutrients on sugarcane that had been treated with calcium slag, as this might indicate a need to reassess Mg fertilization recommendations for sugarcane grown on Histosols in the Everglades.

Materials and methods

The sites, main treatment effects, harvest procedures, dates of data collection, and cultural practices were as previously reported for a short-term rice/sugarcane rotation response [Anderson et al. 1987] and a long-term ratoon and rotation cropping system response to application of calcium silicate slag [Anderson et al. 1991]. Planting, harvesting, and all leaf and soil sampling were accomplished at approximately the same times and physiological periods of growth. The sites were approximately 2.5 km apart, and the soil was a Terra Ceia muck (euic, hyperthermic Typic Medisaprists). Calcium silicate slag (Table 1) was broadcast either before previous rice production, or before the planting of sugarcane on plots not previously treated with slag. Rates of slag application were 0, 2.5, 5, 10, and 20 Mg ha$^{-1}$ on 6.1 m by 10 m plots. A randomized complete block design, split-plot in time (plant crop, 1st stubble crop, and 2nd stubble crop) was used with four blocks.

Sugarcane crop responses for three years to a single application of slag were reported by Anderson et al. [1991]. Before each harvest, the number of millable stalks ha$^{-1}$ were counted within each plot from 20 linear feet of row plot$^{-1}$. Stalk weights were estimated from 20 stalk subsamples at harvest. Whole-plot weights of millable cane and sugar (Mg ha$^{-1}$) were measured at harvest [Anderson et al. 1991].

Fifteen 15-cm by 2.5-cm soil cores were sampled within each plot before each year of crop growth. Soils were prepared and analyzed for pH, water and acetic acid-extractable P ($P_w$ and $P_a$), and acetic acid-extractable K, Ca, and Mg using the methods of Sanchez [1990] and Anderson and Beverly [1985]. The ‘top-visible’ dewlap (TVD) leaf tissues were sampled in June (174 ± 6 day-of-the-year) each year of production [Anderson et al. 1991], prepared, and analyzed for Si [Elliot et al. 1988], and for N, P, K, Ca, and Mg using the nitric-perchloric acid digest procedure modified after Anderson and Henderson [1988].

A total leaf nutrient removal estimate (LNRE, kg nutrient ha$^{-1}$) from each crop was developed for each nutrient using the following calculation:

\[
\text{LNRE} = (\text{kg nutrient kg}^{-1} \text{ leaf}) \times (\text{no. millable stalks ha}^{-1}) \times (\text{kg stalk}^{-1}) \times \text{LTF},
\]

where LTF represents the leafy trash fraction estimate (dry-weight fraction of the net cane representing leafy trash, e.g., tops plus all leafy trash) produced for the entire crop. The LTF is derived as:

\[
\text{LTF} = 0.270 \times 0.406/0.594, \quad \text{or} \quad \text{LTF} = 0.184,
\]

where 0.27 is the dry matter fraction of millable stalks (p. 172, van Dillewijn 1952), 0.406 is the fraction of tops and leafy trash in the above ground portion of cane (p. 166, van Dillewijn 1952), and 0.594 is the dry weight fraction of millable stalks in the total crop (p. 166, van Dillewijn 1952). These calculations are based on the LTF, therefore, values are referred to as

Table 1. Composition (g kg$^{-1}$) of calcium silicate slag used

<table>
<thead>
<tr>
<th>CCE</th>
<th>Si</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
<th>Fe</th>
<th>Al</th>
<th>S</th>
<th>Na</th>
</tr>
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<tbody>
<tr>
<td>46.8%</td>
<td>206.0</td>
<td>5.2</td>
<td>4.2</td>
<td>2.0</td>
<td>291.2</td>
<td>9.9</td>
<td>51.8</td>
<td>3.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Analyses by Alabama Testing Laboratories, Birmingham, AL 35202 USA Calcium carbonate equivalent.
estimates of the total leaf nutrient removed by each crop.

The influence of the main treatment effects (crop, rate, timing) and soil extraction and leaf nutrient effects on cane and sugar yields were evaluated using analysis of variance and correlation procedures [SAS 1985]. Regression equations were determined using step-wise regression procedures to select independent variables that improved model $R^2$ by more than 0.01 (PROC REG, p. 656–709, SAS, 1985). Only statistically significant ($\alpha \leq 0.1$) linear, quadratic, or simple 1:1 interaction term regressions and variables were evaluated and included in final partial-regression equations. Auto-correlated variables were not considered in the partial regression models. Non-linear models were evaluated using the multivariate secant method [Ralston & Jennrich 1979] computed by SAS (PROC NLIN, p. 575–606, SAS, 1985).

**Results and discussion**

**Influence on soil and yield**

The calcium carbonate equivalence of the slag used in these studies was 46.8%, which explains why soil pH increased with rate of application during the first two years of cropping (Table 2). Although soil pH was significantly ($\alpha \leq 0.01$) correlated to yield, pH was also significantly correlated with the other soil and leaf nutrient concentrations (Table 3). Auto-correlation of various parameters with yield introduces a difficulty in determining true correlation between parameters (i.e., yield as a function of independent variables). It has been shown that yield response to slag application is due to Si application rather than to a liming effect [Fox et al. 1967; Gascho & Andreis 1974; Silva 1971]. Therefore, in the evaluation of conditions influencing yield, soil pH is considered to be an artifact of slag liming which did not enhance yield.

Application of 20 Mg slag ha$^{-1}$ represents a contribution of 4012 kg Si ha$^{-1}$, 104 kg P ha$^{-1}$, 84 kg K ha$^{-1}$, 5824 kg Ca ha$^{-1}$, and 40 kg Mg ha$^{-1}$ to the soil. This constitutes a substantial nutrient contribution that was not generally reflected in soil extraction and TVD leaf nutrient data (Table 2).

Silva [1971] reported that increased P uptake occurred following Si application to Hawaiian Oxisols. In our studies, however, slag application was poorly correlated ($\alpha > 0.10$) with either $P_w$ (P intensity) or TVD leaf P (plant uptake). The $P_a$ (P capacity) was determined because it is a soil extraction that represents the capacity of soil to supply P ($\Sigma$ [fraction of the total soil P + $P_w$]). Although $P_a$ increased with applied slag, it remained unavailable, as indicated by unchanged levels of $P_w$ and tissue P (Table 2). Similarly, soil K and Mg were poorly correlated ($\alpha > 0.10$) with slag application. Changes in soil P and K at both sites between crops 1 and 2 reflected P and K fertilizer application rather than the application of slag.

Soil extractable Mg (kg L$^{-1}$) was better correlated with cane and sugar yields than pH or the other extractable soil nutrients (Table 3). Significant ($\alpha \leq 0.01$) curvilinear relationships between sugarcane yield and soil Mg accounted for up to 64% of the variability in yield observed at both locations and for all crops (Fig. 1). Approximately 40 kg Mg ha$^{-1}$ was added to the soil at the highest rate of slag application (20 Mg ha$^{-1}$). This addition was marginally reflected by increases of extractable soil Mg with the rate of slag application at Site 1, but there were no increases in extractable soil Mg at Site 2. Across all data, however, there was no correlation between either soil or leaf Mg with the rate of Mg applied as slag (Table 3). This indicates that soil Mg is an independent variable unrelated to the rate of slag application. Positive correlations of soil extractable Mg and negative correlation of tissue Mg concentrations with yield are not a consequence of residual Mg in the slag becoming available to the crop.

At these locations, the decline of soil Mg associated with the decline in sugarcane stubble yields is of considerable interest. The reduction of extractable soil Mg with each successive crop may be a result of significant nutrient removal of soil Mg by the crop (Fig. 1). Annual decline of soil extractable Mg suggests that the cation buffer capacity is low, and that soil Mg potentially is in short supply, although deficient leaf Mg
<table>
<thead>
<tr>
<th>Site</th>
<th>Crop</th>
<th>Slag rate (Mg ha(^{-1}))</th>
<th>Soil pH</th>
<th>Soil P(_{e}) (mg L(^{-1}))</th>
<th>Soil K (mg kg(^{-1}))</th>
<th>Soil Ca (mg kg(^{-1}))</th>
<th>Soil Mg (mg kg(^{-1}))</th>
<th>TVD Leaf N (g kg(^{-1}))</th>
<th>TVD Leaf P (g kg(^{-1}))</th>
<th>TVD Leaf K (g kg(^{-1}))</th>
<th>TVD Leaf Ca (g kg(^{-1}))</th>
<th>TVD Leaf Mg (g kg(^{-1}))</th>
<th>TVD Leaf Si (g kg(^{-1}))</th>
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<td>238</td>
<td>44</td>
<td>14.0</td>
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<td>341</td>
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<td>11.8</td>
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<td>1.1</td>
<td>7.0</td>
<td>16</td>
<td>210</td>
<td>32</td>
<td>1.0</td>
<td>0.1</td>
<td>1.5</td>
<td>0.4</td>
<td>0.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Slag applied before crop 1.

Mean across time of slag application and replication (LSD at \(\alpha = 0.10\)).
Table 3. Simple correlations (r) between the rate of slag application, yield, soil Mg, and leaf Mg concentrations and soil and plant tissue data (n = 216)

| Soil TVD Leaf | N  | P  | K  | Ca | Mg | Si |
|---------------|--|--|--|--|--|--|---|
| Slag          | 0.41 | -0.05 | 0.27 | 0.00 | 0.66 | 0.08 | -0.05 | -0.06 | -0.09 | -0.00 | -0.07 | 0.35 |
| Rate          | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** |
| Cane          | 0.74 | 0.25 | 0.20 | 0.23 | 0.37 | 0.78 | 0.41 | 0.53 | 0.06 | -0.14 | -0.82 | 0.56 |
| Sugar         | 0.71 | 0.15 | 0.16 | 0.11 | 0.38 | 0.76 | 0.45 | 0.58 | 0.15 | -0.13 | -0.79 | 0.59 |
| pH            | -0.19 | 0.39 | 0.22 | 0.49 | 0.62 | -0.13 | 0.25 | 0.09 | -0.26 | -0.63 | 0.44 |
| Soil          | 0.62 | 0.25 | 0.18 | 0.25 | 0.47 | - | 0.37 | 0.50 | 0.04 | -0.19 | -0.71 | 0.44 |
| Mg            | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** |
| Leaf          | -0.63 | -0.22 | 0.17 | -0.22 | -0.27 | -0.71 | -0.45 | 0.58 | -0.11 | 0.33 | - | -0.54 |
| Mg            | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** | ** ns ** |

**, *, and ns indicates α ≤ 0.01, 0.05, and α > 0.10, respectively, by the F-test.

concentrations generally were not indicated (< 1.5 g Mg kg⁻¹).

The variability in cane and sugar yields is explained more fully when crop age (1st, 2nd, or 3rd) and rate of slag application (0, 2.5, 5, 10 and 20 Mg Slag ha⁻¹) are also regressed with soil Mg level using step-wise regression [SAS 1985]:

Cane (Mg ha⁻¹) = 90.3 - 9.55 (crop)² + 0.72 rate + 0.053 (crop × soil Mg) R² = 0.80, and,

Sugar (Mg ha⁻¹) = 14.1 - 5.38 crop + 0.095 rate + 0.00883 (crop × soil Mg) R² = 0.76.

Partial-regression shows that these three independent variables (crop, rate of slag application, and soil Mg) explain 80% to 76% of the cane and sugar yield variability. Slag application alone has been shown to increase cane yield by as much as 39% and sugar yields by as much as 50% [Anderson et al. 1991].

Soil Mg was positively correlated with yield. From the equations above, for each 100 mg L⁻¹ drop in extractable soil Mg, cane yields decreased by 5.3, 10.6, to 15.9 Mg cane ha⁻¹ and sugar yields by 0.9, 1.8, to 2.6 Mg sugar ha⁻¹ after each successive crop (1st, 2nd, and 3rd, respectively). At both sites in these studies, soil Mg levels decreased with successive cropping of sugarcane. Magnesium stubble fertilization may therefore be advisable in order to maintain pre-plant soil test Mg levels (> 500 kg Mg L⁻¹).

Influence on plant nutrition and nutrient removal

If yield decrease of stubble crops is related to decreasing soil Mg levels, then an important question to answer is why did plant Mg increase with stubble crops (Table 2)? Kidder and Gascho [1977] reported that Mg deficiency symptoms may occur after application of calcium silicate slag (plant crop). Application of slag resulted in a significant (α ≤ 0.01) increase in leaf Si concentration and a corresponding decline in leaf Mg concentration (Fig. 3).

Luxury consumption may have undesirable effects on plant composition [Marschner 1986]. At higher Si concentrations, greater Mg concentrations may be required to ensure adequate nutritional status. In principle, critical deficiency levels of a specific nutrient may increase as the concentration of another nutrient increases. Optimum yields were reached with leaf Si concentrations above 10 g Kg⁻¹, confirming critical Si concentrations recognized by Kidder and Gascho [1977] and Gascho and Andreis [1974]. During Crop 1, leaf Si concentrations exceeded 10 g Kg⁻¹, and leaf Mg concentration levels approached a critical concentration of 1.28 gkg⁻¹ (Fig. 3). By Crop 2, leaf Si concentrations significantly declined and Mg concentrations increased to the range of nutrient adequacy (≥ 1.5 g kg⁻¹).

The amount of a given leaf nutrient is a func-
Fig. 1. The relationship between extractable soil Mg (mg L\(^{-1}\)) and cane and sugar yield (Mg ha\(^{-1}\)). [** indicates \(\alpha < 0.01\).]
tion of nutrient availability and the plant nutrient demand for biomass production. Ideally, nutrient availability should match the plant nutrient demand. In many instances, however, as the final biomass yield increases, nutrient concentrations in the plant decline; this has been referred to as the plant nutrient dilution effect [Jarrell & Beverly 1981]. Apart from changes linked with physiological age, the dilution effect becomes apparent when a specific nutrient has limited plant availability. Low leaf Mg concentration associated with high biomass yield may demonstrate this effect (Fig. 2).

Limitations in nutrient supply may be a result of unavailability of soil nutrients (low capacity) or excesses of another nutrient reducing specific

![Graph showing the relationship between leaf Mg and Si concentrations (g Kg⁻¹) and cane yield (Mg ha⁻¹).](image1)

Fig. 2. The relationship between leaf Mg and Si concentrations (g Kg⁻¹) and cane yield (Mg ha⁻¹). [** indicates α < 0.01].
uptake (antagonism). An example of nutrient antagonism is Mg deficiency in sugarcane (<1.5 mg Mg kg⁻¹; El Wali & Gascho 1984), which is accentuated under conditions of increasingly low soil Mg or high levels of applied K or N [Clements 1980; Evans 1959]. It was observed that increased uptake of leaf Si from slag resulted in decreasing leaf Mg concentrations (Fig. 3), an example of nutrient antagonism under declining soil Mg conditions. It is reasonable to assume that Mg nutrition was marginal to inadequate during Crop 1 when high leaf Si concentrations were observed, and that higher Mg availability is required under high yielding conditions.

For a specific nutrient, if the rate of nutrient uptake markedly declines with respect to other nutrients, that nutrient is suspected of limiting plant growth [Steenbjerg & Jakobsen 1962]. Conversely, if the nutrient supply is not limiting, then the amount of nutrients removed per unit area of production should increase with biomass yield. The ratio of any nutrient with another should be in a narrow range (balance), otherwise a problem in nutrient supply limiting yield should be expected.

The LNRE was plotted as a function of cane yield (Mg millable cane ha⁻¹) and graphically indicates nutrient demands (Fig. 4). The LNRE assumes that the TVD leaf nutrient content represents the nutrient content of all other leaves. Since nutrient contents change with physiological age of the leaf, the LNRE is used only as a tool for plant nutrient diagnosis and is not an absolute quantification of the total leaf nutrient removed by each crop. The LNRE can also be used to confirm nutrient imbalances or to indicate luxury consumption across a range of conditions. The threshold value approach is also used to interpret leaf tissue analysis, but is limited in usefulness when nutrient imbalances change critical nutrient leaf concentrations impacting yield.

Relationships of the LNRE of N, P, K, and Ca versus cane were linearly significant (P ≤ 0.10). The LNRE of Si exponentially increased with cane yield (Fig. 4). Although these changes reflect the rapid assimilation of Si in the plant crop, the rapid decline of leaf Si concentration with crop and yield (Fig. 2) and the exponential decline in the Si LNRE with yield indicate that slag applied at planting was only sufficient to meet the Si requirement of the plant and first ratoon crops. Unlike the other leaf nutrients, the LNRE of Mg did not change with the yield. This indicates that plant Mg availability did not meet

![Figure 3](image-url)  
Fig. 3. The relationship between leaf Mg and Si concentration (g Kg⁻¹). [** indicates α ≤ 0.01].
nutrient demand at the higher biomass cane yields. Across the range of 40 to 140 Mg cane ha$^{-1}$ yields, approximately 33 kg Mg ha$^{-1}$ was removed from the soil by the total leaf biomass produced for each crop. The strong negative correlation of leaf Mg concentration with yield and leaf Si concentration ($r = -0.83$ and $r = -0.54$, respectively) may indicate a notable dilution effect caused by rapid biomass accumulation at higher yields occurring during the plant crop and/or nutrient antagonism between leaf Si and Mg.

**Conclusion**

Results indicated that calcium silicate slag significantly increases leaf silica concentrations, which are used to indicate probable response of sugarcane to slag applications. There were indications that low plant Mg availability ($\leq 1.5$ g Mg kg$^{-1}$ in TVD leaves) may also be limiting the extent of observed crop responses to calcium silicate slag. Low availability of Mg may have been caused by nutrient antagonism with Si and low soil Mg. At sites where sugarcane responded to calcium silicate slag, levels of soil Mg declined with each successive crop. Although Mg is also applied as slag, Mg remained unavailable for plant uptake.

Stubble fertilization with Mg is not currently recommended to maintain soil Mg levels, to improve yields, or to reduce decline in stubble production. In these studies, highest yields were achieved when soil test levels greater than 500 kg Mg L$^{-1}$ were found. Maintenance of these soil test levels would be desirable. Research is needed to establish Mg fertilization and nutrition guidelines.

**Acknowledgements**

Appreciation is expressed to Mr. Norman Rozeff, Rio Grande Valley Sugar Growers, Inc., Santa Rosa, TX for his manuscript suggestions, and to Dr. John A. Cornell, Statistics Department, University of Florida, Gainesville, FL for his computing assistance. Partial support of these studies was provided by the Western Ag-Minerals Company, Houston, TX, International Min-
erals & Chemical Corp., Mundelein, IL, and the Potash and Phosphate Institute, Atlanta, GA.

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