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Forms of lime application and use of phosphogypsum in low acid soil in southern Brazil: soybean-wheat yield and soil chemical properties

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ABSTRACT: Brazil is currently the leading country in no-till (NT) farming, particularly on Ferralsols (*Latossolos*), the most abundant soil type. These soils are characterized by subsurface acidity that cannot be effectively corrected by surface application of additives. In this situation, the use of phosphogypsum can be advantageous. This study aimed to assess the residual effects of lime and phosphogypsum application on a clayey Ferralsol, and four soybean and two wheat yields in southern Brazil. The area has been cultivated under no-till since 1975. The soil was limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL). Three combined treatments were also studied: (i) surface liming to 60 % BS plus standard (3.71 Mg ha^{-1}) phosphogypsum dose (60G1), (ii) surface liming to 70 % BS + standard phosphogypsum dose (70G1); and (iii) surface liming to 70 % BS + double (7.42 Mg ha^{-1}) phosphogypsum dose (70G2). Soil samples were collected 48 months after treatment. Soybean and wheat yield was not influenced by BS levels, however IL increased soybean yield in 2012/13, but reduced soybean and wheat yield in later crops. Phosphogypsum increased wheat yield by up to 12.8 % (2012 season) and 5.2 % (2015 season), but soybean was not influenced. Incorporated liming caused a decrease in soil Al^{3+} levels until 0.60 m depth, whereas SL decreased Al^{3+} levels until 0.30 m depth. Surface liming increased Mg^{2+} levels in the 0.40-0.60 m layer. Incorporated liming reduced soil organic matter in the surface layer. A double dose of phosphogypsum (7.42 Mg ha^{-1}) had a greater residual effect in subsurface layers but caused a decrease in Mg^{2+} and K^{+} levels. Therefore, the standard phosphogypsum dose provided the best results. In the very clayey soil in subtropical environment, the effects of SL extend beyond surface layers and are preferable to those of IL, although production was not influenced by BS.

Keywords: base saturation, nutrient leaching, organic matter, liming incorporation.

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INTRODUCTION

One of the main challenges of our society is to intensify agricultural production in a sustainable manner. Brazil is currently the second-largest food supplier and is expected to have a pivotal role in meeting the growing food demand (OECD-FAO, 2015). The country's immense territory, favorable climate, and deep soils provide the potential to boost production through agricultural intensification and controlled expansion (Withers et al., 2018).

Acidic soils account for 70 % of all soils in Brazil (Quaggio, 2000) and 78 % of arable lands in the world (von Uexküll and Mutert, 1995). Low soil pH increases the phytotoxic potential of aluminum (Al^{3+}) (Singh et al., 2017) and negatively affects root growth, water and nutrient absorption, and crop yield (von Uexküll and Mutert, 1995; SBCS/NEPAR, 2019). Soil pH correction is, therefore, an indispensable agricultural practice worldwide.

Liming is performed to correct soil pH, neutralize Al^{3+}, and increase calcium (Ca^{2+}) and magnesium (Mg^{2+}) levels (Ratke et al., 2018), thereby providing suitable conditions for root development (Cassol, 2019). With the advent of no-till (NT) systems, surface application of lime has become a common practice. However, lime has low solubility and its dissolution products have limited soil mobility, promoting a very slow reduction of subsurface acidity (Caires et al., 1998, 2011). Surface application was less effective than incorporation to mitigate soil acidity and provide nutrients to depths below 0.10 m in Inceptisols (Auler et al., 2019). On the other hand, regardless of the method of dolomitic lime application, soil pH was similar at 12 years after correction (Vargas et al., 2019). Determining the residual effect of lime doses applied by different methods is necessary for understanding pH correction dynamics in the soil profile.

Although liming is the primary method for reducing Al toxicity, other strategies may be used. For instance, phosphogypsum application mitigates the negative effects of Al^{3+} and increases Ca^{2+} content in NT soils (Pivetta et al., 2019). Phosphogypsum, a sulfate-rich byproduct ($CaSO_4{\cdot}H_2O$) of phosphoric acid production, is widely available in Brazil and the most economical source of sulfur (S). Chemically, phosphogypsum is a neutral salt with no effects on soil pH (Schenfert et al., 2020), but it is 150 times more soluble than calcium carbonate (Vitti and Priori, 2009). The protective effects of phosphogypsum against Al toxicity in plants may be related to increase Ca^{2+} supply to deeper soil layers, precipitation of Al with SO_4^{2-}-S to form alunite and basaluminite, formation of the nontoxic ionic pair $AlSO_4^{+}$, and induction of Al complexation with fluorine to form AlF_2^{+} (Ernani, 2016). Araújo et al. (2019) found that the improvement in chemical properties of subsurface soil (0.20-2.00 m layer) caused by phosphogypsum application led to an increase in carbon sequestration in an Oxisol.

A thicker soil layer is required for root development under NT and that modern cultivars are more sensitive to Al^{3+} than older crops (Dalla Nora et al., 2017). Additionally, in a systematic review, Tiecher et al. (2018) reported that the critical soil levels (Al saturation >20 % and/or exchangeable Ca^{2+} <0.5 $cmol_c$ dm^{-3} in the 0.20-0.40 m soil layer) used for phosphogypsum recommendation in tropical soils are not the same as those observed for subtropical soils under NT in Brazil. They suggest that for grasses on subtropical Oxisols, the recommendation criteria based on 10 % saturation of Al [$m\% = Al^{3+} / (Al^{3+} + Ca^{2+} + Mg^{2+} + K^{+}) \times 100$] and/or 3.0 $cmol_c$ dm^{-3} of Ca^{2+} in the subsurface layer (0.20-0.40 m) are better than the current recommendation based on Al^{3+} saturation of 20 % and/or 0.5 $cmol_c$ dm^{-3} Ca^{2+}. These findings reveal the possibility of responses to phosphogypsum, even in soils with low acidity, as it is not common for agricultural areas to present 3.00 $cmol_c$ dm^{-3} of Ca^{2+}.

The combined application of lime and phosphogypsum may be a beneficial practice for NT systems. However, there is little information about the residual effects of phosphogypsum on limed clayey soils in Brazil. Liming methods have been widely studied, but gaps still exist in our understanding of the long-term effects of different lime doses and modes of application in subtropical agroecosystems. In addition, as cited by Fontoura et al. (2019), most studies with lime and phosphogypsum in NT, consider a small number of season, sometimes less than two, and present contrasting results. Measuring soil acidity and fertility properties at different depths in NT systems and determining the residual effects of different liming methods are of great importance for a better understanding of soil dynamics after lime and phosphogypsum application.

The majority of the Brazilian agricultural acidic soils have already received applications of lime, increasing the pH, Ca^{2+}, and Mg^{2+} contents in the soil. Over time, lime reapplications have changed little the crops yield in NT system. These have been proposed in the field with no scientific basis that the incorporation of lime and increased doses of lime and phosphogypsum can increase crop yield in NT. Considering that the response to phosphogypsum and lime in soils with high subsurface acidity is well documented in the literature, in soils with low acidity and/or without the presence of Al^{3+}, it remains poorly understood.

Our hypotheses are as follows: i) after 48 months of the lime application in soil with moderate acidity, the improvements imposed by the superficial liming are restricted to the superficial layer of the soil (0.00-0.20 m); ii) the incorporation of lime will be more effective in improving acidity, but this does not reflect on grain yield; iii) phosphogypsum in high doses decreases cations content in the surface layer and is ineffective to provide SO_4^{2-}-S after four years of application. This study aimed to: (i) assess the effects of soil liming to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface lime application and incorporated lime and the effects of combined application of lime and phosphogypsum at different doses on the chemical properties of a Ferralsol in southern Brazil; (ii) and measure yield of soybean and wheat after these treatments.

MATERIALS AND METHODS

Study location and site description

The experiment was installed in May 2012 at the Experimental Farm of COAMO belongs to COAMO Agroindustrial Cooperative (24° 05′ 28″ S and 52° 21′ 31″ W, 605 m a.s.l.), Campo Mourão, Paraná State, southern Brazil. The climate is humid temperate with hot summers (Cfa type in the Köppen climate classification system), average annual temperatures of 20 to 21 °C, and annual precipitation ranging from 1600 to 1800 mm. The soil of the experimental area was classified as a *Latossolo Vermelho distroférrico*, which corresponds to a Ferralsol (WRB, 2015) with very clayey texture (74 % clay). Soil chemical properties before starting the experiment are described in table 1.

Since 1975 the area has been cultivated under NT system. It was not possible to specify the number of times and doses of lime applied to the soil since the beginning of the cultivation of the area. However, it is known that after 1985 the lime was applied whenever the BS was less than 60 %, and after 1980 the lime was always applied on the surface without incorporation and that dolomitic lime was always used. No agricultural phosphogypsum was applied to the area in high doses. From 2008 until the beginning of the experiment, the area was managed using NT practices. The following crops were grown: oat (2008), corn (2008–2009), oat (2009), soybean (2009–2010), wheat (2010), soybean (2010–2011), and corn (2011–2012).

Study design and experimental procedures

A randomized complete block design with 2 × 4 + 3 crossed factorial arrangement, and four replications was used. The first factor was liming method and the second factor was BS level. Lime was applied on soil surface or incorporated. The BS tested in both liming methods were 50 % (unlimed soil), 60, 70, and 90 % BS. These factorial treatments are

Table 1. Chemical properties of the *Latossolo Vermelho distroférrico* before implementation of the experiment and interpretation of the values for the surface layer (0.00-0.20 m) according to SBCS/NEPAR (2019)

Property	Layer 0.00-0.20 m	Layer 0.20-0.40 m	Interpretation
pH($CaCl_2$)	5.25	4.96	High
P (mg dm^{-3})	20.7	6.53	Very High
Ca^{2+} (cmol$_c$ dm^{-3})	3.82	2.37	High
Mg^{2+} (cmol$_c$ dm^{-3})	0.81	0.54	Medium
K^+ (cmol$_c$ dm^{-3})	0.51	0.37	Very High
Al^{3+} (cmol$_c$ dm^{-3})	0.00	0.00	Very low
CEC$_{pH\ 7}$ (cmol$_c$ dm^{-3})	10.40	8.91	Medium
m (%)	0	0	Very low
BS (%)	50	37	Medium
SOC (g dm^{-3})	25.05	21.51	Very low

pH($CaCl_2$) (0.01 mol L^{-1}): soil: solution rate of 1:2.5; Ca^{2+}, Mg^{2+}, and Al^{3+} contents were extracted using KCl 1 mol L^{-1}; K^+ and P contents were extracted using Mehlich-1; BS: percent base saturation; m%: aluminum saturation; SOC (soil organic carbon) was determined using the Walkey and Black method.

coded as SL (surface liming) or IL (incorporated liming), followed by subscript number indicating the BS level. Three additional treatments combining surface liming and phosphogypsum application were included: 60G1, soil limed to 60 % BS and treated with a standard phosphogypsum dose (3.71 Mg ha^{-1}); 70G1, soil limed to 70 % BS and treated with a standard phosphogypsum dose; and 70G2, soil limed to 70 % BS and treated with a double phosphogypsum dose (7.42 Mg ha^{-1}). Combined treatments were based on lime doses commonly applied to soybean (60 % BS) and corn (70 % BS) crops as well as standard and double doses of phosphogypsum recommended for the study site.

Dolomitic limestone was used with relative total neutralization power (RTNP) of 80.6 %, Neutralizing power of 96 %, reactivity of 84 %, CaO percentage of 29 %, and MgO percentage of 18 %. The phosphogypsum had 15 % S and 18 % Ca. Lime doses were calculated from initial soil BS values according to the relationship between BS and soil pH (SBCS/NEPAR, 2019). First, we calculated the sum of bases ($SB = Ca^{2+} + Mg^{2+} + K^+$), cation-exchange capacity at pH 7 ($CEC = SB + H + Al$), and initial BS ($BS = SB \times 100/CEC$). With this information in hand, it was possible to determine the required lime dose (LD, Mg ha^{-1}), as shown in equation 1.

$$LD = \left[\frac{(BS_2 - BS_1) \times CEC}{RTNP}\right] \qquad \text{Eq. 1}$$

in which BS_1 is the initial soil BS (50 %), BS_2 the desired BS (60, 70, or 90 %), and RPTN is the relative power of total neutralization (74 %), which is a property of the lime used in the study.

Phosphogypsum doses were calculated from soil clay contents according to the equation proposed by Souza et al. (2005) (standard phosphogypsum dose = 50 × clay content in %). The regular dose was 3.71 Mg ha^{-1} (G1), and the double dose was 7.42 Mg ha^{-1} (G2). These phosphogypsum doses are recommended for decreasing Al^{3+} toxicity and increasing Ca^{2+} availability at depths greater than 0.20 m. Table 2 provides a summary of lime and phosphogypsum doses applied in each treatment.

Each plot measured 12 × 7 m, totaling 84 m^2. Lime and phosphogypsum were applied to the soil surface. Lime incorporation was carried out using a two-bottom moldboard plow set at 0.20 m depth, followed by moderate (20 discs, 0.71 m diameter) and light (42 discs, 0.51 m diameter) harrowing.

Table 2. Lime and phosphogypsum doses applied in each treatment (May 2012)

Treatments	Lime dose	GY dose
	Mg ha^{-1}	
SL50 and IL50$^{(1)}$	-	-
SL60 and IL60$^{(1)}$	1.5	-
SL70 and IL70$^{(1)}$	2.9	-
SL90 and IL90$^{(1)}$	5.5	-
60G1$^{(2)}$	1.5	3.7
70G1$^{(2)}$	2.9	3.7
70G2$^{(2)}$	2.9	7.4

$^{(1)}$ Soils were limed to the target base saturation (BS) by surface liming (SL) or incorporated liming (IL). $^{(2)}$ Lime and phosphogypsum were applied by surface broadcasting.

Soil sampling and analysis

After liming and phosphogypsum application, four cropping cycles of soybean (summer) and wheat (winter) were carried out. Soil sampling was performed on May 18 and 19, 2016, 48 months after treatment. From products application to soil sampling, the cumulative rainfall was 7.031 mm. Samples from the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers were collected using a flat shovel, and samples from the 0.20-0.30, 0.30-0.40, and 0.40-0.60 m layers were collected using a Dutch auger. Two samples were collected from each experimental unit and mixed to form a composite sample.

Soil samples were oven-dried at 40 °C, sieved through a 2 mm sieve, and subjected to analysis (SBCS/NEPAR, 2019). Soil pH was determined in a $CaCl_2$ 0.01 mol L^{-1} suspension (at a ratio do soil solution of 1:2.5). Potassium was extracted by Mehlich-1 solution (H_2SO_4 0.0125 mol L^{-1} and HCl 0.05 mol L^{-1}) at a ratio of 1:10 (v/v) soil/solution and determined by flame emission spectroscopy (Micronal® B462). Exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted using a KCl 1 mol L^{-1} (1:10 v/v soil/solution). Exchangeable Ca^{2+} and Mg^{2+} contents were determined by atomic absorption spectrophotometry (Varian® AA 240FS) with air–acetylene flame and 5 % lanthanum solution to prevent interference. Aluminum was determined by titration with NaOH 0.0125 mol L^{-1}. The extraction of SO_4^{2-}-S was performed using calcium phosphate (500 mg L^{-1} P) in acetic acid 2.0 mol L^{-1} (1:2.5 v/v), and the concentration was determined by barium sulfate turbidimetry on a UV/VIS spectrophotometer (Metash UV-5100) (Silva, 2009). Soil organic matter (SOM) was estimated by colorimetric determination of Cr(III) (green color) reduced by organic carbon (1:10 v/v soil/solution) (van Raij et al., 2001). The extraction solution contained $Na_2Cr_2O_7$ 0.667 mol L^{-1} and H_2SO_4 5 mol L^{-1}.

Soybean and wheat yield

After lime and phosphogypsum application, until soil sampling, four wheat and four soybean crops were grown in succession. In 2012 and 2015 the wheat cultivar used was BRS Gaivota, fertilized with 150 kg ha^{-1} of 8-20-20 (N-P_2O_5-K_2O). Wheat yield in 2013 and 2014 is not shown, due to the occurrence of frosts during flowering. The soybean cultivar used was NA 5909, with sowing fertilizer of 250 kg ha^{-1} of formulated 02-20-18 (N-P_2O_5-K_2O). Seeds were inoculated with *Bradyrhizobium japonicum*. Cultural treatments followed the technical recommendations for the region.

Statistical analysis

Data were subjected to analysis of variance using *F*-test ($p<0.05$). Regardless of the significance of the *F*-test for interaction effects, main effects were analyzed separately. The quantitative factor (BS level) was subjected to regression analysis. For lime application method (SL and IL), which had only one degree of freedom, significance was determined by the *F*-test. Comparisons between combined treatments (lime + phosphogypsum) were performed using Tukey's test at the 5 % significance level. Factorial treatments (lime application method × BS level) and combined treatments (lime + phosphogypsum) were compared using Dunnett's test at the 5 % significance level.

RESULTS

Soil pH($CaCl_2$)

Incorporated lime increased soil pH at all layers sampled. The increase in soil pH was linear in the 0.00-0.05, 0.05-0.10, and 0.40-0.60 m layers and quadratic in the 0.10-0.20, 0.20-0.30, and 0.30-0.40 m layers, with maximum pH at 73, 72, and 73 % BS, respectively, reaching 5.53, 5.28, and 5.02 (Figure 1). Soil pH increased linearly with SL dose to a

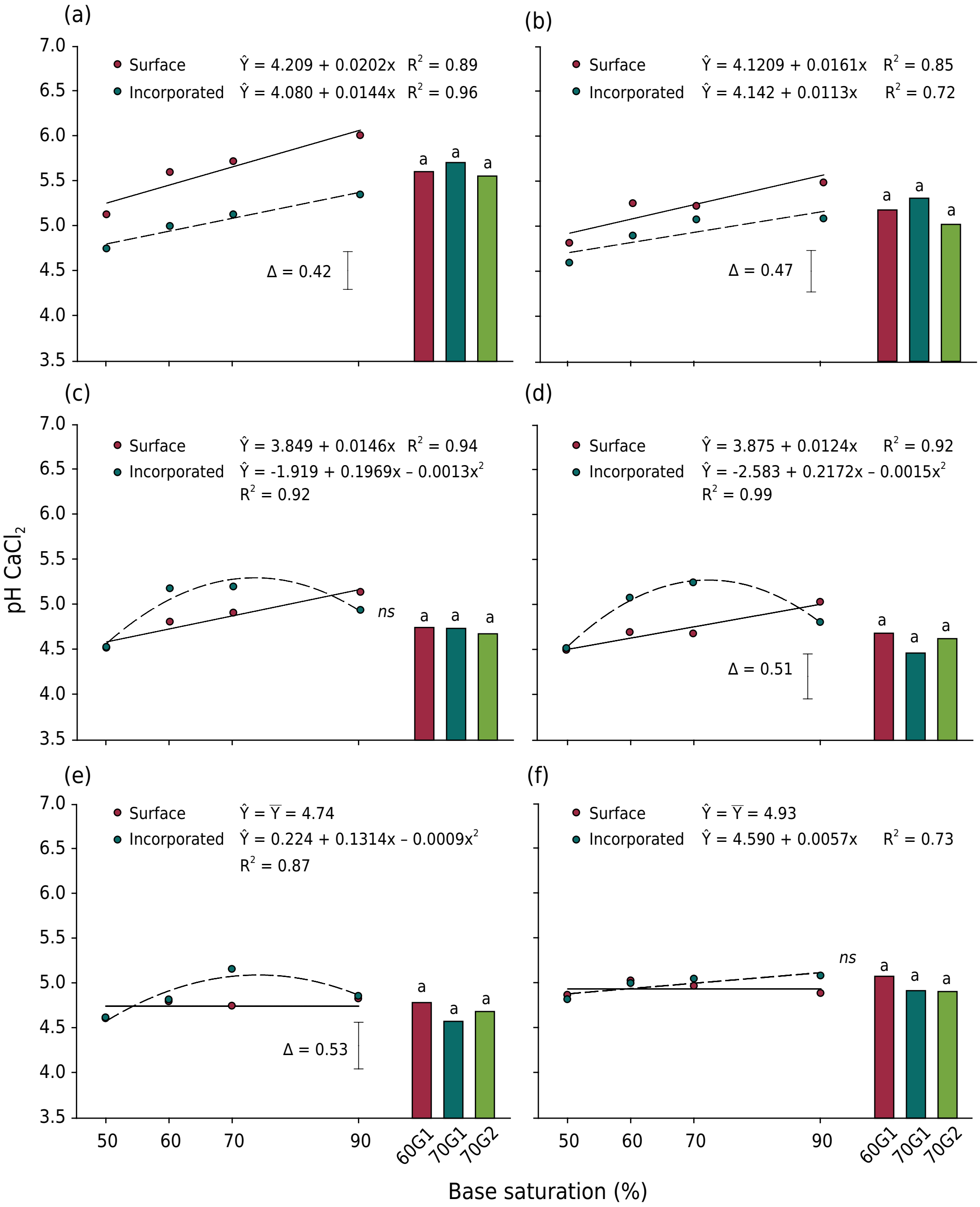

Figure 1. Soil pH($CaCl_2$) in the 0.00-0.05 (a), 0.05-0.10 (b), 0.10-0.20 (c), 0.20-0.30 (d), 0.30-0.40 (e), and 0.40-0.60 m (f) layers 48 months after treatment. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G1) or double (G2) dose of phosphogypsum as 60G1, 70G1, and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, $p<0.05$). Vertical bars represent least significant differences between treatments (Dunnett's test, $p<0.05$).

depth of 0.30 m (Figure 1). The angular coefficient of the linear models adjusted for the soil pH decreased in depth for SL (0.0202, 0.0161, 0.0146, and 0.0124).

The treatments 60G1, 70G1, and 70G2 did not change significantly soil pH at any depth (Figure 1). In comparing factorial (SL and IL) and phosphogypsum treatments, we found that 60G1, 70G1, and 70G2 resulted in a higher pH at the 0.00-0.05 m layer than IL50, IL60, IL70, and SL50 (Figure 1a). In the 0.05-0.10 m layer (Figure 1b), phosphogypsum treatments afforded a higher pH than SL50 and IL50 (unlimed soil). At this layer, the soil pH was higher with 70G1 treatment than with SL50 and SL90, and SL90 resulted in a higher soil pH than 70G2 treatment. In the 0.20-0.30 m layer, IL70 afforded a higher soil pH than phosphogypsum treatments, and IL60 resulted in a higher pH than 70G1 (Figure 1d). In the 0.30-0.40 m layer, the soil pH obtained with 70G1 treatment was lower than that obtained with IL70 (Figure 1e). At layers of 0.10-0.20 and 0.40-0.60 m (Figures 1c and 1f), no significant differences were observed between phosphogypsum and other treatments. Overall, phosphogypsum treatments had a similar soil pH to SL treatments with the same lime dose.

Exchangeable Al

No differences in Al^{3+} were detected in 0.00-0.05 m layer in the soil treated by SL (Figure 2a), because of this there is no model for SL. On the other hand, Al^{3+} levels decreased linearly with IL dose increasing at 0.00-0.05 and 0.05-0.10 m layers (Figures 2a and 2b) and quadratically at 0.20-0.30 and 0.30-0.40 m layers (Figures 2d and 2e). The soil Al^{3+} content decreases up to 74 and 78 % BS at 0.20-0.30 and 0.30-0.40 m layers (Figures 2d and 2e). Although it was not possible to fit any of the tested models to Al^{3+} data for the 0.10-0.20 m layer (Figure 2c), we observed a reduction in Al^{3+} with liming. In average, liming treatments decreased soil Al^{3+} content by 42 % compared with unlimed. Surface liming decreased soil Al^{3+} levels up to the depth of 0.10 m (Figures 2a and 2b). Aluminum levels at 0.10-0.20 m layer (Figure 2c) were very low in limed soil and low in unlimed soil (SBCS/NEPAR, 2019). No significant changes in Al^{3+} levels were observed in 0.40–0.60 m layer, regardless of lime dose or application method (Figure 2f).

Aluminum was not detected in the 0.00-0.05 m layer with the use of lime plus phosphogypsum (Figure 2a). Phosphogypsum treatments did not differ in Al^{3+} level at any depth. In the 0.05-0.10 m layer (Figure 2b), phosphogypsum treatments reduced Al^{3+} levels compared with IL50. At the other layers, no significant differences were observed between phosphogypsum and factorial treatments (Figures 2c, 2d, 2e, and 2f). The highest m% were observed for IL50 in the layers of 0.20-0.30 and 0.30-0.40 m, reaching values of 29 and 27 %, respectively (Figure 3).

Exchangeable Ca

Incorporated lime increased soil Ca^{2+} in the 0.00-0.05, 0.10-0.20, and 0.20-0.30 m layers, in which maximum Ca^{2+} levels (3.43, 2.92, and 1.70 $cmol_c\ dm^{-3}$) were estimated to be achieved at 73, 72, and 72 % BS, respectively (Figures 4a, 4c, and 4d). The average Ca^{2+} content in the 0.05-0.10 m layer was 1.97 $cmol_c\ dm^{-3}$ (Figure 3b). In SL soil, Ca^{2+} levels increased linearly with BS only at the 0.00-0.05 m layer, with 4.82 $cmol_c\ dm^{-3}$ Ca^{2+} at SL90 (Figure 3a). In the other layers, SL treatment did not influence Ca^{2+} levels, the Ca^{2+} content were 2.69, 1.80, and 0.99 $cmol_c\ dm^{-3}$ in the 0.05-0.10, 0.10-0.20, and 0.20-0.30 m, respectively. Treatments did not influence Ca^{2+} availability at 0.30-0.40 and 0.40-0.60 m layers, with mean Ca^{2+} values of 0.97 and 1.08 $cmol_c\ dm^{-3}$, respectively.

In the 0.00-0.05 m layer, Ca^{2+} levels were higher with 60G1 and 70G2 treatments than with IL50, IL60, and IL90 (Figure 3a). The treatment 70G2 afforded a higher Ca^{2+} level (5.53 $cmol_c\ dm^{-3}$) than IL treatments and SL50 (Figure 4a). In the 0.05-0.10 m layer, 70G1 increased Ca^{2+} (4.14 $cmol_c\ dm^{-3}$) compared with IL50, IL60, IL70, and SL50 (Figure 4b). No differences were observed between phosphogypsum and other treatments at 0.10-0.20 or 0.20-0.40 m layers (Figures 4c and 4d).

Exchangeable Mg

Soil Mg^{2+} levels increased linearly with SL doses at 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.40-0.60 m layers (Figures 5a, 5b, 5c, and 5f). The highest values were 2.83, 1.60, 0.97, and 0.58 $cmol_c\ dm^{-3}$ at 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.40-0.60 m layers, respectively. In the 0.20-0.30 and 0.30-0.40 m layers, no significant differences in Mg^{2+}

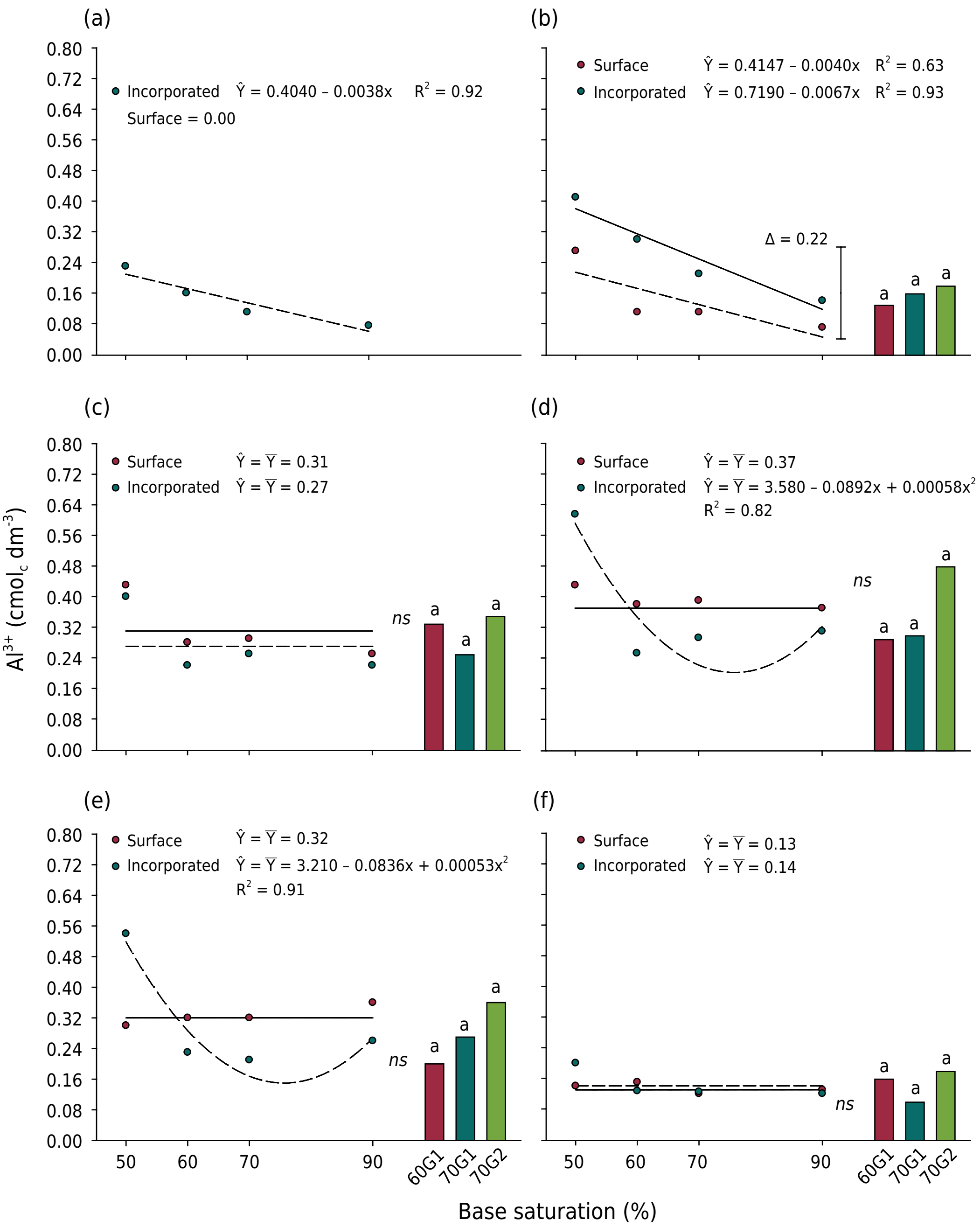

Figure 2. Soil aluminum (Al^{3+}) content in the 0.00-0.05 (a), 0.05-0.10 (b), 0.10-0.20 (c), 0.20-0.30 (d), 0.30-0.40 (e), and 0.40-0.60 m (f) layers 48 months after treatment. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G1) or double (G2) dose of phosphogypsum as 60G1, 70G1, and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, $p<0.05$). Vertical bars represent least significant differences between treatments (Dunnett's test, $p<0.05$).

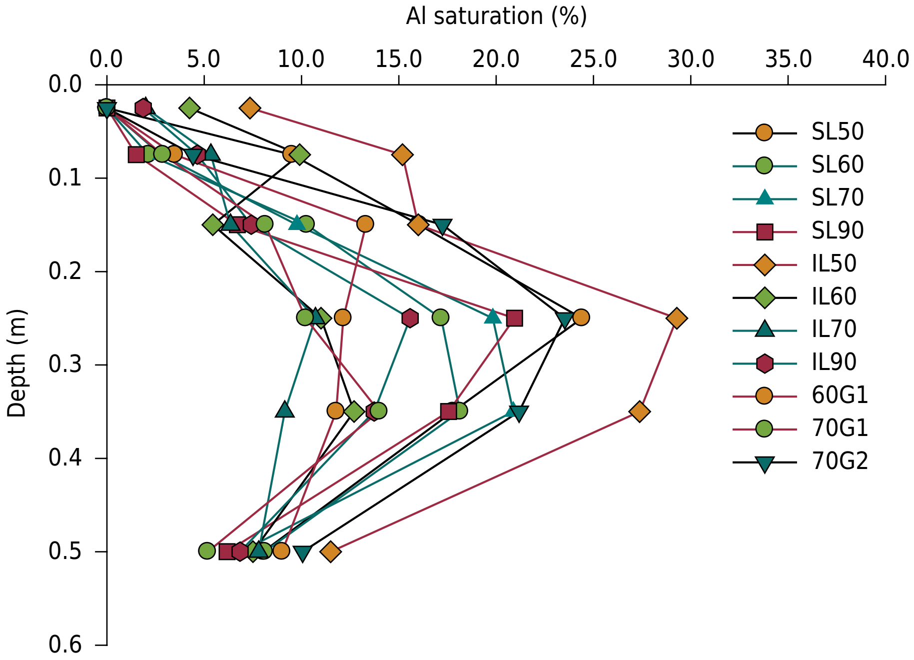

Figure 3. Saturation by aluminum (m%) at different depths 48 months after application of lime. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G1) or double (G2) dose of phosphogypsum as 60G1, 70G1, and 70G2.

levels were observed (Figures 5d and 5e), with Mg^{2+} content in the soil of 0.40 and 0.38 $cmol_c$ dm^{-3}, respectively. Incorporated liming increased Mg^{2+} levels in all studied soil layers. The increase of Mg^{2+} followed a quadratic behavior in the 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m layers, with estimated maximum values at BS levels of 79, 82, 77, 81, and 74 %, respectively. In the 0.40-0.60 m layer (Figure 5f), Mg^{2+} levels increased linearly from 0.41 (IL50) to 0.55 $cmol_c$ dm^{-3} (IL90).

The treatments with phosphogypsum differed only in the 0.05-0.10 m layer, in which 70G2 afforded lower Mg^{2+} levels than 70G1 (Figure 5b). Significant differences in soil Mg^{2+} content were observed between lime and lime plus phosphogypsum treatments in all layers. In the 0.00-0.05 m layer, SL90 resulted in a higher Mg^{2+} level than phosphogypsum treatments, as did SL70 compared with 60G1 and 70G2 (Figure 5a). At the 0.05-0.10 m layer, Mg^{2+} content was higher with SL90 (1.60 $cmol_c$ dm^{-3}) than with any phosphogypsum treatment. It was also observed that 70G1 resulted in higher soil Mg^{2+} than unliming, and 70G2 decreased Mg^{2+} levels compared with SL60 and SL70 (Figure 5b). In the 0.10-0.20 m layer, Mg^{2+} were lower in 70G2 than IL60, IL70, and SL90 (Figure 5c). Magnesium level in the 0.20-0.30 m layer was lower with 70G2 treatment (0.24 $cmol_c$ dm^{-3} of Mg^{2+}) than with IL60, IL70, and IL90 (Figure 4d). Similarly, in the 0.30-0.40 and 0.40-0.60 m layers, 70G2 decreased Mg^{2+} levels compared with IL60, IL70, IL90, and SL90 (Figure 5e). Magnesium content in the 0.40-0.60 m layer was lower in 60G1 than in treatments with BS 90 % (regardless of application method) and IL70. At this layer, SL70 increased soil Mg^{2+} compared with 70G2 (Figure 5f).

Exchangeable K

Liming method (SL and IL) and BS level (50, 60, 70, and 90 %) did not influence K^+ content at any layer (Figure 6). No differences were observed between phosphogypsum treatments. In the 0.00-0.05, 0.05-0.10, and 0.30-0.40 m layers, no differences in K^+ contents were observed between lime and lime plus phosphogypsum treatments. At the 0.10-0.20 m depth, 70G2 significantly decreased K^+ availability compared with IL60, IL70, IL90, and SL60 (Figure 6). In the 0.20-0.30 m layer, 70G2 also decreased soil K^+ compared with

IL60, IL70, and SL90. The use of higher phosphogypsum dose 70G2 afforded a low K^+ content in the 0.40-0.60 m layer compared with SL90. In general, higher K^+ levels were detected in surface layers, as levels decreased with depth (Figure 6).

Sulfate content

Sulfate levels increased with depth (Figure 7). There was no effect of SL on SO_4^{2-}-S levels. Soil SO_4^{2-}-S levels were classified as high in topsoil (0.00-0.20 m) (SBCS/NEPAR,

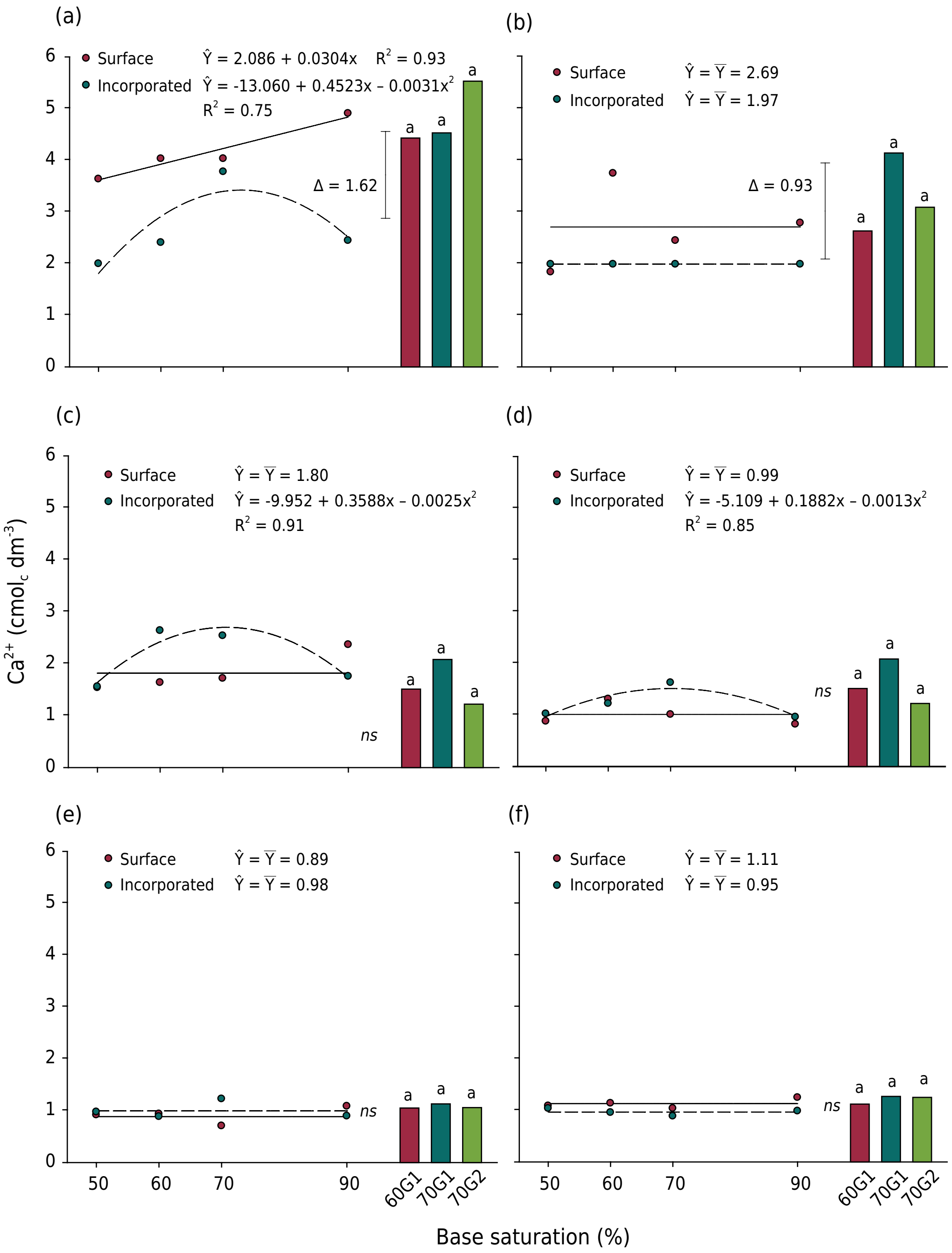

Figure 4. Soil calcium (Ca^{2+}) content in the 0.00-0.05 (a), 0.05-0.10 (b), 0.10-0.20 (c), 0.20-0.30 (d), 0.30-0.40 (e), and 0.40-0.60 m (f) layers 48 months after treatment. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G1) or double (G2) dose of phosphogypsum as 60G1, 70G1, and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, $p<0.05$). Vertical bars represent least significant differences between treatments (Dunnett's test, $p<0.05$).

2019). Incorporated liming doses had a quadratic effect on SO_4^{2-}-S in the 0.20-0.30 m layer, with the lowest SO_4^{2-}-S content (4.28 mg dm^{-3}) estimated to occur at 69 % BS (Figure 7d).

Phosphogypsum treatments did not differ from each other at any layer. Compared with lime treatments, lime + phosphogypsum treatments had a low residual effect. The treatment 60G1 afforded a higher SO_4^{2-}-S content than SL50 and SL60 in the 0.05-0.10 m layer. In the 0.10-0.20 m layer, 60G1 and 70G2 increased SO_4^{2-}-S content compared with SL50, SL60, SL70, IL60, and IL90. In the 0.20-0.30 m layer, 60G1 and 70G2 increased soil

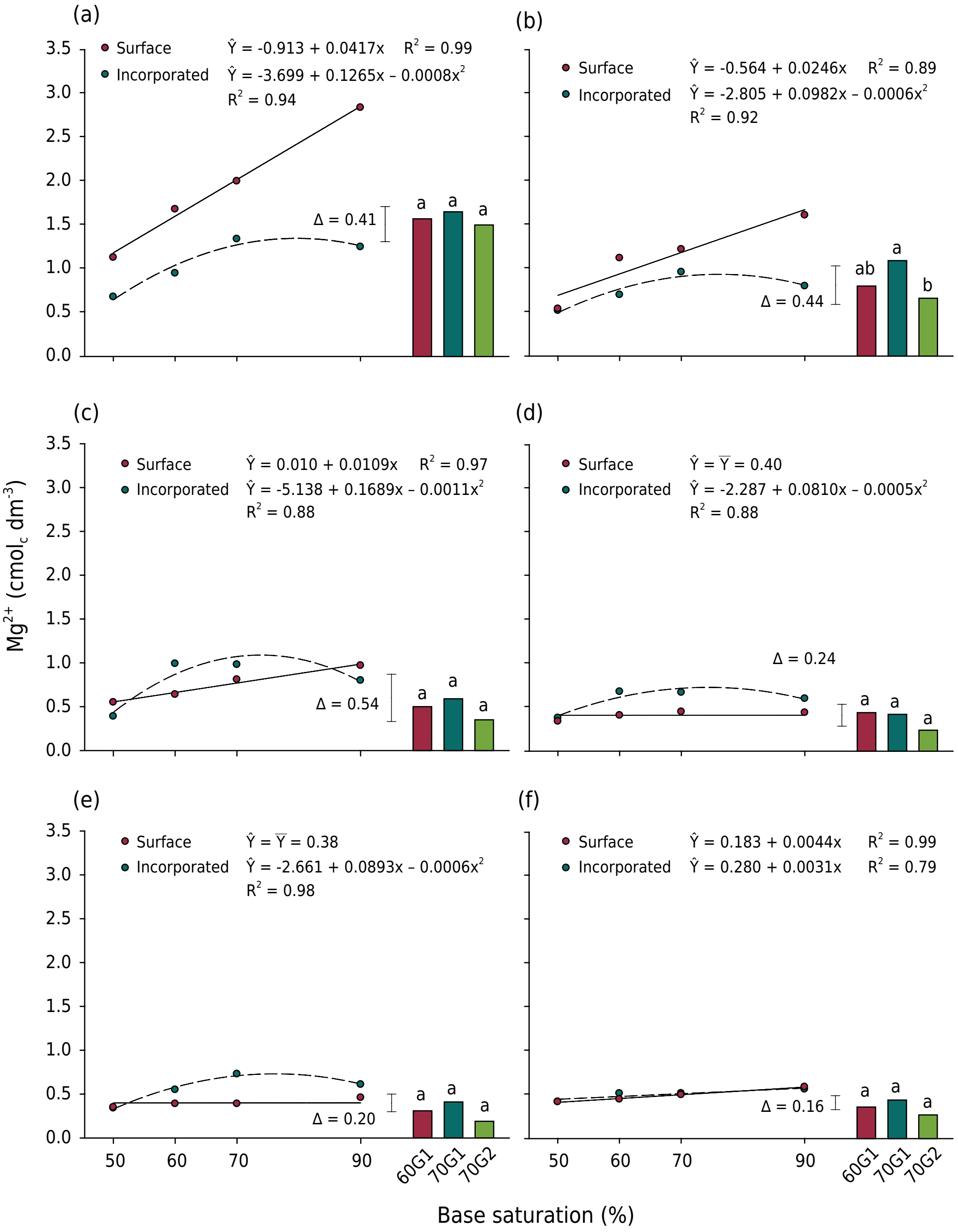

Figure 5. Soil magnesium (Mg^{2+}) content in the 0.00-0.05 (a), 0.05-0.10 (b), 0.10-0.20 (c), 0.20-0.30 (d), 0.30-0.40 (e), and 0.40-0.60 m (f) layers 48 months after treatment. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G1) or double (G2) dose of phosphogypsum as 60G1, 70G1, and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, p<0.05). Vertical bars represent least significant differences between treatments (Dunnett's test, p<0.05).

SO_4^{2-}-S in comparison with IL60 and IL70. In the 0.30-0.40 m layer, SO_4^{2-}-S levels were higher with 60G1 than with SL50, SL60, SL70, IL60, and IL90, whereas 70G2 afforded higher SO_4^{2-}-S levels (17.04 mg SO_4^{2-}-S) than IL treatments, SL50, and SL60.

Soil organic matter

Base saturation levels and phosphogypsum treatments did not influence SOM at any layer. Incorporated liming reduced SOM by 8.76 g dm^{-3} in the 0.00-0.05 m layer and increased SOM by 2.75 g dm^{-3} in the 0.10-0.20 m soil layer compared with SL (Figure 8). Soil organic matter was highest in topsoil and decreased with depth.

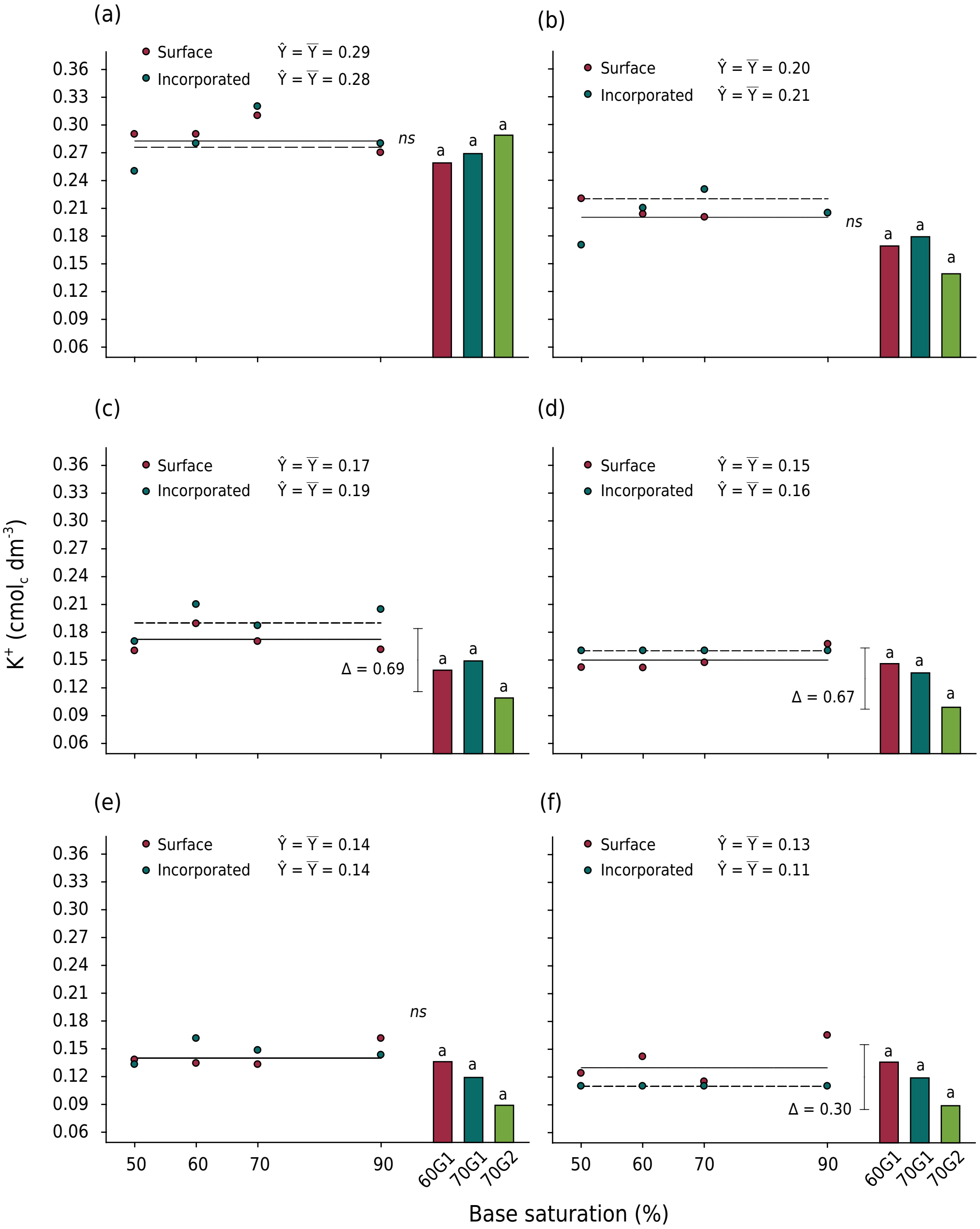

Figure 6. Potassium (K^+) levels in in the 0.00-0.05 (a), 0.05-0.10 (b), 0.10-0.20 (c), 0.20-0.30 (d), 0.30-0.40 (e), and 0.40-0.60 m (f) layers 48 months after treatment. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (*IL*) or treated by surface application of lime (60 and 70 % BS) and a standard (G*1*) or double (G*2*) dose of phosphogypsum as 60G1, 70G1, and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, p<0.05). Vertical bars represent least significant differences between treatments (Dunnett's test, p<0.05).

Soybean and wheat yield

Soybeans and wheat yield were not influenced by the base saturation levels in any season, however, they responded to the way of applying lime and phosphogypsum (Figure 9). Similary, the additional treatments with lime and phosphogypsum did not differ in any season. For the 2012 wheat season, IL reduced yield by 235 kg ha^{-1} in relation to the SL. The 60G2 treatment increased the grain yield by 7.7 % compared to 50IL. When considering the same base saturation in IL and with phosphogypsum, it is noted that 70G1 increased grain yield by 12.8 % and 60G1 by 8.7 %. For the 2015 wheat season, the only difference was the 5.2 % increase in 70G1, compared to 60IL.

For soybean 2012/13 season, IL increased the yield by 122 kg ha^{-1}, however, in 2013/14 it reduced productivity by 172 kg ha^{-1}, with no effect on other seasons. In the comparison

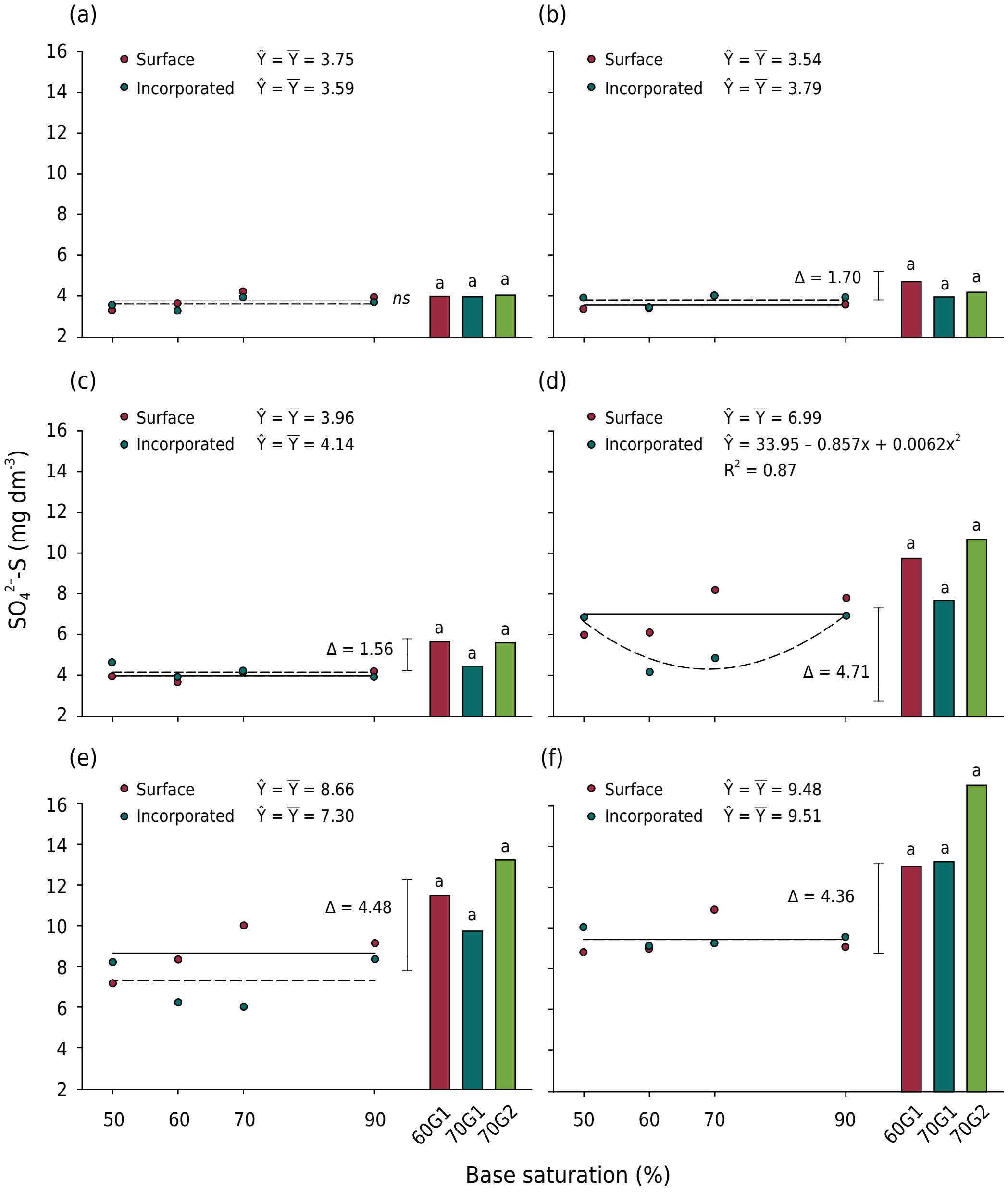

Figure 7. Sulfate (SO_4^{2-}-S) content in the 0.00-0.05 (a), 0.05-0.10 (b), 0.10-0.20 (c), 0.20-0.30 (d), 0.30-0.40 (e), and 0.40-0.60 m (f) layers at 48 months after treatment. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G*1*) or double (G*2*) dose of phosphogypsum *as* 60G1, 70G1, and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, p<0.05). Vertical bars represent least significant differences between treatments (Dunnett's test, p<0.05).

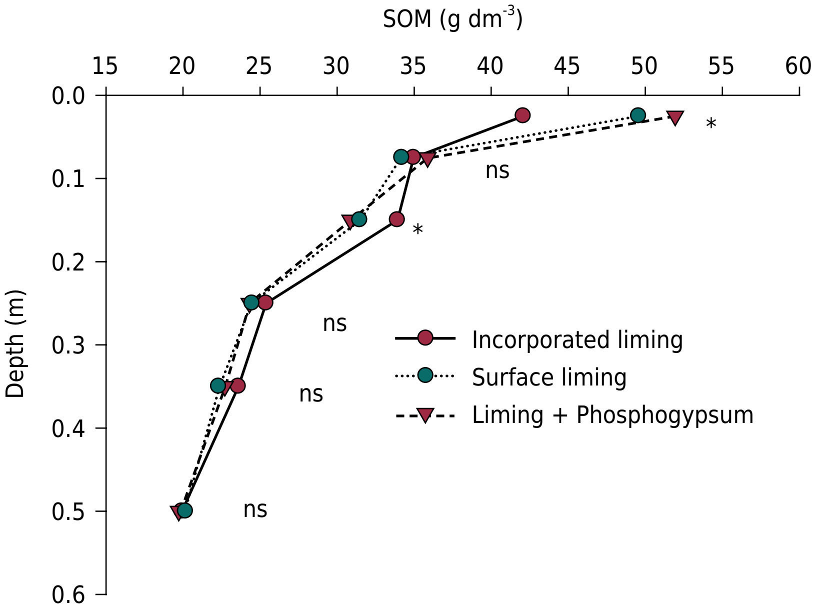

Figure 8. Soil organic matter (SOM) content in the soil profile as a function of liming method (surface application or incorporation) and combined surface treatment with lime and phosphogypsum (GY). Surface application, *n* = 16; lime incorporation, *n* = 16; lime + GY, *n* = 12.

between factorial vs. additional treatments, we observed that 50IL, 60IL, and 90IL increased grain yield in relation to treatments with lime plus phosphogypsum in 2012/13, however in 2013/14, 60G1 with 5068 kg ha^{-1} increased yield in compared to 50, 60, and 90IL (Figure 9). For the 2014/15 and 2015/16 seasons, no changes were observed, with yields of 5028 and 3418 kg ha^{-1}, respectively (Figure 9).

DISCUSSION

In our study, at 48 months after liming and a cumulative rainfall of about 7931 mm, the residual effects of liming on soil acidity attributes were more pronounced in IL than in SL soil (Figures 1, 2, 3, 4, and 5). Surface liming had a limited effect on soil pH until a depth of 0.20 m, whereas IL reduced acidity up to 0.60 m depth (Figure 1). The reaction of the lime in the soil was faster and deeper when it was incorporated, because there was a better distribution of the lime in the 0.00-0.20 m soil layer and the dissolution was accelerated with the increase of the lime contact with the soil. The average time for most of the reaction to raise the soil pH is three months, depending on the type and granulometry of lime and main application mode (Rheinheimer et al., 2018; Auler et al., 2019). In the areas where the lime was applied on the surface and without incorporation, the reaction was slower because it concentrated the entire dose on the surface and because the lime solubility is low (0.014 g L^{-1}). The reaction of the lime applied on the surface without incorporation can take from 15 to 36 months (Oliveira et al., 1997); however, it depends on variables such as rainfall, soil texture and porosity, particle size, and lime reactivity, as well as on the plant material present in the soil or on its surface (Corrêa et al., 2018).

Presence of plant residues on surface soil in NT reduces Al^{3+} content through the formation of highly stable complexes (chelates) (Miyazawa et al., 1993). Therefore, the carbon accumulated in NT soil ensures that the predominant form of Al is linked to organic compounds, maintaining phytotoxic species and Al^{3+} activity below the critical limit for plant growth (Martins et al., 2020). This explains the absence of Al^{3+} in the 0.00-0.05 m layer and the low levels observed in unlimed surface layers in SL. In addition, we observed that the highest values of m% are found precisely in IL50, without lime, and with soil turning (Figure 3).

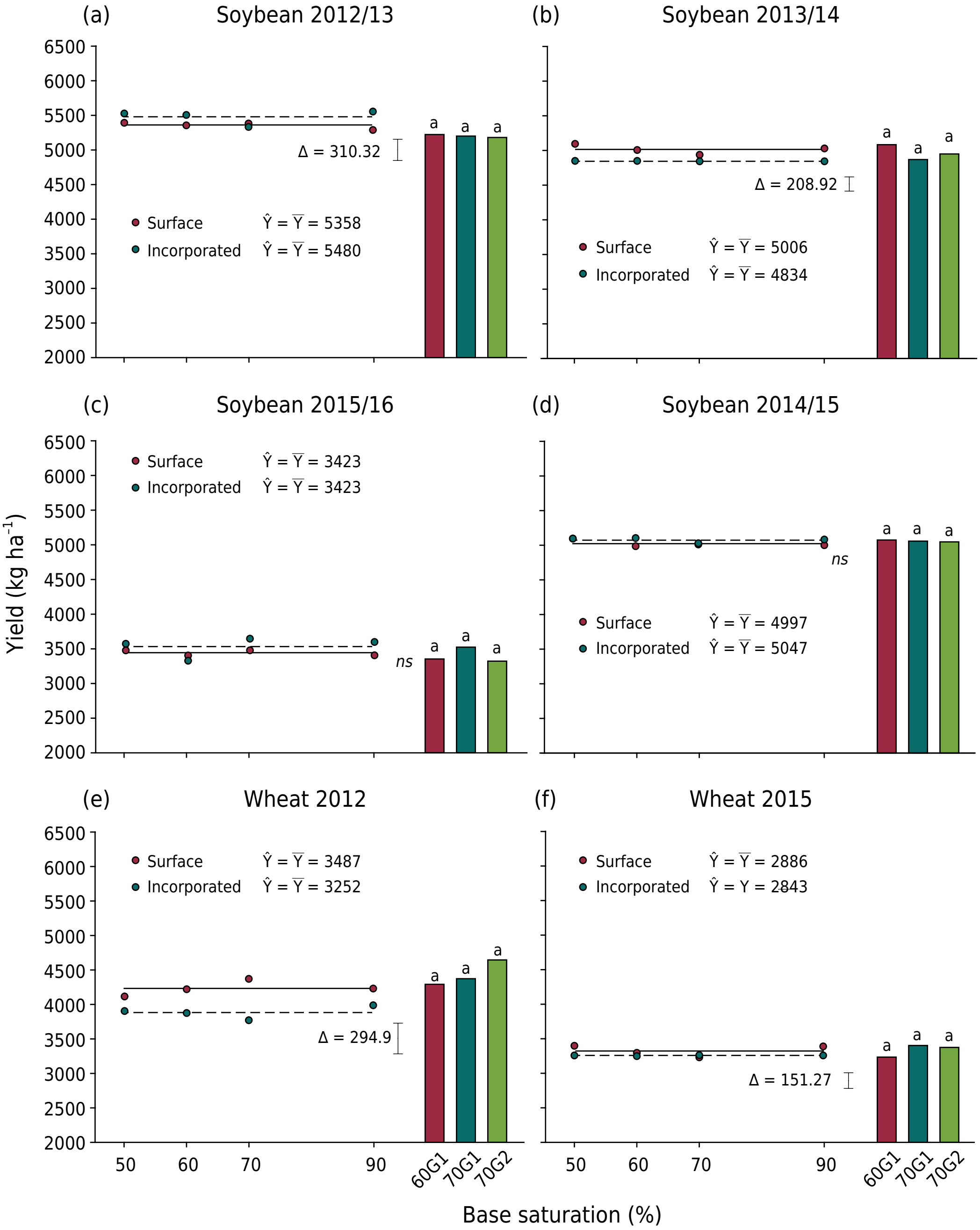

Figure 9. Yield of soybeans and wheat due to the application of lime and phosphogypsum. Soils were limed to different base saturation (BS) levels (50, 60, 70, and 90 %) by surface application (SL) or lime incorporation (IL) or treated by surface application of lime (60 and 70 % BS) and a standard (G1) or double (G2) dose of phosphogypsum as 60G1, 70G1 and 70G2. Different letters above columns indicate significant differences between phosphogypsum treatments (Tukey's test, $p<0.05$). Vertical bars represent the least significant differences between treatments (Dunnett's test, $p<0.05$), and "ns"means that there was no difference in the comparison between additional treatments and factorials.

Using phosphogypsum together with lime did not bring extra benefits to the decrease in soil acidity at 48 months post-application, as also observed by Costa and Crusciol (2016). In our study, phosphogypsum did not alter Al^{3+} levels, in agreement with Zambrosi et al. (2007), who found no effects at 55 months after applying up to 9 Mg ha^{-1} phosphogypsum. Such a result may be attributed to the low soil Al^{3+} content (Fontoura et al., 2019). However, Caires et al. (1999) observed a reduction in soil Al^{3+} in the 0.05-0.10, 0.20-0.40, 0.40-0.60, and 0.60-0.80 m layers at 14 months after phosphogypsum application to a Latossolo (pH 4.5 and 0.6 $cmol_c$ dm^{-3} Al^{3+} in the 0.00-0.20 m layer). The basic dissociation rate of phosphogypsum is 8.3×10^{-13}, which is considered to be very low. Under soil conditions, phosphogypsum cannot generate hydroxyls (OH^-) to react with H^+ and/or Al^{3+} reducing the concentration of both in the soil (Alcarde, 2005). Pavan (1986) state that phosphogypsum, in addition to supplying Ca to the soil, decreasing the chemical activity of Al^{3+}, it can reduce the concentration of Al^{3+} in the soil due to the precipitation of alunite, basaluminite, and jurbanite. Additionally, the base saturation usually recommended (70) + the standard phosphogypsum dose, i.e., 70G1, kept m% below 14 % in the all soil profile (Figure 3).

Although the effects of IL were more evident, SL also produced significant alterations in soil chemical properties (Figure 1). At 48 months after application, Costa and Crusciol (2016) observed that SL increased soil pH up to 0.20 m depth; such effects extended throughout the soil profile at 60 months after reapplication. At 35 months after SL to acidic soil at NT, Pöttker and Ben (1998) observed changes in soil chemical properties mainly in the 0.00-0.05 m layer and, to a lesser extent, in the 0.05-0.10 m layer. Gonçalves et al. (2011) observed that the beneficial effects of liming on pH were maintained for up to 36 months but were restricted to the 0.10 m depth layer. Caires et al. (2008), on the other hand, found that at 108 months after SL there was an increase in pH and a decrease in exchangeable Al^{3+} up to a depth of 0.60 m.

The effects of SL in subsurface layers only occur after the zone of lime dissolution reaches a pH of 5.2-5.5. As long as there are acid cations (H^+ and/or Al^{3+}), neutralization of acidity will be limited to surface layers, slowing the effect in deeper layers (Rheinheimer et al., 2000). In our study, prior to experiment implementation, the pH was 5.25 in the 0.00-0.20 m layer, which might have contributed to the increase in soil pH up to 0.30 m depth. The efficiency of SL in subsurface layers depends on several factors, such as rainfall, soil texture, porosity, particle size, lime reactivity, presence of plant residues, and time (Corrêa et al., 2018). Under tropical conditions in Brazil, Tiritan et al. (2016) monitored the chemical properties of soil at 6, 12, and 18 months after liming and observed that SL exerted similar effects to IL, increasing pH levels in 0.00-0.30 m soil layer, as observed in our study. According to the authors, the absence of detrimental physical factors favored the efficiency of SL.

One factor that can contribute to the incorporation of surface liming into the soil is repeated sowing. In the present study, eight sowings were performed after liming, four of soybean and four of wheat. Sowing contributes to the downward movement of lime particles, especially in wheat crops, whose row spacing (0.17 m) promotes greater horizontal action, and soybean crops, whose row spacing (0.45 m) and greater planting depth allow greater vertical mobility.

Surface liming was not as effective as IL in increasing Ca^{2+} levels in subsurface layers (Figure 4). Our results agree with those of Alleoni et al. (2005), who observed an increase in Ca^{2+} levels in the 0.00-0.10 m layer at 30 months after lime application. In a study conducted in an Oxisol under subtropical conditions, Fontoura et al. (2019) observed short-term (one year) effects of liming on Ca^{2+} levels only in the 0.00-0.10 m soil layer and long-term effects (11 years) up to 0.20 m depth. An acidic medium with low Ca^{2+} content is required for effective lime dissolution (Zocca and Penn, 2017). Prior to liming, soil Ca^{2+} levels were 3.82 and 2.37 $cmol_c\ dm^{-3}$ in the 0.00-0.20 and 0.20-0.40 m layers, respectively, values considered high (SBCS/NEPAR, 2019).

Lime plus phosphogypsum application did not increase Ca^{2+} levels in subsurface soil (Figure 3). These results differ from those of Vicensi et al. (2020), who found that Ca^{2+} levels increased linearly with increasing phosphogypsum doses in all soil layers at 42 and 54 months after application. The authors also reported that 0.00-0.10 and 0.10-0.20 m soil layers had a BS of 15 and 4 % and Ca^{2+} contents of 1.00 and 0.40 $cmol_c\ dm^{-3}$, respectively. Caires et al. (1999) observed a positive effect of phosphogypsum on Ca^{2+} levels at all evaluated depths, with an initial BS of 32 % and Ca^{2+} content of

1.6 $cmol_c$ dm^{-3}. Therefore, the effects of phosphogypsum on increasing Ca^{2+} levels at subsurface layers tend to be more expressive in acidic soils with low Ca^{2+} content.

Another explanation for the absence of residual phosphogypsum effects is the leaching of Ca^{2+} to depths greater than those sampled in this study. Caires et al. (2001) observed rapid Ca^{2+} leaching at 24 months after phosphogypsum application: 40 % of applied Ca^{2+} leached below 0.80 m depth. In our study, cumulative rainfall between soil treatment and sampling exceeded 7.931 mm. Thus, the lack of Ca and S (Figure 7) may indicate intense leaching of the ion pair $CaSO_4^0$ to subsurface soil layers.

Soil Mg^{2+} levels increased with IL and SL doses up to 0.60 m depth (Figure 4f). Fidalski and Tormena (2005) also observed an increase in Mg^{2+} levels up to 0.60 m depth in a *Latossolo* subjected to SL. According to the authors, Mg^{2+} content was the best chemical indicator of SL efficiency. In a study conducted by Caires et al. (1999), Mg^{2+} levels were higher in the 0.40 m layer at 40 months after application, revealing slow and gradual movement of Mg^{2+}. Our results also corroborate Fontoura et al. (2019) and Vargas et al. (2019), who observed that liming effects were more pronounced on Mg^{2+} than on Ca^{2+}. High Mg^{2+} mobility can be attributed to the lower oxygen-binding energy of soil colloid functional groups, which leads to the accumulation of this nutrient in soil solution and facilitates desorption compared with other cations (Vargas et al., 2019). Magnesium was more sensitive to the use of high doses of phosphogypsum.

The effect of treatments on soil acidity (pH and Al^{3+}) and exchangeable cations (Ca^{2+} and Mg^{2+}) was found to depend on the soil layer (Figures 1, 2, 3, and 4). Gonçalves et al. (2011) argued that the effect of SL is not the same across soil layers. It is important to point out that during dolomitic lime dissolution, neutralizing ions (CO_3^{2-}, HCO_3^-, OH^-), Ca^{2+}, and Mg^{2+} are released. Because soil layers have different physicochemical parameters (physical properties, aeration, water availability, and ionic interaction), the behavior of dissolution products differs with depth. Therefore, it cannot be expected that soil acidity and exchangeable cation levels will increase in the same magnitude or in the same layers.

Lime dose influenced its movement throughout the soil profile. Significant reductions in acidity and Ca^{2+} and Mg^{2+} increased availability were only observed at the highest doses (Gonçalves et al., 2011). In our study, SL dose played an important role in improving chemical properties in deeper soil layers. However, in IL, this effect was less evident. Incorporated liming doses had mainly a quadratic relationship with the evaluated variables; beneficial effects were observed at 72 to 82 % BS but not at the highest dose (BS of 90 %).

Low K^+ availability in 70G2-treated soil was due to the high phosphogypsum dose and, consequently, $K_2SO_4^0$ formation (Pavan, 1986). Rampim et al. (2011) observed that phosphogypsum doses of up to 5 Mg ha^{-1} linearly reduced K^+ levels up to 0.10 m depth. Ramos et al. (2013) found that phosphogypsum application was effective in improving the root environment but reduced K^+ level in deeper layers (>0.85 m depth). Treatment of a *Latossolo* with calcium sulfate reduced K^+ in surface layers and increased K^+ in deeper layers (Silva et al., 1997). However, in the referred study, leaching was found to be lower when calcium sulfate was applied together with lime (Silva et al., 1997). The mobility and availability of K^+ after phosphogypsum treatment depend on certain soil characteristics. Of note, K^+ leaching tends to be lower in clayey NT soils subjected to SL because of an increase in effective CEC and K^+ retention. Our results of Mg^{2+} and K^+ mobility in a 74 % clay soil differ from those obtained by Basso et al. (2015) for 70 % clay soil. The authors found that, in this type of soil, surface application of phosphogypsum was not effective in promoting vertical displacement of Mg^{2+} and K^+ at 36 months after application; effects were limited to topsoil (0.10 m depth).

Higher levels of SO_4^{2-}-S were observed in deeper layers, not differing between phosphogypsum doses (3.71 and 7.40 Mg ha^{-1}) (Figure 7). The conditions of the surface layer of soil in NT are unfavorable to SO_4^{2-}-S adsorption because of the presence of phosphate fertilizers, lime, and organic matter (Churka Blum et al., 2013). Churka Blum et al. (2013) observed that at 3.5 years after phosphogypsum application, SO_4^{2-}-S had not migrated toward deeper layers, even in soil with high SO_4^{2-}-S adsorption capacity. Caires et al. (2004) observed an increase in SO_4^{2-}-S levels up to 0.60 m depth at 43 months after phosphogypsum application, as observed in our study for 70G2. However, the low residual effect and high SO_4^{2-}-S levels at 0.40-0.60 m depth indicate that SO_4^{2-}-S probably reached deeper soil layers (>0.61 m). The Fertilization and Liming Manual of Paraná State, Brazil (SBCS/NEPAR, 2019), reports that the application of 700-3.200 kg ha^{-1} phosphogypsum exerts minimal residual effects for five years. However, little is known about the residual effect of larger doses. Vicensi et al. (2020) observed that split phosphogypsum application is an important strategy to reduce SO_4^{2-}-S leaching. Other studies observed residual effects of phosphogypsum on SO_4^{2-}-S levels in subsurface layers after 5 (Costa and Crusciol, 2016) and 11 years (Fontoura et al., 2019).

Reduction of surface SOM in IL is also associated with the soil C loss to the atmosphere by soil disturbance induced by tillage (Figure 8), in addition to the increase in temperature on the soil surface (Iamaguti et al., 2015). Increases in SOM in the subsurface layer in IL are more related to soil plow and crop residue incorporation, while there is a more intense soil C stratification in NT areas without lime incorporation (Alcântara et al., 2016; Chenu et al., 2019). The increase in SOM content with depth in IL soil may be associated with the less favorable conditions of subsurface layers for microbial decomposition. This factor, associated with the incorporation of plant residues and high soil clay content, promotes chemical and physical protection of organomineral complexes through cation bond formation (Yagi et al., 2014).

Our results agree with those of Alleoni et al. (2005), who observed no effect of lime doses on SOM at 30 months after application. However, there was an effect of the application method SOM levels were higher in the 0.00-0.05 m layer in SL soil and the 0.05-0.10 m layer in IL soil. Auler et al. (2019) observed that liming increased SOM in the 0.00-0.10 m layer compared with baseline values. However, no differences were found between application methods. In the referred study, the soil had high acidity (pH 3.7 and 3.6) at depths of 0.00-0.10 and 0.10-0.20 m, respectively.

Throughout the seasons, the different base saturation tested (50, 60, 70, and 90 %) and the different forms of lime application (SL and IL) did not significantly change the soybean and wheat yields (Figure 9). Bortolini et al. (2016) mentioned that base saturation of 50 % must be adopted as the liming criterion for the main crops grown under consolidated NT. Our results show that, although IL acts on the acidity at deeper soil layers, it does not influence crop yield, suggesting that continuous NT promotes benefits that were maximized with phosphogypsum application for wheat yield and soil chemical properties. We emphasize the importance of long-term studies in experiments with soil management because although IL increased soybean yield in the first harvest, it reduced yield in subsequent crops.

Recently, Alves et al. (2021) also did not observe a yield increasing of two soybean and two corn crops after liming, and before the implementation of the experiment, the saturation by Al (m%) was 0.0, 2.7, and 7.4 at the soil layers of 0.00-0.10, 0.10-0.20 and 0.20-0.30 m, respectively, that is, low acidity, as in our study. Although the crops have not responded to base saturation levels, we propose that farmers should pursue values of 60 to 70 % without the need to increase to 90 %. This is because, in this range of base saturation of 60 to 70 %, we provide the soil with adequate levels of Ca^{2+} and Mg^{2+}, while base saturation of 90 % can cause imbalance, decreasing the potassium availability, and be an unnecessary economic investment for farmers. Also, clay soils with a high content of organic matter and consequently high buffering power will have difficulty in increasing pH and base saturation, with practical liming being indispensable.

As observed in our study and by Pias et al. (2020) and Tiecher et al. (2018), after analyzing a robust data set, wheat is more responsive to phosphogypsum than soybean. Soybean is less responsive to phosphogypsum than are grass crops by the effect of its increased ability to absorb exchangeable Ca from the soil solution and its lesser dependence on nitrogen uptake from the soil, as soybean obtains most of the nitrogen by biological fixation (Vicensi et al., 2016; Alves et al., 2021). According to Tiecher et al. (2018), the possibility of soybean response to phosphogypsum application once with acidity at 0.20-0.40 m, is higher when there are also periods of water deficit.

When considering wheat, our results corroborate those of Tiecher et al. (2018), who proposed that the critical level for recommending phosphogyspum for grasses in subtropical Oxisols under NT is 3.0 $\text{cmol}_c\ \text{dm}^{-3}$ of Ca^{2+} in the 0.20-0.40 m layer (or Al saturation greater than 10 %), in contrast to the recommendations for tropical soils in Brazil, where phosphogypsum is recommended in soils with 0.5 $\text{cmol}_c\ \text{dm}^{-3}$ or 20 % aluminum saturation in the 0.20-0.40 m layer (Souza et al., 2005).

Another aspect that may have contributed to the increase in wheat yield is the levels of sulfur observed in the soil, which are lower than those proposed by Pias et al. (2019), who, after evaluating 58 seasons, proposed that the critical levels of sulfur in the soil surface (0.00-0.20 m) and the subsurface layer (0.20-0.60 m) are 7.5 and 8.5 mg dm^{-3}. When considering the Fertilization Manual for the state of Paraná (SBCS/NEPAR, 2019), the availability of SO_4^{2-}-S for treatments without phosphogypsum were above the critical level in the 0.20 m layer, but below the critical level in the layer of 0.20-0.40 m, which is 3 and 9 mg dm^{-3}, respectively. According to Pias et al. (2019), the main factor that controls the crop response to sulfur fertilization in NT soils in Brazil is the content of SO_4^{2-}-S available in the soil, with 50 % of the crops showing increased yield when the levels of SO_4^{2-}-S were below the mentioned critical level.

CONCLUSION

Surface liming increased pH value and Ca^{2+}, Mg^{2+}, K^+, and SOM levels in surface layers (0.00-0.20 m). However, SO_4^{2-}-S levels were higher in subsurface layers (>0.20 m). In deeper layers, SL exerted significant effects on pH (up to 0.30 m depth) and Mg^{2+} mobility (0.40-0.60 m layer). Surface liming effects were not homogeneous throughout the soil profile and varied according to the layer and chemical properties evaluated. Incorporated liming altered soil properties in a more homogenous manner and up to greater depths. However, soil organic matter levels were low in the surface layer, even at 48 months after tillage. A double phosphogypsum dose (70G2 = 7.42 Mg ha^{-1}) was not more effective than a regular dose (3.71 Mg ha^{-1}) in increasing Ca^{2+} levels and had the added disadvantage of reducing Mg^{2+} and K^+ levels. Thus, the application of high phosphogypsum doses should be avoided. The standard phosphogypsum dose improved soil SO_4^{2-}-S and Ca^{2+} contents. Based on our findings, for places with a previously liming and consequently low acidity, we do not recommend the incorporation of lime and it is also not necessary to apply lime to achieve a base saturation of 90 %. Lime and phosphogypsum association increases wheat yield; however, soybean does not respond to phosphogypsum.

AUTHOR CONTRIBUTIONS

Conceptualization: Marcos Renan Besen (lead) and Marcelo Augusto Batista (lead).

Data curation: Bruno Maia Abdo Rahmen Cassim (supporting), Carolina Fedrigo Coneglian (equal), Marcos Renan Besen (lead).

Formal Analysis: Wagner Deckij Kachinski (lead).

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