Improvement in Chemical Attributes of Oxisol Subsoil and Crop Yields under No-Till

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ABSTRACT

The natural chemical qualities of the subsoil of Oxisols often restrict root growth, water use efficiency, and crop yield. The practice of continuous no-till farming creates a fertile topsoil but generally does not affect the subsoil. This study aimed to evaluate the effectiveness of gypsum in improving the chemical attributes of the subsoil and increasing crop yields. To this end, the experiment was conducted at two sites in distrophic Red Oxisols located in southern Brazil. The experimental design was a randomized complete block with three replications. Treatments consisted of broadcast gypsum rates of 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.5 Mg ha^{-1}. Soil samples were collected from the root zone at the beginning of the experiment and after six and 22 mo to evaluate soil pH and extractable P, K$^+$, Ca^{2+}, Mg^{2+}, Al^{3+}, and SO$_4$–S concentrations. After 6 mo of gypsum application, an increase in exchangeable bases associated with a decrease in Al^{3+} concentrations in the subsoil was noted, and this improvement was intensified further by 22 mo. An increase in crop yields was related to the increase in base saturation and Ca^{2+} saturation and a decrease in Al^{3+} saturation in the 25- to 40-cm soil depth. Surface application of gypsum was an effective method of improving the chemical quality of the rooting zone in Oxisols under continuous no-till farming and resulted in a higher impact on corn (*Zea mays* L.) grain yield than soybean [*Glycine max* (L.) Merr.] yield.

In many regions of world, agricultural production is constrained to some degree by soil acidity, which is related to Al^{3+} toxicity and low base saturation (Clark et al., 1997) that can confine the root growth of annual crops to a shallow soil layer (Coleman and Thomas, 1967; Caires et al., 2006; van Raij, 2010). According to Oliveira et al. (2009), the low calcium (Ca^{2+}) saturation associated with high Al^{3+} concentrations in the subsoil are the main impediments to root growth in distrophic Oxisols; poor root growth, in turn, increases the vulnerability of annual crops to water stress and nutritional deficiency (Sá et al., 2010).

The occurrence of acidic and infertile subsoil has been identified as one of the major factors limiting crop yields in tropical soils (Shainberg et al., 1989; Farina et al., 2000a, 2000b). Oxisol is the most extensive soil order used in Brazilian agriculture production and constitutes approximately 30% of cropland (Anjos et al., 2012). Improving the chemical quality of the root zone has become a challenge for tropical farmers (Sumner, 1995; Farina et al., 2000a), especially in environments subject to water scarcity. This situation may be aggravated under continuous no-till (NT) that creates an abrupt gradient of soil quality between the topsoil and subsoil (Farina et al., 2000b; Amado et al., 2007, 2009; Bayer et al., 2011; Caires et al., 2011b), particularly when practices such as crop rotation and the use of cover crops are not adopted.

The use of gypsum, which reduces the subsoil Al^{3+} concentration and increases Ca^{2+} and Mg^{2+} concentrations (Shainberg et al., 1989; van Raij et al., 1998), can be an alternative way of improving the soil quality under conservation tillage (Farina et al., 2000b; Caires et al., 2003, 2011c; Nava et al., 2012). Due to the rapid action of gypsum (Cabrera, 2009), a sharp increase in Ca^{2+} concentrations in the soil solution is expected, causing the displacement of the Al^{3+}, Mg^{2+}, and K$^+$ from the soil exchange complex (Farina et al., 2000a; Favaretto et al., 2008; Souza et al., 2012). This process is intensified under continuous NT, where a chemically enriched topsoil layer (Amado et al., 2009; Dalla Nora et al., 2013) with high nutrient concentrations supplies base cations to the soil solution. Once in solution, these cations are subject to downward movement with drainage water throughout the soil profile; Ca^{2+} and Mg^{2+} are especially affected due to their high propensity to form ion pairs with SO$_4^{2-}$ (Market et al., 1987; Sumner et al., 1986; Sumner, 1995; Caires et al., 2011c). Additionally, gypsum favors the formation of SO$_4$–Al compounds, which are less toxic to plants (Favaretto et al., 2006; Zambrosi et al., 2007), and promotes an increase in base saturation in the subsoil (van Raij, 2010; Caires et al., 2011c), which stimulates deeper root growth.

The beneficial effect of improving the chemical quality of the soil profile on corn yield was reported previously in several studies (Ritchey et al., 1982; Sumner, 1995; Farina et al., 2000a; Caires et al., 2004, 2011c). In addition, Sousa et al. (1996), van Raij et al. (1994), and van Raij (2010) reported increases in soybean yield when the soil was treated with gypsum rates up to 6.0 Mg ha^{-1}; they suggested that the decreased Al^{3+} activity was responsible for the increased soybean yield, especially during periods of water scarcity when a deep root system mitigates the effects of water stress. Caires et al. (2006, 2011b) reported that

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Abbreviations: NT, no-till; SCa, calcium saturation.

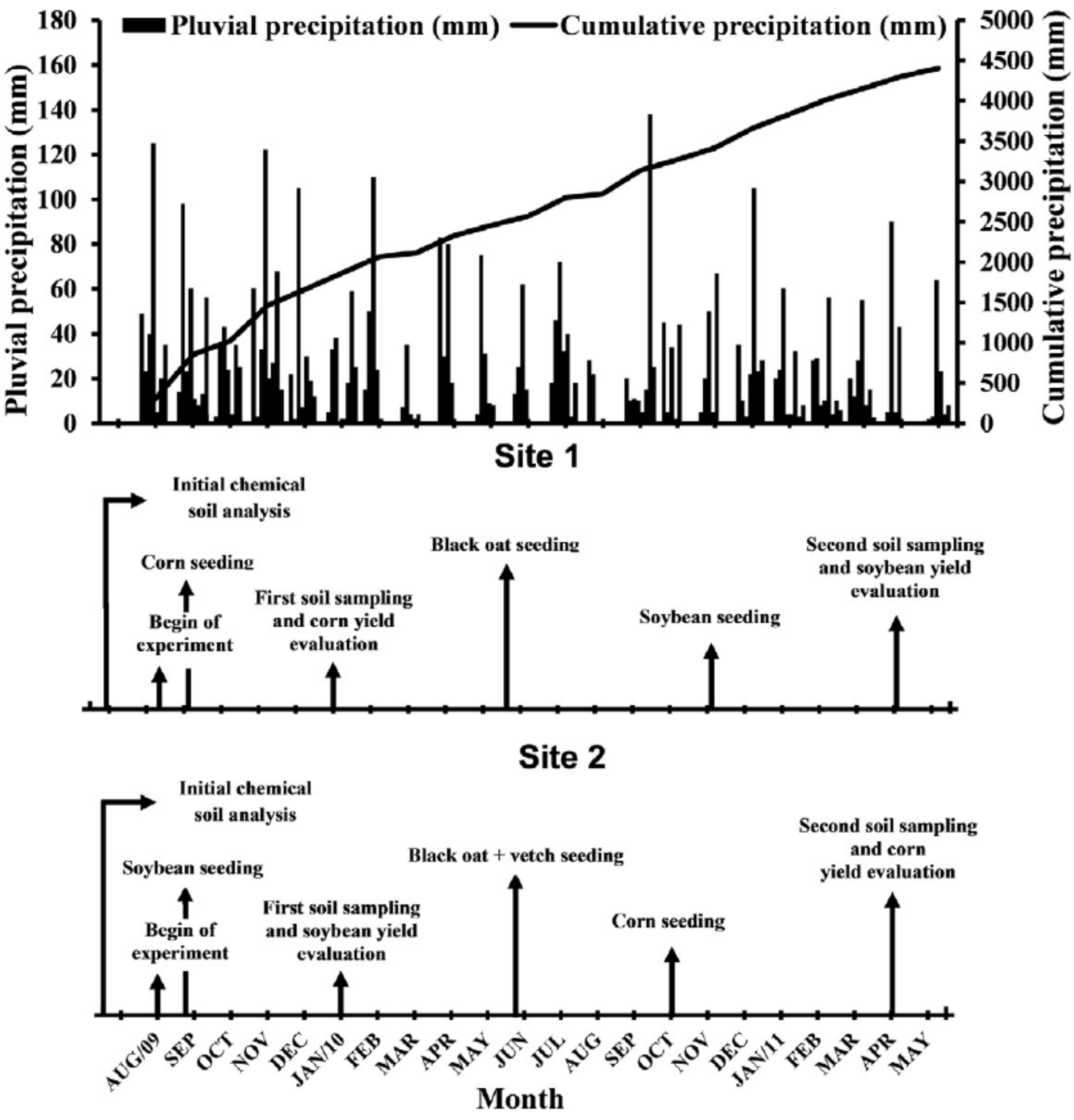


Fig. 1. Daily and cumulative precipitation during the experimental period and main experimental details.

soybean is usually less responsive to gypsum application than wheat (*Triticum aestivum* L.) and corn.

Strategies for improving the quality of the chemical attributes of rooting zones in soils under continuous NT are not yet well established, and few studies have related the soil attributes of subsurface layers with crop grain yield. The hypothesis of our study was that gypsum increases base saturation and decreases Al^{3+} saturation of distrophic Oxisol subsoil managed under long-term NT, resulting in crop grain yield increases. The main objective was to assess the effectiveness of gypsum applied at the soil surface without soil disturbance in promoting the improvement of the chemical quality of the root zone.

MATERIAL AND METHODS

Site Descriptions

The experiment was conducted at two sites in Carazinho, Rio Grande do Sul State, Brazil. The first site is located at 28°19′ S and 52°55′ W, at an altitude of 595 m, while the second site is at 28°17′ S and 52°47′ W at an altitude of 617 m. The soil at both sites is a kaolinitic, typically distrophic Red Oxisol (Typic Hapludox) (Embrapa, 2006), hereafter referred to as an Oxisol. The original vegetation in the region of the experimental sites was composed of Brazilian pine forest or natural pastures formed by grass, predominantly of *Paspalum notatum* Fluegge. The climate in this region is classified as wet subtropical (Cfa) according to Köppen (1938), with an average temperature of 16°C and normal rainfall of 2020 mm. The precipitation at each location was monitored by rain gauges installed 10 m from the experiment. Precipitation during the experimental period is shown in Fig. 1; due to the short distance between sites, the precipitation distribution was practically the same for both sites.

The two experimental sites consisted of annual crops that have been managed under long-term NT (>20 yr) and received close to 2.0 Mg ha^{-1} of limestone with 80% effective $CaCO_3$ equivalent every 4 yr. Both sites were sown to black oat (*Avena strigosa* Schreb) as winter cover crops and were desiccated with glyphosate [*N*-(phosphonomethyl)glycine] and treated with increasing rates of gypsum applied on the soil surface.

At the first site, the experiment began after desiccation of the black oat cover crop; the corn was fertilized with 190 kg ha^{-1} of N (20 kg ha^{-1} N at seeding and 170 kg ha^{-1} N split in two topdressing applications), 120 kg ha^{-1} of P, and 120 kg ha^{-1} of K.

Table 1. Soil chemical attributes before gypsum application at the two Oxisol sites.

Depth	pH (H_2O)	Al	Ca	Mg	K	Ca/Mg	(Ca+Mg)/K	ECEC†	CEC (pH 7.0)‡	P	S	BS§	Al sat.¶	Clay
cm		$\text{mmol}_c\ \text{L}^{-1}$								mg L^{-1}		%		g kg^{-1}
Site 1														
0–10	5.6	0.0	41.3	34.2	3.6	1.2	20.1	104.3	152.3	38.5	6.8	67.8	0.0	410.0
10–20	5.3	3.0	32.2	30.1	1.8	1.1	34.5	84.3	149.4	8.9	5.2	54.2	3.2	500.0
20–40	4.8	8.0	17.1	25.4	0.9	0.7	46.6	62.5	156.3	1.3	6.3	34.1	13.2	570.0
40–60	4.4	9.0	15.0	21.3	0.7	0.7	51.4	56.3	153.2	0.8	5.8	30.8	16.0	620.0
Site 2														
0–10	5.8	0.0	45.2	22.5	3.9	2.0	17.2	72.3	105.2	44.5	15.9	68.2	0.0	260.0
10–20	5.6	0.0	29.3	19.2	3.4	1.5	14.1	53.2	91.4	10.3	9.2	54.3	0.2	350.0
20–40	5.2	4.0	18.1	13.2	2.8	1.4	11.1	38.2	93.2	2.4	9.7	37.2	9.5	480.0
40–60	4.8	12.0	6.1	7.3	1.7	0.8	7.6	27.1	95.3	1.0	7.2	16.4	44.9	520.0

† Effective cation exchange capacity.

‡ Cation exchange capacity at pH 7.0.

§ Base saturation = 100[(Ca + Mg + K)/CEC at pH 7.0].

¶ Al saturation = 100(Al/ECEC).

The source of N was urea, $[CO(NH_2)_2]$ (45% N), the source of P was triple superphosphate, $Ca(H_2PO_4)_2 \times H_2O$ (21% P_2O_5), and the source of K^+ was KCl (60% K_2O). Wheat was grown in the crop rotation sequence and fertilized with 230 kg ha^{-1} of 5–25–25 N–P–K fertilizer and 45 kg ha^{-1} of N topdressed as urea. The wheat was not harvested due to a freeze at flowering stage. In the rotation sequence, the soybean was fertilized with 240 kg ha^{-1} of 2–20–20 N–P–K fertilizer. At the second site, following desiccation of a black oat cover crop, soybean was grown with the same fertilization scheme as at Site 1. In the rotation sequence, a mixture of black oat and oilseed radish (*Raphanus sativus* L.) was grown as a cover crop during the winter and corn was grown in the spring with the same fertilization scheme as for corn at Site 1. The cultivars and hybrids used in this study were Pioneer 3069 corn and Nidera 5909 soybean. The corn was sown at a seeding rate of 7 seeds m^{-1} with a row spacing of 50 cm; soybean was sown at a seeding rate of 12 seeds m^{-1} (inoculated with *Bradyrhizobium japonicum*) with a row spacing of 50 cm. Details of the cropping systems are presented in Fig. 1.

Initial chemical characterization of the soil was performed at the beginning of the experiment at both sites by collecting five random subsamples from depths of 0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm. Soil chemical and physical properties are presented in Table 1.

Experimental Procedures

The experimental design for both sites was a randomized complete block with three replications. Each plot had an area of 64 m^2, with dimensions of 8 by 8 m. The treatments consisted of different gypsum rates of 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.5 Mg ha^{-1}, creating a range of gypsum rates having as an intermediate rate the optimum rate, determined as

$$GR = \text{clay} \times 6.0 \qquad [1]$$

where GR is the gypsum rate (kg ha^{-1}) and clay is the clay content (g kg^{-1}) in the 20- to 40-cm soil layer. All the treatments were applied broadcast to the soil surface after cover crop management in spring 2009 at both sites.

The gypsum ($CaSO_4 \cdot 2H_2O$) was composed of 210.0 g kg^{-1} Ca^{2+}, 155.0 g kg^{-1} SO_4–S, 0.024 g kg^{-1} F^-, and 9.0 g kg^{-1} P; the physical characteristics consisted of a density of 1.17 g kg^{-1} and relative humidity of 6.5%.

Equation [1], reported by Quaggio and van Raij (1996), has been recommended for the application of gypsum in Brazilian tropical soils. This equation is used when the Ca^{2+} concentration in the subsoil (20–40 cm) is <4 mmol_c L^{-1} and when the Al^{3+} saturation is >40% (van Raij, 2010). Other proposed critical values are Ca^{2+} concentrations <5 mmol_c L^{-1} and Al^{3+} saturations >20% (Sousa and Lobato, 2002).

Main Experimental Determinations

The soil was sampled, with three replications to compose one sample per pit, 6 and 22 mo after treatment application at depths of 0 to 5, 5 to 10, 10 to 15, 15 to 25, 25 to 40, and 40 to 60 cm. The soil samples were collected with a spatula from the front side of small pits, manually dug, with dimensions of 30 by 30 by 60 cm. The soil samples were cleaned of roots, air dried, and ground to pass through a 2-mm sieve.

The main soil chemical parameters analyzed were determined according to the standard methods described in Tedesco et al. (1995). The pH was determined in water (1:1 soil/water). Exchangeable Ca^{2+} and Mg^{2+} were extracted with 1.0 mol L^{-1} KCl, followed by determination by atomic absorption spectrophotometry. Phosphorus and K^+ were extracted with Mehlich-I solution. The P content was determined colorimetrically, using molybdenum blue, and K^+ was determined by flame photometry. Aluminum (KCl-exchangeable acidity) was determined by titration with 0.025 mol L^{-1} NaOH solution. Sulfate-sulfur was extracted with $Ca(H_2PO_4)2CH_2O$ and subsequent determination by turbidimetric measurement (Beaton et al., 1968).

When grain crops reached physiological maturity, plant samples were manually collected close to the site of soil sampling for the measurement of yield. Four linear meters of crop row were harvested, totaling 2 m^2 plot^{-1}, and grain yield results were determined. The results were adjusted to a moisture level of 13%.

Statistical Analysis

Results from each site were subjected to analysis of variance (ANOVA) with SAS (SAS Institute, 1985), using a randomized complete block design in a split-split-plot arrangement with three replications. Gypsum rate was the main factor, and soil depth was the subplot factor. The gypsum rates and soil chemical properties in each depth were compared by calculating the least significant difference (LSD) (Tukey's test) with a significance level of $P < 0.05$. Regression analysis was performed between grain yield and individual soil chemical properties (Ca, base, and Al saturations) in the 25- to 40-cm soil layer. Regression analysis was performed with the REG procedure of SAS (SAS Institute, 1985).

RESULTS AND DISCUSSION

Characterization of Chemical Attributes of Soil Profiles before Gypsum Application

The main nutrients added to the soil by gypsum are Ca^{2+}, SO_4–S, and, to a lesser extent, P. To assess the effectiveness of gypsum in improving the soil quality, the chemical characteristics of the soil profiles before treatment application were evaluated; the results are presented in Table 1.

In the 0- to 10-cm soil layer, the chemical attributes of pH, base saturation, and Al^{3+} saturation were similar between the sites (Table 1). Therefore, the topsoil of both sites had chemical attributes that were above the critical limits (pH >5.5, base saturation >65%, Al^{3+} saturation <10%) proposed for South Brazil (Comissão de Química e Fertilidade do Solo, 2004). In contrast, the S concentration was 2.3-fold higher at Site 2 than Site 1. At Site 1, the S concentration was below the critical limit proposed for soybean (10 mg L^{-1}) (Fontes et al., 1982). As a consequence, it was expected that this site would be more responsive to SO_4 inputs than Site 2. In the adjacent soil layer (10–20 cm), the chemical attributes were slightly reduced but still satisfactory for plant nutrition (Table 1). Therefore, the chemical qualities in the 0- to 20-cm soil layer at both sites were similar and adequate for plant growth, except for the S concentration at Site 1.

Decreases in pH, decreases in base saturation, and increases in Al^{3+} saturation were observed in the subsoil (20–40 cm) of both sites, with values below the critical limits cited above. Therefore, as expected, the soil quality was lower in the subsoil than in the topsoil. The P concentrations in the subsoil were only 3.4 and 5.4% of the topsoil concentrations at Sites 1 and 2, respectively. Base saturation in the subsoil was 50.3 and 54.5% of that in the topsoil at Sites 1 and 2, respectively. In the deepest soil layer (40–60 cm), the soil quality was poor at both sites, with significant increases in Al^{3+} saturation and decreases in pH and base saturation (Table 1). High Al^{3+} saturation frequently restricts root growth and crop productivity (Farina et al., 2000a; Alleoni et al., 2005). In addition, the Site 1 had 0.4 units lower pH, 8.3% lower base saturation, and 28.0% higher Al^{3+} saturation than Site 2 in the 20- to 40-cm soil layer. As a consequence, the first site had inferior subsoil chemical quality compared with the second site. In the deepest soil layer (40–60 cm), the second site had poorer chemical quality than the first; however, we expected more roots in the 20- to 40-cm soil layer than in the 40- to 60-cm layer.

The recommended gypsum rate in Brazil is based on Al^{3+} saturation and Ca^{2+} concentrations in the subsoil (Sousa and Lobato, 2002). According to these criteria, neither site required gypsum inputs. At both sites, the levels of exchangeable Ca^{2+} were above the critical level (>4 or 5 $mmol_c$ L^{-1} in the topsoil and subsoil); however, the ratio of Ca^{2+} to Mg^{2+} was below the critical range (Ca/Mg = 3:1) (Munoz Hernandez and Silveira, 1998) throughout the root zone. The narrow Ca/Mg ratio creates conditions where crops have a higher probability of response to Ca^{2+} application.

The P concentrations were above the critical levels in the 0- to 20-cm soil depth. As a result, it is unlikely that the crop would respond to P fertilization. In summary, both NT sites had good topsoil chemical qualities but inferior subsoil qualities, although with exchangeable Ca^{2+} above and Al^{3+} saturation below the critical values. These results show variations from topsoil to subsoil similar to those reported by Amado et al. (2009) under long-term NT conditions in Oxisols.

Changes in Soil Chemical Attributes with Gypsum Application

As expected, there was little change in pH with gypsum application at both sites. Previous studies have also shown only slight pH changes with gypsum application (Pavan et al., 1984; Farina et al., 2000b; Favaretto et al., 2008; Caires et al., 2011c). In our study, the 25- to 40-cm soil layer at Site 1 showed a slight pH increase (0.26) for gypsum rates of 3.0, 4.0, and 5.0 Mg ha^{-1} (Table 2). As increasing pH in an acid soil exponentially decreases exchangeable Al^{3+} (Caires et al., 2008), slight pH changes can cause large differences in plant growth. The increase in subsoil pH can probably be attributed to ligand exchange reactions of Fe- and Al-hydrated oxides with sulfates on the surface of soil particles, which displace the hydroxide and thus promote partial neutralization of acidity (Reeve and Sumner, 1972; Caires et al., 2003).

Regardless of site and soil sampling period, K^+ concentrations throughout the root zone were not affected by the gypsum application (Table 2). Sumner (1995) and Zambrosi et al. (2007) reported low K^+ leaching losses associated with gypsum application, especially in clay soils managed under NT where increases in the soil organic C content and effective cation exchange capacity in the topsoil layer are promoted (Amado et al., 2006; Caires et al., 2002, 2011b).

Gypsum application increased the exchangeable Ca^{2+} concentrations throughout the root zone at both sites (Table 2). Twenty-two months after application of 6.5 Mg ha^{-1} of gypsum, increases in Ca^{2+} concentrations of 44.7 and 76.5% in the 0- to 5-cm soil layer and of 43.7 and 32.3% in the 25- to 40-cm layer were observed at Sites 1 and 2, respectively. At soil depths of 40- to 60-cm, these increments were 25.2 and 35.3%, respectively. Caires et al. (2011c) reported that 30% of the Ca^{2+} derived from gypsum was leached in a subtropical Oxisol to soil layers up to a depth of 60 cm 9 mo after application. These results indicate an important downward movement of Ca^{2+} through the root zone. Rampim et al. (2011) also observed increases in Ca^{2+} concentrations in the 0- to 40-cm soil layer 12 mo after gypsum application at rates up to 5.0 Mg ha^{-1}. The mobility of Ca^{2+} in the root zone is due to the formation of neutral ion pairs with SO_4^{2-} (Dias, 1992). Increases in exchangeable Ca^{2+} concentrations in Oxisols due to gypsum application were also reported by Quaggio et al. (1993), Oliveira and Pavan (1996), Soratto and Crusciol (2008), and Caires et al. (2003, 2011c).

At both sites, with the exception of the 40- to 60-cm soil layer where increases in Mg^{2+} concentrations were observed, Mg^{2+} concentrations in the treated soils changed little 22 mo after gypsum application (Table 2). The increased Mg^{2+} concentrations

Table 2. Soil chemical attributes after 22 mo of gypsum application in two sites under Oxisol.

Gypsum rate	Site 1							Site 2						
	pH	K	Ca	Mg	Al	P	S	pH	K	Ca	Mg	Al	P	S
Mg ha^{-1}		mmol$_c$ L^{-1}				mg L^{-1}			mmol$_c$ L^{-1}				mg L^{-1}	
0.0–0.05-m depth														
0.0	5.4 (0.1)†	5.5 (0.9)	71.3 (1.4)	41.3 (1.1)	0.0 (0.0)	43.07 (9.3)	6.73 (1.0)	5.8 (0.1)	4.4 (0.4)	49.0 (2.7)	21.6 (3.5)	0.0 (0.0)	45.36 (4.2)	16.91 (4.6)
1.0	5.4 (0.2)	4.7 (0.7)	76.8 (1.7)	35.1 (2.2)	0.0 (0.0)	41.62 (6.6)	8.59 (4.4)	5.9 (0.1)	4.4 (0.1)	76.6 (4.4)	20.1 (3.5)	0.0 (0.0)	53.96 (4.1)	19.33 (4.1)
2.0	5.6 (0.1)	5.9 (0.3)	86.0 (2.6)	34.5 (2.1)	0.0 (0.0)	48.86 (5.5)	7.78 (1.3)	6.1 (0.1)	4.5 (0.5)	73.8 (0.9)	23.6 (1.3)	0.0 (0.0)	52.37 (9.8)	23.98 (2.4)
3.0	5.5 (0.1)	4.5 (0.8)	100.6 (5.6)	35.9 (1.2)	0.0 (0.0)	52.80 (5.2)	9.13 (3.3)	5.9 (0.2)	5.2 (0.8)	75.8 (8.1)	18.6 (0.8)	0.0 (0.0)	54.95 (3.1)	23.36 (5.8)
4.0	5.5 (0.2)	4.3 (0.9)	104.0 (8.7)	31.6 (1.2)	0.0 (0.0)	46.83 (8.7)	11.42 (1.1)	5.7 (0.1)	5.2 (0.5)	73.9 (3.0)	18.8 (2.3)	0.0 (0.0)	48.34 (6.1)	21.41 (3.3)
5.0	5.8 (0.1)	5.4 (0.2)	101.9 (5.8)	34.0 (1.2)	0.0 (0.0)	51.97 (2.7)	10.90 (2.3)	6.0 (0.2)	4.4 (0.8)	83.0 (7.1)	21.1 (2.2)	0.0 (0.0)	55.61 (3.2)	25.97 (0.9)
6.5	5.5 (0.1)	4.5 (0.9)	103.2 (3.0)	32.0 (1.2)	0.0 (0.0)	53.08 (1.2)	11.63 (0.8)	5.9 (0.1)	4.9 (0.6)	86.5 (3.4)	18.5 (1.9)	0.0 (0.0)	54.80 (2.2)	23.36 (5.3)
0.5–0.10-m depth														
0.0	5.6 (0.1)	3.7 (0.4)	66.6 (4.9)	39.1 (1.4)	0.0 (0.0)	33.13 (5.4)	5.43 (1.1)	5.9 (0.1)	3.7 (0.2)	46.0 (1.9)	21.8 (1.0)	0.0 (0.0)	28.62 (9.3)	14.50 (1.0)
1.0	5.6 (0.2)	2.9 (0.3)	76.4 (2.5)	33.5 (2.1)	0.0 (0.0)	27.86 (3.6)	4.70 (0.6)	6.0 (0.1)	3.5 (0.1)	69.0 (8.1)	22.3 (2.4)	0.3 (0.2)	31.55 (8.3)	14.50 (2.4)
2.0	5.5 (0.1)	3.2 (0.5)	77.3 (3.3)	36.0 (1.2)	0.0 (0.0)	29.00 (2.3)	7.47 (1.3)	6.0 (0.2)	3.0 (0.5)	57.3 (3.9)	24.7 (0.5)	0.0 (0.0)	24.67 (6.3)	16.84 (0.9)
3.0	5.5 (0.1)	2.7 (0.6)	84.6 (9.5)	38.9 (1.2)	0.0 (0.0)	29.42 (3.0)	10.82 (2.4)	5.9 (0.1)	3.7 (1.1)	73.9 (5.3)	17.4 (0.3)	0.0 (0.0)	35.10 (7.1)	19.46 (3.3)
4.0	5.5 (0.3)	2.5 (1.4)	91.4 (9.9)	38.9 (1.2)	0.0 (0.0)	43.55 (2.3)	14.38 (4.5)	5.8 (0.2)	4.0 (1.2)	66.7 (9.1)	22.0 (1.2)	0.3 (0.2)	35.21 (4.9)	23.36 (5.8)
5.0	5.7 (0.1)	3.6 (1.0)	92.8 (3.1)	30.6 (1.2)	0.0 (0.0)	42.50 (2.6)	11.37 (2.6)	5.9 (0.2)	3.0 (0.6)	69.3 (10.1)	21.5 (2.7)	0.0(0.0)	36.62 (1.2)	24.50 (4.0)
6.5	5.5 (0.1)	3.5 (0.6)	92.6 (9.7)	30.7 (0.5)	0.0 (0.0)	42.98 (2.7)	13.16 (0.8)	5.9 (0.1)	3.3 (0.1)	75.0 (9.4)	17.1 (2.8)	0.0 (0.0)	33.27 (9.2)	21.41 (4.3)
0.10–0.15-m depth														
0.0	5.4 (0.1)	2.7 (0.2)	60.1 (3.5)	37.2 (2.3)	1.1 (0.5)	10.53 (2.5)	4.75 (0.7)	5.9 (0.2)	3.2 (0.5)	42.5 (2.5)	21.9 (2.0)	0.0 (0.0)	10.13 (1.8)	10.47 (3.6)
1.0	5.3 (0.2)	1.6 (0.2)	63.4 (5.3)	31.0 (3.1)	1.3 (0.6)	18.28 (2.3)	5.23 (1.3)	6.1 (0.2)	2.7 (0.2)	56.5 (5.0)	24.5 (1.7)	0.0 (0.0)	12.40 (3.2)	11.27 (1.4)
2.0	5.4 (0.1)	1.8 (0.4)	69.7 (6.1)	34.9 (3.1)	0.7 (0.3)	9.39 (3.1)	7.66 (0.5)	5.9 (0.1)	2.2 (0.1)	50.5 (1.1)	24.1 (1.6)	0.0 (0.0)	12.48 (5.0)	20.12 (2.8)
3.0	5.5 (0.1)	1.7 (0.4)	71.1 (9.9)	32.4 (1.2)	0.4 (0.3)	20.89 (2.8)	10.45 (2.1)	5.9 (0.2)	3.2 (0.7)	62.6 (7.8)	19.6 (3.0)	0.0 (0.0)	12.24 (1.9)	32.26 (2.9)
4.0	5.4 (0.2)	1.9 (0.6)	79.2 (9.6)	37.6 (1.2)	0.7 (0.5)	22.31 (2.3)	15.63 (2.0)	5.8 (0.1)	3.3 (0.9)	56.4 (1.5)	22.0 (1.6)	0.0 (0.0)	11.37 (3.2)	32.45 (1.8)
5.0	5.3 (0.2)	2.5 (0.7)	71.8 (9.8)	37.8 (2.2)	0.3 (0.1)	17.97 (1.3)	14.20 (3.9)	5.8 (0.2)	2.1 (0.1)	57.4 (3.9)	23.4 (1.4)	0.0 (0.0)	19.43 (1.0)	35.62 (5.1)
6.5	5.4 (0.1)	1.5 (0.5)	74.8 (4.5)	30.5 (2.2)	0.7 (0.3)	13.86 (1.2)	15.63 (3.1)	5.7 (0.1)	2.4 (0.2)	61.0 (5.7)	20.7 (2.7)	0.0 (0.0)	11.08 (3.2)	36.10 (4.1)
0.15–0.25-m depth														
0.0	5.2 (0.1)	1.5 (0.2)	48.3 (1.9)	30.1 (1.2)	3.3 (0.7)	3.20 (1.1)	6.45 (1.5)	5.8 (0.3)	2.7 (0.2)	36.4 (2.4)	19.9 (3.8)	0.0 (0.0)	4.21 (0.7)	8.05 (1.4)
1.0	5.2 (0.3)	1.3 (0.1)	50.6 (7.8)	33.1 (3.2)	3.6 (1.4)	6.62 (3.4)	4.82 (1.0)	6.0 (0.2)	2.5 (0.4)	49.2 (2.3)	23.0 (0.9)	0.0 (0.0)	6.26 (1.2)	12.08 (1.2)
2.0	5.2 (0.1)	1.3 (0.2)	55.5 (9.8)	36.2 (2.1)	2.0 (1.6)	5.99 (0.8)	7.77 (2.1)	5.9 (0.1)	1.8 (0.4)	49.6 (2.3)	25.2 (1.8)	0.0 (0.0)	6.87 (1.7)	21.52 (3.1)
3.0	5.3 (0.1)	1.2 (0.1)	60.8 (6.2)	32.7 (1.2)	1.0 (0.6)	6.20 (0.8)	10.11 (1.2)	5.8 (0.2)	3.1 (0.3)	4.89 (6.3)	21.0 (0.6)	0.0 (0.0)	5.58 (1.2)	28.37 (5.1)
4.0	5.2 (0.2)	1.7 (0.9)	57.8 (4.4)	35.8 (1.2)	2.8 (1.2)	6.37 (0.2)	16.01 (2.3)	5.7 (0.2)	2.9 (0.3)	50.0 (3.3)	24.2 (1.4)	0.0 (0.0)	6.47 (2.1)	32.26 (2.4)
5.0	5.2 (0.2)	1.6 (0.9)	59.8 (7.9)	32.1 (2.2)	2.8 (1.4)	8.09 (1.7)	15.49 (2.6)	5.7 (0.1)	2.0 (0.3)	52.6 (1.6)	24.5 (0.6)	0.0 (0.0)	6.62 (2.3)	36.98 (5.9)
6.5	5.1 (0.2)	1.2 (0.4)	60.8 (2.3)	31.2 (1.2)	3.3 (1.3)	6.18 (0.6)	15.96 (1.8)	5.7 (0.2)	1.9 (0.3)	53.7 (8.3)	24.4 (2.9)	0.0 (0.0)	7.13 (2.3)	31.14 (3.3)
0.25–0.40-m depth														
0.0	4.7 (0.1)	0.9 (0.3)	29.8 (1.4)	21.6 (1.1)	12.2 (1.5)	2.89 (0.3)	6.35 (2.8)	5.3 (0.1)	2.3 (0.1)	17.3 (3.7)	29.6 (4.2)	4.3 (1.0)	3.18 (0.3)	9.66 (2.4)
1.0	4.8 (0.2)	0.7 (0.1)	31.3 (1.3)	25.8 (1.3)	10.8 (2.9)	2.07 (0.1)	9.74 (3.1)	5.5 (0.1)	2.0 (0.3)	20.2 (0.9)	25.8 (0.9)	3.3 (0.3)	3.18 (0.3)	8.86 (1.4)
2.0	4.8 (0.1)	1.0 (0.2)	41.3 (2.8)	31.0 (2.1)	6.3 (2.1)	3.43 (0.7)	10.73 (3.9)	5.5 (0.1)	1.6 (0.5)	21.2 (1.7)	31.0 (0.7)	1.0 (0.3)	3.68 (1.2)	20.74 (4.1)
3.0	5.0 (0.1)	1.0 (0.7)	41.7 (7.0)	36.2 (1.7)	5.3 (1.8)	4.53 (0.4)	15.05 (4.1)	5.7 (0.2)	2.6 (1.2)	22.9 (3.5)	36.2 (2.1)	0.8 (0.3)	4.10 (0.2)	25.30 (3.3)
4.0	5.0 (0.1)	1.1 (0.4)	42.7 (3.0)	34.8 (1.2)	5.2 (2.2)	2.77 (0.4)	16.04 (3.8)	5.5 (0.1)	1.9 (0.5)	20.0 (1.8)	34.7 (0.7)	0.8 (0.1)	5.06 (1.1)	30.32 (0.9)
5.0	5.0 (0.1)	0.9 (0.2)	52.3 (4.7)	34.6 (2.2)	5.2 (1.0)	4.38 (0.4)	19.33 (1.5)	5.5 (0.1)	1.7 (0.1)	24.2 (1.0)	34.6 (1.2)	0.5 (0.1)	4.10 (0.5)	30.14 (6.9)
6.5	4.8 (0.1)	0.9 (0.2)	51.9 (0.9)	29.2 (2.3)	7.8 (1.7)	4.66 (0.9)	21.53 (2.3)	5.4 (0.1)	1.4 (0.5)	25.4 (2.4)	33.2 (1.0)	1.0 (0.3)	5.27 (0.9)	31.58 (2.4)
0.40–0.60-m depth														
0.0	4.6 (0.1)	0.6 (0.1)	27.4 (2.6)	21.6 (1.0)	12.7 (1.5)	1.67 (0.2)	4.86 (0.9)	5.1 (0.2)	1.5 (0.6)	12.6 (3.7)	26.6 (1.6)	13.3 (0.5)	2.98 (0.6)	7.25 (2.4)
1.0	4.8 (0.2)	0.7 (0.3)	29.5 (2.3)	24.7 (3.6)	11.5 (2.5)	1.07 (0.3)	10.78 (3.8)	5.3 (0.2)	1.6 (0.8)	17.0 (4.1)	24.7 (3.3)	11.6 (2.0)	3.49 (0.8)	8.05 (1.4)
2.0	4.8 (0.1)	1.0 (0.5)	27.0 (1.7)	29.8 (3.7)	8.0 (0.7)	2.53 (0.2)	15.62 (3.1)	5.1 (0.2)	1.3 (0.7)	16.5 (3.2)	29.8 (4.1)	9.6 (1.8.)	3.12 (1.3)	15.70 (3.1)
3.0	4.8 (0.2)	0.7 (0.1)	29.3 (3.7)	30.9 (1.2)	7.8 (2.4)	2.37 (0.3)	20.28 (5.3)	5.0 (0.2)	1.7 (0.7)	15.2 (4.1)	30.9 (3.7)	9.1 (0.4)	3.08 (0.8)	27.25 (3.4)
4.0	4.8 (0.1)	0.7 (0.2)	34.0 (1.2)	34.2 (2.2)	7.3 (2.1)	2.17 (0.3)	24.81 (1.6)	5.0 (0.2)	1.5 (0.4)	14.6 (3.1)	34.2 (2.0)	10.3 (1.0)	4.55 (1.1)	31.14 (3.4)
5.0	4.8 (0.1)	0.6 (0.1)	33.5 (4.5)	34.4 (1.7)	5.6 (1.1)	1.57 (0.2)	27.56 (0.7)	5.1 (0.2)	1.2 (0.2)	19.5 (3.9)	30.4 (2.6)	11.1 (3.0)	3.98 (0.8)	33.09 (4.1)
6.5	4.7 (0.1)	0.6 (0.1)	36.3 (3.2)	34.4 (2.1)	9.2 (0.8)	2.52 (0.4)	28.36 (1.9)	5.1 (0.2)	1.0 (0.2)	19.4 (4.8)	32.4 (3.7)	11.6 (1.0)	4.32 (1.1)	35.04 (7.2)

† ± Standard deviation in parentheses.

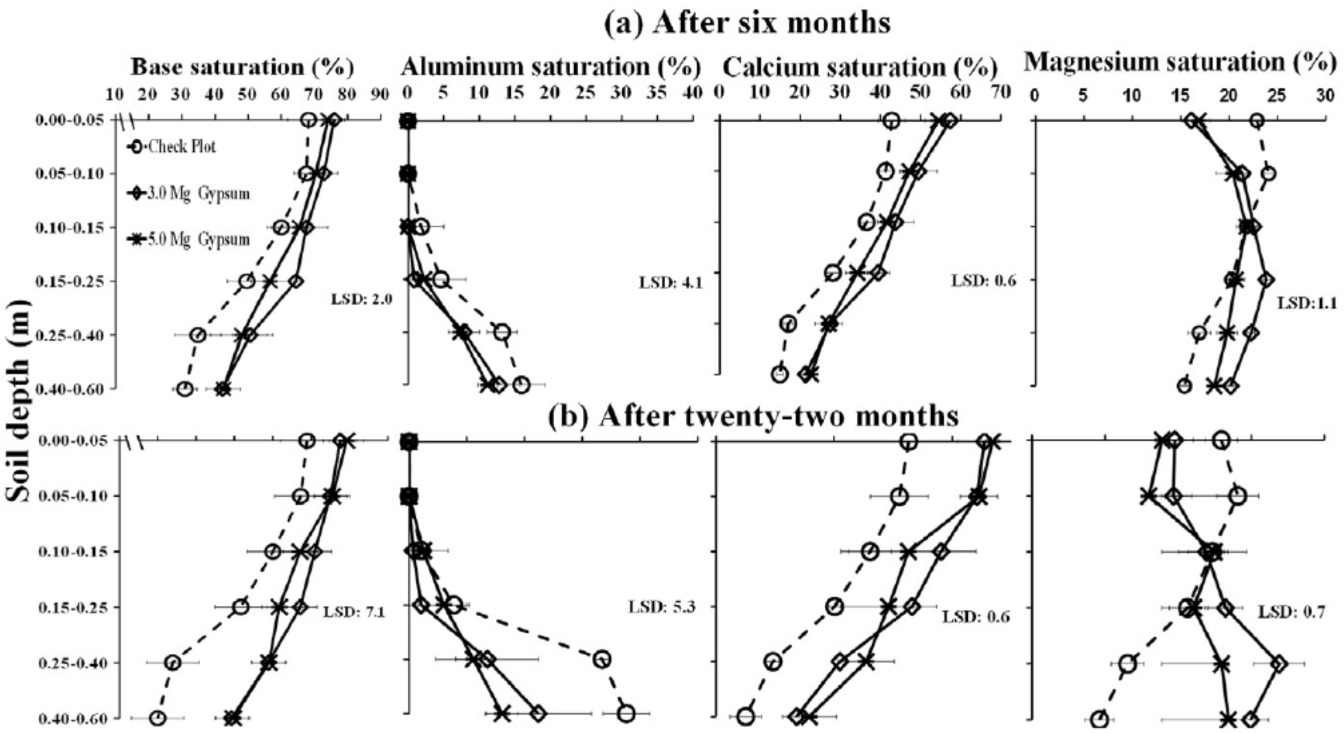


Fig. 2. Base saturation, Al saturation, Ca saturation, and Mg saturation as affected by gypsum applications of 0, 3.0, or 5.0 Mg ha^{-1} after (a) 6 and (b) 22 mo after application at Site 1; LSD by Tukey's test ($P < 0.05$).

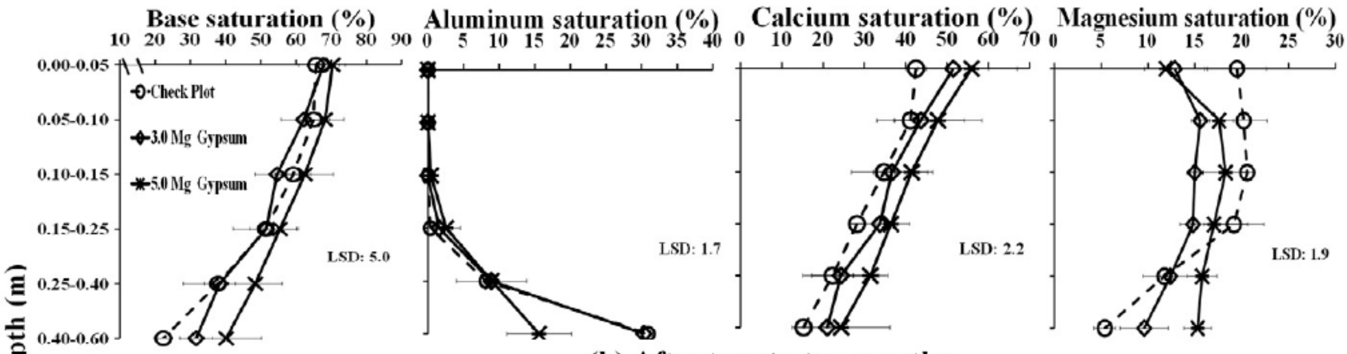
in the subsoil occurred at the expense of a decrease in the topsoil. Caires et al. (2011c) also reported that gypsum promotes the decrease of Mg^{2+} concentrations in surface soil layers and an increase in deeper layers. Farina et al. (2000b) and Zambrosi et al. (2007) attributed the increase in Mg^{2+} concentrations in the subsoil to the formation of Mg sulfate compounds over other forms of ionic SO_4^{2-}. The redistribution of Mg^{2+} throughout the root zone with gypsum application has been extensively reported in the literature (Syed-Omar and Sumner, 1991; Farina et al., 2000b; Soratto and Crusciol, 2008). Caires et al. (2011a) found that as much as 72% of exchangeable Mg^{2+} in the 0- to 20-cm soil layer moved downward after 27 mo. Shainberg et al. (1989) suggested that the decrease in Mg^{2+} concentrations in the topsoil layer may lead to plant Mg^{2+} deficiency. In our study, however, regardless of treatment, all soil layers sampled had Mg^{2+} concentrations above the critical limit (10 mmol$_c$ L^{-1}) throughout the experimental period (Table 2).

Exchangeable Al^{3+} concentrations in the subsoil were decreased by gypsum surface applications >2.0 Mg ha^{-1} (Table 2). At Site 1, where the subsoil acidity was higher in the 25- to 40-cm soil layer (Table 1), 5.0 Mg ha^{-1} of gypsum decreased the exchangeable Al^{3+} by 57.6%; at Site 2, this decrease was even more impressive, with Al^{3+} decreases of 88.1% (Table 2). Zambrosi et al. (2007) and Rampim et al. (2011) also reported a decrease in exchangeable Al^{3+} concentrations with gypsum application in Oxisols of southern Brazil. The decrease in the subsoil Al^{3+} concentration is the result of an ion exchange whereby Ca^{2+} displaces Al^{3+} from the soil exchange complex to the soil solution, where it is temporarily immobilized by SO_4^{2-} (Pavan et al., 1984; Soratto and Crusciol, 2008) and soil organic C (Zambrosi et al., 2007).

In our study, surface application of gypsum induced incremental changes in P concentrations throughout the root zone (Table 2). In the 25- to 40-cm soil layer, the highest rate of gypsum produced increases of 61.2 and 65.7% in P concentrations at Sites 1 and 2, respectively. In the 15- to 25-cm soil layer, the incremental changes were even greater, with P concentration increases of 93.1 and 69.3% at Sites 1 and 2, respectively. This increase in subsoil P concentration could be related to better development of the root system, to improvement in subsoil chemical quality expressed by the decrease in Al activity and increase in Ca^{2+}, or to the increase in water infiltration due to improvement in soil aggregation. In the present study, it was not possible to isolate the causes of this process. In contrast, Caires et al. (2011c) found only slight changes in subsoil P concentrations with gypsum application. The redistribution of P throughout the soil profile, which is important to stimulate root growth, is a challenge under continuous NT with surface or shallow P fertilization as regularly used in Brazil (Crusciol et al., 2005). The role of gypsum in promoting the redistribution of P in the root zone should be investigated in future studies.

The increase in SO_4–S concentrations in the gypsum-treated soils were, as expected, consistent throughout the entire root zone, with greater increases in the deeper soil layers and under higher rates of gypsum application (Table 2). Thus, at both sites, the highest rate of gypsum application (6.5 Mg ha^{-1}) resulted in a 72.8 and 38.1% increase in SO_4–S concentration in the 0- to 5-cm soil depth for Sites 1 and 2, respectively (Table 2). In the 25- to 40-cm layer, the SO_4–S concentration increased 239 and 235%, respectively. In the deepest soil layer (40–60 cm), this increase reached 583.2 and 483.3% for Sites 1 and 2, respectively. Farina et al. (2000b) reported that 10 Mg ha^{-1} of gypsum resulted in increases in SO_4–S concentration at depths of up to 0.90 m. Rampim et al. (2011) reported similar results in a clayey Oxisol (730 g kg^{-1}), with increases in SO_4–S concentrations at depths of up to 40 cm 6 mo after the application of 5.0 Mg ha^{-1}

(a) After six months



(b) After twenty-two months

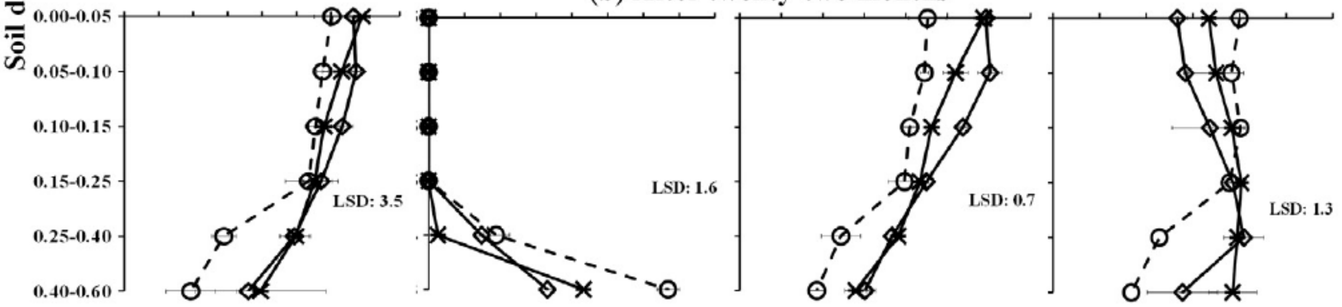


Fig. 3. Base saturation, Al saturation, Ca saturation, and Mg saturation as affected by gypsum applications of 0, 3.0, or 5.0 Mg ha^{-1} after (a) 6 and (b) 22 mo after application at Site 2; LSD by Tukey's test ($P < 0.05$).

of gypsum. In addition, Caires et al. (2011a) found that the application of 6.0 Mg ha^{-1} increased the SO_4–S concentrations at depths of 20- to 40- and 40- to 60-cm.

The Ca/Mg relation should be in the range of 3:1 (Munoz Hernandez and Silveira, 1998). At the beginning of the experiment, this relation was lower in the root zone at both sites (Table 1). Twenty-two months after the gypsum application, there was an improvement in the Ca/Mg ratio in the topsoil layers at both sites, although at the second site, the ratio was below the critical limit in the subsoil layers (25–40 and 40–60 cm) due to the increase in the Mg^{2+} concentration (Table 2).

In summary, gypsum application in distrophic Oxisols altered neither the pH nor the exchangeable K^+ concentrations throughout the root zone. In the subsoil, however, moderate increases in Mg^{2+} and P concentrations, large increases in SO_4–S and Ca^{2+} concentrations, and a strong decrease in Al^{3+} concentrations were observed. As expected, increases in Ca^{2+} and SO_4–S concentrations were observed in the topsoil layer at both sites.

Temporal Changes in Base, Calcium, and Aluminum Saturations in Oxisols Treated with Gypsum

To facilitate the visualization of the temporal effect of gypsum in increasing the base saturation and decreasing the Al^{3+} saturation throughout the root zone, three treatments were selected (Fig. 2 and 3). Given the clay content in Site 1 (570 g kg^{-1} in the 20–40-cm soil layer), the recommended gypsum application rate was 3.4 Mg ha^{-1}; for Site 2 (480 g kg^{-1} clay), the recommended rate was 2.9 Mg ha^{-1}. Therefore, for the visualization process, we selected an average rate of 3.0 Mg ha^{-1} as the recommended rate for both sites, a rate of 5.0 Mg ha^{-1} for its economic feasibility compared with the highest rate tested, and a control treatment (Fig. 2 and 3).

At both sites, the application of gypsum promoted a gradual increase in base saturation throughout the root zone, with a significant increase in the deeper soil layers (Fig. 2 and 3). Six months after the application of 5.0 Mg ha^{-1} of gypsum, increases in base saturation of 8.5 (Fig. 2a) and 7.2% (Fig. 3b) in the 0- to 5- and 25- to 40-cm soil layers and 37.8 (Fig. 2a) and 22.7% (Fig. 3b) for the same depths were observed at Sites 1 and 2, respectively. At 22 mo, these increases for the same soil depths reached 14.9 (Fig. 2a) and 12.5% (Fig. 3b) and 43.5 (Fig. 2b) and 35.6% (Fig. 3b) for Sites 1 and 2, respectively. These results are in agreement with those of Soratto and Crusciol (2008) and Ravazzi (2009).

The accumulated rainfall of 1898 and 4440 mm at 6 and 22 mo, respectively (Fig. 1), contributed to the downward movement of SO_4–S through the soil profile, increasing the exchangeable bases and decreasing Al^{3+} concentrations (Table 2), resulting in a decrease of Al^{3+} saturation in the subsoil (Fig. 2 and 3). Dalla Nora et al. (2013) reported that Ca^{2+} and Mg^{2+} concentrations in the Oxisol acid subsoil were related to downward movement of SO_4–S. Thus, 6 mo after application of 5.0 Mg ha^{-1}, a decrease of 44.5 (Fig. 2a) and 16.0% (Fig. 3a) in Al^{3+} saturation was observed in the 25- to 40-cm soil layer at Sites 1 and 2, respectively. Similar results were noted for the 3.0 Mg ha^{-1} treatment. After 22 mo, these decreases reached 67.5 (Fig. 2b) and 79.8% (Fig. 3b) for Sites 1 and 2, respectively, for the 5.0 Mg ha^{-1} treatment rate. In a study under a distrophic Oxisol, Soratto and Crusciol (2008) also showed that 12 mo of treatment with 5.0 Mg ha^{-1} of gypsum decreased the Al^{3+} concentration at soil depths up to 60 cm. As shown in Fig. 2 and 3, the treatment with 5.0 Mg ha^{-1} of gypsum decreased the Al^{3+} saturation in the subsoil more than the 3.0 Mg ha^{-1} treatment.

The Ca^{2+} saturation (SCa) was one of the chemical attributes that was most influenced throughout the root zone by the gypsum application (Fig. 2). At Site 1, SCa was increased by 27.1% at 6 mo and 42.9% at 22 mo in the 0- to 5-cm soil layer and by 35.8% at 6 mo and 80.5% at 22 mo in the 25- to 40-cm layer with a treatment rate of 5.0 Mg ha^{-1} (Fig. 2). For the 3.0 Mg ha^{-1} treatment, these increases were 34.1 and 41.1% in the 0- to 5-cm layer and 35.8 and 36.6% in the 25- to 40-cm soil layer, respectively. At Site 2, for the 5.0 Mg ha^{-1} treatment these increases were 31.3 and 29.8% in the 0- to 5-cm layer and 29.4 and 36.1% in the 25- to 40-cm soil layer at 6 and 22 mo, respectively (Fig. 3). For the 3.0 Mg ha^{-1} treatment, these increases were 21.2 and 29.9% in the 0- to 5-cm layer and 8.3 and 33.7% in the 25- to 40-cm soil layer at 6 and 22 mo, respectively (Fig. 3).

In agreement with the findings of Caires et al. (2011a), the increase in Mg^{2+} saturation (SMg) in the subsurface soil layers occurred at the expense of a decrease in the topsoil layer. Therefore, the gypsum application resulted in a more uniform distribution of SMg throughout the root zone at both sites (Fig. 2 and 3). For the 5.0 Mg ha^{-1} treatment rate, the SMg in the 0- to 5-cm soil layer decreased 35.5 and 37.7% at 6 mo and 21.4 and 19.6% at 22 mo at Sites 1 and 2, respectively. Both sites showed increases of approximately 20.2 and 27.4% in the 25- to 40-cm soil depth at 6 and 22 mo, respectively (Fig. 2 and 3).

The increases in base saturation, SCa, and SMg and the decrease in Al^{3+} saturation (Fig. 2 and 3) in the subsoil create an environment favorable for root growth and, consequently, for the crop use of soil water (Farina et al., 2000a, 2000b; Silva et al., 2006; Favaretto et al., 2008).

Effect of Gypsum Rates on Corn and Soybean Yields

In response to the improvement in chemical attributes throughout the root zone, a significant relationship between gypsum rates and corn yield was observed for both sites (Fig. 4a). Rainfall during the experimental period was favorable for crop growth (Fig. 1), as reflected in the corn yields achieved in the control treatments (10,693 and 9946 kg ha^{-1} at Sites 1 and 2, respectively). At Site 1, yields increased linearly, with the highest yield obtained at the highest gypsum rate (6.5 Mg ha^{-1}); however, the difference in corn yield between the control and the highest gypsum rate was only 599 kg ha^{-1}. At Site 2, the maximum corn yield based on a quadratic relationship was obtained with the 5.6 Mg ha^{-1} gypsum rate. In this case, the increase in corn yield was 2422 kg ha^{-1}, comparing the control with the optimum gypsum rate. Corn yield increases related to gypsum application were approximately fivefold higher at Site 2 than at Site 1 because Site 2 had higher Al^{3+} saturation (44.9%) than Site 1 (16.0%) in the deepest soil layer, as well as lower Ca^{+2}and Mg^{+2} concentrations and a (Ca + Mg)/K ratio below the critical limit (Table 1).

The maximum corn yields based on the regression equation were 11,292 and 12,368 kg ha^{-1} at Sites 1 and 2, respectively, representing increases of 5.6 and 19.5% compared with yields in the control. In an Oxisol of South Brazil, Caires et al. (2011c) also reported a 9% increase in corn yield with gypsum applications of 6.0 Mg ha^{-1}. In addition, in an Oxisol of South Africa, gypsum application increased corn yield 25%, as reported by Farina et al. (2000a), in an average of 11 crop harvests.

As observed for corn, the soybean control treatments achieved high grain yields (4500 and 3780 kg ha^{-1} at Sites 1 and 2, respectively) (Fig. 4b). Despite the high yields achieved, the treatment with a gypsum rate of 3.0 Mg ha^{-1} produced a yield 2.6% higher than that of the control treatment at Site 1. These results confirm, for soybean, the effectiveness of the recommended gypsum rate of 3.4 Mg ha^{-1}, determined with Eq. [1] according to the clay content of the subsoil at Site 1 (Quaggio and van Raij, 1996).

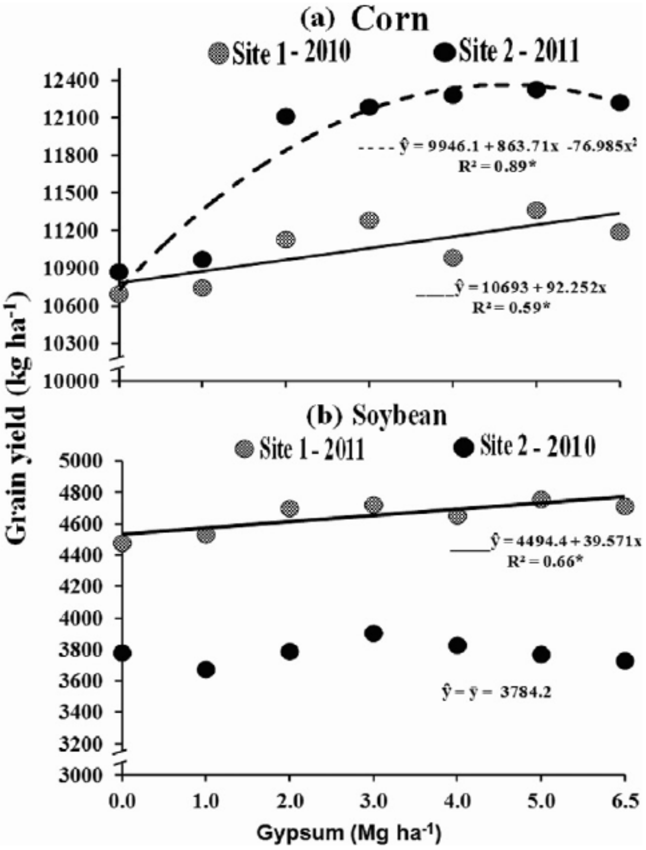


Fig. 4. Relationship of gypsum application rate and (a) corn yield for Site 1 after 6 mo and for Site 2 after 22 mo and (b) soybean yield for Site 1 after 22 mo and for Site 2 after 6 mo.

At Site 1, the highest soybean yield was achieved with the highest gypsum rate, 6.5 Mg ha^{-1}, with a yield that was 5.7% greater than that of the control treatment according to the linear equation (Fig. 4b). Under similar conditions, Caires et al. (2011a) reported a soybean yield increase of 3.1%, and Quaggio et al. (1993) observed soybean yield increases of 10% with a gypsum rate of 6.0 Mg ha^{-1}. Van Raij et al. (1994) and van Raij (2010) also reported soybean yield increases with gypsum rates in the range of 4.0 to 6.0 Mg ha^{-1}.

At Site 2, no effect of gypsum application on soybean yield (Fig. 5b) was observed, and the average soybean yield across treatments was 3784 kg ha^{-1}. This lack of change in soybean yield may be related to the short time span (6 mo) of the treatment application because the improvement in chemical attributes of the subsoil is a gradual process (Fig. 3b). Also, it could be due to the S concentration in the root zone, which was above the critical limit and as a consequence there was a low probability of response to S application. The lack of increase in soybean yield for gypsum application is consistent with the results of Caires et al. (2006).

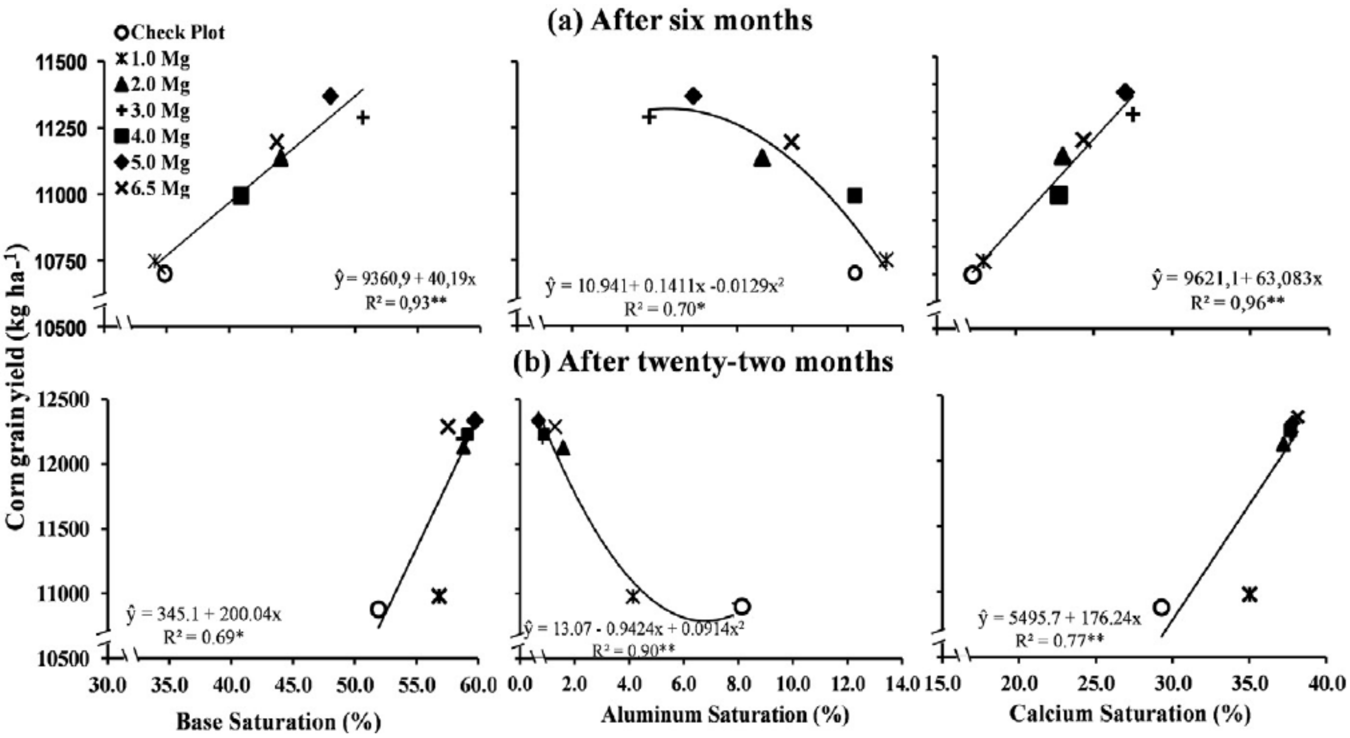


Fig. 5. Relationship of corn yield and base saturation, Al saturation, and Ca saturation at gypsum application rates from 1.0 to 6.5 Mg ha^{-1} in the 25- to 40-cm soil layer (a) 6 mo after gypsum application for Site 1, and (b) 22 mo after application for Site 2. *, Significant at *P* < 0.05 and 0.01, respectively.**

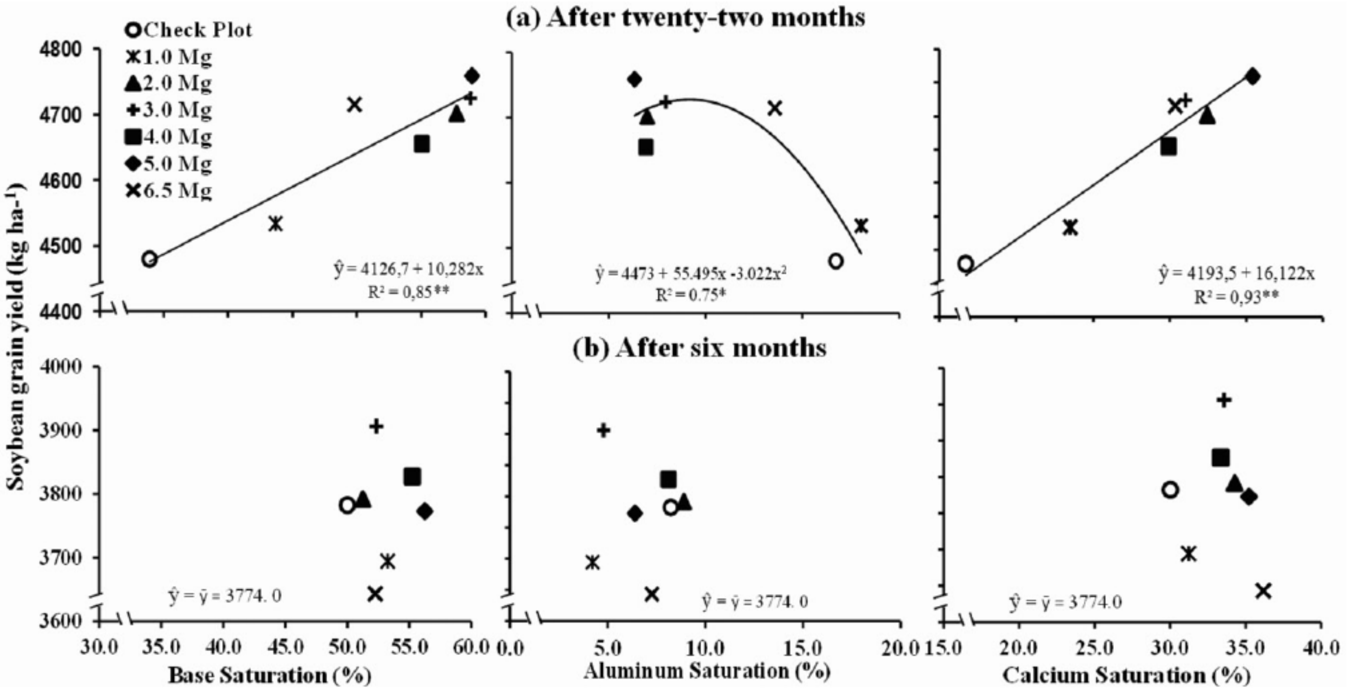


Fig. 6. Relationship of soybean yield and base saturation, Al saturation, and Ca saturation at gypsum application rates from 1.0 to 6.5 Mg ha^{-1} in the 25- to 40-cm soil layer (a) 22 mo after gypsum application for Site 1, and (b) 6 mo after application for Site 2. *, Significant at *P* < 0.05 and 0.01, respectively.**

Relationships of Subsoil Chemical Attributes and Corn and Soybean Yields

The improvement in chemical properties related to gypsum application was observed throughout the entire root zone (Table 2). After 22 mo, there was an improvement in the Ca/Mg ratio and an increase in Ca^{2+} saturation and base saturation in the surface soil layers. There was a decrease in Mg^{2+} saturation; however, it was not restrictive to crop yield (Fig. 2 and 3). The improvement in chemical soil quality in surface soil layers for broadcast gypsum application was expected, and it has been well documented in the literature (Caires et al., 2004, 2011c; Dalla Nora et al., 2013). In contrast, the improvement in deep soil layers is less documented.

Three of the four grain crop harvests investigated were affected by changes in chemical attributes in the 25- to 40-cm soil layer (Fig. 5 and 6); only the soybean crop at Site 2 was not affected by the improved chemical attributes of the subsoil. The corn yield at both sites responded positively to the increases in base saturation and SCa and the decrease in Al^{3+} saturation in the subsoil (Fig. 5). The soybean yield was affected by the chemical subsoil improvement only at Site 1, where the effects were similar to those observed for the corn crop.

The control treatments had different chemical attributes in the 25- to 40-cm soil layer at the beginning of the experiment (33.9, 16.7, and 18.1% in Site 1 and 40.9, 9.7, and 24.3% in Site 2 for base saturation, Al^{3+} saturation, and SCa, respectively) (Fig. 2 and 3). In addition, Site 1 had lower SO_4–S concentrations and narrower Ca/Mg ratios throughout the root zone than Site 2 (Table 1). Therefore, corn, which is sensitive to soil quality (Amado et al., 2007), showed yield increases at both sites, while soybean responded only at the site with the lower chemical quality at the 25- to 40-cm soil depth.

Caires et al. (2011a) reported a linear increase in corn grain yield with increasing rates of applied gypsum, even when subsoil chemical attributes were above the critical limits. Similar results were observed in our study, where, even though the base saturation and Ca^{2+} concentrations were above critical values and Al^{3+} saturation was below the critical value for the subsoil, improvements in these attributes significantly impacted grain yields. These results indicate that there is a need to revise the subsoil critical limits for achieving high yields in tropical soils.

The maximum corn yield, according to the adjusted linear equations, was 5.6% higher at Site 2 than at Site 1, and yields generally remained higher at Site 2 for all gypsum treatments. In contrast, the maximum soybean yield, according to the adjusted equations, was 19.5% higher at Site 1 than Site 2, and the strongest soybean yield response to gypsum was also observed at Site 1 (Fig. 4). As a result, the crop yield response to subsoil treated with gypsum was greatest under conditions of high grain yield, regardless of the crop.

Oxisols have beneficial plant growth characteristics, such as deep soil profiles, good soil structure, adequate aeration, and rapid water drainage; however, chemical constraints on deep plant root growth are common. The vertical redistribution of nutrients in NT systems may be an important strategy for achieving high yields of annual grain crops and for reducing crop vulnerability to short-term water scarcity. Therefore, gypsum application should be considered an important tool for preserving continuous NT conditions favorable to plant growth in tropical and subtropical environments.

CONCLUSIONS

Surface application of gypsum in Oxisols managed under continuous NT proved to be an effective management tool for improving the vertical distribution of nutrients, such as Ca^{+2} and Mg^{+2}, and decreasing Al toxicity throughout the rooting zone.

At two experimental sites, corn yield was increased by gypsum application. Soybean yield was less influenced by gypsum application, with yield increases observed only at one site with poor subsoil quality and an S concentration below the critical limit.

The increases in base and Ca^{2+} saturations were associated with a decrease in Al^{3+} saturation in gypsum-amended subsoil, which had positive effects on crop grain yields on distrophic Oxisols. Therefore, surface application of gypsum was an efficient alternative to ameliorate the chemical soil quality, allowing high and stable grain yields under continuous NT.

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