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Subsoil chemical amelioration and crop yields under continuous long-term no-till in a subtropical Oxisol

Douglas Dalla Nora[1]*, Telmo Jorge Carneiro Amado[1], Rafael Pivotto Bortolotto[1], Ademir Oliveira Ferreira[1], Klaus Reichardt[2] and Antônio Luis Santi[3]

[1]Department of Soil, Universidade Federal de Santa Maria (UFSM), Av. Roraima 1000, Santa Maria 97105-900 Rio Grande do Sul, Brazil.
[2]Centro de Energia Nuclear na Agricultura (CENA), Universidade de São Paulo (USP), Av. Centenário 303, Piracicaba 13400-970 São Paulo, Brazil.
[3]Centro de Educação Superior Norte do Rio Grande do Sul, Universidade Federal de Santa Maria (UFSM), Linha Sete de Setembro s/n BR 386 KM 40, Frederico Westphalen 98400-000 Rio Grande do Sul, Brazil.

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Long-term no-till with shallow fertilizer input results in a chemical enriched topsoil but has minor effect of subsoil. The sub-optimal use of water and mobile nutrients stored in the subsoil layers is a frequent limiting factor to crop grain yield in tropical acid soils. This study aim assesses the corn and soybean grain yield response to gypsum combined with lime surface input as a tool for subsoil chemical quality improving. A Brazilian distrophic Oxisol located in Carazinho (RS State, BR) managed under continuous no-till with characteristics of good chemical soil quality in the topsoil and with a poor condition in the subsoil was select for this study. The experiment design was a randomized block with three replications. The following chemical treatments were broadcast on soil surface as followS: (a) control; (b) 2.5 Mg ha^{-1} of gypsum + 2.0 Mg ha^{-1} of dolomitic lime; and (c) 5.0 Mg ha^{-1} of gypsum + 2.0 Mg ha^{-1} of lime. Both chemical inputs were applied simultaneously, the rates were determined based on lime requirement according to South state fertilizer recommendation and gypsum according to Midwest (Savanna) recommendation. The soil samples were stratified in the 0.00 to 0.60 m soil layer with four sampling times at 0, 6, 22 and 34 months after experiment establishment. An increase in the calcium and magnesium soil contents, as well as soil base saturation, and a decrease in aluminum content, was verified in subsoil layers (0.15 to 0.25 m and 0.25 to 0.40 m) just after six months of chemicals application. These subsoil ameliorate effect was intensified with the conducting time of the experiment notedly at 22 months after chemical application. Moreover, it was found crop grain yield increments statistically significant ranging of 9 to 16%. The gypsum combined with lime was an effective alternative for improving vertically nutrient content of the Oxisol's decreasing the abrupt transition in chemical quality of topsoil and subsoil helping to the maintenance of competitive grain yield under non-disturbed long-term no-till.

Key words: Gypsum, subsoil acidity, soil fertility, calcium, sulfate.

INTRODUCTION

During the period of 1990/91 to 2012/13, the Brazilian agriculture had an increase of 37% in cropland area, but reaching an increase of 127% in grain production based on improvement in grain yield (CONAB, 2013). This way, the main cash crop yield has grown in an annually rate close to 3% in last three decades. However, achieve and sustain high grain crop yields is as important as obtain high efficiency in chemical inputs that is still a challenge in tropical environment.

The adoption of NT combined with cover crops and crop rotation is the main agriculture alternative for the sustainable use of soil in tropical environment (Amado et al., 2006). However, studies carried out in distrophic Oxisols have been suggesting that the NT chemical improvement associated to shallow fertilizer or surface lime application is restricted to topsoil, creating a profile non favorable for deep root growth, increasing the risk to crop water stress (Shainberg et al., 1989; Blanco-Canqui and Lal, 2008; Caires, 2012; Dalla Nora and Amado, 2013).

Naturally, the subsurface layers here defined as below 0.20 m, are acid and unfertile for most of the Brazilian tropical and subtropical Oxisols (Rampim et al., 2011). The high concentration of Al associate to low Ca concentration and basis saturation are the most frequent chemical impediments for deep root growth (Raij, 2010). The occurrence of short-term drought associate to shallow crop root growth has led to recurrent economic agricultural losses in Brazil (Caires et al., 2011a).

Lime, the main chemical input used for alleviate soil acidity, has low water solubility and its reaction is slow especially when soil surface-applied as in continuous NT. In this scenario, the improvement of the subsoil chemical attributes under NT is less probable, and depends on frequency and intensity of lime input, leaching of salts and organic compounds through the soil profile (Toma et al., 1999; Caires et al., 2003) and by the adoption of cover crops (Miyazawa et al., 2002). However, some studies where was investigated treatments with high rates and frequent lime application show the chemical soil quality improvement in the subsoil (Oliveira and Pavan, 1996; Caires et al., 2008). The NT disturbed aiming lime incorporation in 0-0.20 m increases the lime reaction but did not guarantee that subsoil layers deeper than tillage operation will be ameliorated (Farina et al., 2000a). Also, discontinuities of NT will have important environmental impact due the increase in soil erosion risk, high fuel consumption and soil organic matter oxidation (Amado et al., 2006).

The gypsum + lime surface-application is increasing gradually in Brazilian NT in conditions tropical and subtropical as an alternative for ameliorate subsoil chemical attributes and decrease short drought crop stress (Caires et al., 2003, 2011b; Rampim et al., 2011; Dalla Nora and Amado, 2013). After gypsum application there is a sharp increase in soil solution Ca content causing the displacement of Al, magnesium (Mg) and potassium (K) of the soil exchange complex (Farina et al., 2000a, b; Zambrosi et al., 2007; Favaretto et al., 2008). In wet tropical and subtropical climate under high precipitation there is a downward sulphate movement following water drainage causing basis leaching, mainly Ca and Mg, and boosts the formation of Al-sulfate, which is less toxic to plants (Carvalho and Raij, 1997; Favaretto et al., 2008). The consequence of this process is subsoil chemical amelioration preserving soil structure and soil organic matter (Dalla Nora and Amado, 2013).

The use of gypsum has been recommended preferably after or at least applied together with dolomitic lime, due to the synergistic effect of these chemical inputs (Raij, 2010). The gypsum enhances the action of the superficial application of lime enhancing the deep root growth (Caires et al., 2004).

The effect of gypsum on grain yield has been contradictory and crop type dependent (Farina et al., 2000a; Raij, 1994; Caires et al., 2004, 2011b). Farina et al. (2000a) evaluating long term gypsum effect (10 corn harvests which most had significant increase at $p<0.05$), reported an average grain yield increments of 135 kg ha^{-1} year^{-1}. Caires et al. (2004) report corn yield increments of 17% statistically significant at $p<0.01$. Rampim et al. (2011) report linear and statistically significant ($p<0.05$) wheat yield increments significance as a response to gypsum rates up to 5.0 Mg ha^{-1}. Raij (1994) found increases of 184 kg ha^{-1} ($p<0.05$) in soybean yield for the rate of 6.0 Mg ha^{-1} of gypsum. However, Caires et al. (2011b) did not find increases in soybean yield for gypsum rates varying from 0 to 9 Mg ha^{-1}, in agreement with data reported by Rampim et al. (2011). The authors reported that the soybean yield was less sensitive to gypsum than the corn and wheat. In addition, Reeve and Sumner (1972) and Dalla Nora et al. (2014) sustain that the gypsum positive effect on grain crop yields is more pronounced under water stress conditions.

There are few studies reporting the synergic effect of lime and gypsum on crop yields in long-term NT. In order to fill up this gap an Oxisol at Rio Grande do Sul State (RS), Brazil, with good chemical quality in topsoil but with poor in subsoil was selected to test the hypothesis that is possible ameliorate subsoil chemical quality allowing achieve high corn-soybean crop yields without soil disturbance.

MATERIALS AND METHODS

Field site description

The experiment was carried out during 2009 to 2012 in a cropland located at Carazinho, Rio Grande do Sul State, Brazil, with coordinates of 28° 17' S and 52° 47' W, in a distrophic Oxisol (Typic

*Corresponding author. E-mail: douglasdnpg@gmail.com, Tel:+5532208916. Fax:+5532208916..

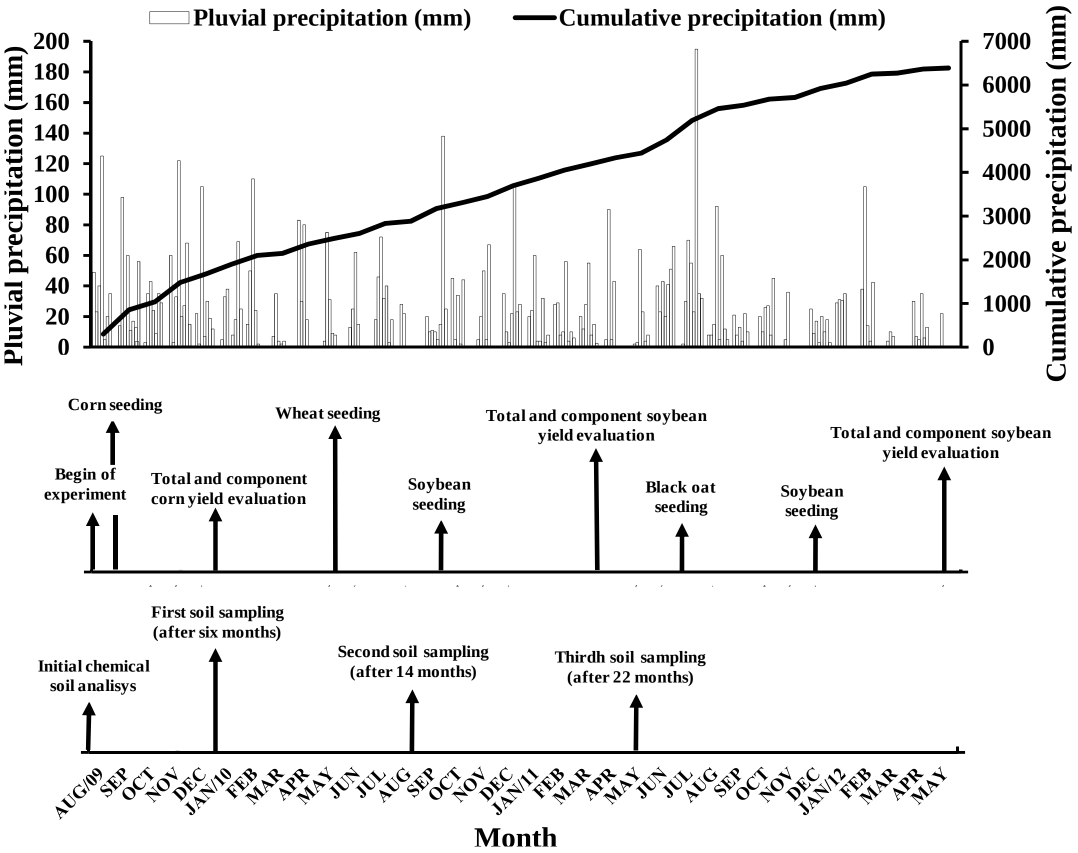

Figure 1. Daily and cumulative precipitation during experimental period and main experimental details.

Hapludox) (Soil Survey Staff, 2010). According to Köppen classification the climate of the region is wet subtropical (Cfa) with a mean annual temperature of 16°C, and mean annual rainfall of 2,020 mm. During the experimental period, rainfall accumulated are 1,864 mm after six months, 3,140 after 14 months, 4,440 after 22 months, and 6,389 after 34 months when the experiment was discontinued (Figure 1).

The experimental field site consists of 0.6 ha of a farm with 280 ha. The experimental field has been managed continuously under NT system for approximately 20 years with a cropping system composed of black oat (*Avena strigosa* Schreb)/maize (*Zea mays* L.)/wheat (*Triticum aestivum* L.)/soybean/black oat/soybean. This cropping system is typical in South Brazil. Liming rate applied in this field was 2.0 Mg ha^{-1} arbitrarily definied by farmers, with 75% effective calcium carbonate equivalent, input every five years always broadcast on soil surface. Before installing the experiment, the area was cultivated with black oats, as cover crop, which was managed with GLYPHOSATE [N-(phosphonomethyl)glycine] to, thereafter, homogeneously apply gypsum and lime (August, 2009). In sequence, a corn crop was seeded in September receiving 200 kg ha^{-1} of N (20 kg ha^{-1} at seeding + 180 kg ha^{-1} split in two equal doses as topdress N fertilization), 125 kg ha^{-1} of P_2O_5 and 130 kg ha^{-1} of K_2O. This corn crop was evaluated in relation to total grain and component yield. In the cropping system the wheat was seeded in July 2010, receiving: 250 kg ha^{-1} of the 5-25-25 fertilizer formulation and 30 kg ha^{-1} of N as a topdress N fertilization. This winter crop was not harvested due a severe frozen at flowering stage. In sequence a soybean crop was seeded in November 2010, which received 240 kg ha^{-1} of the 2-20-20 fertilizer formulation and was harvested in March 2011, when the evaluation of grain yield and component were done. During the winter the area had black oat as cover crop. In sequence, soybean crop was planted in December 2011, which received 240 kg ha^{-1} of the 2-20-20 fertilizer formulation and was harvested in May 2012, the soybean crop was evaluated in relation to total grain and components yield. The crop sequence and plant evaluations are shown in Figure 1.

Before installing the experiment the soil was sampled in four layers: 0.0-0.10; 0.10-0.20; 0.20-0.40 and 0.40-0.60 m soil depths with five replicates taken randomly in the experiment site.

Experimental design

A random block design with three replicates and plots size of 8 × 8 m was used in this study. Treatments consisted of: (1) T_0 - control without gypsum and lime applications; T_1 - 2.5 Mg ha^{-1} of gypsum + 2.0 Mg ha^{-1} of dolomitic lime; T_2 - 5.0 Mg ha^{-1} of gypsum + 2.0 Mg ha^{-1} of dolomitic lime. The gypsum applied had 29% of CaO, 16% of S and 1% of P. The dolomitic lime had 30% of CaO and 20% of MgO with 75% effective calcium carbonate equivalent and 75% reactivity.

Soil sampling and analysis

Six months after treatments application soils were sampled at the following depth layers: 0.00-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.25, 0.25-0.40 and 0.40-0.60 m. A second and a third soil samplings were performed after 14 and 22 months of the beginning of the experiment, respectively, at the same soil depths.

Table 1. Soil chemical attributes prior to treatments application.

Depth	pH $_{H2O}$	Al	Ca	Mg	K	Ca/Mg	Ca+Mg/K	CEC	P	S	BS%	m%	Clay
m				cmol$_c$ dm^{-3}					mg dm^{-3}		%		g kg^{-1}
						Begin of experiment							
0.0-0.10	5.6	0.0	7.7	3.8	0.26	2.02	44.2	11.86	23.1	13.2	72.0	0.0	540.0
0.10-0.20	5.0	0.7	4.2	2.4	0.08	1.75	82.2	7.78	8.3	8.2	42.0	13.0	630.0
0.20-0.40	4.6	3.1	2.2	1.2	0.04	1.83	85.0	6.77	3.4	17.0	21.0	47.0	680.0
0.40-0.60	4.4	3.7	1.4	0.9	0.04	1.55	57.5	6.18	2.1	31.0	13.0	61.0	700.0

BS%, Basis saturation; m%, aluminium saturation.

The main soil chemical parameters analyzed were determined according to the standard methods described in Tedesco et al. (1995). Soil chemical analysis consisted of: pH water measured in a 1:1 proportion of soil/water; Al concentration obtained by KCl 1 mol L^{-1} extraction and titrated with NaOH 0.0125 mol L^{-1}, Ca and Mg concentrations also obtained from KCl 1 mol L^{-1} extraction and evaluated by atomic absorption spectrometry, P and K extracted with the double acid Mehlich-I extractor and measured by atomic spectrometry and flame photometry, respectively. The evaluation of S concentration was made in Ca phosphate extractor adopting the treatment with HNO_3-$HClO_4$ (Beaton et al., 1968), to determine sulfate after precipitation in a $BaCl_2$ gel solution (Tedesco et al., 1995).

At the physiologic maturation stage of corn and soybean crops, plant material was sampled close to the location of soil sampling pits, for grain total and components yield evaluation. The total area of Plant samples were 2 m^2 were 4 m (2 m from each planting row), and grain yield values were corrected for 13% water content.

For corn crop the following yield components were evaluated: Ears per meter of row; grain rows per ear; grain per row in ear; and weight of 1,000 grains. For soybean yield the components were: Pods per plant; grains per pod; and weight of 1,000 grains.

Statistical analysis

Results were submitted to analysis of variance by SISVAR (Sisvar, version 5.3) with the Tukey test at 5% probability. Regression analysis were made by JMP (JMP IN software, 3 ed., version 7.0.1). The temporal effect of the treatments for each layer of the soil sampled was evaluated by regression analysis between the concentrations of Ca, Mg, K and S and the sampling soil intervals of 0, 6, 14 and 22 months after the begin of the experiment.

RESULTS AND DISCUSSION

Soil chemical attributes at beginning of the experiment

For the topsoil (0.00-0.10 m) the values of pH and BS% were above the critical values (pH > 5.5; BS% ≥ 65%) while m% was bellow (m% < 10%) as established by two-state fertilizer and lime recommendation (CQFS-RS/SC, 2004) applied in Southern Brazil. This result implies in no need of lime input in experimental area based on topsoil chemical quality. However, already in the adjacent soil layer, 0.10-0.20 m, these chemical attributes were lower, being 5.0, 42 and 13% for pH, BS% and m%, respectively, indicating the need of lime input (Table 1). Therefore, there was an abrupt gradient of the acidity soil parameters through the soil profile. Comparing the soil layers of 0.0-0.10 and 0.10-0.20 m, there is decreases in BS%, P and K of 42, 64 and 71%, respectively, and comparing the topsoil with the typical diagnostic subsoil layer (0.20-0.40 m) the decreases were 72, 86 and 86%, respectively, characterizing a gradual loss of chemical soil quality with the increase in soil depth under continuous NT with lime application based on shallow topsoil (Amado et al., 2009).

For gypsum recommendation, Raij (2010) suggested as critical the value of m% > 40% for the layer 0.20-0.40 m (diagnostic subsoil layer), this way, as the soil of experimental site had m% = 47% (Table 1), it has a high probability to positive responses to gypsum input. Considering the clay content of 680 g kg^{-1}, the recommended gypsum rate would be equivalent to 4.1 Mg ha^{-1} that is in the range of gypsum rates investigated (2.5 and 5.0 Mg ha^{-1}).

In relation to the Ca and Mg contents and Ca/Mg ratio in the topsoil, the values are above the critical levels (Ca > 4.0 cmol$_c$ dm^{-3}, Mg > 1.0 cmol$_c$ dm^{-3} and Ca/Mg optimum range of 4-2:1) (Escosteguy, 2012). However, the Ca+Mg/K is out of the critical ratio (optimum range of 17-35:1) (Escosteguy, 2012), due to the low K concentration in relation to these two cations. The S concentration in topsoil is above the critical value of 5.0 and 10 mg dm^{-3} for corn and soybean, respectively, according to two-state South Brazil fertilizer recommendation (CQFS-RS/SC, 2004) (Table 1).

In summary, at the time of experiment implantation based on the chemical attributes of the topsoil layer the crop response to gypsum + lime treatments is unlikely. On the other hand, based on the chemical attributes of subsoil BS% these chemicals are needed.

Improvement of subsoil chemical attributes due to gypsum and lime input

The concentrations of Al, Ca, Mg, S and K, pH value, in addition of SB% and m% index, show significant relationships with gypsum + lime input as a function of

Table 2. Analysis of variance of chemical soil attributes under gypsum + lime rates, soil depth and soil sampling periods of six, 14 and 22 months after the begin of the experiment.

Causes of variation	pH H_2O	Al	m%	S	Ca	Mg	K	BS%
After six months		**cmol$_c$ dm^{-3}**	**%**	**mg dm^{-3}**		**cmolc dm^{-3}**		**%**
Gypsum + lime	*	*	*	*	*	*	ns	*
CV (%)	7.65	32.72	49.43	33.61	37.82	24.22	3.78	39.72
Soil depth	*	*	*	*	*	*	*	*
Gypsum + lime x depth	*	*	*	*	*	*	*	*
CV (%)	*3.00*	22.72	35.79	24.37	8.41	12.08	1.71	10.72
After 14 months								
Gypsum + lime	*	*	*	*	*	*	ns	*
CV (%)	9.21	33.21	41.22	13.61	41.27	13.21	31.1	22.94
Soil depth	*	*	*	*	*	*	*	*
Gypsum + lime x depth	*	*	*	*	*	*	*	*
CV (%)	1.84	8.12	23.43	10.84	14.2	4.12	3.42	6.69
After 22 months								
Gypsum + lime	*	*	*	*	*	*	ns	*
CV (%)	9.73	37.3	45.65	32.34	13.80	31.34	6.25	19.81
Soil depth	*	*	*	*	*	*	*	*
Gypsum + lime x depth	*	*	*	*	*	*	*	*
CV (%)	3.25	14.41	21.09	21.75	3.79	4.95	4.85	10.99

n.s, Non significative; *, Significative at 5%; CV, coefficient of variation.

soil depth, at all soil sampling periods (Table 2). For the topsoil the pH increases can be taken as an expected effect of liming (Figure 2) (Caires et al., 2005), however, due to its low water solubility and as a consequence slow down movement through the soil profile, the pH increase in the subsoil layers would not be expected (Ritchey et al., 1980; Pavan et al., 1984; Farina et al., 2000b). The movement of lime particles with drainage water may be also a mechanism of correction of soil subsurface soil acidity in continuous no-tillage notadely under high rates of lime input (Amaral et al., 2004). The pH increase in the subsoil layers verified in our study may be attributed to the gypsum effect, due to ligand exchange reaction, involving Fe and Al hydrated oxides with the sulfate, in this way dislocating hydroxides which partially promote the neutralization of soil acidity (Reeve and Sumner, 1972). Also, the plant uptake of high quantity of sulfate could result in hydroxide plant excretion increasing the pH (Soratto and Crusciol, 2008). Previously, Raij et al. (1994), Caires et al. (2003) and Rampim et al. (2011) reported increase in subsoil pH with lime + gypsum input similar to those here presented.

The high accumulated rainfall up to 14 and 22 months corresponding to 3,140 and 4,407 mm, respectively (Figure 1), must have contributed to the displacement of sulfate and to the increase in pH through the root growth zone (Figure 2). In this way, the subsoil layer of 0.25-0.40 m presented pH increases of 6 and 11% for the lowest and highest rates of gypsum + lime treatments, respectively, in relation to the control elapsed 22 months of experiment set up (Figure 2c). For this subsoil layer the decreases in Al concentration were 21 and 36% for the same rates and time elapsed (Figure 2c).The decrease of Al concentration in the subsoil noted in our study (Figure 2), is in agreement with previously reported by Pavan et al. (1984) and Farina et al. (2000b). The decrease in Al concentration probably is the result of ionic exchanges of Al by Ca, displacing the Al to the soil solution, being temporarily immobilized by sulfates (Pavan et al., 1984; Shamshuddin et al., 2009). Furthermore, even a small increased pH in the subsurface can reduce the concentration of Al.

Elapsed 22 months of the beginning of the experiment, the m% index for the 0.15-0.25 m subsoil layer presented decreases of 50 and 51% for the lowest and highest gypsum + lime rates, respectively, in relation to the control. For the 0.25-0.40 m these decreases were of 37 and 56%, respectively (Figure 2c). Farina et al. (2000b), in an experiment with gypsum input, also reported ameliorate in the chemical quality of a deep soil layer (0.45-0.75 m).

In treatments ameliorated with gypsum + lime the increase in S concentration through root zone growth was faster and intense (Figure 2). Previously, Farina et al. (2000b) reported S concentration increases up to 0.90 m soil depth, however, with a gypsum rate as high as 10 Mg ha^{-1}. The fast downward movement of S through soil profile in our study could have been favored by the lime application, because this input while increasing the pH promotes the increase of negative charges that reduce

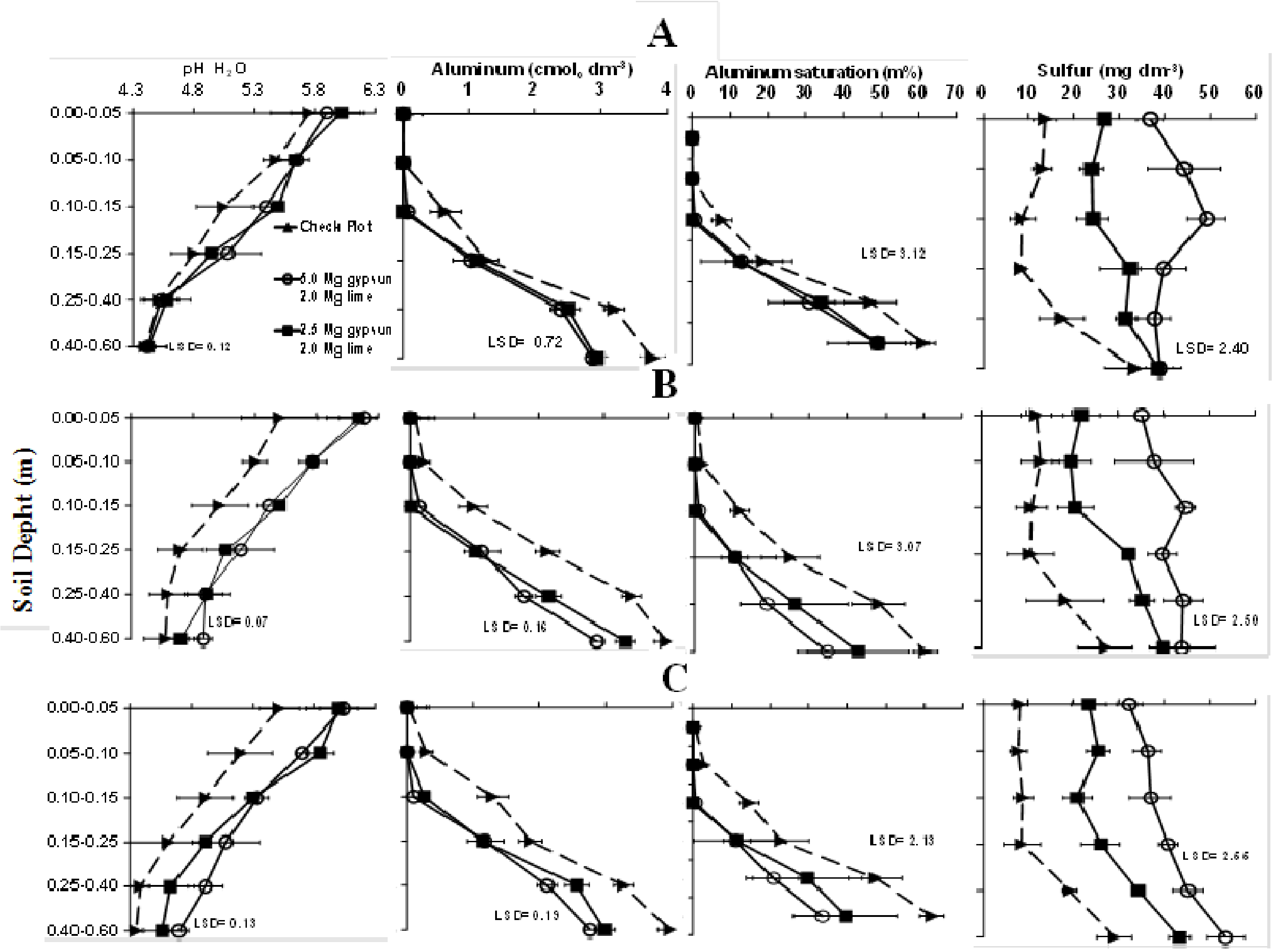

Figure 2. Values of pH, aluminium concentration, aluminium saturation (m%) and sulfur concentration affected by gypsum + lime after six (A), 14 (B) and 22 (C) months after the input. LSD by Tukey test ($p<0.05$).

the adsorption of the sulfate with the soil exchange complex (Farina et al., 2000b).

It was also observed that the application of gypsum + lime promoted an increase in the Ca and Mg concentrations along the soil profile (Figure 3). Elapsed only six months of the highest gypsum + lime rate treatment increments in the concentrations of Ca and Mg of 19 and 22%, respectively, were observed in the 0.40-0.60 m subsoil layer in relation to control (Figure 3a). Elapsed 14 months, these increments were amplified to 39 and 62%, respectively, and further to 48 and 64%, after 22 months (Figure 3b and c), in agreement with previously reported by Farina et al. (2000b). Therefore, in our study the relative increase in Mg was higher than Ca in subsoil.

As a consequence of the increases in the Ca and Mg content and at same time of the decrease in Al concentration, an expected increase of BS% was verified in subsoil (Figure 3). Similar results were previously presented by Caires et al. (2011a). So, after six elapsed months, increments of 32% and 34% in BS% were observed in the 0.25-0.40 m subsoil layer for the lowest and highest gypsum + lime rates, respectively in relation to the control (Figure 3a). After 22 elapsed months, these increments were 45 and 48%, respectively (Figure 3c).

The increments in Ca, Mg, BS%, S and pH, and the decreases in Al and the m% index (Figures 2 and 3) render a subsoil environment more adequate to plant root growth and, consequently, stimulate a better use of the soil water, as reported by Farina et al. (2000a, b), Caires et al. (2003); Favaretto et al. (2008); Shamshuddin et al. (2009). In this way, the lime + gypsum effect in ameliorate chemical soil quality through the root zone growth occurs in a gradual manner and is dependent of the rate of chemical inputs and of the accumulated rainfall volume. In addition, the long-term NT preserves

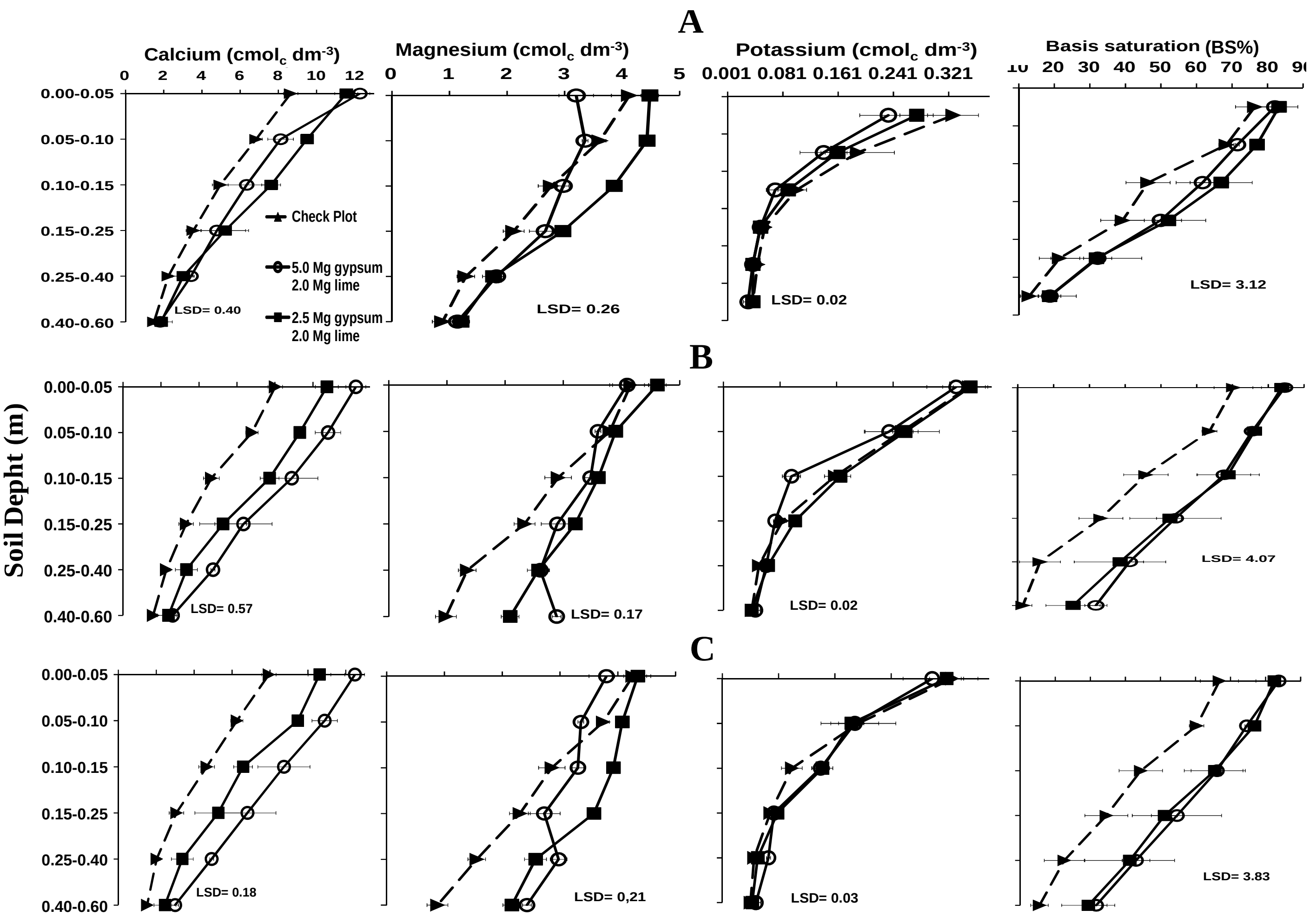

Figure 3. Values of calcium, magnesium, potassium concentration and basis saturation (BS%) affected by gypsum + lime after six (A), 14 (B) and 22 (C) months after the input. LSD by Tukey test (p<0.05).

the biopores that are vertically continuous through the root growth zone enhancing the downward solute movement following the preferential flow of water (Vervoort et al., 2001). The presence of biopores in long-term NT is a likely explanation for fast ameliorates in subsoil chemical quality under superficial gypsum + lime application.

The available K concentration in the soil layers investigated in general was not affected by rates of gypsum + lime input (Figure 3). It is important to note that the high clay contents (varying in depth from 540 to 700 g kg^{-1}), the increase of SOM in shallow soil layer and the CEC (11.86 cmol$_c$ dm^{-3}) (Table 1) might have disfavored the expected K leaching. Caires et al. (2011a) also reported that K leaching losses associated to the application of gypsum in Oxisol NT was reduced.

The concentration of Ca and SB%, in the soil layers of 0.15-0.25, 0.25-0.40 m and 0.40-0.60 m, and concentration of Mg in the layer of 0.15-0.25 m were related ($p < 0.05$) with the S concentration in the respective layers (Table 3). This relationship is probably due to neutral ion-pair formation with subsequent leaching through the soil profile (Caires et al., 2011a). Moreover, in our study no relationship was observed between the S and K concentrations in the subsoil layers (Table 3), as previously reported by Sumner et al. (1986) and Caires et al. (2011a) under Oxisols.

Corn and soybean grain yields affected by gypsum and lime input

The corn grain yield and some yield components (number of ears m^{-1} and number of grain rows^{-1}) shows significant relationships with gypsum + lime input (Table 4). Averaged of gypsum + lime treatments, the corn yield increase of 9% was found in relation to check plot (Figure 4a). Although, the check plot had achieved high corn yield (≅ 11 Mg ha^{-1}) as a result of good chemical soil quality of topsoil and long-term NT adoption. Farina et al.

Table 3. Regression equation between the results of all sampling times of calcium, magnesium, potassium and basis saturation (BS%) taken as dependent variable (y) with sulfur taken as the independent variable (x) affected by gypsum + lime in soil layers.

Gypsum + lime	Chemical soil atributte	Soil depth	Equation	R^2
Mg ha^{-1}		m		
2.5 + 2.0	Ca	0.00-0.05	$\hat{y} = \bar{y} = 9.95$	-
		0.05-0.10	$\hat{y} = \bar{y} = 7.33$	-
		0.10-0.15	$\hat{y} = \bar{y} = 6.71$	-
		0.15-0.25	$\hat{y} = 1.7693 + 0.2478x - 0.0043x^2$	0.95*
		0.25-0.40	$\hat{y} = 2.2038 - 0.0283x + 0.0018x^2$	0.98**
		0.40-0.60	$\hat{y} = -6.8353 + 0.3578x - 0.0033x^2$	0.88*
	Mg	0.00-0.05	$\hat{y} = \bar{y} = 3.80$	-
		0.05-0.10	$\hat{y} = \bar{y} = 3.48$	-
		0.10-0.15	$\hat{y} = 2.1354 + 0.0756x$	0.92*
		0.15-0.25	$\hat{y} = 1.4299 + 0.0961x - 0.0018x^2$	0.99**
		0.25-0.40	$\hat{y} = \bar{y} = 2.06$	-
		0.40-0.60	$\hat{y} = \bar{y} = 1.83$	-
	K	0.00-0.05	$\hat{y} = \bar{y} = 0.32$	-
		0.05-0.10	$\hat{y} = \bar{y} = 0.20$	-
		0.10-0.15	$\hat{y} = \bar{y} = 0.12$	-
		0.15-0.25	$\hat{y} = \bar{y} = 0.05$	-
		0.25-0.40	$\hat{y} = \bar{y} = 0.04$	-
		0.40-0.60	$\hat{y} = \bar{y} = 0.03$	-
	BS%	0.00-0.05	$\hat{y} = \bar{y} = 83.9$	-
		0.05-0.10	$\hat{y} = \bar{y} = 75.6$	-
		0.10-0.15	$\hat{y} = \bar{y} = 61.9$	-
		0.15-0.25	$y = 28.761 + 1.4121x - 0.0212x^2$	0.98*
		0.25-0.40	$y = 42.921 - 2.3725x + 0.0653x^2$	0.93*
		0.40-0.60	$y = -19.13 + 0.3391x + 0.0182x^2$	0.94*
5.0 + 2.0	Ca	0.00-0.05	$\hat{y} = \bar{y} = 10.72$	-
		0.05-0.10	$\hat{y} = \bar{y} = 8.45$	-
		0.10-0.15	$\hat{y} = \bar{y} = 7.23$	-
		0.15-0.25	$\hat{y} = 50.268 - 3.1463x + 0.0511x^2$	0.95*
		0.25-0.40	$\hat{y} = 4.5186 - 0.2192x + 0.0051x^2$	0.99**
		0.40-0.60	$\hat{y} = -4.9876 + 0.2602x - 0.0021x^2$	0.95*
	Mg	0.00-0.05	$\hat{y} = \bar{y} = 4.34$	-
		0.05-0.10	$\hat{y} = \bar{y} = 4.00$	-
		0.10-0.15	$\hat{y} = \bar{y} = 3.54$	-
		0.15-0.25	$\hat{y} = 1.9681 + 0.0166x + 8e{-}05x^2$	0.92*
		0.25-0.40	$\hat{y} = 2.397 - 0.1486x + 0.0035x^2$	0.97*
		0.40-0.60	$\hat{y} = \bar{y} = 2.06$	-
	K	0.00-0.05	$\hat{y} = \bar{y} = 0.30$	-
		0.05-0.10	$\hat{y} = \bar{y} = 0.19$	-
		0.10-0.15	$\hat{y} = \bar{y} = 0.10$	-
		0.15-0.25	$\hat{y} = \bar{y} = 0.05$	-
		0.25-0.40	$\hat{y} = \bar{y} = 0.05$	-
		0.40-0.60	$\hat{y} = \bar{y} = 0.04$	-
	BS%	0.00-0.05	$\hat{y} = \bar{y} = 84.18$	-
		0.05-0.10	$\hat{y} = \bar{y} = 72.02$	-
		0.10-0.15	$\hat{y} = \bar{y} = 60.46$	-
		0.15-0.25	$\hat{y} = 39.829 - 0.1974x + 0.0139x^2$	0.99**
		0.25-0.40	$\hat{y} = 33.402 - 1.2482x + 0.0323x^2$	0.99**
		0.40-0.60	$\hat{y} = -142.55 + 6.8332x - 0.0667x^2$	0.91*

R^2, Coefficient of determination; *$p<0.05$; **$p<0.01$.

Table 4. Analysis of variance of yield and yield components of corn (six months), soybean (22 months) and soybean (34 months) affected by gypsum + lime rates.

		Corn (after six months)			
Cause of variation	**Yield (kg ha^{-1})**	**Ears m^{-1}**	**Rows ear^{-1}**	**Grain row^{-1}**	**Weight of 1000 grains (kg)**
Gypsum + lime	*	*	ns	*	ns
CV (%)	2.77	3.47	5.79	4.73	14.23
Soybean (after 22 months)					
	Yield (kg ha^{-1})	**Pods plant^{-1}**	**Grains pod^{-1}**		**Weight of 1000 grains (kg)**
Gypsum + lime	*	*	ns		ns
CV (%)	2.98	10.96	2.56		12.96
Soybean (after 34 months)					
Gypsum + lime	*	ns	ns		*
CV (%)	3.06	13.41	3.00		3.22

ns, Non significative; cv, variation coefficient.

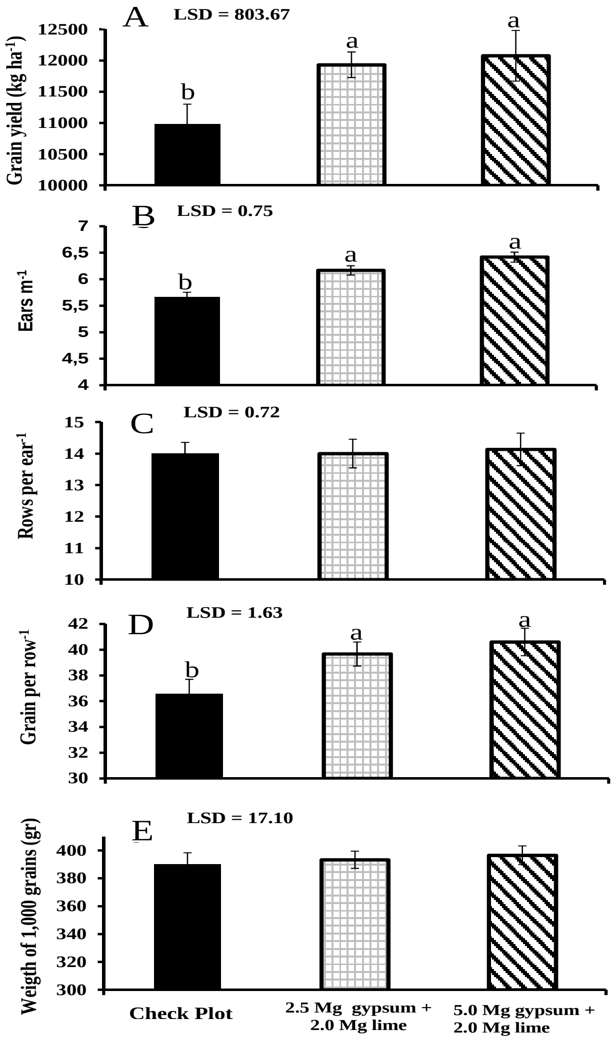

Figure 4. Corn yield (kg ha^{-1}) (A), number of ears m^{-1} (B), rows ear^{-1} (C), grain row^{-1} (D), weight of 1,000 grains (E) affected by gypsum + lime treatments after six months. LSD by Tukey test ($p<0.05$).

(2000a) reported an average increase of 25% in corn yield by gypsum input in an Oxisol, resulting in 3.8 Mg ha^{-1} of grain increase in accumulate production of 11 crop-seasons. These authors reported that the largest corn yield increases were observed in years with water stress. Caires et al. (2004, 2011b) also reported increases in corn yields in distrophic Oxisols ameliorated with gypsum + lime.

The soybean grain yield and following yield components: Pods per plant and weight of 1,000 grains show significant relationships with gypsum + lime input (Table 4). In our study it was found increments of 13 and 16% in soybean grain yield for rates of 2.5 to 5.0 Mg ha^{-1} gypsum + lime, respectively, compared to control (Figure 5a), in first soybean crop (elapsed 22 months after of the experiment beginning). In the second soybean crop, elapsed 34 months, these increments were amplified to 16 and 18% (Figure 5b). Similar results were reported by Raij et al. (1994) and Sousa et al. (1996) under water stress conditions, in which the combined effect of gypsum and lime allowed better efficiency use of soil water.

Among soybean yield components, the number of pods per plant shows an increase of 12% in highest gypsum + lime rate compared to check plot (Figure 5c) in first soybean year under satisfactory rainfall. Moreover, the number of grains per pod and the weight of 1,000 grains were not altered by gypsum + lime treatments (Figure 5e and g). In the second soybean crop, under water stress conditions, the component weight of 1,000 grains shows an increase of 4% ($p<0.05$) in highest gypsum + lime rate compared to check plot (Figure 5h). This result maybe was associate to water scarcity at soybean grain fill (Salinas et al., 1996; Desclaux et al., 2000) (Figure 1). Although, the number of grains per pod and the pods per plant were not affected by gypsum + lime treatments (Figure 5d and f).

In this study the highests crop grain yield achieved (12.1 Mg ha^{-1} to corn and 4.2 Mg ha^{-1} to soybean) under

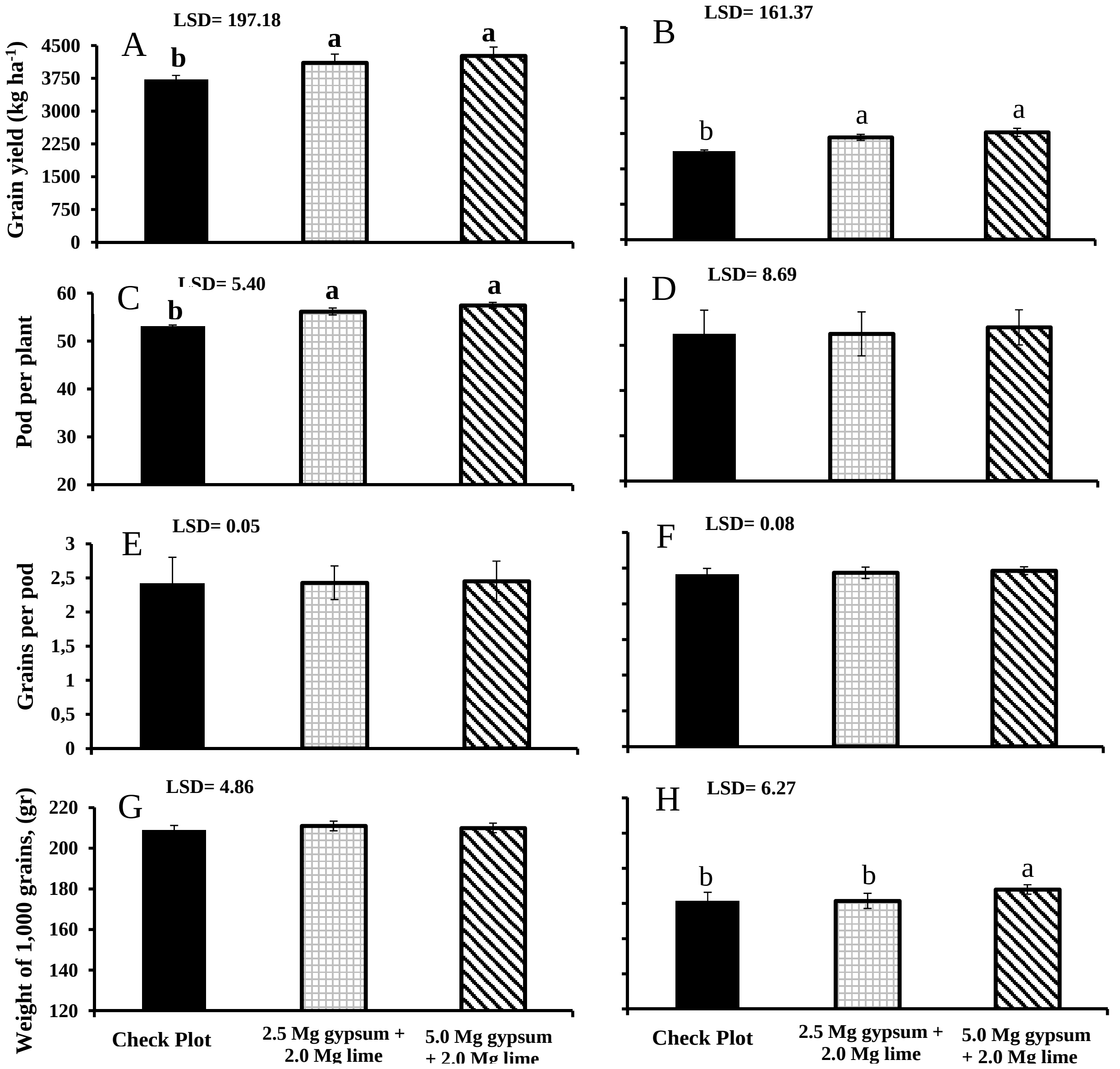

Figure 5. Soybean yield (kg ha^{-1}) (A), number of pods per plant (C), grains per pod^{-1} (E), weight of 1,000 grains (G) affected by gypsum + lime treatments after 22 months and soybean yield (kg/ha) (B), number of pods plant^{-1} (D), grain pod^{-1} (F), weight of 1,000 grains (H) affected by gypsum + lime treatments after 34 months. LSD by Tukey test ($p<0.05$).

NT with ameliorate chemical subsoil quality could be classified as high for non-irrigated cropland. With this, it is inferred that the soil management systems here evaluated were satisfactory to plant growth and, in this case, the adoption of practices such as conventional tillage to physically mix soil layers in order to reduce the chemical attributes gradient between top and subsoil layers and stimulate deeper root growth could be dispensable saving time, fuel, CO_2 emissions, decreasing soil loss, mantaining soil organic matter and preserving soil structure. In this scenario, the use of gypsum + lime in Oxisols could be a promising strategy to mantain continuous NT with competitive crop grain yields.

Conclusions

The long-term Oxisol NT with superficial lime input showed good chemical soil quality in the topsoil but had poor in the subsoil due acidity characteristics. The lime + gypsum input resulted in ameliorate subsoil, expressed by increases in concentration of Ca and basis saturation associate to reduction in concentration of Al and Al saturation. This amelioration was linked to sulfate movement following the preferential flow of water through the soil profile. In response to the amelioration of Oxisol subsoil, corn and soybean yields were increased in the range of 9 to 18% supporting the maintenance of undisturbed no-till with high crop grain yields.

Abbreviations: NT, No-till; **Al,** aluminum; **Ca,** calcium; **Mg,** magnesium; **NH_4,** ammonia; **K,** potassium; **RS,** Rio Grande do Sul State; **N,** nitrogen; **F,** fluor; **m%,** aluminum saturation; **S,** surfur; **BS%,** basis saturation; **Br,** Brazil.

Conflict of Interest

The author(s) have not declared any conflict of interests.

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