Surface application of gypsum in low acidic Oxisol under no-till cropping system

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ABSTRACT: The conditions in which a favorable response to a gypsum application can be expected on crop yields are not clear. A 3-year field trial was carried out to evaluate the effects of gypsum application on soil chemical attributes and nutrition and yield of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merrill) on a clayey Typic Hapludox of high fertility and low acidity under no-till in Guarapuava, Parana State, Brazil. Treatments were arranged in a randomized complete block design with four replications, and consisted of gypsum application on the soil surface at 4, 8, and 12 Mg ha^{-1}. Gypsum application increased the P content in the soil most superficial layer (0.0 – 0.1 m) and also the exchangeable Ca and S-SO4^{2-} contents and the Ca/Mg ratio in the soil profile (0.0 – 0.6 m). Gypsum also caused leaching of Mg and K exchangeable in the soil. An increase in Ca concentrations in the corn leaves, and in P and S concentrations in the corn and soybean leaves occurred following the gypsum application. A yield response of corn to initial application of gypsum was found, but subsequent soybean crops did not respond. Gypsum application proved to be an effective practice to maximize no-till corn grain yield.
Key words: *Zea mays*, *Glycine max*, Brazil, phosphogypsum, calcium, sulfur

Aplicação superficial de gesso num Latossolo de baixa acidez sob sistema plantio direto

RESUMO: Não estão claras as condições em que se podem esperar efeitos favoráveis da aplicação de gesso na produção das culturas. Em um experimento de campo avaliaram-se, durante três anos, os efeitos da aplicação de gesso nos atributos químicos de um Latossolo Vermelho argiloso de alta fertilidade e baixa acidez sob plantio direto e na nutrição e produção de milho (*Zea mays* L.) e soja (*Glycine max* L. Merrill), em Guarapuava (PR). Os tratamentos, dispostos em blocos completos ao acaso com quatro repetições, constaram da aplicação superficial de gesso nas doses 4, 8 e 12 Mg ha^{-1}. A aplicação de gesso aumentou a concentração de P na camada mais superficial (0.0 – 0,1 m), bem como os teores de Ca trocável e de S-SO$_4^{2-}$ e a relação Ca/Mg no perfil do solo (0.0 – 0,6 m). A adição de gesso também ocasionou movimentação de Mg e K trocáveis no solo. A concentração de Ca nas folhas de milho e as concentrações de P e S nas folhas de milho e soja foram aumentadas com a aplicação de gesso. Houve aumento na produção de milho após aplicação de gesso, mas as culturas de soja subseqüentes não responderam ao gesso. A aplicação de gesso foi eficiente para maximizar a produção de grãos de milho no sistema plantio direto.
Palavras-chave: *Zea mays*, *Glycine max*, Brasil, fosfogesso, cálcio, enxofre

Introduction

A no-till system (NT) with diversified crop rotations is an effective strategy to improve the sustainability of farming in tropical and sub-tropical regions . To control soil acidity in NT, lime is broadcasted on the soil surface without incorporation. Because surface liming is more effective in controlling acidity only at the soil most superficial layers (Ernani et al., 2004; Caires et al., 2005), management strategies have been developed to reduce acidity in the subsoil.

Gypsum is a by-product of the phosphoric acid industry which contains mainly calcium sulfate and small concentrations of phosphorous (P) and fluorine (F) and is largely available worldwide. Gypsum application on the soil surface followed by its leaching to acidic subsoils results in the improvement of root growth and higher absorption of water and nutrients by root plants (Sumner et al., 1986; Carvalho and van Raij, 1997).

Differences in crop responses to gypsum have been observed (Hammel et al., 1985; Caires et al., 1999); however, their causes are still unclear. In several field studies a gypsum application increased corn yields (Caires et al., 1999; Farina et al., 2000a; Caires et al., 2004), but not soybean yields (Quaggio et al., 1993; Oliveira and Pavan, 1996; Caires et al., 2003, 2006). Gypsum may increase crop yield due to increase of Ca and sulfate (SO$_4^{2-}$) available to the plants (Caires et al., 2002, 2004). In a field trial conducted on an Oxisol under a NT, corn yield was increased by increasing the Ca saturation levels up to 56%

and by reducing the Mg saturation levels to about 12% in the soil surface layers (Caires et al., 2004). In addition, despite the P present in gypsum as an impurity is important for plant nutrition when high gypsum rates are applied this effect has often been neglected in studies with gypsum use (Sumner et al., 1986; Caires et al., 2003).

This study reports a field trial that examined the effects of gypsum application on soil chemical attributes and nutrition and yield of corn and soybean sowed on a NT established on an Oxisol of high fertility and low acidity. Because the cation exchange capacity of roots is lower in corn than in soybean (Fernandes and Souza, 2006) we hypothesize that (i) corn and soybean crops would present different responses to gypsum and (ii) the increase in crop grain yield with the gypsum addition is not associated only with amelioration of subsoil acidity conditions.

Material and Methods

The experiment was performed in Guarapuava, Paraná State, Brazil (25°17' S, 51°48' W), on a dystrophic clayey Typic Hapludox. According to Köppen-Geiger System (Peel et al., 2007) the climate of this region is Cfb, with mild summer and frequent frosts during the winter. Table 1 presents the results on chemical (Pavan et al., 1992) and particle-size distribution (EMBRAPA, 1997) analyses of the soil profile before the beginning of the experiment. Prior to the study, the field was used for grain cropping under a NT system for 15 years, with black oat (*Avena strigosa* Schreb) as the previous crop.

Treatments were arranged in a randomized complete block design with four replications and consisted of gypsum application at rates of 4, 8, and 12 Mg ha^{-1}. Plot size was 49 m^2 (7 × 7 m). Gypsum contained 205 g kg^{-1} of Ca, 172 g kg^{-1} of sulfur (S), 2 g kg^{-1} of phosphorus (P) and 150 g kg^{-1} of moisture. Gypsum rates were calculated to raise the exchangeable calcium/magnesium (Ca/Mg) ratio of the topsoil (0.0 – 0.2 m), at values between 4 and 8 according to data from previous studies (Caires et al., 1999, 2004). Gypsum was applied on the soil surface on September 28, 2005. Between June 2005 and November 2007, the crop rotation was: black oat (*Avena strigosa* Schreb) (2005), corn (*Zea mays* L.) (2005 – 06), black oat (2006), soybean (*Glycine max* L. Merrill) (2006–07), black oat (2007), and soybean (2007 – 08).

Corn, hybrid P 30R50 was sown on October 07, 2005, at seeding rate of five seeds m^{-1} and row spacing of 0.75 m. Fertilizers were applied at rates of 204 kg ha^{-1} of nitrogen (N) (42 kg ha^{-1} at sowing and 162 kg ha^{-1} in topdressing), 102 kg ha^{-1} of P$_2$O$_5$, and 120 kg ha^{-1} of K$_2$O. Soybean, Magic cultivar, was sown on November 06, 2006, and November 24, 2007, at seeding rate of 10 seeds m^{-1} and row spacing of 0.4 m. In 2006, soybean was sown without a fertilizer application and in 2007, 250 kg ha^{-1} of a 2–20–20 complete fertilizer was applied at seeding. In both crops, soybean seeds were inoculated with *Bradyrhizobium japonicum*.

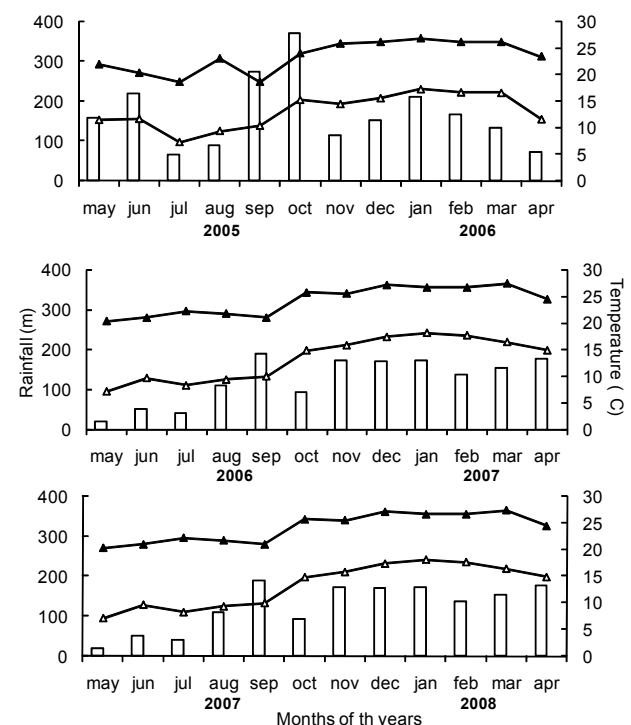The monthly average data on rainfall and on maximum and minimum air temperature, registered during

Figure 1 – Monthly rainfall (vertical bars) and maximum (▲) and minimum (△) temperatures of the air, registered during the experiment (May 2005 to April 2008), in Guarapuava, PR.

Table 1 – Chemical and particle-size distribution analyses on soil samples at different depths, prior to initiation of the experiment in 2005.

Layers	pH in CaCl$_2$	Exchangeable cations					P (Mehlich-1)	C	Base saturation	Sand	Silt	Clay
		H + Al	Al	Ca	Mg	K						
m		---------------- mmol$_c$ dm^{-3} ----------------					mg dm^{-3}	g dm^{-3}	%	---------- g kg^{-1} --------		
0.00 - 0.05	6.1	36.9	0	55	28	4.8	6.3	36	70	80	320	600
0.05 - 0.10	5.9	42.8	0	48	24	4.4	6.3	28	64	77	303	620
0.10 - 0.20	5.7	49.6	0	44	18	3.9	3.1	24	57	72	228	700
0.20 - 0.40	5.2	62.1	0	23	29	2.4	1.8	20	47	64	216	720
0.40 - 0.60	5.0	66.9	0	15	10	4.2	1.5	17	30	67	193	740

the field experiment, are shown in Figure 1. The weather conditions were normal for the region. The rainfall distribution was appropriate throughout the period of development of the corn and soybean crops in the field.

During the flowering period of the corn (in the 2005–06 year) and soybean (2006–07) crops, leaves were collected from 30 plants (third leaf from the apices of the soybean plant and first leaf below and opposite to the corn ear) of each plot (Malavolta et al., 1997). These samples were rinsed in deionized water, dried in a forced-air oven at 60ºC until constant mass, and ground in a Wiley-type mill to pass a 0.75-mm screen. The concentrations of N, P, K, Ca, Mg, and S were determined according to methods described by Malavolta et al. (1997).

Soil samples were collected after harvesting both the corn in 2006, and the soybean, in 2007 and 2008, at 9, 18, and 30 months after the gypsum application. Twelve soil core samples per plot were taken with a soil probe sampler to obtain a composite sample of the 0.0 – 0.1 and 0.1 – 0.2 m depths, and five cores of the 0.2 – 0.4 and 0.4 – 0.6 m depths. The soil samples were air dried, sieved through 2 mm sieve and stored in permeable plastic bags.

Soil pH was measured in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 v v^{-1}, soil/solution); exchangeable calcium (Ca), magnesium (Mg) and potassium (K), as well as phosphorus (P, by the Mehlich-1 method) were determined according to Pavan et al. (1992). In addition, the soil S-SO_4^{2-} contents were extracted with the solutions of calcium phosphate 0.01 mol L^{-1} (Cantarella and Prochnow, 2001) and ammonium acetate 0.5 mol L^{-1} in acetic acid 0.25 mol L^{-1} (Vitti and Suzuki, 1978), in a 1:2.5 (v v^{-1}) soil/solution ratio.

Corn and soybean yields were evaluated after physiological maturation of the crops through manual harvesting. Corn grain was harvested from 12 m^2 plots, and soybeans were harvested from 9.6 m^2 plots. Grain yields were expressed at 130 g kg^{-1} moisture content.

Results were submitted to polynomial regression analyses. The criterion for choosing the regression model was the magnitude of the determination coefficients provided it was significant at $p < 0.05$.

Results and Discussion

Surface-applied gypsum did not influence soil pH, at the four soil depths analyzed. The average soil pH values (0.01 mol L^{-1} $CaCl_2$), after 9, 18, and 30 months of gypsum application, varied from 5.6 to 5.8 at 0 – 0.1 m depth, from 5.4 to 5.5 at 0.1 – 0.2 m depth, from 5.3 to 5.4 at 0.2 – 0.4 m depth, and from 5.0 to 5.2 at 0.4 – 0.6 m depth.

Because gypsum is a neutral salt that has no ability to consume protons (H^+), no effect of gypsum application on soil acidity was expected. However, gypsum application may increase the pH in the subsoil layers (Caires et al., 2002, 2003; Carvalho and van Raij, 1997) due to a reaction of ligand substitution on the surface of soil particles, involving Fe and Al hydrated oxides, SO_4^{2-} displacing OH^-, thus promoting a partial neutralization of soil acidity (Reeve and Sumner, 1972). Since in the present study, the pH (0.01 mol L^{-1} $CaCl_2$) was ≥ 5.0

throughout soil profile (0.0 – 0.6 m), exchangeable Al was not detected in the soil.

The content of exchangeable Ca has increased linearly in all soil depths proportionally to gypsum rates, after 9, 18 and 30 months of the application (Figure 2). Gypsum application caused leaching of exchangeable Ca in the soil profile over time, having registered the highest increment in the Ca content in the 0.0 – 0.1 m soil depth, after 9 months, and in the soil deepest layer (0.4 – 0.6 m), after 30 months. The movement of exchangeable Ca in the soil profile after the gypsum application may vary according to soil type, applied gypsum rate and volume of water applied. Quaggio et al. (1993) observed leaching of exchangeable Ca in the soil below the layer at 0.4 – 0.6 m, after 18 months of the application of 6 Mg ha^{-1} of gypsum on an Oxisol under conventional tillage. Caires et al. (2001) verified that 80% of the exchangeable Ca in the soil had been leached to depths greater than 0.6 m after 64 months of the gypsum application at 12 Mg ha^{-1} on a loamy Oxisol under NT. In a trial conducted on a clayey Oxisol under NT, a gypsum application increased the exchangeable Ca content throughout the soil profile (0.0 – 0.6 m) with the greatest movement of exchangeable Ca be occurring under an application of gypsum at 9 Mg ha^{-1} after only 32 months (Caires et al., 2003). In a kaolinitic soil, in Georgia State (USA), there was a residual effect of the gypsum application at 35 Mg ha^{-1} on exchangeable Ca content up to 1.2 m soil depth, after 16 years (Toma et al., 1999).

Gypsum rates increased linearly the Ca/Mg ratio in the soil, after 9, 18, and 30 months of the application, at the four soil depths studied (Figure 2); an exception was for the deepest layer (0.4 – 0.6 m), after 9 months. According to the adjusted regression equations, the highest gypsum rate (12 Mg ha^{-1}) raised the Ca/Mg ratio in the soil to 7.4 (0.0 – 0.1 m), 3.5 (0.1 – 0.2 m), and 2.3 (0.2 – 0.4 m), after 9 months, and to 5.6 and 5.9 (0.0 – 0.1 m), 2.9 and 4.8 (0.1 – 0.2 m), 2.3 and 3.7 (0.2 – 0.4 m), and 2.0 and 4.3 (0.4 – 0.6 m), respectively after 18 and 30 months. Gypsum application was able to increase the Ca/Mg ratio in the soil (0.0 – 0.2 m) to values between 4 and 8, reaching the target values mainly in the soil surface layer (0.0 – 0.1 m).

Exchangeable Mg content in the soil was reduced with the gypsum rates at 0.0 – 0.1 m depth, after 9 months, and at 0.0 – 0.1 and 0.1 – 0.2 m depths, after 18 and 30 months (Figure 3). The leaching of exchangeable Mg from the most superficial soil layers resulted in an increase of this nutrient in the deepest layer (0.4 – 0.6 m), after 18 months of the gypsum application. This effect on subsoil was no longer observed 30 months after gypsum application, showing that gypsum rates resulted in the leaching of exchangeable Mg from the soil over time. The leaching of exchangeable Mg in the soil with a gypsum application is facilitated by the formation of the ionic pair $MgSO_4^0$ and it has been observed in several studies carried out under different conditions of soil and climate (Oliveira and Pavan, 1996; Caires et al., 1999; Toma et al., 1999; Farina et al., 2000b; Zambrosi et al., 2007). Thus, when gypsum is applied at high rates the loss of exchangeable Mg can be minimized by the use of dolomitic lime when correct-
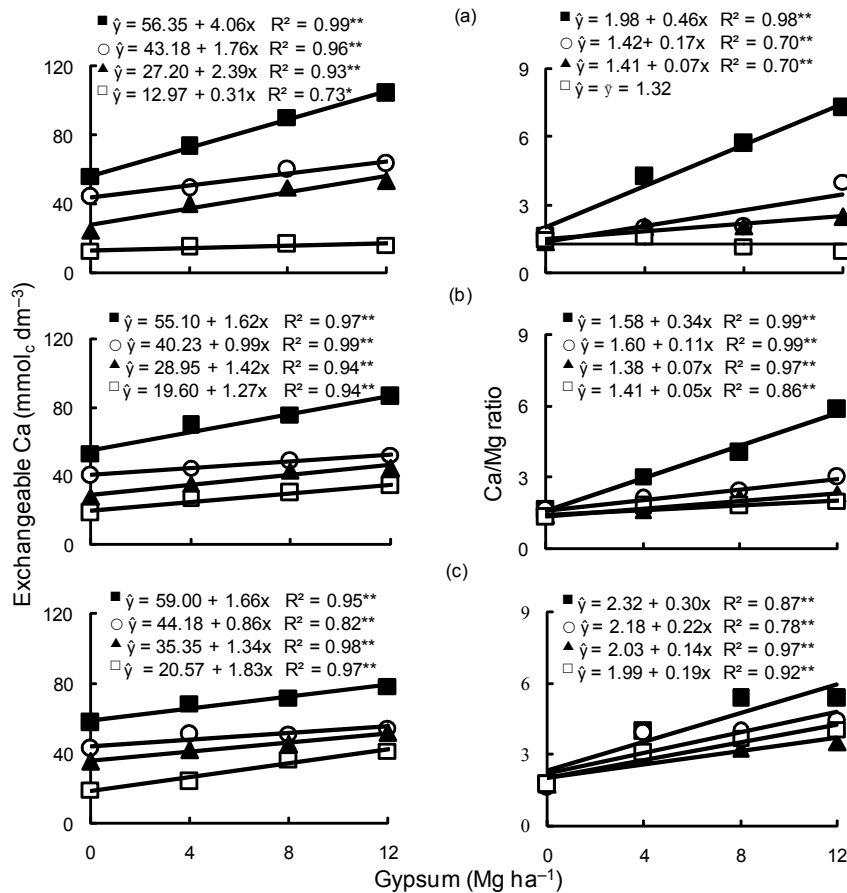
Figure 2 – Changes in Ca exchangeable and Ca/Mg ratio for different soil depths: 0.0 – 0.1 m (■), 0.1 – 0.2 m (o), 0.2 – 0.4 m (▲), and 0.4 – 0.6 m (□), at 9 (a), 18 (b), and 30 (c) months after surface application of gypsum under a no-till system. $*p < 0.05$ and $**p < 0.01$.

ing soil acidity. However, the leaching of exchangeable Mg after gypsum application can be beneficial for Ca and K plant nutrition and crop yield, when the soils present elevated exchangeable Mg levels and low Ca/Mg ratio in the most superficial layers. An increase in the Ca/Mg ratio occurred following a gypsum application due to an increase in exchangeable Ca (Figure 2) followed by reduced levels of Mg (Figure 3) due to leaching of $MgSO_4^0$.

Gypsum rates reduced the exchangeable K content in the soil at 0.0 – 0.1 m depth, after 9 months, at 0.0 – 0.1 and 0.1 – 0.2 m depths, after 18 months, and at 0.0 – 0.1, 0.1 – 0.2, and 0.2 – 0.4 m depths, after 30 months (Figure 3). The leaching of exchangeable K after gypsum application in our study occurred during the first nine months and was more accentuated than that observed in other studies carried out under NT (Caires et al., 2002, 2004). This may be because the soil in our study had a high exchangeable K content and a low acidity level throughout the profile. Even so, the exchangeable K contents remained at levels higher than 2.5 $mmol_c$ dm^{-3} at 0.0 – 0.1 m soil depth after gypsum application.

The $S-SO_4^{2-}$ contents, extracted both with calcium phosphate $[Ca(H_2PO_4)_2]$ solution and ammonium acetate in acetic acid (NH_4OAc) solution, increased in the soil pro-

file at 9, 18, and 30 months after the gypsum application (Figure 4). Great leaching of $S-SO_4^{2-}$ from gypsum applied was observed along time. The extensive leaching of $S-SO_4^{2-}$ in the soil may have been caused by the low acidity and high organic carbon content, associated with high P content, especially in the soil surface layers (Table 1). The lower soil adsorption capacity of $S-SO_4^{2-}$ in such conditions favors its leaching to subsoil layers. The speed which $S-SO_4^{2-}$ leaches in the soil might vary according to soil and climate conditions (Camargo and van Raij, 1989; Quaggio et al., 1993; Toma et al., 1999; Caires et al., 2003).

There is a positive linear relationship ($p < 0.01$) between the $S-SO_4^{2-}$ content in the soil profile (0.0 – 0.6 m) extracted with $Ca(H_2PO_4)_2$ solution ($\hat{y}$, in mg dm^{-3}) and NH_4OAc solution (x, in mg dm^{-3}) ($\hat{y}= 4.92 + 0.99x$, $R^2 = 0.92$). The $S-SO_4^{2-}$ content in the soil was slightly higher when extracted with $Ca(H_2PO_4)_2$ solution than extracted with NH_4OAc solution. It is important to realize that the soil had high contents of clay and organic carbon (Table 1). The $Ca(H_2PO_4)_2$ solution extracts more $S-SO_4^{2-}$ adsorbed to oxides and hydroxides of Fe and Al than $S-SO_4^{2-}$ binding to the soil organic fraction (Fox et al., 1964); furthermore, while the NH_4OAc solution extracts the soluble $S-SO_4^{2-}$ adsorbed to oxides and part of
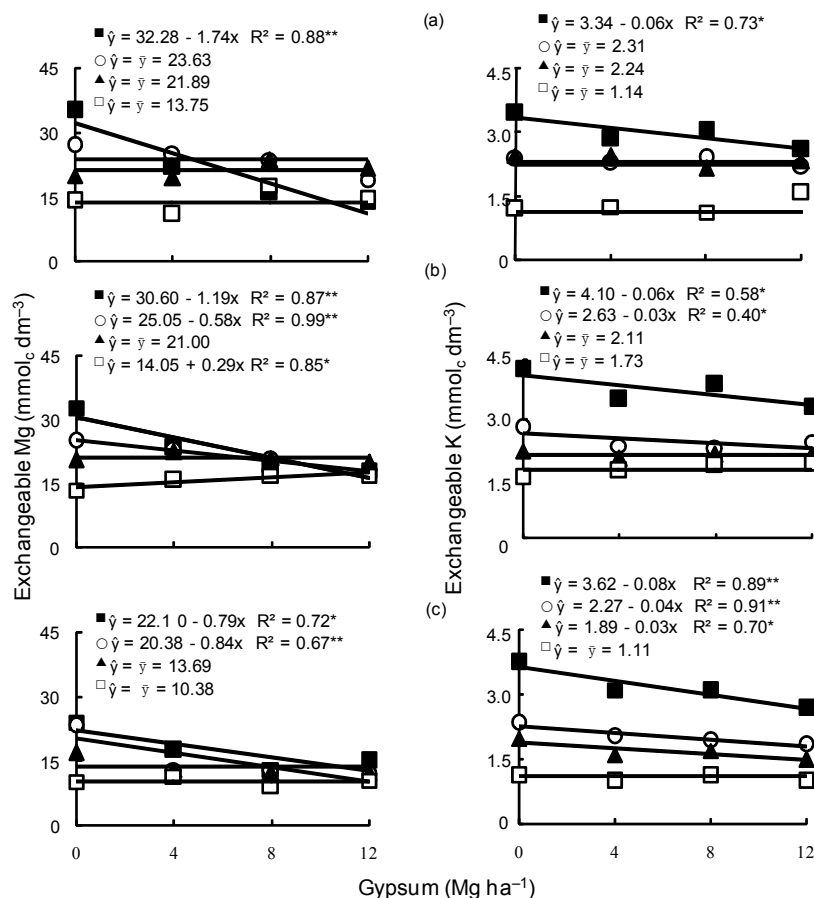
Figure 3 – Changes in exchangeable Mg and K for different soil depths: 0.0 – 0.1 m (■), 0.1 – 0.2 m (o), 0.2 – 0.4 m (▲), and 0.4 – 0.6 m (□), at 9 (a), 18 (b), and 30 (c) months after surface application of gypsum under a no-till system. *$p < 0.05$ and **$p < 0.01$.

the sulfur binding to the soil organic fraction. The extraction of $S\text{-}SO_4^{2-}$ from the soil was slightly higher with the solution of $Ca(H_2PO_4)_2$ certainly because of the high clay content in the soil. Ribeiro et al. (2001) reported that in soils with high capacity of sulfate adsorption, the sulfur extracted with the $Ca(H_2PO_4)_2$ solution as well as with the NH_4OAc solution presented close positive correlation with S uptake by the plants.

The P content (Mehlich-1) in the 0.0 – 0.1 m layer increased linearly with gypsum rates, after 9, 18, and 30 months of the application (Figure 5). Because the precipitation of insoluble calcium phosphates occurs at high soil pH values (Haynes, 1982), an increase in available Ca did not lead to a decrease in phosphate availability. In our study, besides the soil is acid (pH 0.01 mol L^{-1} $CaCl_2$ 5.6 – 5.8 at 0.0 – 0.1 m depth), soil pH was not affected by gypsum application. Increases in P content (Mehlich-1) at the 0.00 – 0.05 m soil layer in response to gypsum application, were also observed by Caires et al. (2003).

Gypsum rates caused an increase in Ca concentrations in the corn leaves, and in P and S concentrations in the corn and soybean leaves (Figure 6). The increase in P and especially S concentrations in leaves with the applied gypsum rates was higher in the corn than in the soybean. Gyp-

sum did not affect N, K, and Mg concentrations in the corn and soybean leaves. Increases in Ca and S concentrations in corn leaves and in P and S concentrations in soybean leaves due to gypsum application under NT systems have been obtained in others studies (Caires et al., 1999, 2003, 2004). As has been shown previously (Sumner et al., 1986; Caires et al., 2003, 2006), the P contained in the gypsum composition as an impurity is important for plant nutrition when high rates of gypsum are applied.

Surface-applied gypsum rates increased quadractically corn grain yield and it did not change grain yields in both soybean crops (Figure 7). According to the adjusted regression equation, the maximum corn yield would be obtained at a rate of 7.8 Mg ha^{-1} of gypsum, which caused an increase of 11% in the grain yield. Yield at 12 Mg ha^{-1} compared to the 8 Mg ha^{-1} rate was slightly lower likely because of more accentuated leaching of exchangeable Mg and K in the soil surface layer (Figure 3). Caires et al. (1999) described an experiment in which the gypsum application increased the yield of corn, but not of soybean, similarly to what was verified in our study. Positive responses to gypsum application on the corn yield were also obtained in several other studies carried out under varied soil and climate (Toma et al., 1999; Farina et al., 2000a;
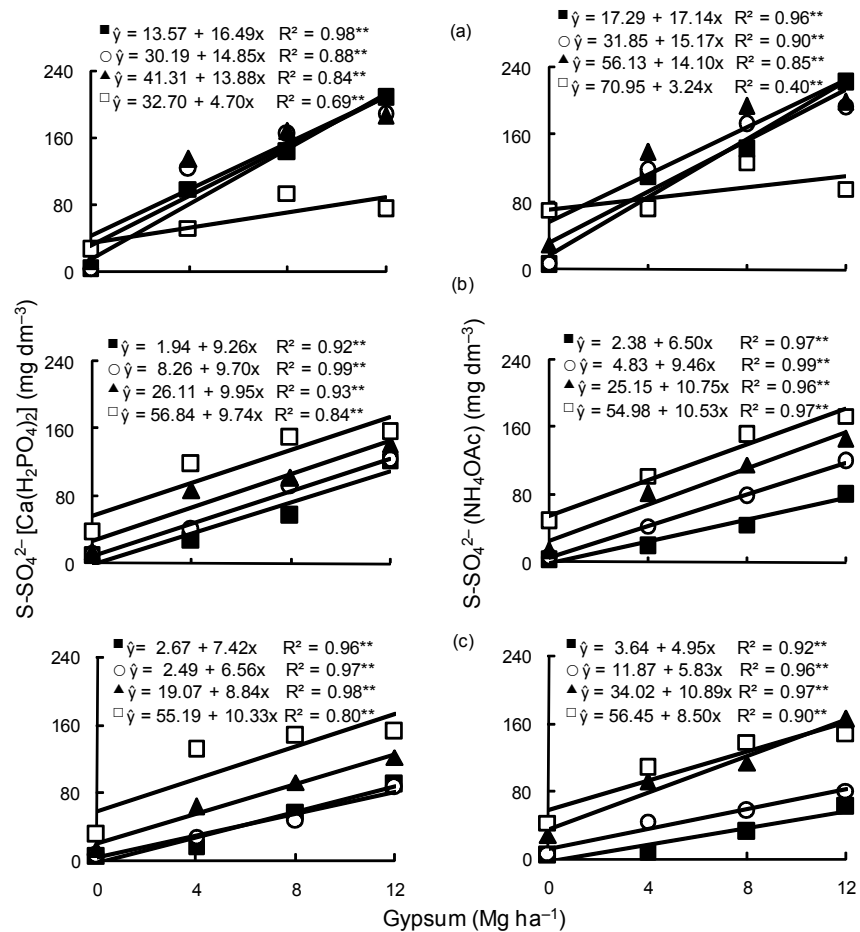
- $\hat{y} = 13.57 + 16.49x$ $R^2 = 0.98**$
- $\hat{y} = 30.19 + 14.85x$ $R^2 = 0.88**$
- $\hat{y} = 41.31 + 13.88x$ $R^2 = 0.84**$
- $\hat{y} = 32.70 + 4.70x$ $R^2 = 0.69**$
(a)

- $\hat{y} = 17.29 + 17.14x$ $R^2 = 0.96**$
- $\hat{y} = 31.85 + 15.17x$ $R^2 = 0.90**$
- $\hat{y} = 56.13 + 14.10x$ $R^2 = 0.85**$
- $\hat{y} = 70.95 + 3.24x$ $R^2 = 0.40**$
(a)

(b)

- $\hat{y} = 1.94 + 9.26x$ $R^2 = 0.92**$
- $\hat{y} = 8.26 + 9.70x$ $R^2 = 0.99**$
- $\hat{y} = 26.11 + 9.95x$ $R^2 = 0.93**$
- $\hat{y} = 56.84 + 9.74x$ $R^2 = 0.84**$

- $\hat{y} = 2.38 + 6.50x$ $R^2 = 0.97**$
- $\hat{y} = 4.83 + 9.46x$ $R^2 = 0.99**$
- $\hat{y} = 25.15 + 10.75x$ $R^2 = 0.96**$
- $\hat{y} = 54.98 + 10.53x$ $R^2 = 0.97**$

(c)

- $\hat{y} = 2.67 + 7.42x$ $R^2 = 0.96**$
- $\hat{y} = 2.49 + 6.56x$ $R^2 = 0.97**$
- $\hat{y} = 19.07 + 8.84x$ $R^2 = 0.98**$
- $\hat{y} = 55.19 + 10.33x$ $R^2 = 0.80**$

- $\hat{y} = 3.64 + 4.95x$ $R^2 = 0.92**$
- $\hat{y} = 11.87 + 5.83x$ $R^2 = 0.96**$
- $\hat{y} = 34.02 + 10.89x$ $R^2 = 0.97**$
- $\hat{y} = 56.45 + 8.50x$ $R^2 = 0.90**$

y-axis (upper left/middle left): $S-SO_4^{2-}$ [Ca(H$_2$PO$_4$)$_2$] (mg dm^{-3})

y-axis (middle right): $S-SO_4^{2-}$ (NH$_4$OAc) (mg dm^{-3})

x-axis: Gypsum (Mg ha^{-1})

Figure 4 – Changes in $S-SO4^{2-}$ extracted with calcium phosphate 0.01 mol L^{-1} [Ca(H$_2$PO$_4$)$_2$] solution and 0.5 mol L^{-1} ammonium acetate in 0.25 mol L^{-1} acetic acid (NH$_4$OAc) solution, for different soil depths: 0.0 – 0.1 m (■), 0.1 – 0.2 m (o), 0.2 – 0.4 m (▲), and 0.4 – 0.6 m (□), at 9 (a), 18 (b), and 30 (c) months after surface application of gypsum under a no-till system. * $p < 0.05$ and ** $p < 0.01$.
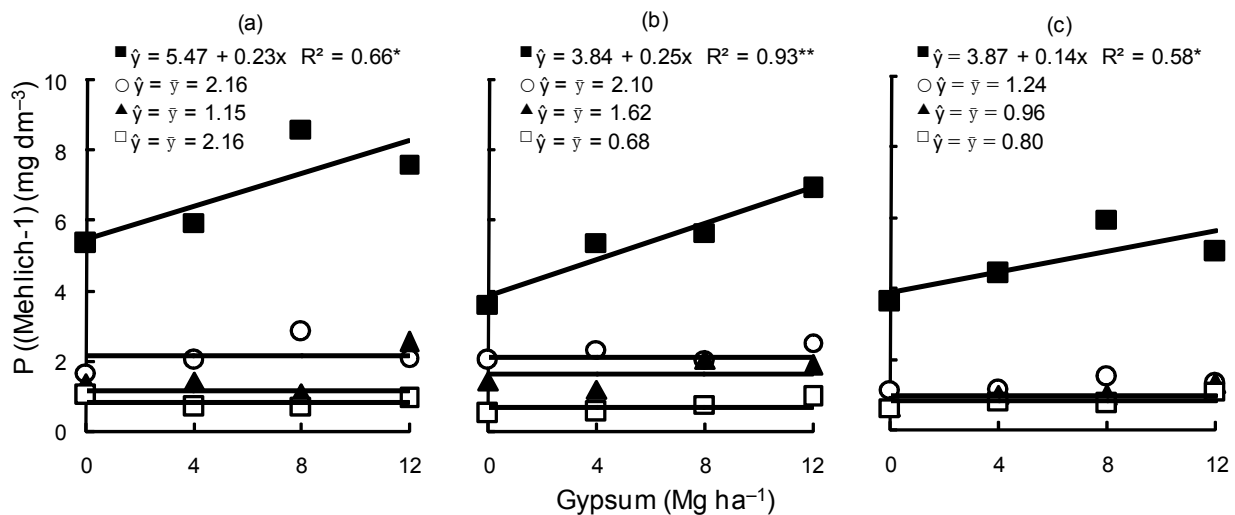

(a)
- $\hat{y} = 5.47 + 0.23x$ $R^2 = 0.66*$
- $\hat{y} = \bar{y} = 2.16$
- $\hat{y} = \bar{y} = 1.15$
- $\hat{y} = \bar{y} = 2.16$

(b)
- $\hat{y} = 3.84 + 0.25x$ $R^2 = 0.93**$
- $\hat{y} = \bar{y} = 2.10$
- $\hat{y} = \bar{y} = 1.62$
- $\hat{y} = \bar{y} = 0.68$

(c)
- $\hat{y} = 3.87 + 0.14x$ $R^2 = 0.58*$
- $\hat{y} = \bar{y} = 1.24$
- $\hat{y} = \bar{y} = 0.96$
- $\hat{y} = \bar{y} = 0.80$

y-axis: P ((Mehlich-1) (mg dm^{-3})

x-axis: Gypsum (Mg ha^{-1})

Figure 5 – Changes in P (Mehlich-1) for different soil depths: 0.0 – 0.1 m (■), 0.1 – 0.2 m (o), 0.2 – 0.4 m (▲), and 0.4 – 0.6 m (□), at 9 (a), 18 (b), and 30 (c) months after surface application of gypsum under a no-till system. * $p < 0.05$ and ** $p < 0.01$.

Caires et al., 2004). In our study, the soil had no exchangeable Al and had elevated levels of exchangeable Ca in the subsoil (0.0 - 0.6 m), making it unlikely that a yield increase in response to gypsum application was caused by amelioration of subsoil acidity. No response of soybean yield to gypsum (Quaggio et al., 1993; Oliveira and Pavan, 1996; Caires et al., 2003, 2006) has been attributed to the lower Al toxicity to the root growth in NT systems during cropping seasons that have adequate and well-distributed rainfall (Caires et al., 2001, 2008). This reasoning does not apply in this study because the soil did not present chemical limitations for root growth (Table 1).

Based on soil test calibrations, P content was medium (Figure 5) and S content was low (Figure 4) at 0.0 – 0.1 m depth in the no gypsum control plots (Oleynik et al., 1998; EMBRAPA, 2005). Because the gypsum rates

caused an increase in P and S concentrations in the corn and soybean leaves (Figure 6), but they only increased corn grain yield (Figure 7), we can point out that the soybean crop has higher P and S uptake efficiency than corn crop. Silva et al. (2003) found different behaviors in S absorption and redistribution by corn and soybean plants. In spite of having larger root absorption, corn retained great part of that S in the root, while soybean absorbed considerably less, but presented greater translocation efficiency (Silva et al., 2003). In addition, because the gypsum rates increased the Ca concentrations in corn leaves and not in soybean leaves (Figure 6), soybean crop should not be affected by the balance of cations when the exchangeable cations levels in the soil are sufficient. Caires et al. (2004) verified that the increase of corn yield with gypsum application under NT was re-
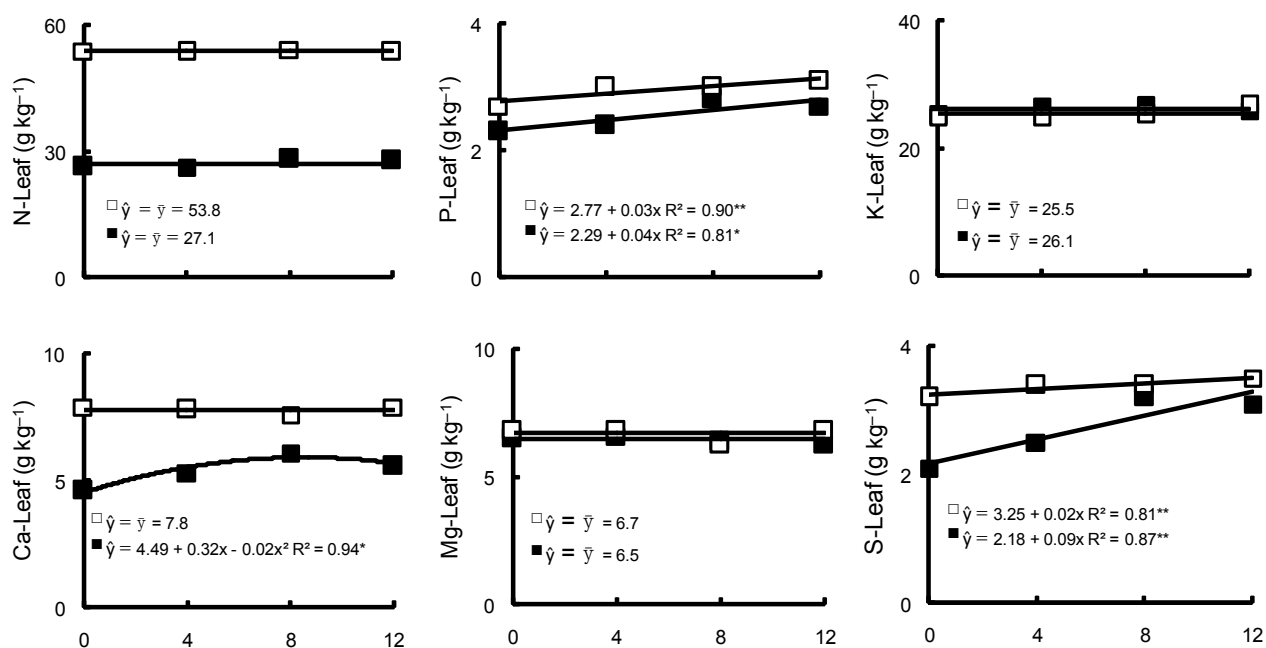

Figure 6 – Nutrient concentrations in leaves of corn grown in 2005–06 (■) and soybean grown in 2006–07 (□) as affected by surface application of gypsum under a no-till system. *p < 0.05 and **p < 0.01.
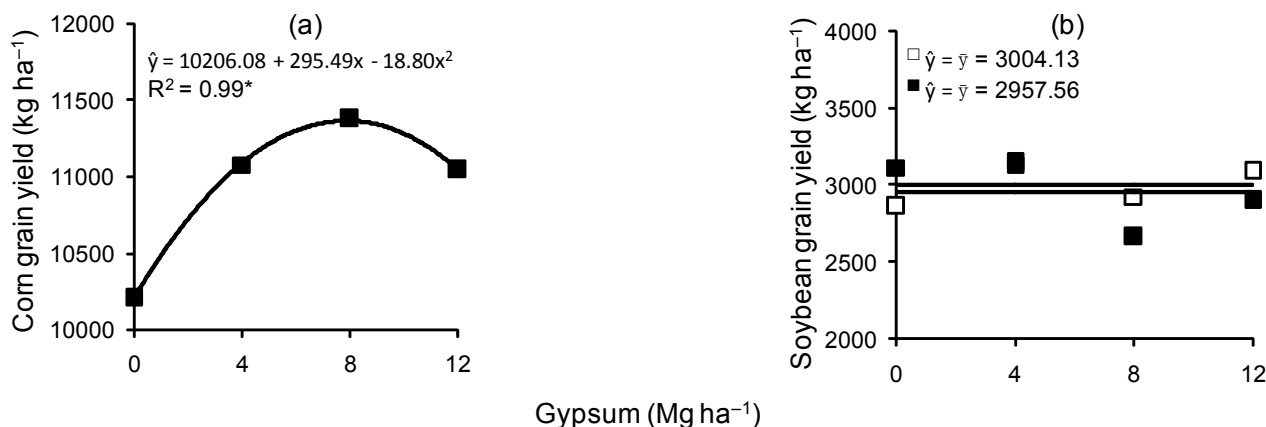

Figure 7 – Corn in 2005-06 (a) and soybean in 2006-07 (□) and 2007-08 (■) (b) grain yield as affected by surface application of gypsum under a no-till system. *: p < 0.05.

lated to the increment in Ca saturation at cation exchange capacity at pH 7 in the soil surface layers. The cation exchange capacity of roots is lower in corn than in soybean (Fernandes and Souza, 2006). Roots having a high charge density tend to accumulate bivalent ions in contrast to roots of low charge density differentially absorbing univalent ions (Wallace and Smith 1955 cited by Broyer and Stout, 1959). So, corn plants are less efficient than soybean plants in Ca^{2+} uptake from soil solution and an increase in soil exchangeable Ca content followed by decreased level of exchangeable Mg with gypsum addition must have favored the Ca^{2+} uptake by corn plants. The results suggest that gypsum application is an effective practice to improve P, Ca, and S nutrition and grain yield of corn in an Oxisol of high fertility and low acidity under a NT.

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