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The residual effect of gypsum on subsoil conditioning, nutrition and productivity of sugarcane crops

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Abstract

Although the benefits of gypsum for subsoil conditioning are known, there is still a lack of information regarding the duration of its effects on soil chemical attributes and sugarcane productivity. Therefore, the objective of this work was to evaluate the residual effect of gypsum doses on soil chemical attributes, root density and productivity in seven sugarcane crops (ratoon). The experiment was conducted in an experimental area located at Embrapa Cerrados, in Planaltina, DF, Brazil. The experimental design consisted of four gypsum doses (0, 0.5, 5 and 10 t ha^{-1}) distributed in randomized blocks with four replications. Gypsum was applied only one time to the soil surface after sugarcane planting in July 2009. After 13 and 87 months of gypsum application under sugarcane cultivation, the soil was collected from layers up to 120 and 200 cm deep, respectively. For evaluation of the soil chemical attributes: sulfate ($S\text{-}SO_4^{2-}$), calcium (Ca^{2+}), magnesium (Mg^{2+}) and aluminum saturation (m) were assessed. Also, the root dry mass density was evaluated after the first and seventh sugarcane crops, in September 2010 and 2016, respectively. Furthermore, the variables leaf macronutrient concentrations (N, P, K, S, Ca and Mg), stalk yield and total reducing sugars (TRS) were analyzed in all seven crops/ratoons (first is the main crop and other six are ratoons). The application of 5 t ha^{-1} gypsum increased SO_4^{2-} and Ca^{2+} and reduced the aluminum saturation after 13 and 87 months, with higher intensities in the subsurface layers of the soil. As a consequence of this chemical conditioning of the subsurface soil layers, the root dry mass density was increased by 18 and 37% in the 0-120 and 0-200 layers, respectively, after the first (main) and seventh sugarcane crops (ratoons) in relation to the absence of gypsum application. Furthermore, treatments with 5 and 10 t ha^{-1} of gypsum increased the leaf contents of S, Ca and N in relation to treatments with 0 and 0.5 t ha^{-1} of gypsum. As a consequence of the increased root growth and better nutrition of sugarcane, the use of gypsum provided a long residual effect, observed in the increase of stalk and sugar yields.

Keywords: *Saccharum* spp., total reducing sugars, sugarcane nutrition, root system.
Abbreviations: m_aluminum saturation; V_base saturation; OM_organic matter; TRS_ total reducing sugars; SYTW_Stalk yield per total water.

Introduction

In Brazil, sugarcane occupies 8.7 million hectares, which represents 38% of the area planted with this crop around the world (Faostat, 2016). In the last ten years, expansion of sugarcane cultivation in Brazil was 2.5 million hectares, with greater representation in the Central-South region (Conab, 2016), mainly occupying areas under pasture (Adami et al., 2012).

To improve the economic efficiency of sugarcane production, it is necessary to increase the longevity of sugarcane plantations by maintaining adequate productivity in the ratoons, since replanting is one of the highest costs associated with this crop (Barros and Milan, 2010). Among the factors affecting the longevity of sugarcane plantations, the chemical properties of the soil at the surface and subsurface (Landell et al., 2003) and intensity of the water deficit during crop growth (Monteiro and Sentelhas, 2017) have been highlighted due to the effect on productivity and mortality of the ratoons.

Most of the cultivation sugarcane areas in the Center-South region of Brazil are composed of Latosols (Cherubin et al., 2015), where the majority present low calcium contents and high aluminum saturation on the surface and subsurface (Sumner, 2012). These factors hinder development of the root system of several crops due to the fundamental role of calcium in cell division and growth of apical meristems (Marschner, 2012). Furthermore, calcium has low mobility in plants (White and Broadley, 2003), and aluminum, in high concentrations in the soil, is associated with several morphological and physiological abnormalities in the root tissues, resulting in lower absorption of water and nutrients (Arunakumara et al. 2013).

In the case of sugarcane, the roots play an essential role in the growth of ratoons because after harvest the energy and nutrients needed for regrowth are supplied by the root system, as mentioned by Trivelin et al. (2002). Therefore, restriction of the root system to the superficial layers of the soil can limit the productivity of ratoons, and consequently the longevity of sugarcane plantations.

Calcium from gypsum is different from limestone. They accompany anion (carbonate) which is consumed in neutralizing the acidity of the soil surface layer. It also has the capacity to reach the subsurface soil layers, accompanying sulfate leaching (Reeve and Sumner, 1972; Ritchey et al., 1980). In this sense, studies have demonstrated the increase in calcium availability and reduction of aluminum saturation of the deeper soil layers due to the application of gypsum (Caires et al., 2011; Araújo et al., 2016), constituting an improvement of the root environment in the subsurface soil layers.

For annual crops subjected to no-till planting, a prolonged residual effect of gypsum on the increase of sulfur contents (Caires et al., 2011), as well as reduction of the potential acidity in the subsurface layers of the soil (Souza et al., 2012) have been verified. Also in this system, Pauletti et al. (2014) verified a reduction in aluminum saturation and increases in calcium contents after 36 and 72 months of gypsum application, increasing corn and soybean yields.

Despite the numerous studies on cultivation systems with annual crops, studies evaluating the residual effect of gypsum doses on soil chemical attributes and sugarcane productivity are still scarce. Therefore, this work was performed with the objective of evaluating the residual effect of gypsum doses on soil chemical attributes, root density and productivity in seven sugarcane crops (1 main + 6 ratoons).

Results

Chemical properties of the soil and root dry mass density

The rapid initial effect of gypsum application was verified in the increase of $S\text{-}SO_4^{2-}$ and Ca^{2+} contents and reduction in aluminum saturation in the soil profile after 13 months of application. With 5 t ha^{-1} dose gypsum there was an increase in the levels of $S\text{-}SO_4^{2-}$ to a depth of 60 cm, while the dose of 10 t ha^{-1} promoted this increase for depths up to 105 cm compared to the doses of 0 and 0.5 t ha^{-1} (Fig. 2a). Similarly, doses of 5 and 10 t ha^{-1} promoted an increase in Ca^{2+} levels in the 0-45 cm layer, compared to the 0 and 0.5 t ha^{-1} treatments, observed after 13 months of application (Fig. 2c). Reduction in aluminum saturation was observed in 30-60 and 30-90 cm soil layers for the application of 5 and 10 t ha^{-1} of gypsum, respectively, compared to the control treatment (Fig. 2g).

In addition to its rapid initial effect, the use of gypsum presents a high residual effect, observed by the maintenance of the higher $S\text{-}SO_4^{2-}$ and Ca^{2+} levels and reduced aluminum saturation in soil depths even after 87 months of its application. These increases in the $S\text{-}SO_4^{2-}$ and Ca^{2+} levels reached depths of 100 cm for the 5 t ha^{-1} dose and 200 cm for the dose of 10 t ha^{-1} (Fig. 2b, d). The reduction in aluminum saturation for the treatments with 5 and 10 t ha^{-1} of gypsum reached depths of 100 and 140 cm, respectively, compared to the control treatment (Fig. 2h).

Besides the effect of gypsum on $S\text{-}SO_4^{2-}$ and Ca^{2+}, this input affects the distribution of other nutrients in the soil, especially when applied at high doses (Figures 2e and 2f), where the gypsum dose of 10 t ha^{-1} promoted greater movement of Mg^{2+} to the soil subsurface layers, compared to the other treatments. This behavior was observed at 13 months after application of 10 t ha^{-1} of gypsum due to the reduction of Mg^{2+} contents in the 0-15 cm layer (Fig. 2e).

Application of 5 t ha^{-1} of gypsum positively improved the chemical environment by increasing the root dry mass density in the 0-120 cm layer by 18%, compared to the control after the first sugarcane cutting. The largest increases in root dry mass density were observed in the 30-45 and 45-60 cm layers with increases of 46 and 56%, respectively (Fig. 3a).

There was a residual effect of gypsum on chemical improvement of the environment and on the root density. This was well pronounced after the seventh sugarcane crop, with a 37% increase in root density in the soil profile (0-200 cm) with the application of 5 t ha^{-1} of gypsum. These gains was occurred in the layers below 40 cm, generating increases of 41 to 157% in root dry mass density (Fig. 3b).

Leaf macronutrient content and stalk and sugar yield

In general, the gypsum doses of 5 and 10 t ha^{-1} provided adequate macronutrient contents for the seven sugarcane crops, with the exception of nitrogen (Fig. 4).

In all sugarcane crops the gypsum doses of 5 and 10 t ha^{-1} provided higher leaf S contents compared to the doses of 0 and 0.5 t ha^{-1} ($p \leq 0.05$) (Fig. 4a). On the other hand, only in the fifth crop a difference in the leaf S content between the two highest gypsum doses was observed, in which 10 t ha^{-1} presented values statistically higher to the recommended dose (5 t ha^{-1}).

The gypsum doses of 5 and 10 t ha^{-1} also resulted in higher leaf Ca contents in all sugarcane crops compared to the treatments with 0 and 0.5 t ha^{-1} of gypsum ($P \leq 0.05$). These latter treatments showed similar leaf Ca levels from third to seventh crops, while in the first and second crops the contents were higher for the treatment with 0.5 t ha^{-1} of gypsum.

Gypsum doses did not promote changes in the leaf magnesium (Mg) content in the first, second, third and seventh sugarcane crops (Fig. 4c). However, in the fourth and fifth crops there was a reduction in leaf Mg contents for treatment with 10 t ha^{-1} of gypsum compared to application of 0.5 t ha^{-1}.

Treatments with gypsum applications of 5 and 10 t ha^{-1} resulted in an increase in N contents compared to the doses of 0 and 0.5 t ha^{-1} in most of the evaluated sugarcane crops. In the third crop a similar leaf N contents for all gypsum doses was observed (Fig. 4d). However, only in seventh cut the leaf N content was considered adequate (Raij et al 1996), in treatments receiving 5 and 10 t ha^{-1} of gypsum.

In general, the application of 5 and 10 t ha^{-1} of gypsum promoted higher stalk and total reducing sugars (TRS) yields compared to the control (Fig. 5). This effect remained in the seven sugarcane crops. The gypsum dose of 5 t ha^{-1} increased the stalk yield compared by 10, 19, 20, 29, 28 and 25%, for the first to the seventh crop, respectively, compared to the control treatment. In addition, the observed productivities at the recommended dose (5 t ha^{-1}) were similar to the treatment with 10 t ha^{-1} of gypsum for all evaluated crops.

Compared to the control treatment, the gypsum application of 5 t ha^{-1} increased the TRS production by 14, 18, 20, 19, 29, 35 and 24% from the first to the seventh crop, respectively

(Fig. 5b). There were no differences in the TRS production for the seven sugarcane crops between treatments with 5 and 10 t ha^{-1} of gypsum.
Considering the accumulated stalks yield, the gypsum doses of 0.5, 5 and 10 t ha^{-1} promoted increases of 9, 22 and 20%, respectively, compared to non-application of this input (Fig. 6a). The average gains observed in the cumulative TRS yield equivalent to those of the stalks yields of 9, 22 and 20% for the doses of 0.5, 5 and 10 t ha^{-1}, respectively, compared to the control treatment (Fig. 6b).

Discussion

The pronounced residual effect of gypsum resulted to $S\text{-}SO_4^{2-}$ adsorption in the soil subsurface layers (Ritchey et al., 1980), due to the lower pH and lower organic matter content in these layers. This causes greater development of positive charges in the soil, greater $S\text{-}SO_4^{2-}$ adsorption and concomitant adsorption of Ca^{2+} and Mg^{2+} (Marcano-Martinez and McBride, 1989).
The movement of $S\text{-}SO_4^{2-}$ in the soil profile at 13 and 87 months after application of 5 t ha^{-1} of gypsum (Fig. 2a, b) corroborates the recommendation of gypsum based on the soil clay content for perennial crops (Sousa and Lobato, 2004), since it considers the correction of a 60 cm soil layer, which summed with the 40 cm layer, where limestone was incorporated as a corrected profile at 100 cm.
The higher Ca^{2+} levels in the subsurface layers of the soil due to application of 5 and 10 t ha^{-1} of gypsum, even after 87 months (Fig. 2c, d), demonstrate its prolonged residual effect on chemical conditioning of the subsurface soil layers and are associated with its movement as an ion accompanying the $S\text{-}SO_4^{2-}$ (Reeve and Sumner, 1972; Ritchey et al., 1980), resulting in greater availability of this nutrient for root growth (Pauletti et al., 2014).
However, by application of high gypsum doses such as 10 t ha^{-1}, which is twice the recommended dose for this soil (Sousa and Lobato 2004), there is greater intensity of movement of other cations in the soil profile, mainly Mg^{2+} (Fig. 2 e, f). This can cause problems on supply of this nutrient. A similar result was found by Caires et al. (1999) in a study conducted in Red Latosol, where they observed a reduction in Mg^{2+} content in the 0-20 cm layer and consequent increase in the 20-60 cm layer 14 months after application of 12 t ha^{-1} of gypsum.
Distribution of Mg^{2+} in the soil profile was promoted by high gypsum doses. This results from the cation exchange reaction with Ca^{2+} provided by product dissolution, leading to increase in its concentration in the soil solution and leaching as the cation accompany $S\text{-}SO_4^{2-}$ (Pavan and Volkweiss, 1985).
The effect of gypsum on the reduction of aluminum saturation (m), which occurred 13 months after application, persisted even after seven sugarcane cuts (Fig. 2g, h), corroborating with Pauletti et al. (2014) who also verified a long residual effect of gypsum for reducing the m value, after 72 months of gypsum application. This reduction in the aluminum saturation value observed for the 5 and 10 t ha^{-1} gypsum doses at 13 and 87 months of application, which is associated with increase in the exchangeable bases contents (Ca^{2+} and Mg^{2+}) in the soil profile (Fig. 2c, d, e, f) and the small reduction in exchangeable aluminum contents (Araújo et al., 2016). The use of gypsum may reduce the exchangeable aluminum contents of the soil (Caires et al., 1999), either by the effect of ligand exchange between the $S\text{-}SO_4^{2-}$ and OH^-, raising the soil pH, known as “self-liming” (Reeve and Sumner, 1972), or aluminum leaching due to formation of the $AlSO_4^+$ ion pair (Pavan and Volkweiss, 1985).
Increases in $S\text{-}SO_4^{2-}$, Ca^{2+} and Mg^{2+} levels and the reduction of aluminum saturation in the deeper soil layers due to the use of gypsum (Fig. 2) are maintained for long periods due to the application of gypsum associated with the high $S\text{-}SO_4^{2-}$ adsorption capacity of clayey Latosols and other highly weathered soils (Caires et al., 2011; Pauletti et al., 2014). This favored the increase of dry mass density of sugarcane roots (Fig. 3), an effect that reached greater depths over time. Better distribution of the sugarcane root system in the soil profile was also verified by Rocha et al. (2008) in response to the use of gypsum for the layers below 40 cm.
The longevity of the gypsum on soil results in greater root deepening, greater absorption efficiency of available nutrients in the soil, such as sulfur, calcium and nitrogen (Fig. 4a, b, d) and possibly favoring the maintenance of high yields in the seven sugarcane crops (Fig. 5).
The leaf S content was observed using treatments with 5 and 10 t ha^{-1} demonstrated the prolonged effect of gypsum on the supply of S to the plants, maintaining adequate levels during seven sugarcane crops. Studies have shown the increase of leaf S concentrations due to the application of gypsum in sugarcane (Viator et al., 2002), which are associated with the presence of this element in gypsum.
Similar to S, the highest leaf concentrations of Ca in treatments with 5 and 10 t ha^{-1} of gypsum are associated with a greater availability of this nutrient in the soil profile. Calcium is the third most exported macronutrient by sugarcane (Franco et al., 2007). Viator et al. (2002) also verified higher leaf Ca contents for sugarcane submitted to gypsum application due to the greater availability of this nutrient in the soil.
The lowest leaf Mg content was observed under treatment with 10 t ha^{-1} of gypsum in the fourth sugarcane crop compared to the others and fifth crop in relation to the dose of 0.5 t ha^{-1} (Fig. 4c). It may be related to the greater leaching of Mg^{2+} from the surface layer and the higher Ca/Mg ratio of the soil due to application of the greater gypsum dose, resulting in a higher Ca compared to Mg. According to Medeiros et al. (2008), the increase in Ca uptake reduced Mg uptake by corn due to higher Ca/Mg ratios of the soil.
The increase in leaf N levels using 5 and 10 t ha^{-1} of gypsum compared to zero application (Fig. 4d) may be related to the increased root density in the subsurface layers (Figure 3), favoring higher nitrogen fertilizer efficiency (Table 2), because the nitrate presents great mobility in the soil profile. Caires et al. (2016) reported an increase in the efficiency of N use due to the higher uptake of nitrate from the subsoil as a result of the increase in root length of corn after gypsum application. Furthermore, there is synergism in the process of N and S uptake in sugarcane (Franco et al., 2007), with S deficiency reducing N absorption and assimilation by the plants (Prosser et al., 2001).
The soil subsurface layers after application of 5 t ha^{-1} of gypsum (Fig. 2) resulted in greater root growth (Fig. 3) and better nutrient absorption (Figure 4), which justifies the average increase in stalk yield and TRS in seventh sugarcane

Table 1. Chemical characteristics of the soil before correction and fertilization of the experimental area[(1)].

Layer	pH_{H2O}	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	CEC	m[a]	V	OM[b]	$S\text{-}SO_4^{2-}$	P
cm		----------------- $cmol_c\ dm^{-3}$	--------------				---- % ----		$g\ kg^{-1}$		----- $mg\ dm^{-3}$ ----
0 - 20	4.9	1.16	0.19	0.06	0.09	8.6	77	4	2.4	4.4	0.8
20 -40	5.0	0.93	0.27	0.02	0.05	6.9	73	5	1.8	3.4	0.6
40 - 60	5.0	0.61	0.16	0.01	0.03	5.5	75	4	1.4	2.8	0.5

[(1)] According to the methods described in Embrapa (1997), mean values, *n* = 4; [a]Aluminum saturation; [b]Soil organic matter.

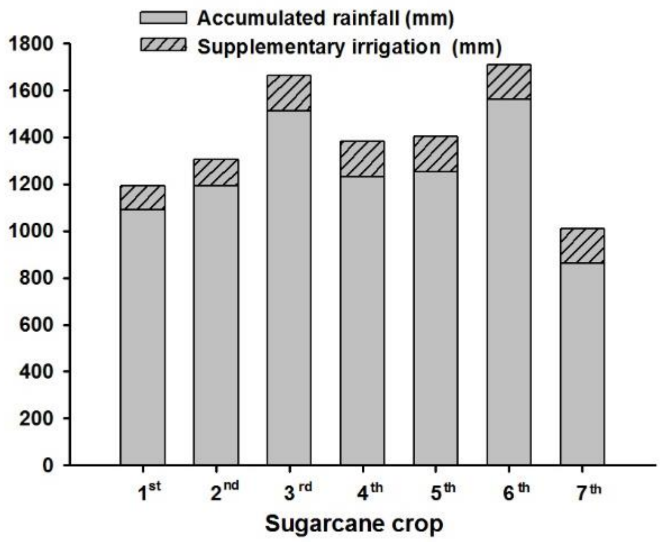

Fig 1. Accumulated rainfall and supplementary irrigation during each sugarcane crop (first, second, third, fourth, fifth, sixth and seventh crops).

crops compared to the doses of 0 and 0.5 t ha^{-1} (Fig. 5).
The responses to gypsum increased over time, with average gains in stalk yields of 19 and 27% from the second to fourth crops and fifth to seventh crops, respectively. The greater increases observed in the second period are probably associated with the exhaustion of sulfate in the soil for the treatment without gypsum and to the deepening of the root system during crop cultivation, as suggested by comparison of the dry mass density of roots in the seventh crop in relation to the first crop (Fig. 3a, b). In addition to the energy and nutrients accumulated in root tissues, which favor better regrowth (Trivelin et al., 2002), the greater quantity and better depth distribution of roots induce better utilization of nutrients such as N, Ca and S to the soil (Figure 4).Considering the average TRS price ($ 0.15 kg^{-1} USD) and the cost for 5 t of gypsum delivered to the property and applied to the soil (USD 310), the gross profit margin resulting from gypsum application (5 t ha^{-1}) was $3,715.00 USD. This evaluation was done by obtaining the difference in the TRS production of seven sugarcane crops under treatments with the recommended gypsum dose and without gypsum application (26.2 t ha^{-1}). Therefore, it was found that over this period each USD 1.00 investment in gypsum yielded a return of USD 12.00.

Materials and methods

Description and management of the experimental area

The experiment was conducted in an experimental area located at Embrapa Cerrados, in Planaltina - DF (15° 36' S latitude, 47° 42' W longitude and elevation of 1014 m). The climate is Cwa according to the Köppen classification (Alvares et al., 2013), with average annual precipitation of 1,500 mm and average annual temperature of 21.3 °C. The original vegetation was considered Cerrado (restricted sense) and the soil classified as dystrophic Red Latosol (Embrapa, 2013), containing 660 g kg^{-1} of clay.
The experimental area had been deforested for about 35 years, kept under spontaneous vegetation with predominance of grasses (*Brachiaria decumbens* and *Andropogon gayanus*). In October 2008, the area was sampled for the determination of the soil chemical attributes that are presented in Table 1.
In February 2009, liming and fertilizer doses were defined according to Sousa and Lobato (2004). The dolomitic limestone was applied at a dose of 7.08 Mg ha^{-1} (100% RTNP) to increase the base saturation by 50% in the 0-40 cm soil layer, incorporated with a harrow, followed by plowing.
For corrective fertilization, magnesium thermophosphate (240 kg ha^{-1} of P_2O_5), potassium chloride (120 kg ha^{-1} of K_2O) and 100 kg ha^{-1} of micronutrients (fritted trace elements - FTE BR 10) were applied and incorporated into the soil.

Table 2. Sources and doses of nutrients (N, K_2O and P_2O_5) used for maintenance fertilization for the third, fourth, fifth, sixth and seventh sugarcane harvests.

Sugarcane harvest	Source	Dose[(1)] – kg ha^{-1} (N, K_2O and P_2O_5)

3^{rd}, 4^{th} and 5^{th}	Ammonium nitrate	120
	Potassium chloride	150
	Monoammonium phosphate	50
6^{th}	Ammonium nitrate	150
	Potassium chloride	200
	Monoammonium phosphate	50
7^{th}	Ammonium nitrate	225
	Potassium chloride	400
	Monoammonium phosphate	50

(1) According to Sousa and Lobato (2004).

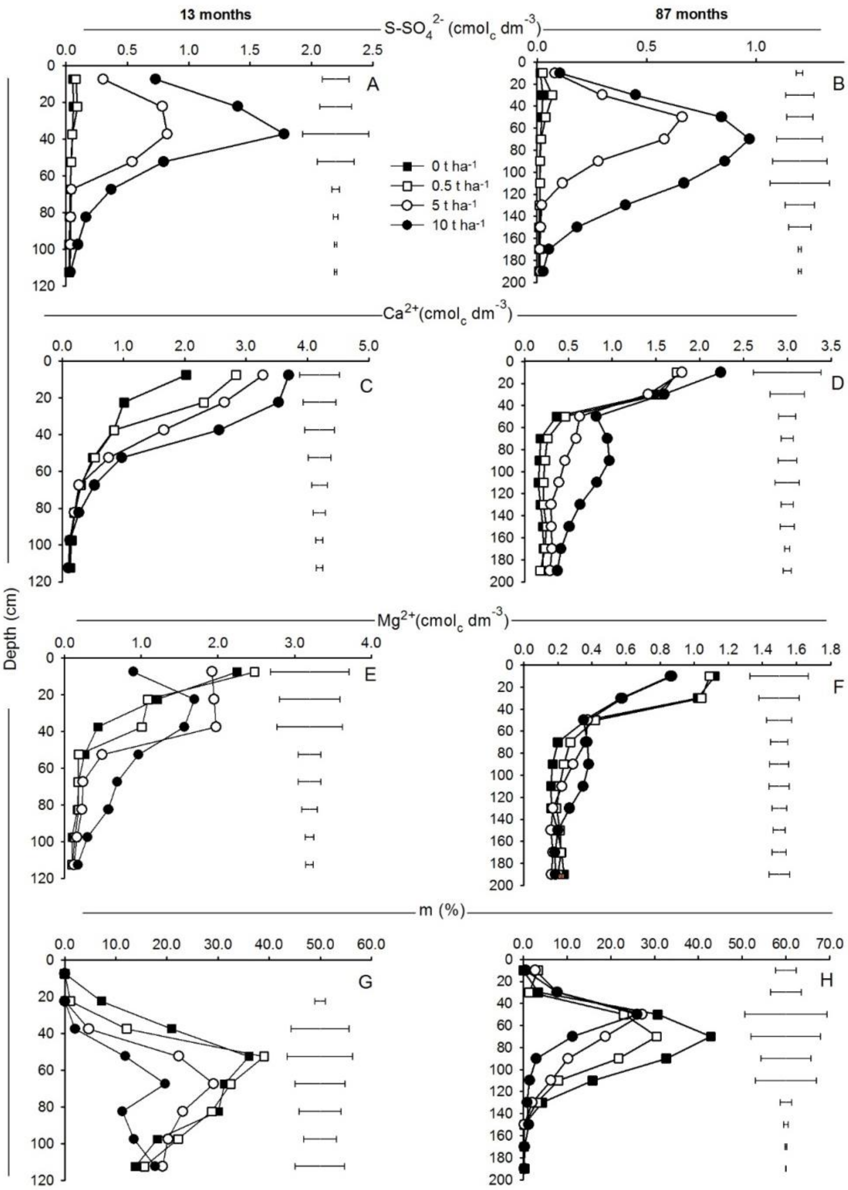

Fig 2. Concentrations of S-SO_4^{2-} (A and B), exchangeable Ca^{2+} (C and D), exchangeable Mg^{2+} (E and F) and aluminum saturation (m%) (G and H) in soil samples at 13 (A, C, E and G) and 87 months (B, D, F and H) after gypsum application at the time of sugarcane planting. Horizontal bars represent the least significant difference by the Tukey test (p≤0.05).

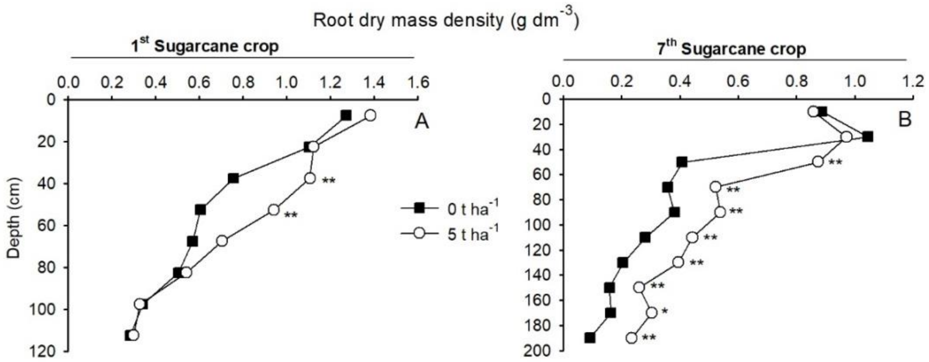

Fig 3. Root dry mass density (g dm^{-3}) after the first (A) and the seventh sugarcane crops (B) in response to the application of gypsum at planting. **, * Significant by the Tukey test p≤0.05 and p≤0.1, respectively.

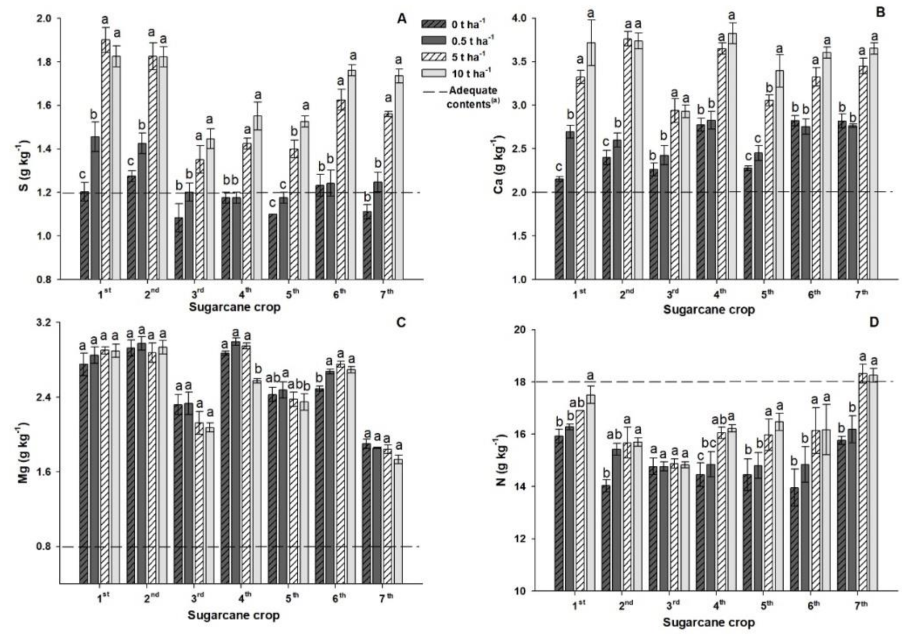

Fig 4. Concentrations of sulfur (A), calcium (B), magnesium (C) and nitrogen (D) in seven sugarcane harvests after the application of gypsum treatments (0, 0.5, 5 and 10 t ha^{-1} of gypsum) at planting. * Means followed by different letters differ significantly by the Tukey test (p≤0.05). Vertical bars represent the standard error of the mean. [(a)] Adequate contents according to Raij et al (1996).

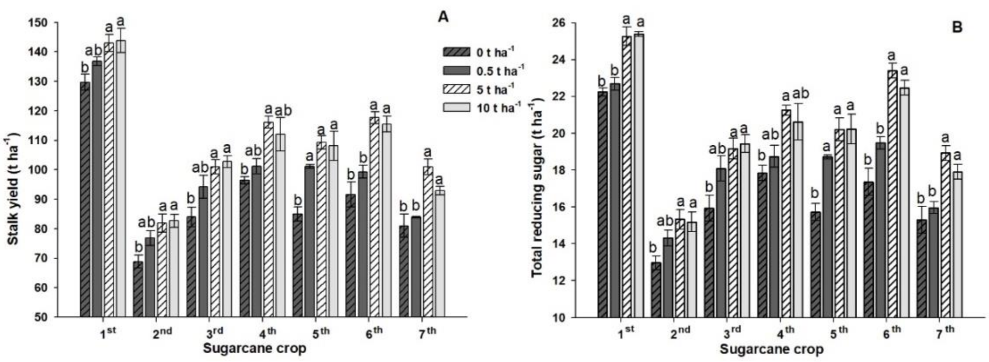

Fig 5. Stalk (A) and total reducing sugar (TRS) (B) yields in seven sugarcane crops, after application of the gypsum treatments (0, 0.5, 5 and 10 t ha^{-1} of gypsum) at planting. * Means followed by different letters differ significantly by the Tukey test (p≤0.05). Vertical bars represent the standard error of the mean.

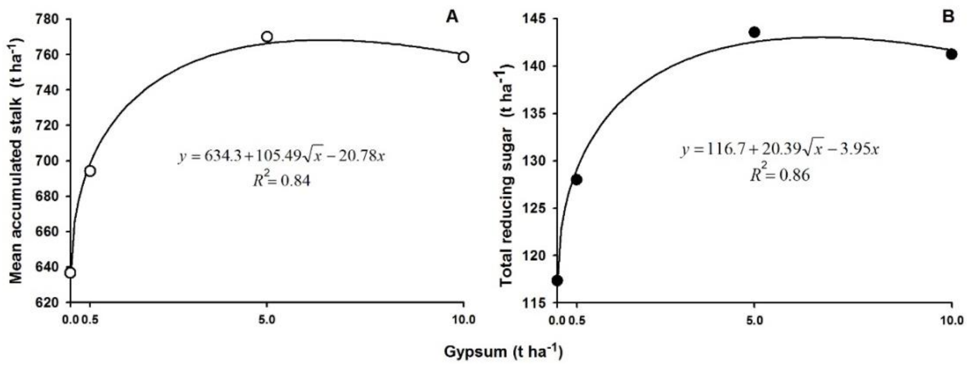

Fig 6. Mean accumulated stalk (A) and total reducing sugar (TRS) (B) yields in seven sugarcane crops, after application of the gypsum treatments (0, 0.5, 5 and 10 t ha^{-1} of gypsum) at planting. Regression equations (and determination coefficients) obtained with data from the four replicates.

Sugarcane characteristics

Sugarcane variety RB867515 was planted in July 2009 during the dry season. The area was plowed at a depth of approximately 40 cm and fertilized in the row with urea (42 kg ha^{-1} of N) and triple superphosphate (183 kg ha^{-1} of P_2O_5). The treatments of agricultural gypsum ($CaSO_4.2H_2O$) were sprayed on the soil surface after sugarcane planting. The gypsum dose was calculated according to the recommendation for perennial crops in the Cerrado region, recommended by Sousa and Lobato (2004), by which the recommended gypsum dose for the soil of this experiment was 5 t ha^{-1}, with treatments 0, 0.1, 1.0 and 2.0 times of the recommended doses. The experimental was setup in a randomized complete block design with 4 replicates. The experimental plots consisted of 60 m^2, including 5 rows, spaced at 1.5 m.

Four sprinkler irrigations (supplemental irrigation) were carried out, each of 25 mm, to ensure bud growth after planting (Fig. 1). In November 2009 coverage fertilization of the sugarcane was performed using urea (60 kg ha^{-1} of N) and potassium chloride (150 kg ha^{-1} of K_2O).

Sugarcane harvesting (first crop) was carried out manually in August 2010 without fire depletion. In order to provide full re-growth of the ratoon, additional irrigation was performed. Therefore, two irrigations of 57 mm were applied, one and two weeks after harvesting (Fig. 1). Fertilization of the first ratoon (second crop) was utilized using ammonium nitrate (120 kg ha^{-1} of N) and potassium chloride (150 kg ha^{-1} of K_2O) in November 2010.

Harvest of the second sugarcane crop was occurred in August 2011. The harvest of the third, fourth, fifth, sixth and seventh crops were conducted in August. The maintenance fertilization is shown in Table 2. Supplementary irrigations were conducted during the first month after each sugarcane crop (Fig. 1), composed of three applications of 50 mm every two weeks, to ensure regrowth.

Sampling and determination of the soil chemical properties

The first soil sampling was carried out in September 2010, one month after harvesting the first sugarcane crop in the treatments receiving 0, 0.5, 5 and 10 t ha^{-1} of gypsum. The soil sampling was done from eight 15 cm layers to a total depth of 120 cm, using the Dutch auger. A composite sampling approach was considered for the working area of each plot, five sub-samples were randomly collected between the rows.

The second soil sampling was performed in September 2016, one month after the seventh sugarcane crop of treatments 0, 0.5, 5 and 10 t ha^{-1} of gypsum, in ten 20 cm layers down to a depth of 200 cm, using the Dutch auger. For each composite sample nine sub-samples were collected, three for each of the 20, 47.5 and 75 cm positions from the planting row. To perform chemical analyses of the soil, the samples were homogenized, air dried and passed through a 2 mm mesh sieve. The determination of the calcium (Ca^{2+}), magnesium (Mg^{2+}), exchangeable aluminum (Al^{3+}), sulfur (S-SO_4^{2-}) and potassium (K^+) contents were carried out as described by Embrapa (1997).

Sampling and determination of the root dry mass density

The first root sampling was conducted in September 2010 under treatments of 0 and 5 t ha^{-1} of gypsum, from eight 15 cm layers to the depth of 120 cm using a Riverside auger, with 10 cm internal diameter. The evaluations were performed by removing two sub-samples at 20 cm from the sugarcane planting row.

The second root sampling was performed in September 2016 under 0 and 5 t ha^{-1} of gypsum treatments, in 10 layers of 20 cm each to the depth of 200, using the same Riverside auger. Three sub-samples were taken at 20 cm from the sugarcane planting row.

The roots were separated from the soil by dispersion in water and gathered on a 0.5 mm mesh sieve and stored in plastic bags for storage in a refrigerator (4 ºC). The roots were then dried in an oven at 65 °C and the root dry matter mass was quantified. Root mass density was calculated by the relationship between the root mass and soil volume sampled at each depth (in g dm^{-3}).

Diagnosis of the nutritional state and stalk yield per total water

The diagnostic leaves were collected during maximum plant development phase at seven sugarcane crops (sixth ratoon), for determination of the macronutrients (S, Ca, Mg, N, P and K) at all gypsum doses (0, 0.5, 5 and 10 t ha^{-1}).

The leaf tissue samples were dried in an oven with forced air circulation (65 °C) and sent to analysis for the macronutrient contents. The Kjeldahl method was used to determine nitrogen. For determination of the other macronutrients (P, K, Ca, Mg and S) digestion was carried out with nitric acid and hydrogen peroxide.

The industrial stalk yield per hectare of the seven sugarcane crops was determined by cutting and weighing stalks from the plot area, which consisted of the 3 central rows measuring 5 m long, after exclusion of 1.5 m at each end of the plot. Sugar contents were determined for samples of ten stalks, expressed as total reducing sugars (TRS) according to Consecana protocols (2006).

Statistical analysis

Results of the soil chemical attributes in each layer, root dry mass density, leaf macronutrient contents, stalk yield and TRS were submitted to analysis of variance (ANOVA) using the F-test. The assumptions of the analysis of variance were verified by the Shapiro-Wilk and Bartlett tests. The ANOVA and regression models were performed using SAS 9.1 software (Statistical Analysis System) and the Tukey test ($p \leq 0.05$) was used to distinguish the means.

Conclusion

The use of gypsum resulted in improvement of the subsoil, expressed in the increase of $S\text{-}SO_4^{2+}$, Ca^{2+} and Mg^{2+} and reduction of aluminum saturation. This effect increases with the gypsum dosage and persists over time with a residual effect of at least 87 months after application. In response to subsoil improvement, the root dry mass density was increased after the first crop, reaching greater depths over time and favoring greater nutrient absorption efficiency, especially N, Ca and S. Higher sugarcane productivity resulted from the residual effect of gypsum with great economic return occurring at the recommended dose for this soil according to the criterion adopted in the region.

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