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Soil acidity correction and nutrient availability as a function of segmental liming[1]

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ABSTRACT - Segmental liming involves the incorporation of lime into the subsoil in narrow strips, typically associated with deep ripping. This study aimed to evaluate the vertical and horizontal distribution of soil acidity and nutrient availability in a Ferralsol under no-tillage five months after segmental liming. The equipment used for lime application featured a chisel of seven rods with a spacing of 70 cm, and a working depth of 40 cm. The lime rate used was 1.0 Mg ha^{-1} of limestone with high effective neutralizing value (ENV = 170%). Soil samples were taken at eight layers (0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, and 35–40 cm), in the passage line of the equipment and at 10, 20 and 30 cm to the side between rods. The available soil phosphors (P) and potassium (K) did not exhibit any horizontal and vertical changes as a result of segmental liming. Conversely, within the 10-25 cm depth along the rod application line, the soil pH increased from 5.3 to 5.9. Additionally, the exchangeable Ca increased from 60 to 78 mmol$_c$ dm^{-3} and the exchangeable Mg increased from 21 to 32 mmol$_c$ dm^{-3}. The base saturation also increased from 56 to 73%, and the Al saturation decreased from 11 to 2%, when compared to samples collected at 10, 20, and 30 cm from the segmental liming application line. Therefore, the correction of soil acidity through segmental liming was limited to the chisel line, accounting for the correction of soil acidity in only 14.2% of the cultivation area.

Key words: Subsurface acidity. Limestone incorporation. No-tillage.

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INTRODUCTION

In Brazil, the area of cropfields under no-tillage (NT) system has experienced rapid growth over the last 20 years (CASÃO JUNIOR *et al.*, 2012). This expansion is primarily driven by the manifold benefits, including reduced production costs, improved water retention and infiltration in the soil, decreased soil erosion and nutrient loss, improved soil capacity to preserve organic materials for longer periods, and an increase in crop yields (BAYER *et al*., 2006; BOLLIGER *et al*., 2006; LAL, 2015; VELOSO *et al*., 2018), when compared to the conventional system involving intensive soil preparation. However, the national average grain yields in areas under NT have stagnated, despite the fact that genetic advancement have provided greater productivity for both summer and winter crops.

One probable cause for the lack of crop response to genetic advancements is the failure to adopt the principles of Conservation Agriculture. Most NT cropfields are far from the ideal no-tillage system (NTS), which would bring benefits to the chemical, physical, and biological quality of the soil, in addition to increasing crop yields (DERPSCH *et al*., 2014). In NT, soil mobilization occurs in the sowing line and there is maintenance of crop residues on the soil surface. In the ideal NTS, in addition to the practices used in NT, there is diversification and rotation of crops, promotion of permanent soil coverage through the harvesting-sowing process, and addition of high amounts of plant residue to the soil — both in quantity and quality and with a frequency compatible with the soil's biologic demand (DENARDIN *et al*., 2012). Moreover, in acidic and weathered soils, achieving a well-managed soil under NTS is impossible if soil acidity in depth is not properly corrected.

One of the most limiting factors for crop yields in NT areas in Brazil is the low soil pH and high toxic Al^{3+} levels in subsurface (CALEGARI *et al*., 2013; TIECHER *et al*., 2017), which restricts root growth and access to water and nutrients from deeper layers. It also increases the susceptibility of crops to drought periods, resulting in low yields in years with water deficit or poor rainfall distribution (HANSEL *et al*., 2017; PIAS *et al*, 2020; TIECHER *et al*., 2018). The effect of the surface limestone application in NT is usually limited to the topsoil in the short-term (i.e., <10 cm) (RHEINHEIMER *et al*., 2018a, b). Therefore, incorporating limestone in areas under established NT with high soil acidity would be the best way to overcome this problem, resulting in a more efficient correction of soil acidity in subsurface. However, this would imply in soil ploughing and, consequently, losing the improvements in several physical, chemical, and biological properties achieved with the long-term use of NT. Moreover, lime incorporation is linked to higher costs and poses a risk of increased erosion due to the soil disturbance.

One alternative to lime incorporation is segmental liming, which entails the incorporation of agricultural lime into the subsoil in narrow bands, generally associated with deep ripping. This approach has been proven to be an effective strategy in mitigating crop yield losses due to toxicity with Al^{3+} in the subsoil (COVENTRY *et al*., 1987; FARINA; CHANNON, 1988; KIRCHHOF *et al*., 1995). However, so far to our knowledge, there is a lack of scientific reports on the impact of using limestone with this new technology in Brazil. Therefore, the objective of this study was to evaluate the effect of segmental liming up to 40 cm depth on the vertical and horizontal distribution of soil acidity and nutrient availability in a Ferralsol under no-tillage in Southern Brazil.

MATERIAL AND METHODS

Description of the study site

The study was carried out in a Ferralsol (FAO, 2015) on a commercial farm owned by the company Sementes Umbu, located in the municipality of São Luiz Gonzaga, state of Rio Grande do Sul, Southern Brazil (latitude 28º 23' 03"S, longitude 54º 44' 54"O, 280 m altitude). The local climate is classified as subtropical humid (Cfa) according to the Köppen classification (ALVARES *et al*., 2013), with an average annual rainfall of 1,910 mm and average annual temperature of 20.6 ºC. The area was originally covered by the Atlantic Forest. In the mid-1970s, the forest was cleared, and grains were grown in both summer and winter under conventional tillage, involving intensive soil preparation with plowing and disc-harrow before each crop. Since 1998, the area has been managed under no-tillage, employing seeders with fertilizer, and various planting mechanisms such as cutting disc, shallow chisel (10 cm), and mismatched double disks, or cutting disks with mismatched double disks. In the summer, the main cash crop is soybean, while in the winter, it alternates between wheat and canola, or black oats for soil cover.

History of fertilization in the study area

In 2016, surface liming was applied at a rate of 1.5 Mg ha^{-1} of dolomitic limestone with 70% of effective neutralizing value (ENV). The summer crop for the past four years has been soybean, while in the winter, wheat, white oats, wheat, and canola were grown in 2014, 2015, 2016, and 2017, respectively. The nutrient application for each crop over the last four years before the beginning of the field trial is detailed in Table 1.

Segmental liming

In October 2017, following the canola harvest, segmental liming was carried out using the "Adubador de perfil SAK-7/75" equipment, manufactured by the

Table 1 - Amount of nitrogen (N), phosphorus (P), and potassium (K) applied in the experimental area in the last four years before the beginning of the field trial

Year	Crop	N	P	K
		kg ha^{-1}		
2014	Wheat	114	26	40
	Soybean	0	26	58
2015	White oats	49	14	30
	Soybean	0	26	58
2016	Wheat	114	26	40
	Soybean	0	26	58
2017	Canola	81	30	50
	Soybean	0	26	58
Total		358	200	392

Kamaq company. The implement featured seven rods spaced 70 cm apart, with a working depth of 40 cm, aimed at breaking the compacted layer of the soil profile (i.e., between 5-20 cm) and neutralizing soil acidity up to a depth of 40 cm. This equipment incorporated a limestone injection system in each chisel stem (see Figure S1 of Supplementary Material). Given the equipment's limited capacity to apply product per hectare, a high ENV limestone (170%) was utilized at the rate of 1.0 Mg ha^{-1}.

Soil sampling

In February 2018, five months after the segmental liming, soil samples were taken during the reproductive stage of soybean. Seven trenches were opened, each with a depth of 50 cm, a width of 40 cm, and a depth of 70 cm, covering the area where segmental liming was performed. Each trench was treated as a block. Within each trench, soil samples were taken at the location where the chisel stem had passed at 0, 10, 20, and 30 cm to the side. Sampling was performed at layers spanning 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, and 35–40 cm, resulting in 32 samples per trench and a total of 224 samples.

Soil analysis

Soil chemical analyses were carried out at the Soil Laboratory of Embrapa Trigo, following the procedures outlined by Tedesco *et al.* (1995). The soil samples were dried in an oven with forced air circulation at ± 50 ºC, grounded, and then passed through a 2 mm sieve. Subsequently, several soil chemical properties were assessed. Soil pH was measured in suspension of soil and distilled water at a 1:1 (v/v) ratio. Potential acidity (H+Al) was obtained through the equation proposed by Kaminski *et al.* (2001), where H+Al is estimated based on the pH equilibrium between the soil and the SMP solution (triethanolamine, paranitrophenol, K_2CrO_4, $Ca(CH_3COO)_2$ and $CaCl_2.2H_2O$) calibrated at pH 7.5 (Shoemaker *et al.*, 1961). Exchangeable Al, Ca, and Mg were extracted with 1.0 mol L^{-1} KCl. Exchangeable Al^{3+} was determined by titration with a NaOH 0.0125 mol L^{-1} solution, while Ca^{2+} and Mg^{2+} were determined using atomic absorption spectrometry. Available P and K were extracted with a Mehlich-1 solution (soil:extractor ratio 1:10). In the extract, K^+ was determined in a flame photometer, and P was determined calorimetrically by the Murphy and Riley (1962) method. The sum of bases (SB) was determined by the sum of Ca, Mg, and K. The effective cation exchange capacity ($CEC_{effective}$) was calculated by the sum of SB and Al. The potential cation exchange capacity at pH 7.0 ($CEC_{pH7.0}$) was calculated by the sum of SB and (H + Al). Base saturation (BS) was calculated as follows: $BS = 100 \times SB/CEC_{pH7.0}$. Al saturation (AS) was calculated as follows: $AS = [Al/(CEC_{effective})] \times 100$ (SOCIEDADE BRASILEIRA DE CIÊNCIA DO SOLO, 2016). Clay content was estimated by the densimeter method, and soil organic carbon was determined by chromic acid wet oxidation (Walkley, 1947).

Statistical analysis

The data underwent analysis of variance (ANOVA) at significance level of $p < 0.05$. When significant, means were compared using the Tukey test ($p < 0.05$). The statistical model employed was:

$$Y_{ijkl} = \mu + B_i + W_j + \text{error a (i, j)} + L_k + WL_{jk} + \text{error b (i, k)}$$

where μ = experimental mean; B = block (trench) (i = 1, 2, 3, 4, 5, 6, 7); W = width from the application line (j = 1, 2, 3, 4); L = layer (k = 1, 2, 3, 4, 5, 6, 7, 8); and error = experimental error.

RESULTS AND DISCUSSION

All parameters were influenced by the evaluated soil layer (Table 2). Clay content, soil organic carbon, and soil available P and K showed no horizontal variations with distance from the groove of the chiselling rod where segmental liming was performed (Table 2). However, a noticeable gradient of these properties was observed in depth, characteristic of areas under long-term NT. This occurs due to the minimal soil disturbance, the deposition of organic residues on the surface, and the superficial application of P and K. Consequently, soil organic carbon content (VELOSO *et al*., 2018) and available P and K (CALEGARI *et al*., 2013; RODRIGUES *et al*., 2016; TIECHER *et al*., 2017) increases mainly in the superficial layers, with a marked decrease as soil depth increases (Table 3).

The soil chemical properties did not exhibit significant changes among samples collected at 10, 20, and 30 cm longitudinally distant from the line where segmental liming was performed. For these samples, the soil pH in water (Fig. 1a), exchangeable Ca and Mg content (Fig. 2a, b), effective CEC (Fig. 2c) and base saturation (Fig. 2d) all decreased with the increasing depth. Conversely, exchangeable Al content (Fig. 1c), saturation by Al (Fig. 1d) and potential acidity (Fig. 1b) increased with increasing depth. This gradient of exchangeable Ca and Mg and parameters related to soil acidity is also

Table 2 - Significance of the variation factors and their interactions in the chemical properties of the soil as a result of the analysis of variance (ANOVA)

Soil parameter	Width	Layer	Width x Layer	CV (%)
Clay	ns	****	ns	8.4
Soil pH	****	****	**	5.9
Available P	ns	****	ns	97.6
Available K	ns	****	ns	46.4
Soil organic carbon	ns	****	ns	13.9
Exchangeable Al	***	****	*	91.7
Exchangeable Ca	****	****	*	18.3
Exchangeable Mg	****	****	**	21.1
Potential acidity (H+Al)	***	***	*	35.9
Effective cation exchange capacity	****	****	**	14.5
Al saturation	***	****	*	98.3
Base saturation	****	****	*	19.2

* Significant at $p < 0.05$. ** Significant at $p < 0.01$. *** Significant at $p < 0.001$. **** Significant at $p < 0.0001$

Table 3 - Clay content, soil organic carbon content, and available phosphorus and potassium in depth

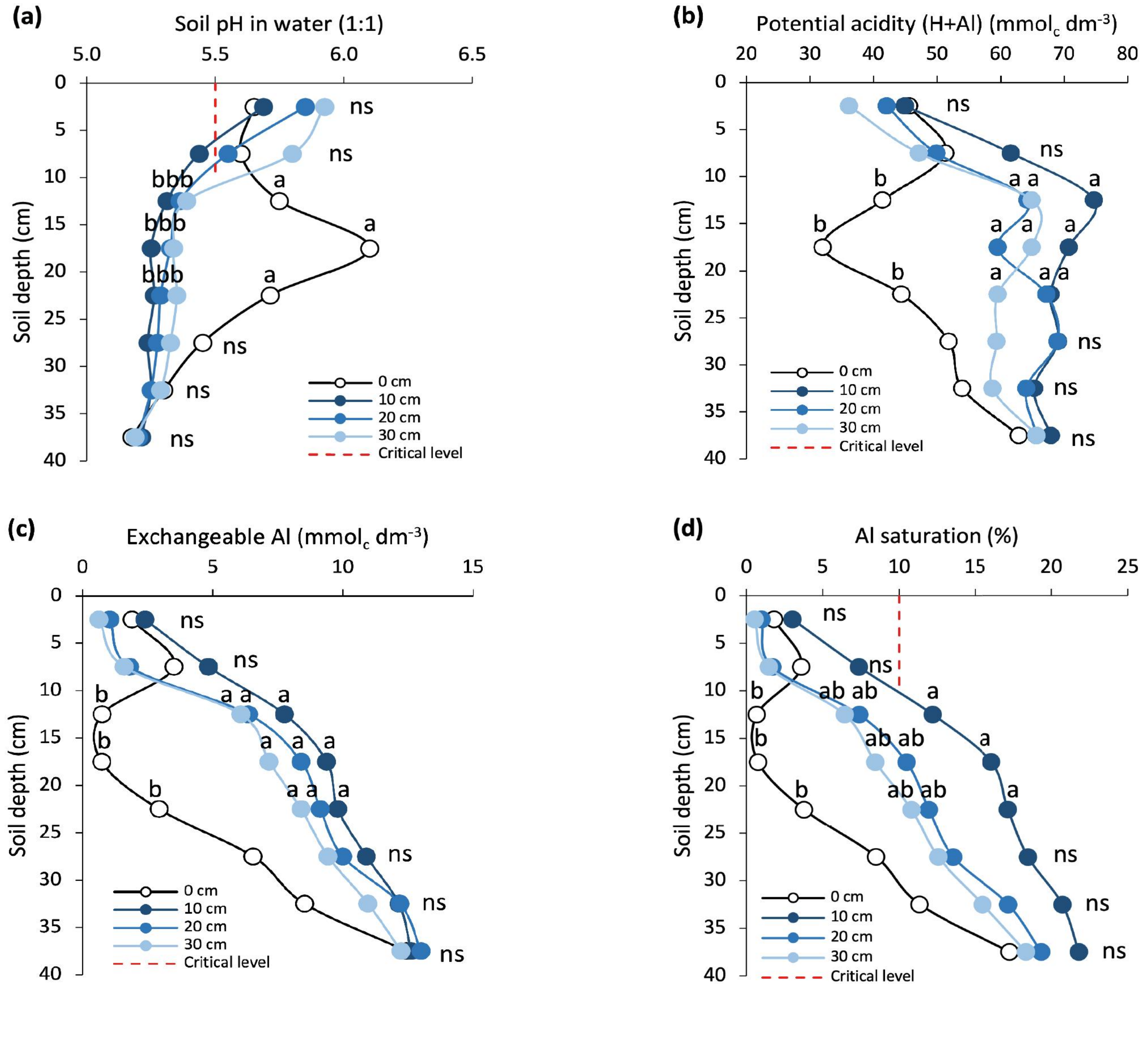
Soil layer	Clay	Soil organic carbon	Available P	Available K
cm	g dm^{-3}	g dm^{-3}	mg dm^{-3}	mg dm^{-3}
0–5	512 d	24 a	25.3 a	245 a
5–10	613 c	20 b	16.3 b	134 b
10–15	682 b	17 c	11.1 b	81 c
15–20	682 b	16 cd	3.5 c	57 cd
20–25	691 b	15 de	2.2 c	44 de
25–30	712 ab	13 ef	1.6 c	37 de
30–35	714 ab	13 f	1.6 c	31 de
35–40	741 a	12 f	1.5 c	28 e

Means followed by the same letter in the column are not statistically different by the Tukey test at $p < 0.05$

characteristic of areas under NT with history of surface liming (INAGAKI *et al*., 2016; NUNES *et al*., 2015, 2017; RHEINHEIMER *et al*., 2018a, b). According to Sociedade Brasileira de Ciência do Solo (2016), the soil of the 0-10 cm layer does not present acidity problems or chemical restriction to root growth. However, below 10 cm, the soil pH is generally below 5.5, potentially reducing the availability of some nutrients. In addition, the soil below 10 cm exhibits Al saturation higher than 10% and base saturation lower than 60%, indicating a potential toxic effect of Al^{3+}. In this context, under conditions of adequate water availability, crops would have suitable conditions for growth and development (HANSEL *et al*., 2017). Nevertheless, deep root growth in this soil would be constrained due to chemical restrictions, potentially resulting in reduced crop yields under water stress conditions (PIAS *et al*., 2020; Tiecher *et al*., 2018).

Conversely, the chemical properties related with soil acidity in the line where segmental liming was performed (0 cm) depositing 1.0 Mg ha^{-1} of limestone with an ENV of 170%, were significantly altered in the soil layers of 10 to 25 cm depth, in comparison to samples collected at 10, 20, and 30 cm to the side (Fig. 1 and 2). The 15-20 cm soil layer showed the most pronounced variations in soil acidity properties. In this layer, where the chiseling rod passed applying lime, there was an increase

Figure 1 - Vertical and horizontal variation of soil pH in water (a), potential acidity (b), exchangeable Al (c) and Al saturation (d) after five months of segmental liming. Means followed by the same letter comparing width from the application line in each soil depth are not statistically different at $p < 0.05$ by the Tukey test



of up to 0.8 units in soil pH (Fig. 1a) and an increase of up to 25 and 14 $mmol_c\ dm^{-3}$ in the exchangeable Ca and Mg content, respectively (Fig. 2a, b). Additionally, there was an increase of up to 22% in base saturation and a decrease in Al saturation from 16 to just 1% (Fig. 1d and 2d). In the 25-40 cm layer, there was no significant effect on the soil chemical properties, indicating an uneven deposition of the limestone at the working depth of the chiselling rod. Overall, the increase in soil pH resulting from liming led to increased base saturation and reduced Al saturation (Fig. 3), as the variables are highly correlated (JORIS *et al*., 2016; RHEINHEIMER *et al*., 2018b).

The obtained results demonstrate that the impact of segmental liming on soil chemical properties is highly confined horizontally. Considering a width correction of 10 cm for a working width of 70 cm for each rod, there is a correction of 14.2% of the area with each segmental liming operation. Consequently, seven segmental liming operations would be required to correct soil acidity up to a depth of 25 cm for the same area. However, it is important to emphasize that due to the technical limitations of georeferencing and precision agriculture, there may be overlapping of limestone application, potentially leading to an excessive increase in pH of the soil (known as over-liming), resulting in a drastic reduction in the bioavailability of cationic micronutrients such as Cu, Zn, Fe, and Mn.

Figure 2 - Vertical and horizontal variation of exchangeable Ca content (**a**), exchangeable Mg content (**b**), effective CEC (**c**) and base saturation (**d**) after five months of segmental liming. Means followed by the same letter comparing width from the application line in each soil depth are not statistically different at $p < 0.05$ by the Tukey test

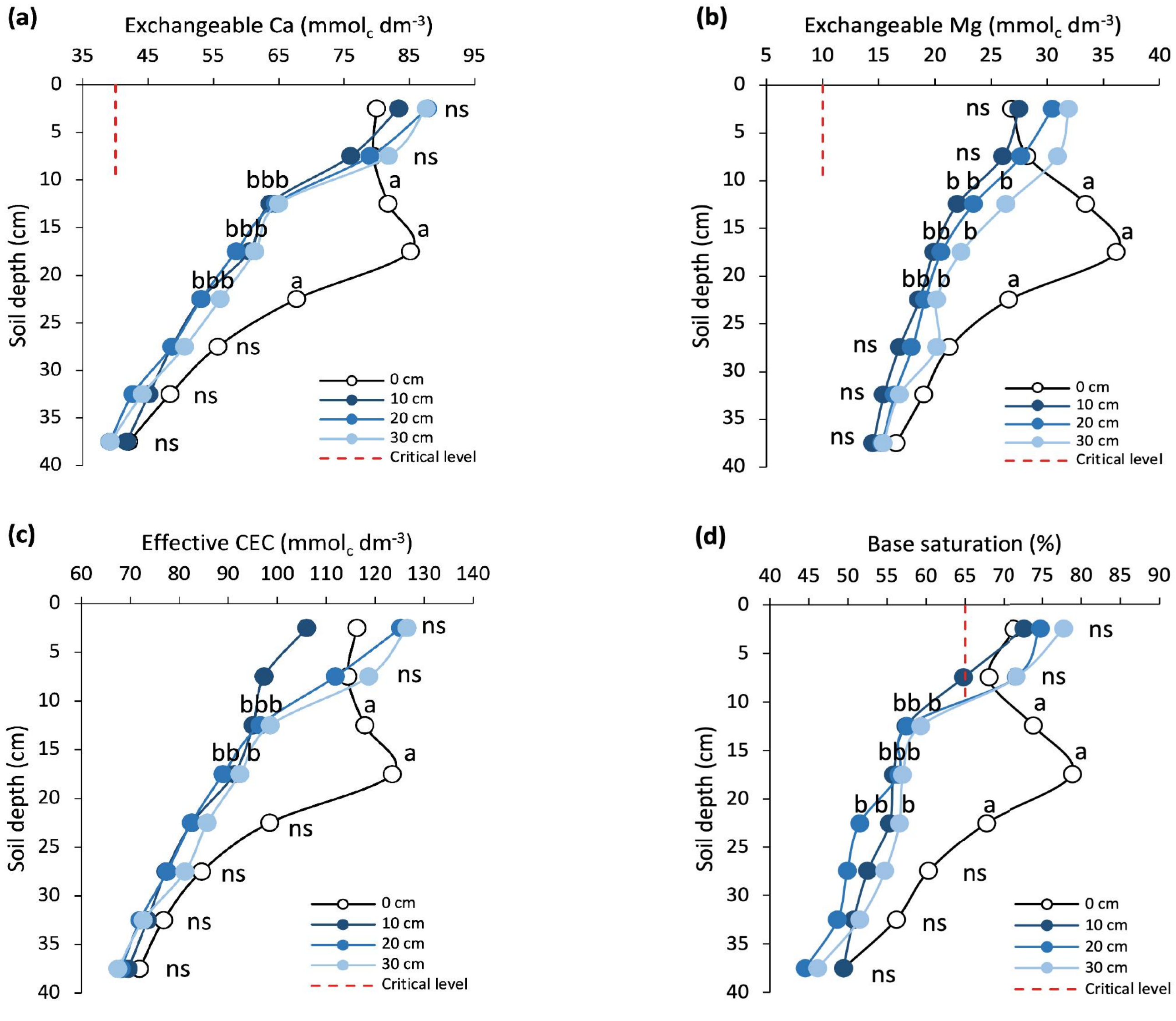
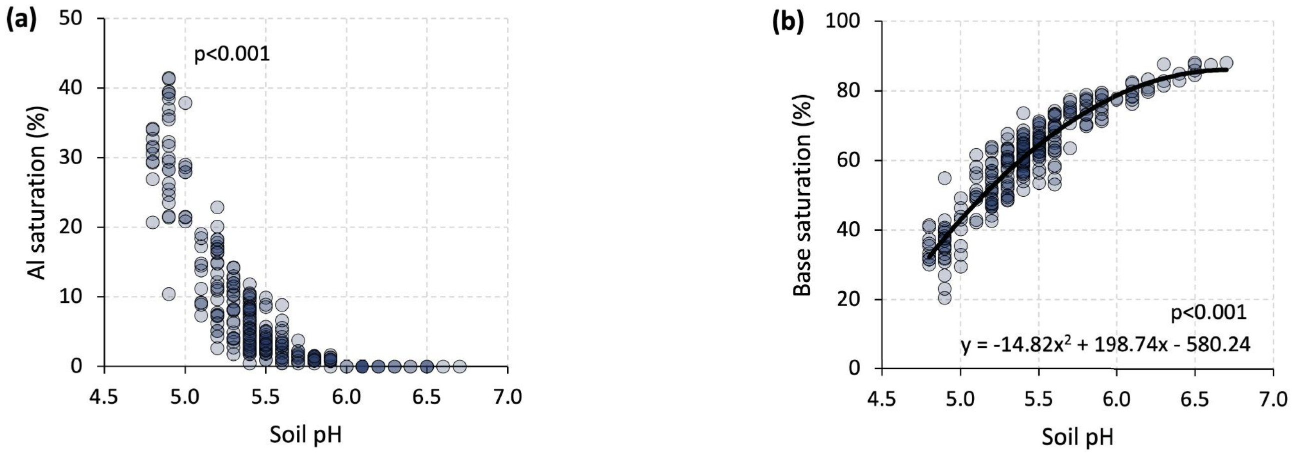


Figure 3 - Variation of Al saturation (**a**) and base saturation (**b**) as affected by soil pH



Therefore, further studies are still required to evaluate the long-term impact of this practice with reapplications. Additionally, research is needed to assess its effects on soil physical properties, on root growth, utilization of water and nutrient stored in the subsoil, and consequently, on crop yields. It is also noteworthy that, following segmental liming, only with a comprehensive and meticulous soil sampling strategy can the effects on soil chemical properties in the soil profile be accurately assessed, both vertically and horizontally.

CONCLUSIONS

Segmental liming was effective in correcting soil acidity solely in the region nearest to the lime application, exhibiting no horizontal effect in the inter-row soil. For the tested equipment with 70 cm spacing between rods, the correction of soil acidity only covered 14.2% of the total area. Moreover, despite the equipment having a working depth of 40 cm, the effect on soil acidity was observed solely in the layer of 10-25 cm and in the line of limestone application, suggesting an uneven deposition of limestone in the soil profile.

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