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Soil acidity correction and fertilization strategies: Effects on acidity, nutrient availability, and crop yield

Lucas Nascimento Brum[(1)], João Pedro Moro Flores[(1)], Lucas Aquino Alves[(2)], Dionata Filippi[(3)], Dayana Jéssica Eckert[(1)], Gustavo Pesini[(1,2)], Tadeu Luis Tiecher[(1)], Jessé Rodrigo Fink[(4)], Djalma Eugênio Schmitt[(5)], Amanda Posselt Martins[(1)], Danilo Reinheimer dos Santos[(6)] and Tales Tiecher[(1)*]

[(1)] Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Solos, Programa de Pós-Graduação em Ciência do Solo, Porto Alegre, Rio Grande do Sul, Brasil.
[(2)] Universidade Regional Integrada do Alto Uruguai e das Missões, Departamento de Ciências Agrárias, Frederico Westphalen, Rio Grande do Sul, Brasil.
[(3)] North Carolina State University, Department of Crop and Soil Sciences, Raleigh, North Carolina, United States of America.
[(4)] Instituto Federal do Paraná, *Campus* Palmas, Palmas, Paraná, Brasil.
[(5)] Universidade Federal de Santa Catarina, Programa de Pós-Graduação em Ecossistemas Agrícolas e Naturais, Curitibanos, Santa Catarina, Brasil.
[(6)] Universidade Federal de Santa Maria, Departamento de Solos, Programa de Pós-Graduação em Ciência do Solo, Santa Maria, Rio Grande do Sul, Brasil.

*** Corresponding author:**
E-mail: tales.tiecher@ufrgs.br

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ABSTRACT: High soil acidity and low nutrient availability in the deeper soil layers of no-tillage systems (NTS) can restrict crop yield potential. This study aimed to evaluate the impact of different soil acidity correction strategies and P and K application methods on the vertical variation of soil acidity, nutrient availability, and on corn and soybean yields. A randomized block factorial experiment was established in 2020 on a Plinthosol (*Plintossolo Argilúvico Distrófico típico*) under NTS since 2004. The first factor consisted of soil acidity correction strategies: (i) control, (ii) surface application of dolomitic limestone, (iii) surface application of calcium and magnesium oxide (CaO·MgO), and (iv) incorporation of dolomitic limestone to 0.20 m depth. The second factor corresponded to P and K application methods: (i) control without fertilization, (ii) in-furrow application, and (iii) surface broadcast application. The corrective amendment rates were calculated to raise the soil pH in the 0.00–0.20 m layer to 6.0. Six months after treatment application, soil samples were collected down to a depth of 0.40 m. Application of CaO·MgO increased soil pH, $Ca^{2+}+Mg^{2+}+K^+$ saturation, and Ca^{2+} and Mg^{2+} contents, but these effects were confined to the surface soil layer (0.00–0.10 m). In contrast, limestone incorporation reduced soil pH, and $Ca^{2+}+Mg^{2+}+K^+$ and Al^{3+} saturation gradients over a greatest soil depth (0.00–0.15 m), demonstrating greater effectiveness than both surface-applied limestone and CaO·MgO. Improvements in soil acidity resulting from limestone incorporation led to a 66 % increase in corn yield compared to other correction strategies. Soil chemical properties were minimally affected by P and K application methods, with higher available P observed only in the 0.00–0.05 m layer under surface broadcast application. Nevertheless, in-furrow P and K fertilization increased corn yield by 35 % compared to surface application. Soybean yield was not influenced by any of the treatments. In soils with high subsurface acidity, incorporating soil amendments is essential for effective acidity correction and yield improvement, while in-furrow P and K fertilization remains an efficient strategy to sustain high crop yields.

Keywords: calcium and magnesium oxide, dolomitic limestone, no-tillage, corn, soybean.

INTRODUCTION

Tropical and subtropical soils in Brazil generally exhibit low natural fertility, which limits the productivity of major crops relative to their genetic potential and favorable climatic conditions (Battisti et al., 2018). Although irregular rainfall contributes to this limitation, the main restriction to water-use efficiency arises from reduced root development, caused by soil acidity and low nutrient availability in the subsurface layers under no-tillage systems (NTS) (Bellinaso et al., 2021; Artuso et al., 2024).

In soils managed under NTS, the surface layer (0.00–0.10 m) usually presents high chemical fertility, with elevated levels of P, K, Ca, and Mg, along with low soil acidity. However, in the subsurface layers this condition is reversed, with high soil acidity and exchangeable aluminum (Al^{3+}), and low nutrient availability (Calegari et al., 2013). Subsurface acidity restricts root growth, impairing water and nutrient uptake, especially in areas that did not receive adequate correction before NTS adoption. Under water-limiting conditions, these constraints are intensified by nutritional deficiencies and physiological stresses. In the context of climate change and potential reduction in water availability in southern Brazil, mitigating these limitations is essential for the sustainability of agricultural systems (Siqueira et al., 2021; Maksic et al., 2022).

Liming aims to increase soil pH, reduce Al^{3+} levels, enhance cation exchange capacity (CEC), and supply exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}). However, under NTS, knowledge gaps remain regarding the most suitable strategies for soil acidity correction, particularly concerning the type of amendment and the method of application, which determine both reactivity and the speed of acidity neutralization down in the soil profile (Rheinheimer et al., 2018a). Limestone, the most widely used amendment, has low solubility and limited mobility when broadcast on the soil surface, which restricts its corrective effect at depth, especially in soils with low amendment mobility (Rheinheimer et al., 2018a). As an alternative, Ca and Mg oxides (CaO·MgO) have finer particle size and greater solubility, favoring the downward movement of the alkalinizing front in the soil profile (Li et al., 2019). Comparatively, their neutralizing power and solubility (1,200 mg L^{-1}) are far superior to those of limestone (14 mg L^{-1}) (Alcarde, 2005), enhancing subsurface acidity correction and the supply of Ca^{2+} and Mg^{2+} within a shorter period.

The method of P and K application also influences nutrient availability and crop productivity. Fertilizer placement in-furrow, simultaneously with sowing, promotes nutrient diffusion and absorption, reduces nutrient loss by runoff, and improves plant establishment (Nkebiwea, 2016; Martins et al., 2022). Conversely, surface broadcasting offers operational advantages and lower costs. However, broadcasting tends to concentrate nutrients in the topsoil (0.00-0.05 m), limiting deeper root development and yield potential (Rafain et al., 2020; Artuso et al., 2024).

In this context, the present study was based on the following hypotheses: (i) incorporation of soil acidity amendments is more effective in neutralizing subsurface acidity, regardless of the amendment type; and (ii) applying fertilizers with P and K in-furrow during sowing reduces the vertical gradient of nutrient availability in the soil, thereby enhancing crop yield under NTS. This study aimed to evaluate soil acidity correction strategies and methods of applying P and K fertilizers regarding the vertical distribution of acidity and nutrient availability in the soil, as well as their effects on corn and soybean yields, six months after treatment application, in a Plinthosol under NTS in southern Brazil.

MATERIALS AND METHODS

Experimental site and design

The experiment was established in October 2020 at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul, located in Eldorado do Sul, Rio Grande do Sul, Brazil (latitude 30° 05′ S, longitude 51° 40′ W, altitude 28 m). The regional climate is classified as Cfa (humid subtropical) according to Köppen classification system (Alvares et al., 2013), with an average annual temperature of 20 °C and mean annual rainfall of 1,481 mm (Inmet, 2017). Rainfall and temperature data recorded during the experimental period are presented in figure 1.

The soil at the experimental site is classified as a *Plintossolo Argilúvico Distrófico típico* (Santos et al., 2025), corresponding to a Plinthosol (IUSS Working Group WRB, 2022). In the 0.00–0.40 m layer, the soil contains 177, 251, and 573 g kg^{-1} of clay, silt, and sand, respectively. Chemical properties of the soil before the beginning of the experiment are shown in table 1.

Since 2004, the area had been cultivated with soybean (*Glycine max*) and corn (*Zea mays*) as summer crops, alternating between black oat (*Avena strigosa*) and fallow during winter. In the year prior to the experiment (2019), corn was grown for silage in summer, followed by black oat as a cover crop in winter.

The experiment was arranged in a randomized block design in a factorial scheme with three replications. The first factor consisted of soil acidity correction strategies: (i) control (no amendment), (ii) surface-applied dolomitic limestone, (iii) surface-applied calcium and magnesium oxide (CaO·MgO), and (iv) incorporated dolomitic limestone. The second factor consisted of methods of applying P and K fertilizers: (i) control (no fertilization), (ii) in-furrow application, and (iii) surface broadcasting (Table 2). Each plot measured 6 × 10 m (60 m^2), totaling approximately 0.45 ha, including buffer zones, with 3 m spacing between blocks to avoid machinery traffic over the experimental area. Limestone incorporation was performed using a heavy disk harrow to a depth of 0.20 m. In the other treatments, soil structure was left undisturbed prior to the experiment.

Based on the weighted average of soil properties in the 0.00–0.20 m layer (Table 1), the limestone requirement was estimated to reach a target pH of 6.0, using the SMP index (Shoemaker-McLean-Pratt method). The calculated requirement was 3.2 Mg ha^{-1} of a limestone source with 100 % effective calcium carbonate equivalent (ECCE). According to the chemical and physical analyses, dolomitic limestone had an ECCE of 75 %, calcium carbonate equivalent (CCE) of 94.95 %, and a total fineness efficiency of 80 %, containing 30 % CaO and 16.4 % MgO. The Ca/Mg oxide (CaO·MgO) amendment had an ECCE of 175 %, with 49.3 % CaO and 31.9 % MgO. Therefore, the applied doses were 5.6 Mg ha^{-1} for dolomitic limestone and 2.6 Mg ha^{-1} for CaO·MgO.

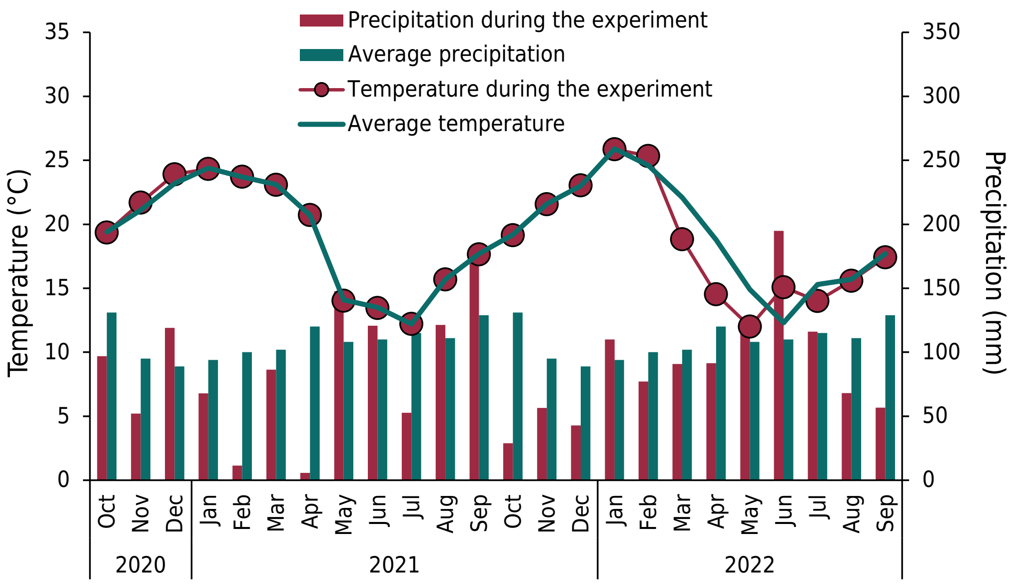

Figure 1. Monthly precipitation and mean temperature during the experimental period (October 2020 to September 2022) and 20-year monthly averages in Eldorado do Sul, Rio Grande do Sul, Brazil.

Table 1. Soil chemical characterization of the experimental area up to 0.40 m depth in a Plinthosol in southern Brazil

Soil chemical property	Soil layer (m)			Interpretation by CQFS-RS/SC (2016) for 0.00-0.10 m soil layer	Reference
	0.00-0.10	0.10-0.20	0.20-0.40		
Clay (g kg^{-1})	148	75	-	Class 4	Textural class 4 (≤200 g clay kg^{-1})
$pH(H_2O)$ (1:1, v/v)	5.4	4.6	4.5	Below reference value	Soil pH below the reference value for no-tillage (pH ≥6.0)
SMP index	6.3	5.8	5.2	-	-
H+Al ($cmol_c$ dm^{-3})	3.1	5.9	11.6	-	-
Available P (mg dm^{-3})	70.3	45.6	21.0	High	Available P high for a soil containing ≤200 g kg^{-1} of clay (60 mg dm^3)
Available K (mg dm^{-3})	159	89	90	High	Available K high for a CEC at pH 7.0 value of 7.6 and 15.0 $cmol_c$ dm^{-3} (90 mg dm)
Exchangeable Al ($cmol_c$ dm^{-3})	0.2	1.2	2.2	-	-
Exchangeable Ca ($cmol_c$ dm^{-3})	2.9	0.6	0.3	Below reference value	Ca^{2+} below the adequate threshold (4.0 $cmol_c$ dm^{-3})
Exchangeable Mg ($cmol_c$ dm^{-3})	1.4	0.4	0.2	Above reference value	Mg^{2+} above the adequate threshold (1.0 $cmol_c$ dm^{-3})
Available Zn (mg dm^{-3})	2.0	0.5	0.5	Above reference value	Zn above the adequate threshold (0.5 mg dm^{-3})
Available Cu (mg dm^{-3})	0.7	0.9	1.0	Above reference value	Cu above the adequate threshold (0.4 mg dm^{-3})
Exchangeable Mn (mg dm^{-3})	37.0	13.5	7.0	Above reference value	Mn above the adequate threshold (5.0 mg dm^{-3})
Sum of Ca^{2+} + Mg^{2+} + K^+ ($cmol_c$ dm^{-3})	4.8	1.3	0.8	-	-
Effective CEC ($cmol_c$ dm^{-3})	4.9	2.4	3.0	-	-
CEC at pH 7.0 ($cmol_c$ dm^{-3})	7.8	7.1	12.4	-	-
Ca^{2+}+Mg^{2+}+K^+ saturation (%)[(1)]	56	18	7	Below reference value	Ca^{2+}+Mg^{2+}+K^+ saturation below thereference value (≥65 %)
Al^{3+} saturation (%)[(2)]	8	50	74	Below reference value	Al^{3+} saturation below the reference value (≥10 %)

[(1)] Ca^{2+}+Mg^{2+}+K^+ saturation (%) = [(Ca^{2+} + Mg^{2+} + K^+) / CTC at pH 7.0)] × 100. [(2)] Al^{3+} saturation (%) = (Al^{3+} / Effective CEC) × 100.

Phosphorus and K fertilization rates were defined to maintain soil nutrient levels at the conditions present when the experiment was established, based on expected yields of 4 Mg ha^{-1} for soybean and 10 Mg ha^{-1} for corn. Fertilizer requirements were calculated according to CQFS-RS/SC (2016) recommendations, with N, P, and K rates of 135, 61, and 133 kg ha^{-1} for corn and 35, 79, and 233 kg ha^{-1} for soybean, respectively. Nitrogen fertilization in corn was determined according to soil organic matter content and the target yield of 10 Mg ha^{-1}. Thus, 35 kg ha^{-1} N was applied at sowing, followed by two topdressings at stages V4 and V8, using urea as the N source.

Sowing dates were October 31, 2020 (corn), April 23, 2021 (black oat), and November 26, 2021 (soybean). The crop varieties used were corn hybrid Balu 388 VIP3, with a population density of 55,000–60,000 plants ha^{-1}; black oat cv. EMBRAPA 139, with a density of 350,000 plants ha^{-1}; and soybean cv. M 5947 IPRO, with a density of 250,000–300,000 plants ha^{-1}. Black oat received only N fertilization at a rate of 50 kg ha^{-1}.

Table 2. Description of the treatments combining soil acidity correction strategies and P and K fertilization

Treatment	Soil acidity correction strategy	P and K fertilization strategy
1	Control (no amendment)	Control (no P and K)
2	Control (no amendment)	Surface broadcasting
3	Control (no amendment)	In the sowing row (in-furrow)
4	Surface limestone	Control (no P and K)
5	Surface limestone	Surface broadcasting
6	Surface limestone	In the sowing row (in-furrow)
7	Surface Ca and Mg oxide	Control (no P and K)
8	Surface Ca and Mg oxide	Surface broadcasting
9	Surface Ca and Mg oxide	In the sowing row (in-furrow)
10	Incorporated limestone	Control (no P and K)
11	Incorporated limestone	Surface broadcasting
12	Incorporated limestone	In the sowing row (in-furrow)

Soil sampling and analyses

Soil samples were collected in April 2021, six months after treatment application, from the 0.00–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, 0.25–0.30, and 0.30–0.40 m soil layers. Samples were taken both from rows and interrows. After collection, soils were air-dried, ground, and sieved through a 2 mm mesh. Soil pH was determined in water using a 1:1 (v/v) soil-to-water suspension, and the SMP index was determined in a 1:1:0.5 ratio of soil, water, and SMP solution (Tedesco et al., 1995). Potential acidity (H+Al) was estimated from the SMP index using the equation proposed by Kaminski et al. (2001) and adopted by the CQFS-RS/SC (2016) (Equation 1):

$$H + Al = e^{10.665 - 1.1483 \times pH\ SMP} / 10 \qquad \text{Eq. 1}$$

Soil available P and K were extracted using Mehlich-1, while exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted using 1.0 mol L^{-1} NH_4Cl. Extracts were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES). From these results, effective CEC, CEC at pH 7.0, saturation by $Ca^{2+}+Mg^{2+}+K^{+}$ and by Al^{3+} saturation were calculated.

Since some treatments involved mechanical soil disturbance, soil penetration resistance was measured on June 21, 2021, from 0 to 0.40 m using a digital penetrometer (Falker PLG 1020). Measurements were taken at 1 cm intervals and grouped into soil layers (0.00–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, 0.25–0.30, and 0.30–0.40 m). On the same date, soil samples were also collected to determine gravimetric water content, following Donagemma (2011). Samples were taken from each layer in the disturbed structure, stored in sealed plastic containers to prevent moisture loss, dried at 105 °C, and weighed to obtain fresh and dry mass.

Statistical analysis

Data normality was verified using the Shapiro–Wilk test, and variance homogeneity was assessed by Levene test, both at a 5 % significance level. When assumptions were met, data were subjected to analysis of variance (ANOVA), considering acidity correction strategies, fertilization methods, and soil layers as fixed effects, and blocks as a random effect. When ANOVA was significant ($p<0.05$), treatment means were compared by Tukey test ($p<0.05$). Statistical analyses were performed using Sisvar software (Ferreira, 2011).

RESULTS AND DISCUSSION

Effect of acidity correction strategies on soil chemical properties

Six months after application, surface liming increased soil pH only in the 0.00–0.05 m soil layer, reaching values >5.5 (Figure 2a), and also increased the exchangeable Ca content at the same soil layer (Figure 2c). No significant changes were observed in the saturation by Ca^{2+}+Mg^{2+}+K^{+}, in exchanheable Mg, or in Al^{3+} saturation compared with the control (Figure 2). These findings reinforce the limited effectiveness of surface-applied liming, which primarily affects only the uppermost soil layers, as reported by Rheinheimer et al. (2018a). Therefore, surface application of limestone is more suitable only when subsurface acidity has already been corrected during the establishment of the NTS (Bortoluzzi et al., 2014). In this sense, recent studies have shown that adequate acidity correction through incorporation has a residual effect of up to 42-year, and that after this deep correction, soil reacidification can be managed with surface-applied liming (Alves et al., 2025), thereby ensuring greater use efficiency of P (Tiecher et al., 2023a) and K (Pesini et al., 2025).

The formation of an alkaline front restricted to the surface-applied limestone has also been observed by Bellinaso et al. (2021). The dissolution of dolomitic limestone depends on the diffusion of H^{+} from the soil solution to the diffuse double layer, a process limited to the contact zone between the limestone particle and the soil solution. Thus, there is no excess of anions (CO_3^{2-} and OH^{-}) that would enable H^{+} neutralization in deeper soil layers, and the downward movement of the amendment depends on turbulent water transport through macropores in the soil profile (Petrere et al., 2001; Borges et al., 2023). Therefore, even if fine limestone particles accumulate at the soil surface, their migration into deeper layers is slow and limited, generally occurring only after several years of application (Rheinheimer et al., 2018a,b).

Limestone incorporation through plowing to a depth of 0.20 m, followed by disking, increased soil pH above 5.5 down to 0.10 m depth (Figure 2a). However, part of the tilled layer still showed high acidity, possibly due to low rainfall during the evaluation period, 29.4 % below the historical average (Figure 1), which may have limited the amendment reaction (Tiritan et al., 2016). As a consequence, Al^{3+} saturation decreased to <30 % down to 0.20 m and remained lower than the control up to 0.30 m depth (Figure 2e). This indicates that only incorporated liming was able to reduce Al^{3+} saturation to levels considered adequate, consistent with results from a long-term study (34 years; Rheinheimer et al., 2024b), where the critical Al^{3+} saturation in the 0.10–0.15 m layer was 44, 24, and 20 % for soybean, wheat, and cover crops, respectively.

Limestone incorporation also increased Ca^{2+}+Mg^{2+}+K^{+} saturation between 0.05–0.30 m and exchangeable Ca contents down to 0.15 m depth, compared with surface-applied limestone (Figure 2b). These results are consistent with the findings of Bellinaso et al. (2021) and Bortoluzzi et al. (2014). Incorporation enhances the solubilization of limestone products, unblocking functional groups of soil organic matter and promoting the deprotonation of sorption sites, which allows the formation of surface complexes with Ca^{2+} and Mg^{2+}. Thus, the greater depth of the alkaline front observed with incorporated limestone agrees with Rheinheimer et al. (2018b). Direct contact between the amendment and soil particles in the tilled layer promotes more efficient and faster acidity correction (Bossolani et al., 2021). In this context, limestone incorporation at the establishment of NTS is essential for creating an initial soil environment free of Al^{3+} toxicity and with fertility levels closer to optimal, especially within the zone of greatest root activity (i.e., 0.00-0.20 m).

When subsurface soil constraints are only related to acidity, CaO·MgO application is an interesting alternative to accelerate Al^{3+} neutralization in deeper soil layers without tillage. This amendment is obtained from limestone, which is heated until the metamorphic rock structure breaks, forming oxides and releasing CO_2 into the atmosphere. The solubilization of CaO·MgO does not depend on H^{+} diffusion to the diffuse double layer; instead, it occurs through simple dissolution into the soil solution, reaching an equilibrium pH close to 12.8.

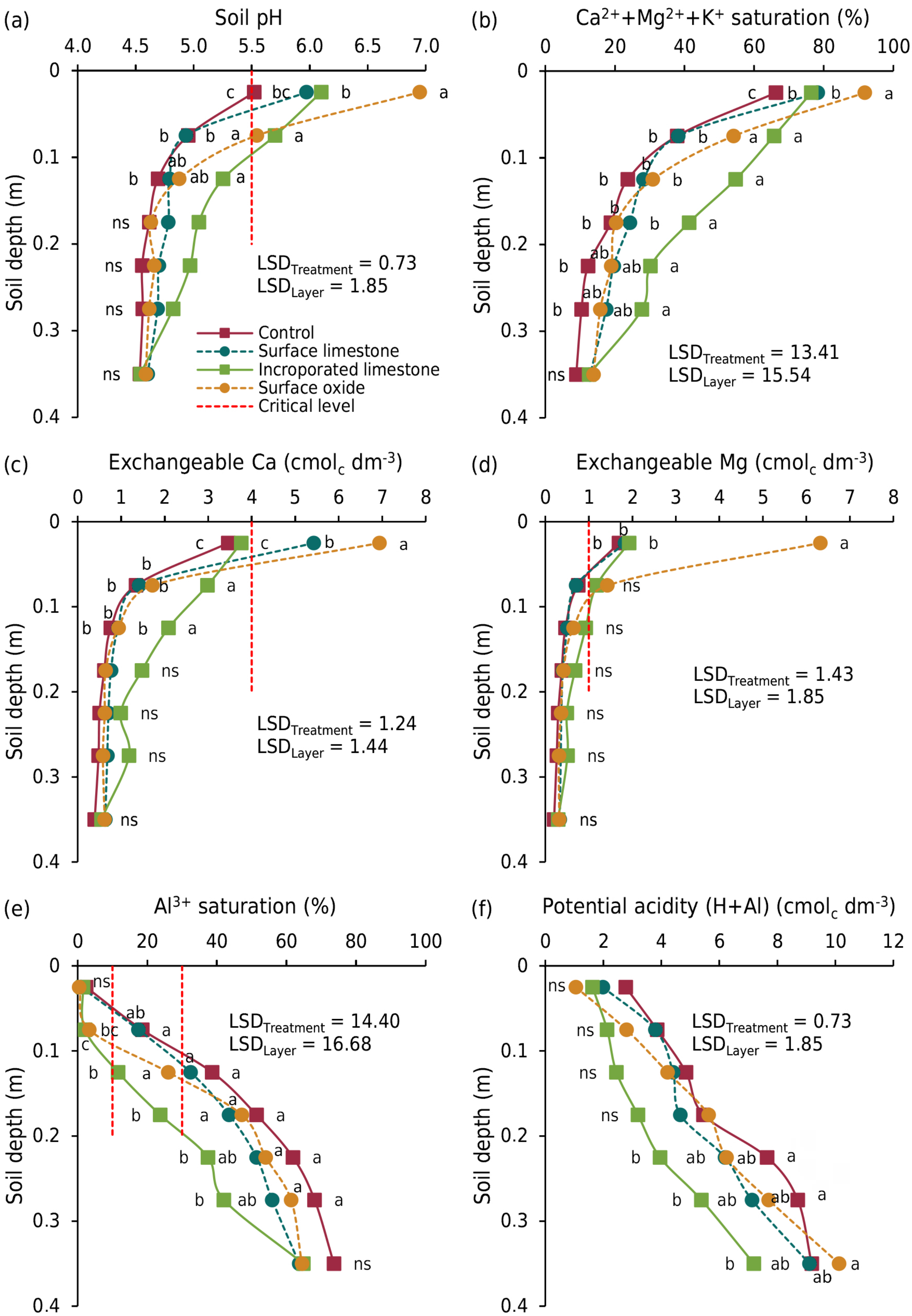

Figure 2. Mean values of soil pH (a), Ca^{2+}+Mg^{2+}+K^{+} saturation (b), exchangeable Ca (c) and Mg (d), Al^{3+} saturation (e), and potential acidity (H+Al) (f) at different soil layers, as affected by soil acidity correction strategies, six months after treatment application in a Plinthosol in southern Brazil. Means followed by different letters indicate significant differences among acidity correction strategies within each soil layer according to Tukey test ($p<0.05$); ns: not significant by Tukey test ($p>0.05$); LSD: least significant difference.

Only six months after surface application of CaO·MgO onto crop residues, all exchangeable Al^{3+} was neutralized, and increases in exchangeable Ca and Mg, as well as $Ca^{2+}+Mg^{2+}+K^{+}$, were observed down to a depth of 0.10 m (Figure 2). These marked changes result from the faster and more intense reaction of the soluble products of CaO·MgO. Soil pH and $Ca^{2+}+Mg^{2+}+K^{+}$ saturation values in the 0.05–0.10 m layer indicate higher short-term efficiency of CaO·MgO than surface-applied limestone. This also suggests that the finer particle size of CaO·MgO is an important factor for its movement into deeper soil layers. CaO·MgO proved effective, similar to incorporated limestone, in correcting Al^{3+} saturation in the 0.05–0.10 m layer compared with the control. Therefore, CaO·MgO application can be an alternative to increase soil pH and reduce Al^{3+} saturation, providing a favorable environment for root growth, improving fertilizer efficiency, and reducing susceptibility to water stress.

Effect of P and K fertilization method on their availability in the soil

In the control treatment, without P, the 0.00–0.20 m soil layer already had P levels above the critical threshold for corn and soybean (CQFS-RS/SC, 2016). A clear excess of Mehlich-1 extractable P was observed in the surface layer (0.00–0.05 m), consistent with long-term experiments (37 and 66 years) under P fertilization in conservation grain production systems (Tiecher et al., 2023b). When exposed to surface runoff, this surplus of P poses a risk of being transported to water bodies, potentially contributing to eutrophication (Grando et al., 2021). This issue is particularly concerning in the southern half of Rio Grande do Sul, where soil erosion processes are becoming increasingly severe (Ramon et al., 2024). According to Gatiboni et al. (2020), the critical environmental P threshold (Mehlich-1) for the soil clay content in this study ranges from 48 to 83 mg dm^{-3}. Surface-applied P increased P concentration in the 0.00–0.05 m soil layer to 137 mg dm^{-3} (Figure 3a). In contrast, in-row P application and the control did not differ, showing an average of 76 mg dm^{-3} of P in the same soil layer. At depths below 0.05 m, the P fertilization method had no significant effect. It is worth noting that the soil has low clay content (Table 1), suggesting that part of the P adsorption sites was already saturated. Therefore, both the mean concentration in the 0.00–0.05 m layer and the weighted average up to 0.10 m depth (106 mg dm^{-3}) in the surface application treatment were well above this critical limit, indicating that additional P fertilization is not recommended for this area.

Likely due to the already high P levels in the 0.00–0.20 m soil layer (mean of 75 mg dm^{-3}), reapplication of P fertilizer in the sowing row (in-furrow) had little impact on nutrient desorption, resulting in P increases of 9.4, 15.5, and 30.9 % in the 0.00–0.05, 0.05–0.10, and 0.10–0.15 m soil layers, respectively, compared to the control (Figure 3a). From an agronomic standpoint, these results may influence fertilizer application decisions, since the CQFS-RS/SC (2016) guidelines consider a variation of 9.9 mg dm^{-3} sufficient to change the availability class for recommending P application in soils with clay content below 200 g kg^{-1}.

Across all treatments, a P availability gradient was evident, with higher concentrations in the surface layer and a sharp decline with depth, which is characteristic of NTS (Tiecher et al., 2017). This gradient can hinder P diffusion to plant roots, especially under water deficit conditions (Silva et al., 2020), as observed in the first year of evaluation. Phosphorus uptake is more efficient when the nutrient is located closer to the rhizosphere (Degryse et al., 2017). Thus, the P placement in-furrow (closer to the roots) may have enhanced nutrient uptake, resulting in higher yields and, consequently, greater nutrient export. It is noteworthy that, even with the application of 61 and 133 kg ha^{-1} of P and K, respectively, nutrient availability did not differ from the control, except for P in the 0.00–0.05 m layer. This may be related to the greater adsorption capacity of soil functional groups in deeper soil layers, which are less saturated with P and K.

Similar to P, Mehlich-1 extractable K levels remained above the critical level throughout the soil profile. In the 0.00–0.05 m soil layer, excessive K was detected, and therefore, reapplication of 134 kg ha^{-1}, either broadcast or in-furrow, did not alter values obtained by the single mild extraction method (Mehlich-1 solution: 0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4). Consequently, K migration through downward water movement in the profile is negligible

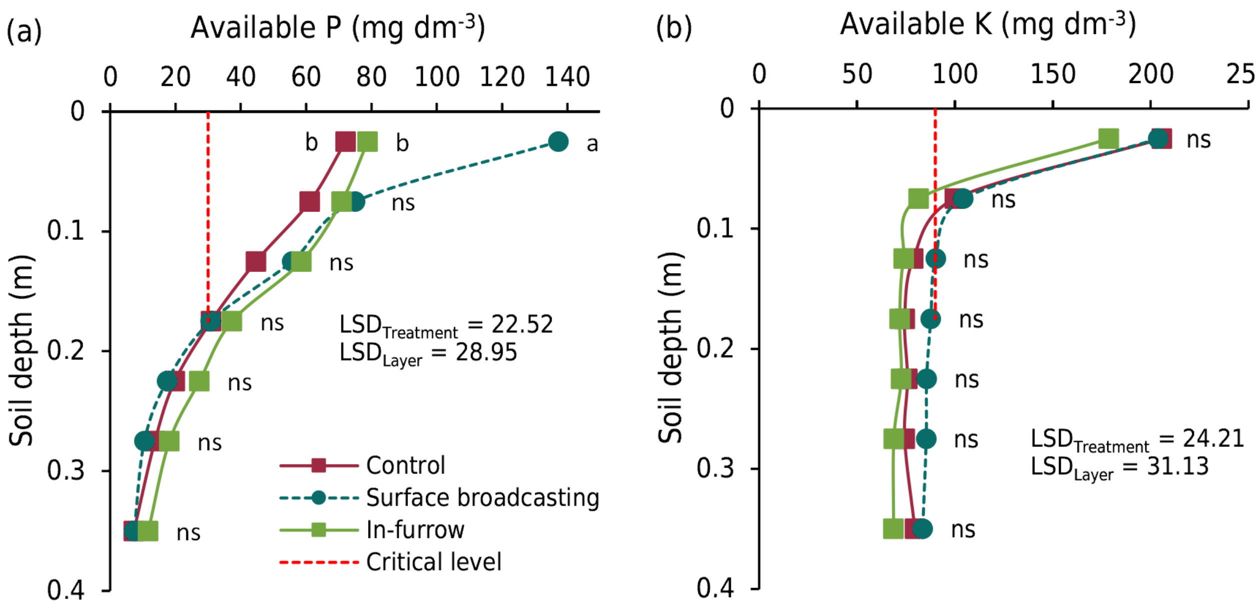

Figure 3. Mean values of available P (a) and K (b) extracted with Mehlich-1 as affected by fertilizer placement at different soil layers, six months after treatment application in a Plinthosol in southern Brazil. Means followed by different letters indicate significant differences among fertilization strategies within each soil layer according to Tukey test ($p<0.05$); ns: not significant by Tukey test ($p>0.05$); LSD: least significant difference.

and may even be less than the amount absorbed by roots in deeper soil layers and returned to the surface via residue decomposition. The binding energy of surface complexes with this cation is high enough to greatly reduce free K concentrations in the soil solution, while still weak enough to be extractable by Mehlich-1 when rhizosphere concentrations are depleted. The gradient of K availability was also evident, with an abrupt decrease below 0.05 m depth (Figure 4b). As with P, this is due to surface fertilizer application and plant residue deposition on the soil surface (Martins et al., 2014; Joris et al., 2016). However, in-furrow K application produced results similar to surface application. Compared with the control, this indicates that K may have migrated into the interlayers of 2:1 clay minerals, as previously reported in another study with the same soil type (Alves et al., 2019). A similar result was reported by Pesini et al. (2024a) in a Planosol containing these minerals, showing that Mehlich-1 extraction was not sensitive enough to detect annual K applications ranging from 0 to 168 kg ha^{-1}. Conversely, in more weathered soils (Oxisols) lacking 2:1 clay minerals, in-furrow K application reduced the K gradient and increased soybean and wheat yields when available K levels were below 64 mg dm^{-3} in the 0.10–0.20 m soil layer (Pesini et al., 2024b).

Effect of acidity correction strategy on soil penetration resistance

Soil penetration resistance was used as a parameter to evaluate the effect of soil incorporation and tillage operations performed in the experiment. In the limestone incorporation treatment, values remained below the limits considered restrictive to root growth, whereas in the other treatments, results approached these thresholds, especially in the 0.05–0.15 m soil layer (Figure 4b). This behavior is associated with the greater soil mobilization caused by plowing and disking, which act down to approximately 0.20 m depth.

In general, tillage operations immediately reduce soil penetration resistance, as also reported by Zhao et al. (2022). Thus, the lower soil penetration resistance is initially due to the physical effect of soil disruption and loosening, which decreases resistance. In the present study, the values obtained with limestone incorporation fell within the range considered adequate for root growth in the evaluated layers. Critical values range from 1,500 to 4,000 kPa (Rosolem et al., 1999), with more evident restrictions occurring above 2,000 kPa (Tormena et al., 1998).

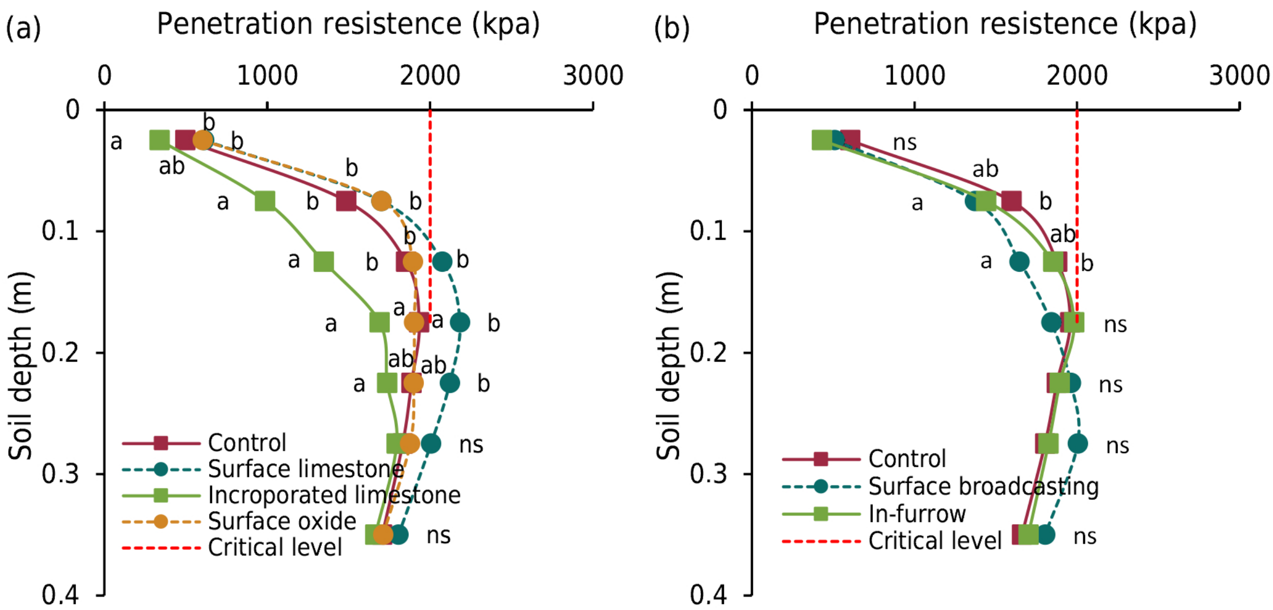

Figure 4. Mean values of soil penetration resistance as affected by soil acidity correction strategies (a) and by fertilizer placement (b) at different soil layers in a Plinthosol in southern Brazil. Means followed by different letters indicate significant differences among treatments within each soil layer according to Tukey test ($p<0.05$); ns: not significant by Tukey test ($p>0.05$); critical threshold according to Tormena et al. (1998).

Surface application of CaO·MgO did not result in soil penetration resistance values that differed from those of the no-liming control. Although values tended to approach the critical threshold from 0.05 m depth onward, they did not reach restrictive levels (Figure 4a). Among the no-tillage strategies (surface-applied lime, surface-applied CaO·MgO, and control), no differences were observed up to 0.15 m depth (Figure 4b). However, between 0.10 and 0.25 m, values may be considered restrictive (Figure 4b). This result, however, cannot be directly attributed to the acidity correction strategy, since surface application was identical in both treatments.

Nevertheless, the effect of incorporation compared with surface application was evident down to 0.25 m, indicating greater improvement in soil physical conditions under this system. It is worth noting that Ca supplied through the dissolution of soil amendments contributes to aggregate formation (Machado et al., 2017). Thus, the lower the movement of corrective particles in the soil profile, the greater the physical restrictions to root development.

It is important to emphasize, however, that a full understanding of these effects requires additional assessments of soil physical properties, particularly in the long term. Although the results suggest a relationship with reduced root growth and depth, this study did not directly evaluate root development. This lack of data limits the ability to associate the observed differences with root system dynamics confidently.

Effects of fertilization method and soil acidity correction strategies on soybean and corn yield

Lime application strategies and fertilization methods did not affect soybean yield (Figure 5). Soybean yield averaged 4.78 Mg ha^{-1}, well above the Rio Grande do Sul State average of 1.53 Mg ha^{-1} in the 2020/21 growing season (CONAB, 2021). The high yield in this study is likely related to the greater rainfall recorded at the experimental site compared with the regional average, particularly in January (Figure 1). Under water deficit conditions, soybean is more susceptible to yield reduction due to high acidity and the presence of toxic Al. It can also be inferred that the lack of response to fertilization methods is explained by the already high levels of available P and K in the soil, which prevented nutritional deficiencies and allowed the crop to maintain its physiological functions even without fertilization, whether in-furrow or surface applied.

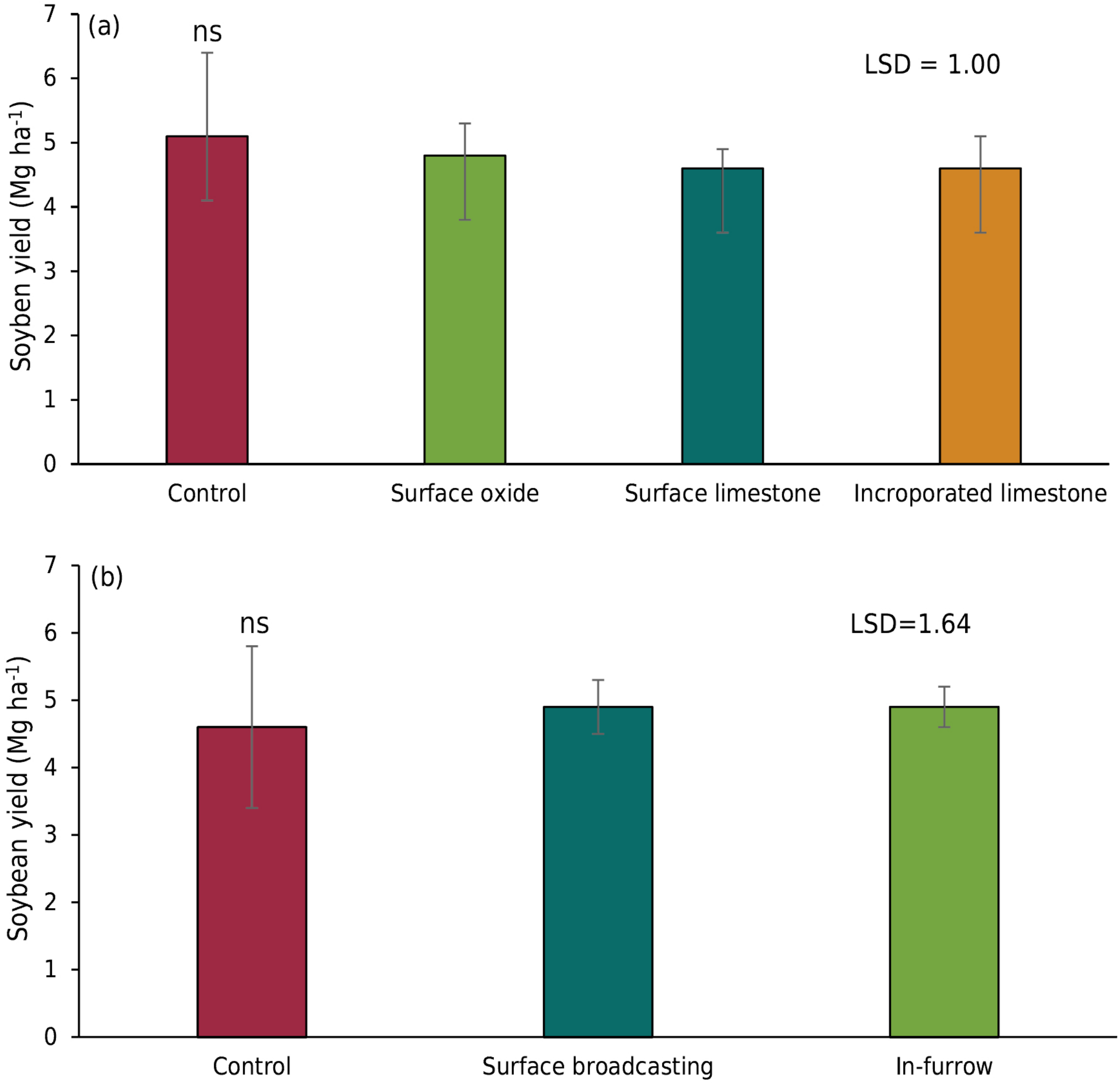

Figure 5. Mean soybean yield as affected by soil acidity correction strategies (a) and by fertilizer placement (b), six months after treatment application in a Plinthosol in southern Brazil. ns: not significant at $p<0.05$. LSD: least significant difference.

The immediate establishment of a favorable chemical profile for root growth through the incorporation of limestone resulted in a more than 100 % increase in corn grain yield, regardless of P and K addition or their replacement in-furrow (Figure 6). In this model of lime reapplication in soil with high Al^{3+} saturation, combined with in-furrow P and K fertilization, corn yield increased by almost 2 Mg ha^{-1}.

Results reported by Pagani and Mallarino (2015) indicated that corn is more responsive to liming than soybean. Similarly, in the meta-analysis conducted by Li et al. (2019), which included 175 studies, corn (n = 71) showed greater yield responses due to acidity correction than soybean (n = 23). According to the authors, this is likely related to the symbiosis between soybean roots and N_2-fixing bacteria. Comparable results were reported by Pias et al. (2020), who showed that under adequate water conditions, soybean tolerates up to 40 % Al^{3+} saturation in the 0.20–0.40 m layer, while corn production is limited at Al^{3+} saturation levels greater than 5 % in the same layer, since it depends on deeper root development to enhance the efficiency of N uptake from fertilization. Rheinheimer et al. (2024b) also observed that soybean was little affected by soil acidity, tolerating up to 31 and 44 % Al^{3+} saturation in the 0.00–0.15 and 0.10–0.15 m soil layers, respectively. In another long-term experiment, Rheinheimer et al. (2025) found that the critical Al^{3+} saturation value for soybean increases with depth, ranging from 15, 24, 37, and 46 % in the 0.00–0.05, 0.05–0.10, 0.10–0.15, and 0.15–0.20 m soil layers, respectively.

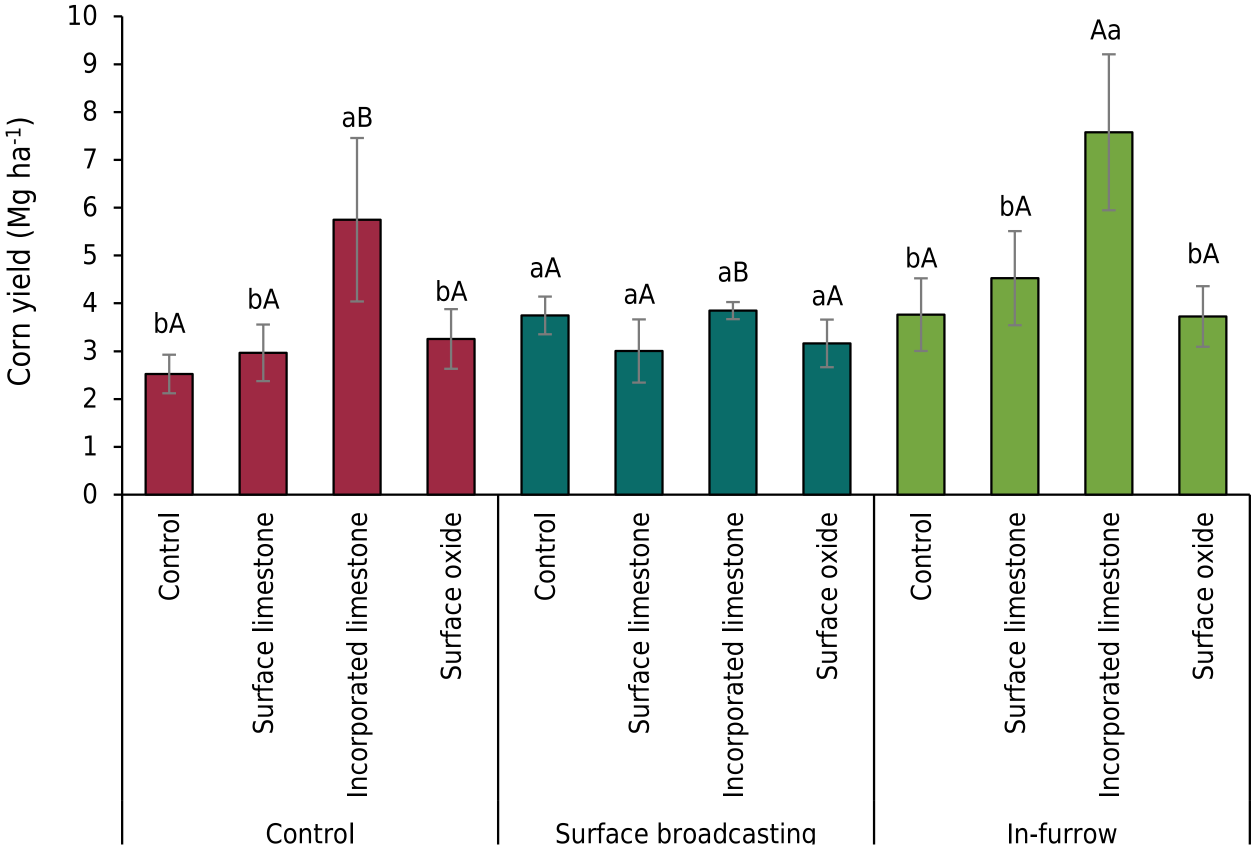

Figure 6. Mean corn yield as affected by soil acidity correction strategies and fertilizer placement in a Plinthosol in southern Brazil. Different lowercase letters indicate significant differences among soil acidity correction strategies within each fertilizer placement, and different uppercase letters indicate significant differences among fertilizer placements within each soil acidity correction strategy, according to Tukey test.

The highest corn yields in this experiment were obtained in treatments combining acidity correction with soil tillage (incorporated limestone) and in-furrow P and K fertilization. This is probably related to the better distribution of nutrients in the deeper soil layers, together with subsurface acidity correction, which enabled the roots to explore a larger soil volume. Furthermore, in treatments with limestone incorporation and in-furrow fertilization, lower penetration resistance values were observed, indicating reduced soil compaction and more favorable conditions for root development and nutrient uptake.

It was also observed that when no fertilizer was added (since soil P and K levels were already adequate), limestone incorporation yielded the highest. However, when fertilizer was surface-applied, acidity correction strategies did not affect grain yield.

In the 0.00–0.10 m soil layer, CaO·MgO increased soil pH by 0.3 units and Ca^{2+}+ Mg^{2+}+K^{+} saturation by 1.86 %, with similar Al^{3+} saturation values compared with incorporated limestone. In the 0.10–0.20 m soil layer, however, the most favorable conditions for crop development were observed with incorporated limestone, which explained a 66 % higher yield compared with surface treatments (Figure 7). The higher pH and base saturation values in areas with incorporated amendments may account for the greater crop yields, enhancing fertilization efficiency even above adequate levels. The CQFS-RS/SC (2016) recommends using the 0.00–0.10 m soil layer to assess soil fertility under NTS, with occasional analysis of the 0.10–0.20 m layer. However, the relationship between corn yield and soil chemical properties in different layers indicates that 0.00–0.10 m analysis is ineffective for diagnosing fertility and yield potential under NTS. Similar results were reported by Condon et al. (2021) and Bellinaso et al. (2021). In this context, stratified analysis of the 0.10–0.20 m layer is necessary to provide more accurate liming recommendations.

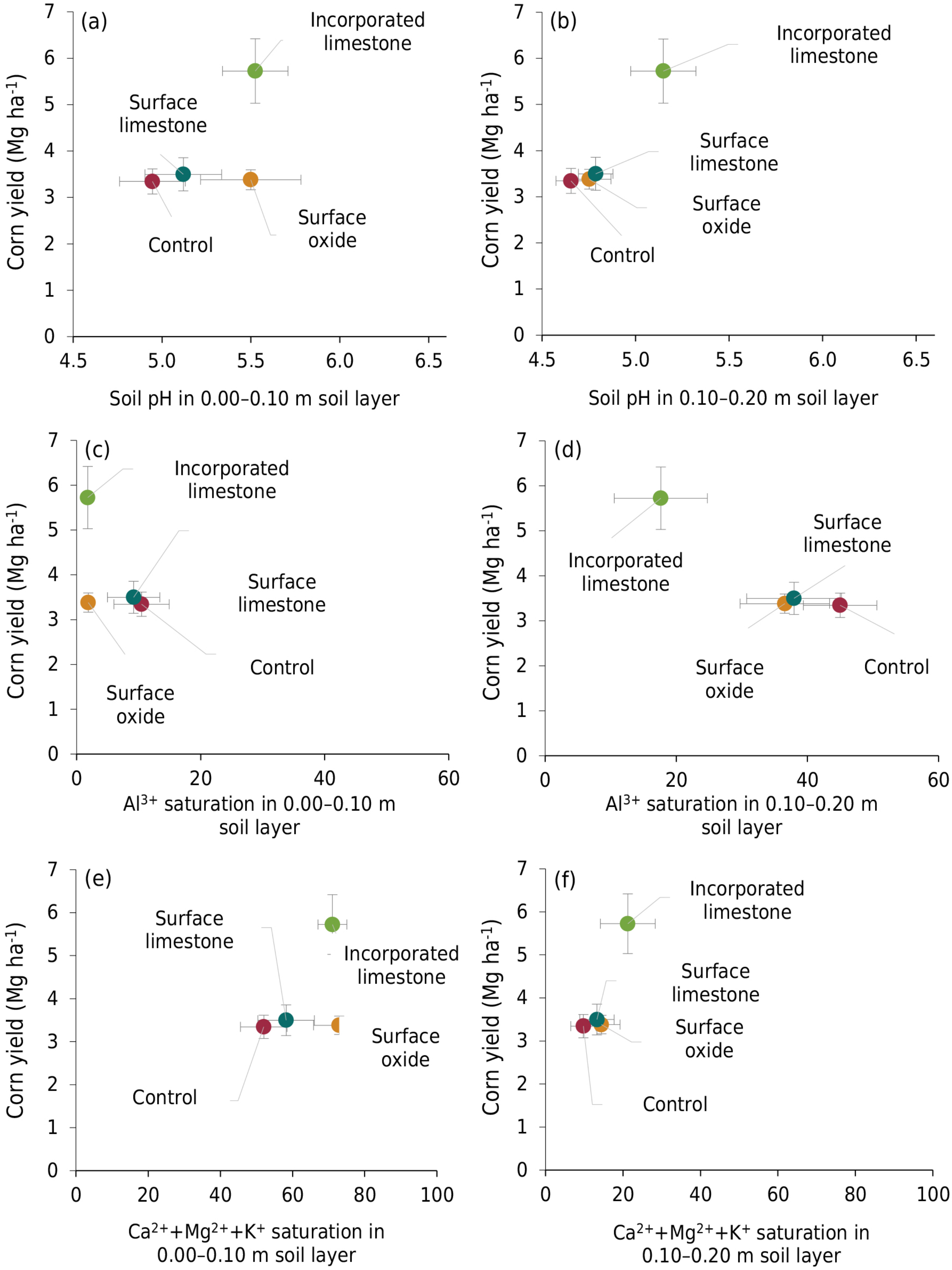

Figure 7. Relationship between corn yield and soil pH at 0.00–0.10 m (a) and 0.10–0.20 m (b), with Al^{3+} saturation at 0.00–0.10 m (c) and 0.10–0.20 m (d), and with Ca^{2+}+Mg^{2+}+K^{+} saturation at 0.00–0.10 m (e) and 0.10–0.20 m (f) in a Plinthosol in southern Brazil. Error bars represent the standard error of treatment means.

CONCLUSIONS

Limestone incorporation was the most effective strategy for correcting acidity in the plow layer, showing significant effects down to 0.15 m depth after six months. This practice created a more favorable physical and chemical environment for the development of cash crops. The improvements resulting from limestone incorporation led to increased corn yield already in the first growing season. Surface application of CaO·MgO without incorporation was effective only in correcting acidity in the soil surface layer (0.00–0.10 m), despite being a more soluble source.

Although different P and K fertilization strategies did not significantly affect nutrient availability in the soil, corn yield was higher when fertilizers were applied in-furrow compared with broadcast application. Soybean yield, however, was not influenced by either acidity correction strategies or fertilization methods.

Therefore, in soils with high subsurface acidity, incorporation of soil amendments is essential for effective correction and yield improvement. In addition, in-furrow application of P and K proved to be the most efficient strategy to secure high yields. Finally, we highlight the importance of this type of study for generating practical recommendations applicable to farmers. Further research under different soil and crop conditions is needed to expand these findings and refine technical recommendations on this subject.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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AUTHOR CONTRIBUTIONS

Conceptualization: Danilo Reinheimer dos Santos (equal), Tadeu Luis Tiecher (equal) and Tales Tiecher (equal).

Data curation: Dayana Jéssica Eckert (equal), Dionata Filippi (equal), Lucas Aquino Alves (equal), Lucas Nascimento Brum (equal), and Tales Tiecher (equal).

Formal analysis: Dayana Jéssica Eckert (equal), Dionata Filippi (equal), Gustavo Pesini (equal), João Pedro Moro Flores (equal), Lucas Nascimento Brum (lead) and Tales Tiecher (equal).

Funding acquisition: Tales Tiecher (lead).

Investigation: João Pedro Moro Flores (equal), Lucas Aquino Alves (equal), Lucas Nascimento Brum (equal), Tadeu Luis Tiecher (equal) and Tales Tiecher (equal).

Methodology: Lucas Nascimento Brum (equal) and Tales Tiecher (equal).

Project administration: Tadeu Luis Tiecher (equal) and Tales Tiecher (lead).

Supervision: Amanda Posselt Martins (equal), Tadeu Luis Tiecher (equal) and Tales Tiecher (equal).

Validation: Amanda Posselt Martins (equal), Danilo Reinheimer dos Santos (equal), Djalma Eugênio Schmitt (equal), Gustavo Pesini (equal), Jessé Rodrigo Fink (equal), João Pedro Moro Flores (equal), Lucas Nascimento Brum (equal) and Tales Tiecher (equal).

Visualization: Amanda Posselt Martins (equal), Danilo Reinheimer dos Santos (equal), Dayana Jéssica Eckert (equal), Dionata Filippi (equal), Djalma Eugênio Schmitt (equal), Gustavo Pesini (equal), Jessé Rodrigo Fink (equal), João Pedro Moro Flores (equal), Lucas Aquino Alves (equal), Lucas Nascimento Brum (equal), and Tales Tiecher (equal).

Writing – original draft: Dayana Jéssica Eckert (equal), Dionata Filippi (equal), Gustavo Pesini (equal), Lucas Aquino Alves (equal), Lucas Nascimento Brum (equal), Tadeu Luis Tiecher (equal) and Tales Tiecher (equal).

Writing – review & editing: Amanda Posselt Martins (equal), Danilo Reinheimer dos Santos (equal), Dayana Jéssica Eckert (equal), Dionata Filippi (equal), Djalma Eugênio Schmitt (equal), Gustavo Pesini (equal), Jessé Rodrigo Fink (equal), João Pedro Moro Flores (equal), Lucas Nascimento Brum (equal), Lucas Aquino Alves (equal), Tadeu Luis Tiecher (equal) and Tales Tiecher (equal).

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