The short-term effects of surface-applied dolomitic lime and gypsum on soil chemical properties and yields of sugarcane ratoon crops in KwaZulu-Natal, South Africa

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This study investigated the effects of surface-application of lime and gypsum on soil properties and yields of ratoon sugarcane crops. Treatments involved once-off surface application of dolomitic lime (L), gypsum (G) and dolomitic lime plus gypsum (LG) in factorial combination, with four replications. Soil chemical properties were measured on samples collected at intervals of 20 between depths of 0 and 80 cm in the first and fifth years after treatment application. Yield parameters were measured annually. In the first year, treatment effects were mainly restricted to a depth of 0–20 cm. The LG increased pH(CaCl2) from 3.9 to 4.5, and calcium from 123 to 350 mg L$^{-1}$. Little treatment effect was observed on yield parameters in the first year. In the fifth year, L and LG generally showed similar impacts on soil properties. The L treatment led to markedly increased pH(CaCl2) and calcium and somewhat decreased magnesium levels in the topsoil. The sucrose and cane yields in LG were significantly higher than in other treatments, which all had similar results. It was, therefore, concluded that LG may be a viable option for the correction of soil acidity through surface application in the sugarcane ratoon crops grown in the sandy soils of KwaZulu-Natal.

Keywords: lime, gypsum, sucrose yield, sugarcane, surface-application

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Introduction

Approximately 30% of the South African sugarcane–producing soils are acidic (Mthimkhulu and Miles 2017) which has led to significant reductions in crop yields. Although sugarcane is fairly tolerant of soil acidity, significantly poor growth and yields attributed to low calcium (Ca) levels have been noted on acid soils. Nixon et al. (2003) and Hartemink (2008) indicated that soil acidity retards sugarcane production. Acid soils are normally characterised by low pH, elevated levels of soluble aluminium (Al) and manganese (Mn), and deficiencies of Ca and magnesium (Mg) (Omollo et al. 2016). According to Krstic et al. (2012), soluble Al causes stunting of primary roots and inhibits cell division and elongation as well as root development. Poor root development reduces the ability of the plant to exploit moisture and nutrient reserves. This makes plant roots vulnerable to drought stress and, thus, decreases crop yields (Nixon et al. 2003). Remediation of acid soils is generally done through the application of dolomitic lime (CaMg(CO3)$_2$) and gypsum (CaSO$_4$2H$_2$O).

Dolomitic lime, which is usually applied to reduce topsoil acidity, requires deep incorporation to reduce subsoil acidity, due to its limited solubility and mobility (Farina et al. 2000). Sugarcane farmers in South Africa are generally advised to correct soil acidity at planting, so that the liming products can be incorporated into the topsoil. However, in some cases where lime is required for the ratoon crop, adequate incorporation is impractical, as it may cause root disturbance and stool damage and, thus, major yield losses. Therefore, farmers apply lime either alone or with gypsum, depending on the recommendation, on the soil surface and rely on rainfall or irrigation water to
move the products downward, so that they can react with the soil.

An investigation by Caires et al. (2002) in highly weathered soils producing various grain crops in Brazil found a significant decrease in exchangeable acidity and an increase in pH_{CaCl2} 23 months after the surface application of lime. Crusciol et al. (2014) studied surface application of calcium magnesium silicate on the soil surface of green-harvested sugarcane fields and found a significant increase in soil pH, decrease in exchangeable acidity, and acid saturation at 0–60 cm soil depth within 12 months. It must be noted, however, that the solubility of calcium magnesium silicate is seven times greater than that of dolomitic lime, and this facilitates the mobility of the former in the soil profile (Crusciol et al. 2014).

Gypsum is used mainly as a soil conditioner, to increase sulphur (S) and Ca levels and reduce subsoil acidity through its high solubility, which enables it to move down the soil profile (Crusciol et al. 2014). As with lime, gypsum is surface-applied in ratoon crops. However, there are no studies confirming the effectiveness of this practice in South African sugarcane-producing soils, as earlier investigations focused on incorporated ameliorants (Nixon et al. 2003). All previous studies that investigated surface application of lime and gypsum to remediate acid soils under sugarcane were conducted in the highly weathered soils of Brazil, in areas with very high rainfall (Crusciol et al. 2014; Araújo et al. 2016; Crusciol et al. 2017; Rossato et al. 2017). Similar studies done on no-till grain production systems show that the effect of lime and gypsum, applied on the surface, varies with rate of application, soil type, climatic conditions, product quality, growing season and time of application (Caires et al. 2005; Rossato et al. 2009; Fontoura et al. 2019). It is therefore not possible to predict reliably the effectiveness of surface-applied lime and gypsum on the soils of the South African sugar industry using the results from the abovementioned studies. Numerous studies that involve incorporation of liming products raise concerns about the high solubility and mobility of gypsum, as it tends to promote leaching of potassium (K), Mg and Al into the subsoil, causing depletion of K and Mg in the topsoil (Sumner 1970; Farina and Channon 1988; Shainberg et al. 1989; Ernani et al. 2006). However, it is not known whether the findings of these authors would be replicated if liming products were surface-applied to the sandy soils under sugarcane production in South Africa, and whether this would benefit sugarcane production. There are reports in the literature that a combination of lime and gypsum, incorporated into the topsoil, is an effective means of ameliorating subsoil acidity (Sumner 2012). However, the rate at which these materials react, and their efficacy when surface-applied without incorporation in sugarcane ratoon fields, remains uncertain. Thus, this study was aimed at investigating the effects of surface applications (without incorporation) of lime and gypsum on soil profile chemical properties and yield parameters under ratoon sugarcane crops.

Materials and methods

Experimental site
The experimental site was situated on a rainfed sugarcane commercial farm, known as Ocean Lodge, near Stanger, KwaZulu-Natal, South Africa (29°18′43.67″ S, 31°14′17.57″ E). The trial was established in December 2011 on second ratoon sugarcane and continued to October 2016. The climate of the region is subtropical and most of the rain falls in summer, between October and March. The average annual precipitation is 1 073 mm, and the average annual temperature is 21 °C (Mthimkhulu et al. 2019). The site is located at an altitude of 276 m above sea level. The soil was locally classified as a Cartref soil form (Soil Classification Working Group 1991) or Gleyic Luvisols (IUSS Working Group WRB 2006), with 140 g kg⁻¹ clay, 30 g kg⁻¹ organic matter and greater than 60% acid saturation in the surface layer. The initial soil pH_{CaCl2} was less than 4, while the levels of all the base cations (Ca²⁺, Mg²⁺, K⁺ and Na⁺) were below 100 mg L⁻¹ (Table 1). The results of this study are presented according to the South African Fertiliser Advisory Services analysis (Mthimkhulu et al. 2019).

Experimental design
The complete trial, made up of 36 plots, covered approximately 1 749 m² (33 m × 53 m). Each plot of 44 m² was 8 m long, with spacing of 1.1 m between sugarcane (variety: N39) rows. Treatments were the once-off surface application of dolomitic lime (L), gypsum (G) and lime plus gypsum (LG) at the rates of 0, 2.5 and 5.0 t ha⁻¹ in a factorial combination with four replications. The intermediate rate treatment (2.5 t ha⁻¹) is not given consideration in this paper, as it yielded no clear results in comparison with the other two rates. All the plots received both macro- and micronutrients as shown in Table 2. Nitrogen and K were applied in three splits throughout the season. Weed and pest management was done according to the hosting farmer’s routine. The crop was harvested five times during the experiment and all the plots were burned prior to harvest in order to remove leafy, non-sucrose containing biomass. The crop was harvested annually and yields were recorded. However, due to the lack of a clear trend in data collected in the second, third and fourth years, this paper reports on the soil properties and yield parameters (sucrose yield, sugarcane yield and sucrose content) measured in the first and fifth years, namely, October 2012 and October 2016, respectively. Soil sampling, conducted shortly after each harvest, involved the collection of seven samples per plot, which were thoroughly mixed to form a composite sample. This was done at various depth intervals, including 0–20, 20–40, 40–60 and 60–80 cm, with midpoints of 10, 30, 50 and 70 cm, respectively.

Soil analyses
All the soil analyses were done at the Fertiliser Advisory Services laboratory of the South African Sugarcane Research Institute. The soil pH determination was done in a 1:2.5 (soil to 0.01 M CaCl₂ solution) solution with a glass electrode (Miles et al. 2014). Exchangeable acidity was measured by titration with 0.1 M sodium hydroxide to a phenolphthalein endpoint, after extraction with 1 M KCl by shaking for 10 minutes (Miles et al. 2014). The extractions of exchangeable base cations (calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), and potassium (K⁺)) were conducted with the Ambic extractant (Van der Merwe et al. 1984) (0.25 M NH₄HCO₃ + 0.01 M NH₃F + 0.01 M EDTA at pH 8.0) and measured by inductively coupled plasma
spectrophotometry with a Varian 720-ES spectrometer. The effective cation exchange capacity (ECEC) was calculated by adding exchangeable acidity to exchangeable cations. Acid saturation percentage was estimated as the ratio of exchangeable acidity to ECEC.

### Crop yield parameters
At each harvest, different plots were cut and weighed in the field using a mechanical grab attached to an electronic scale to measure the sugarcane yield (tonnes ha⁻¹). Twelve stalks of the crop were collected from each plot to determine sucrose content (%). The sugarcane yield and sucrose content (%) were used to calculate the sucrose yield (tonnes ha⁻¹) which serves as a unit for which payment is received for sugar production.

### Statistical analyses
A general analysis of variance (ANOVA), with the main treatment factors being L, G and LG levels, was used to compare treatments at various depths in terms of all investigated soil properties and crop yield parameters (sugarcane yield, sucrose yield and sucrose content) recorded in the first and fifth years. Post-hoc comparisons of treatment means were also carried out using the least significant difference test at the 5% probability level (LSD₉₅%) and Bonferroni test (Genstat 18th Edition, VSN International, Hemel Hempstead, UK). To investigate the relationships between sucrose yield and soil properties (Ca, Mg, pH, acid saturation, ECEC, exchangeable acidity, and Na levels), simple Pearson’s correlations with their respective probability levels (p values) and polynomial graphs were generated for both sampling times (first and fifth years) on XLSTAT software version 2021.5.1.1235. The Pearson’s correlations were only performed for sucrose yield since this parameter showed a similar pattern with sugarcane yield while sucrose content had no clear relationship with all the measured soil properties.

### Results
The effect of treatments on soil pH were largely restricted to 0–20 cm soil depth, with LG (pH 4.5) having the highest pH in the first year compared to other treatments (Figure 1a). However, the overall difference was not significant (p > 0.05) throughout the soil profile (Figure 1a). In the fifth year, treatments of L at 0–20 cm and G in the subsoil had significantly (p = 0.02) higher pH levels than the control treatment. Although L, G and LG treatments had lower exchangeable acidity than the control at 0–20 cm depth in the first year, no significant differences (p > 0.05) were found in the whole profile in either year (Figures 1c and d).

Soils with L, G and LG treatment showed similar values for overall acid saturation, which were significantly lower than those of the control (Figure 1e). Gypsum was generally found to be the most effective (p < 0.01) ameliorant in reducing subsoil acid saturation, although L (p = 0.02) and LG (p = 0.04) proved to be more efficient at a depth of 0–20 cm in the fifth year (Figure 1f). Calcium increased significantly (p < 0.01) with G and LG compared to the control, especially at 0–20 cm soil depth in the first year (Figure 2a). Treatment with L alone did not show any significant differences (p > 0.05) at any of the applied treatments in terms of Ca levels (Figure 2a). In the fifth year, G and LG treatments showed an overall significant (p < 0.01) increase in Ca concentration compared to control treatments, though L (p = 0.01) and LG (p = 0.03) treatments were significantly higher than the control at 0–20 cm depth (Figure 2f). For Mg, no treatment effect was found in the first year (Figure 2c). In the fifth year, at 0–20 cm depth, there was a clear and significant difference in L (p < 0.01) and LG (p = 0.02) treatments compared to the control, as well as L (p = 0.02) compared to G. Magnesium levels in G treatments increased slightly in the subsoil in comparison to the topsoil (Figure 2d). Potassium and Na levels were not affected by the applied treatments across all depths in both sampling times (Figure 2e and f). The ECEC was similar for L, G and LG treatments but significantly (p = 0.01) higher than the control treatment in the first year (Figure 3c). In the fifth year, none of the differences in the average ECEC values for the whole soil profile were significant (p > 0.05) between all the applied treatments (Figure 3d). However, ECEC differed significantly (p = 0.02) in L treatment in comparison with the control treatment at 0–20 cm depth in the fifth year (Figure 3d). There was a generally uniform impact of G and a similar effect for L and LG treatments in most of the soil properties measured at all soil depths.
Comparison of the 2012 and 2016 measurements showed a generally higher acidity in the latter year, though significant \((p = 0.03)\) differences were only found in the pH (CaCl\(_2\)) recorded from the control treatment. The base cations (Ca\(^{2+}\), Mg\(^{2+}\), K\(^+\) and Na\(^+\) and ECEC largely showed no significant differences, except for Mg\(^{2+}\) \((p = 0.04)\) and ECEC \((p = 0.03)\) in the LG treatment. It was found puzzling that the levels of Ca and Mg in the soil were generally below the South African Sugarcane Research Institute’s (SASRI) advised sugarcane target of 300 and 50 mg L\(^{-1}\), respectively in both first year and fifth year, although the products were applied in excess of the highest rates.

**Figure 1:** The average \((n = 4 \pm \text{standard error})\) soil pH measured in calcium chloride (pH\(_{\text{CaCl}_2}\)), exchangeable acidity (EA) and acid saturation (AS), determined at various soil depths under different treatments: G: gypsum application (5 t ha\(^{-1}\)); L: lime application (5 t ha\(^{-1}\)); LG: lime plus gypsum application (5 plus 5 t ha\(^{-1}\)); control: no lime or gypsum application. LSD\(_{0.05}\) (soil pH: First year = 0.15, Fifth year = 0.18; EA: First year = 0.21, Fifth year = 0.25; AS: First year = 6.84, Fifth year = 12.57)
Acid saturation was also above the SASRI advised threshold (20%) at both sampling times. No significant differences were found between treatments in sucrose yield, sugarcane yield and sucrose content in the first year (Figures 4a, c, e). However, by the fifth year, (4 t ha⁻¹ for L and 3 t ha⁻¹ for G) recommended for ratoon crops by the SASRI norms.
LG treatment had a significantly higher sucrose \((p = 0.02)\) and sugarcane \((p = 0.04)\) yield than the other treatments (Figures 4b, d). Sucrose content did not vary between the treatments even after five years of application (Figure 4f). Gypsum and L applied alone had similar effects but showed no significant difference \((p > 0.05)\) compared to the control (Figures 4b, d). Relationships between sucrose yield and soil properties are shown in Figures 5, 6 and S1 (supplementary results). In the fifth year, a significant polynomial relationship was found between sucrose yield and some of the soil properties including Ca \(\left( r^2 = 0.51, p = 0.002 \right)\), Mg \(\left( r^2 = 0.42, p = 0.013 \right)\), pH \(\left( r^2 = 0.46, p = 0.012 \right)\), acid saturation \(\left( r^2 = 0.50, p = 0.003 \right)\) and exchangeable acidity \(\left( r^2 = 0.54, p = 0.005 \right)\) (Figure 5 and Figure S1e). Calcium and acidity levels showed the strongest relationships with sucrose yield in the fifth year. Although some were significant, the relationships found between sucrose yield and soil properties, except for ECEC \(\left( r^2 = 0.46, p = 0.014 \right)\) and Na \(\left( r^2 = 0.42, p = 0.018 \right)\) were weak \((\text{Ca: } r^2 = 0.33, p = 0.020), \text{(pH: } r^2 = 0.30, P = 0.028), \text{(acid saturation: } r^2 = 0.34, P = 0.021)\) in the first year (Figure 6 and Figure S1c and d). Sucrose yields showed no clear relationship with potassium, in both sampling times, and magnesium in the first year.

**Discussion**

The impact of the applied treatments on soil \(\text{pH}_{\text{(CaCl}_2)}\) was largely restricted to the surface layer, and LG is the only treatment that resulted in a significant increase in pH in the first year. These results confirm the findings of McLay et al. (1994), who report that combining L and G increases the solubility and efficacy of L in raising soil pH. Although the differences were not significant, the pH values for L and LG were noticeably higher than that of the control at 20–40 cm depth in the first year, suggesting that the coarse texture of the soil, coupled with favourable rainfall, facilitated the movement of alkalinity to this depth (Carrow et al. 2001). The changes in soil \(\text{pH}_{\text{(CaCl}_2)}\) found in the first year following L application reflected the low buffering capacity of the soil, which is a consequence of low organic matter and clay contents (McLay et al. 1994). In addition, L particles may have descended through root and fauna
channels as the rain water percolated through the soil (Fontoura et al. 2019). Rossato et al. (2017) also report an increase in pH (CaCl2) and a decrease in exchangeable acidity measured at 12 months after the surface application of L to a sandy loam soil planted with sugarcane in Brazil. In our study, liming, either alone or in combination with G, substantially increased pH and decreased acid saturation down to 80 cm depth in the fifth year. Gypsum application was also very effective in increasing pH and decreasing exchangeable acidity and acid saturation, mainly at 0–20 cm depth (in the first year) and throughout the soil depth in the fifth year. However, in the studies of Crusciol et al. (2014) and Rossato et al. (2017) this ameliorant showed no effect on pH and exchangeable acidity after 12 months following surface application. These contrasting results may be associated with the gypsum rates applied, which was 5 t

Figure 4: The mean ($n = 4 \pm$ standard error) sucrose yield, sugarcane (cane) yield and sucrose content determined in the First year (a, c, e) and Fifth year (b, d, f) of lime (L) and gypsum (G) application under different treatments. LG: lime plus gypsum application; control: no lime or gypsum application. Mean associated with the same letter are not significantly different (LSD$_{0.05}$ (sucrose yield: First year = 1.95, Fifth year 3.38, cane yield: First year = 12.47, Fifth year = 22.00, sucrose content: First year = 0.74, Fifth year = 0.97)
−1 in the current study and 1.8 t ha−1 in the studies done by Crusciol et al. (2014) and Rossato et al. (2017). According to Raij (2008), the decrease in acid saturation and exchangeable acidity, and increase in pH in G treatments might be due to the release of OH− by SO4 2− through ligand exchange during the formation of hydroxylated structures of aluminium, and/or leaching of aluminium together with gypsum. The study of Araújo et al. (2016) reports that the displacement of OH− by SO4 2− is encouraged by the effect of higher SO4 2− levels in the soil profile after G application, even though clay exchange sites have less preference for sulphur species compared to OH−. In addition, the decrease in acid saturation could be due to the formation of precipitates such as Al2(SO4)3. In the study of Fontoura et al. (2019), conducted on clayey soil under grain crop production in Brazil, a small change in pH measured after one year due to gypsum application had disappeared 11 years later. Calcium levels in the LG (350 mg L−1) and G (317 mg L−1) treatments were significantly higher than L (191 mg L−1) and control (123 mg L−1) treatments, with the highest values found in LG at 0–20 and 20–40 cm depth, confirming that G applied either alone or in combination with L was very effective in increasing soil Ca levels in both the first year and fifth year. This effect was much clearer in the fifth year, when Ca increased uniformly down the soil profile in G treatment plots. The elevated levels of Ca and Mg resulted from (a) the release of these nutrients from the ameliorants, and (b) increased negative variable electric charges (or ECEC) generated on the surface of colloids by the dissociation of H+ from hydroxyl groups, caused by an increase in soil pH3(CaCl2) after liming (Caires et al. 2005). The increased Na found in LG as compared to the other treatments could also be attributed to the higher ECEC recorded in this treatment. According to Caires et al. (2011), the increased ECEC resulting from liming reduces the mobility of Ca, as it is attracted by the variable charge of soil particles. The lower levels of Mg observed at 0–20 and 20–40 cm compared to the lower depths in the last sampling is consistent with the findings of Fontoura et al. (2019), who demonstrate that G application tends to leach this nutrient and K to the lower horizon, even though K did not respond to any of the applied treatments. The lack of treatment effect on K was also observed in the study by Pauletti et al. (2014). The similarities recorded in LG and L treatments in terms of pH, exchangeable acidity and acid saturation, especially in the fifth year, were previously reported by the study of Nixon et al. (2003), who investigated the impact of combined 5 t ha−1 L and 5 t ha−1 G or 5 t ha−1 L alone on Humic Cambisols for three years. The small changes observed in most soil properties recorded in the first year had little effect on sucrose yield and sugarcane yield and this was attributed to the limited

Figure 5: The relationship of sucrose yield with (a) calcium, (b) magnesium, (c) soil pH measured in calcium chloride and (d) acid saturation at 0–20 cm depth determined in 2016 from soil treated with a single application of dolomitic lime and/or gypsum.
time for ameliorants to fully react with the soil, to the extent that they significantly affected crop yields. The main factor that appeared to raise sucrose yield in the first year was an increase in pH which resulted in an increased ECEC ($r^2 = 0.46$, $p = 0.014$). In contrast, a study carried out over one year on a highly weathered soil with sandy loam texture in Brazil reports a significant increase in sugarcane sucrose and stalk associated with increased S and Ca levels and decreased Al concentrations following G application (Crusciol et al. 2017). A study by Morelli et al. (1992) reports similar yields for L and G treatments although the yields were greater than those measured in the control treatment. After five years of L, G and LG treatments although the yields were greater than those measured in the control treatment. After five years of L, G and LG application, LG showed a significantly higher sucrose yield than the other treatments, confirming the results of Sumner (1990) and Schumann et al. (1999). In addition to the increase in pH and base cations ($Ca^{2+}$ and $Mg^{2+}$) resulting from L application, G also supplies S, through its detoxifying effect of soil Al, which further improves crop yields under the LG treatment (Nixon et al. 2003). The lack of response of sucrose content to the applied liming products has also been reported by Nixon et al. (2003) in two experiments where three different rates were applied to Nomanci and Magwa soil forms.

Conclusions

The results obtained from this study indicate that surface application of L and G, either alone or in combination, to ratoon sugarcane crops can improve soil properties, although treatment impacts were mainly restricted to 0–20 cm soil depth in the first year of application. In the fifth year, L and LG effects were generally similar, but significantly different from the control with respect to most of the soil properties, especially at 0–20 cm. The application of G leached the Mg slightly from 0–20 and 20–40 cm depths to the lower depths and showed no effect on K (despite numerous reports of both nutrients leaching following G application). Lime application increased the pH, which led to an increase in ECEC and higher retention of base cations, such as $Ca^{2+}$ and $Mg^{2+}$. This effect was magnified in the LG treatments, where G increased $Ca^{2+}$ levels further and also supplied S that would detoxify Al through the formation of aluminium sulphate. Sucrose yields recorded in the first year suggest that one year was not sufficient for the applied treatments to have a significant impact on crop yields. Clear treatment effects were evident in the fifth year, when LG had a significantly higher sucrose yield compared to the other treatments. Lime and G were both similar to the control in terms of sucrose and sugarcane yields, even after five years of treatment application. It is, therefore, concluded that (a) the surface application of L and G does improve soil properties, even though the effect may not be immediate, and (b) a combination of lime and gypsum may be the best method for correcting soil acidity in sugarcane ratoon crops.

Conflict of interest — The authors state that there is no conflict of interest.
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