Revista Ciência Agronômica, v. 56, e202391626, 2025
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Soil chemical attributes and soybean performance as a function of acidity management and cover crops[1]

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ABSTRACT - Seeking strategies to promote acidity correction and increase the availability of Ca at depth in the soil are crucial to ensure the sustainability of areas managed under no-tillage practices. The objective of this study was to evaluate the soil chemical attributes and soybean performance after cover crops and acidity management through liming using the method of Ca and Mg saturation in the effective cation exchange capacity (ECEC), and gypsum application at variable rates to increase Ca saturation in the subsurface The experiment was carried out in Guarapuava, PR, Brazil in an Oxisol, assessing two factors, (1) cover crops: fallow, oat + turnip and polyculture; and (2) acidity management: without correction and areas with lime (calcitic + dolomitic) or lime + gypsum. The soil chemical attributes were evaluated: pHCaCl$_2$; exchangeable Al^{3+}; H$^+$ + Al^{3+}; Ca^{2+}; Mg^{2+}; S-SO$_4^{2-}$; V%; Ca^{2+}/ECEC and Mg^{2+}/ECEC. The chlorophyll index and soybean performance were evaluated through yield components. The cover crops of oat + forage turnip and fallow contributed to the reduction of soil acidity in the 0.35 m layer, reaching the range considered ideal (pH = 5.0) for soybean cultivation. Oats + forage turnip accumulate more Mg^{2+} and increase base saturation in the 0.05 m layer compared to fallow and polyculture, while also reducing potential acidity in the 0.15 m layer compared to polyculture. When associated with gypsum, lime increased Ca^{2+} levels in the 0.15 m layer and Mg^{2+} levels in the 0.15 m and 0.35 m layers.

Key words: Polyculture. Liming. Gypsum.

DOI: 10.5935/1806-6690.20250042
Editor-in-Chief: Profa. Mirian Cristina Gomes Costa - mirian.costa@ufc.br
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Received for publication 03/07/2023; approved on 10/04/2024

[1] Part of the first author's dissertation, presented to Graduate Program in Agronomy, State University of Central-West, Guarapuava-PR, Brazil. This study was funded by the Paraná State Araucária Foundation (Fundação Araucária, Brazil), Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil), and National Counsel of Technological and Scientific Development (CNPq)

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INTRODUCTION

In Brazil, the no-tillage system (NTS) is the most widely used for most crops. However, in this system soil acidity correction occurs on the surface, without incorporation, impairing subsurface correction (Auler *et al*., 2017), since lime and its reaction products have low mobility (Crusciol *et al*., 2019). Thus, combining lime and gypsum can be an alternative to improve the plant growth environment in tropical soils (Bossolani *et al*., 2020).

Roots of most cultivated plants do not develop well in acidic soils due to excess Al^{3+} and/or Ca^{2+} deficiency (Caires; Guimarães, 2018). Therefore, management techniques that efficiently correct soil acidity in NTS have been studied with gypsum application or the complimentary use of gypsum with lime (Caires; Guimarães, 2018; Zandoná *et al*., 2015). The alternative of applying agricultural gypsum serves to improve root environment in the subsoil, without the need to incorporate (Michalovicz *et al*., 2014; Rampim; Lana, 2015), because the Ca^{2+} ion present in gypsum displaces Al^{3+}, K^{+}, Mg^{2+} ions into the soil solution, which react with SO_4^{2-} to form $AlSO^{4+}$ (less toxic to plants), in addition to forming neutral ionic pairs (K_2SO_4; $MgSO_4$; $CaSO_4$), with great mobility in the soil, leaching Mg^{2+} to deeper layers (Michalovicz *et al*., 2014), increasing the content of Ca^{2+} and the Ca^{2+}/Mg^{2+} ratio. Furthermore, gypsum applied with limestone improves the levels of exchangeable Ca^{2+} in the surface and subsurface layers of the soil (Caires; Guimarães, 2018).

The use of deep-rooted plants such as forage turnip (*Raphanus sativus* L.), as they have a taproot system capable of forming stable biopores originated through decomposition of the root system of cultivated plant species (Pott *et al*., 2023), can contribute to accelerating acidity correction and increasing nutrient mobility in the soil. They facilitate the vertical movement of limestone and gypsum, as well as promote the movement of corrective particles in water through macropores, correcting acidity in the profile and increasing Ca and Mg saturation in the soil profile (Deus, *et al*., 2020).

The distribution of these correctives also influences the acidity management. The application of very high amounts of these products in certain areas and very low amounts in others compared to their requirement cause considerable losses of inputs and compromise crop yield as the established dose is not being applied in each location (Molin, 2002). In this context, the use of precision agriculture is necessary to increase the efficiency of the distribution of agricultural correctives.

This approach leads to crop homogeneity and increases yield and mainly profitability due to cost reductions (Silva; Nunes, 2014). In addition, it enables the application of appropriate doses according to the demand of each management unit (Rampim *et al*., 2012). Spatial information is organized from georeferenced data collection (Serrano *et al*., 2014), ensuring that each small part of the soil receives the amount of input required rather than an average dose as performed in conventional agriculture.

In light of this, the hypothesis is that the use of cover crops promotes the acceleration of limestone mobility, whether associated with gypsum or not, reducing the time for acidity correction and increasing the levels of exchangeable Ca^{2+} and Mg^{2+} in the surface and subsurface layers of the soil.

The objective of this study was to evaluate the soil chemical attributes and soybean performance in succession to the use of cover crops and acidity management with liming by Ca and Mg saturation in the effective cation exchange capacity (ECEC) and gypsum application at variable rates to increase subsurface Ca saturation.

MATERIAL AND METHODS

Site description, experimental design, and treatments

The present study was carried out in Guarapuava, PR, Brazil (25°23’08.1”S and 51°33’16.2”W, with an average altitude of 1100 m), between June 2019 and April 2020 in experimental area conducted under NTS. The soil was identified as Oxisol in experimental area conducted under NTS or *Latossolo Bruno* in the Brazilian soil classification system (Santos *et al*., 2018). According to Köppen’s classification (Alvares *et al*., 2013), the region’s climate is classified as Cfb (humid mesothermal subtropical).

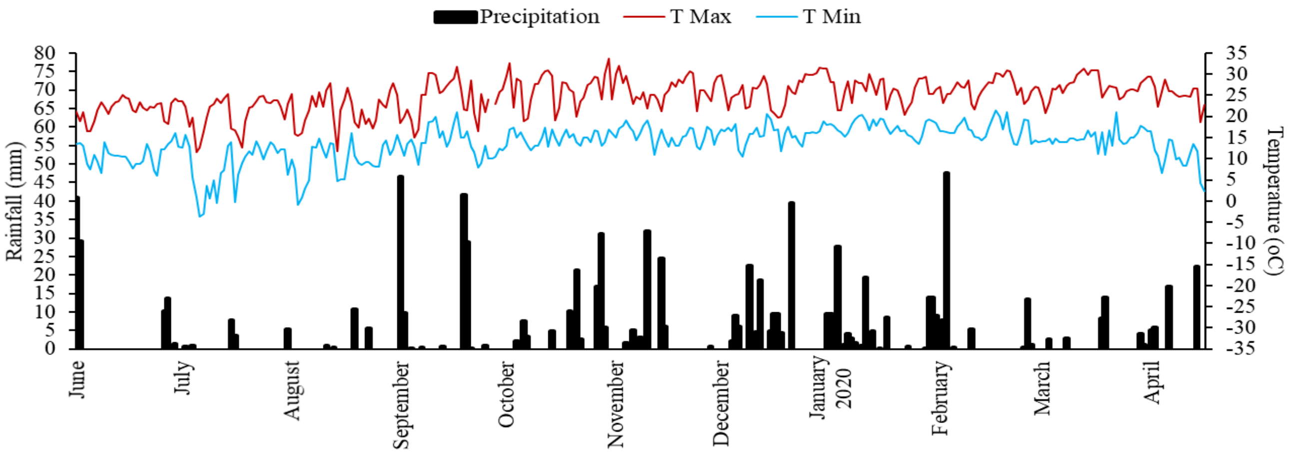
The experiment was conducted in randomized blocks, formed by the combination of three soil acidity management treatments, three winter cover crop management treatments, and one summer crop. The tested soil acidity management treatments were: no correction, lime, and lime + gypsum. The three cover crop management treatments were: fallow (spontaneous vegetation), oat + forage turnip, and polyculture (combination of black oat, forage turnip, white lupin, blue lupin, rye, buckwheat, and vetch). Initially, each plot was randomly seeded with its respective winter cover crop management. Two-thirds of each plot were subdivided to receive lime application, and subsequently, half of each subplot was further subdivided to receive gypsum application. The agricultural practices carried out during the experiment are presented in Figure 1.

Meteorological data during the experiment (Figure 2), obtained from the meteorological station of the Paraná Environmental Technology and Monitoring System - SIMEPAR located at UNICENTRO, Campus Cedeteg, at a distance of 6.13 km from the experiment.

Figure 1 - Chronogram detailing the agricultural practices implemented in each plot and subplot

	2019							2020			
	J	J	A	S	O	N	D	J	F	M	A
Liming	■										
Management of cover crops					■						
Cover crop seeding		■									
Gypsum application						■					
Soyben seeding						■					
Assessment of soybean yield components										■	
Soil sampling											■

Figure 2 - Maximum temperature (T Max), minimum temperature (T Min), and daily precipitation during the experiment from June 2019 to April 2020. Guarapuava, PR, 2020



Acidity Management at variable rates

Considering the recommendations involving precision agriculture (Rampim *et al*., 2012), liming was carried out at a variable rate for each subplot in June 2019 according to chemical analysis conducted in the 0 - 0.2 m layer (Table 1), using the method of calcium and magnesium saturation in effective CEC, aiming to raise the calcium saturation to 50% and magnesium to 15%, which is the recommended ideal range for the implemented crops (Lima *et al*., 2018).This method is based on verifying the charge deficit of each base in the 0 - 0.2 m soil layer, considering the time to reach the ideal saturation (Sfredo, 2008). After that, it calculates the need for liming by mixing two types of lime: calcitic (CaO: 40% and MgO: 4%) and dolomitic (CaO: 30.3% and MgO: 21.4%). Thus, the balance of the two cationic bases saturation in ECEC was sought. The doses of total lime (calcitic + dolomitic) applied at variable rates to the plots under study ranged from 1.34 to 6.27 Mg ha^{-1} (Table 2).

The cover crop population for the oat + forage turnip treatment was 25 kg ha^{-1} of white oat and 5 kg ha^{-1} of forage turnip. Regarding the polyculture, 15 kg ha^{-1} of black oat, 1 kg ha^{-1} of forage turnip, 15 kg ha^{-1} of white lupin, 15 kg ha^{-1} of blue lupin, 15 kg ha^{-1} of rye, 10 kg ha^{-1} of buckwheat, and 10 kg ha^{-1} of vetch were sown, adapted from the recommendation of Lima Filho *et al*. (2014).

In October 2019, mechanical management of the cover crops was performed using a roller-cutter equipment pulled by a 75 hp Agrale tractor. In November 2019, before soybean sowing, half of the lime-corrected area (sub-subplot) received variable-rate gypsum application, according to chemical analysis conducted in the 0.2 - 0.4 m layer (Table 2). Gypsum doses were applied five months after lime application to avoid a large amount of product in just one application, as more than 5 Mg ha^{-1} in NT is not recommended (Pavinato *et al*., 2017).

Table 1 - Results from chemical analysis in the 0 - 0.2 m layer and recommendation for total lime in each subplot

Subplots	Ca^{2+}	Mg^{2+}	Al^{3+}	K^{+}	$H^{+} + Al^{3+}$	SB	CTC	V%	Total lime
	(cmol$_c$ dm^{-3})							%	(Mg ha^{-1})
Fallow 1	5.13	1.53	0.40	0.15	5.19	6.81	12.01	56.75	1.34
Fallow 2	3.28	0.85	0.84	0.07	7.59	4.20	11.79	35.65	4.08
Fallow 3	2.68	0.95	0.51	0.22	6.39	3.85	10.24	37.61	3.68
Fallow 4	2.79	1.07	0.41	0.19	6.54	4.06	10.60	38.28	3.75
Fallow 5	3.68	1.71	0.49	0.27	7.46	5.66	13.12	43.12	4.16
Fallow 6	3.45	1.56	0.32	0.27	7.45	5.29	12.73	41.52	4.25
Fallow 7	4.67	2.48	0.12	0.89	7.12	8.04	15.16	53.01	3.99
Fallow 8	2.42	1.26	0.50	0.70	8.15	4.38	12.52	34.95	5.67
Polyculture 1	4.13	1.72	0.15	0.26	5.53	6.11	11.65	52.49	2.38
Polyculture 2	3.12	1.12	0.41	0.15	7.28	4.39	11.68	37.64	4.09
Polyculture 3	3.85	1.58	0.16	0.5	4.97	5.94	10.91	54.43	2.27
Polyculture 4	3.49	1.39	0.21	0.14	5.53	5.02	10.55	47.57	2.59
Polyculture 5	1.56	0.63	1.43	0.27	8.91	2.47	11.37	21.70	6.27
Polyculture 6	5.26	3.15	0.12	0.22	5.01	8.64	13.65	63.28	1.68
Polyculture 7	1.85	1.04	0.70	0.21	8.74	3.10	11.85	26.17	6.03
Polyculture 8	5.38	3.26	0.07	0.54	5.47	9.18	14.65	62.67	2.24
Turnip + oat 1	3.14	1.79	0.17	0.22	6.67	5.14	11.82	43.53	3.88
Turnip + oat 2	3.80	2.01	0.21	0.39	7.67	6.20	13.88	44.70	4.43
Turnip + oat 3	2.76	1.05	0.79	0.98	6.72	4.79	11.51	41.62	4.50
Turnip + oat 4	4.07	2.00	0.16	0.39	5.70	6.46	12.16	53.15	2.74
Turnip + oat 5	4.32	2.37	0.15	0.10	5.87	6.79	12.67	53.65	2.60
Turnip + oat 6	3.69	1.68	0.25	0.61	6.12	5.97	12.09	49.40	3.36
Turnip + oat 7	3.48	1.06	0.58	0.18	7.31	4.72	12.03	39.21	3.89
Turnip + oat 8	4.48	1.74	0.13	0.45	5.27	6.67	11.94	55.85	2.11

Table 2 - Results from chemical analysis in the 0.2-0.4 m layer and recommendation for gypsum in each subplot

Subplot	Ca^{2+}	Mg^{2+}	Al^{3+}	K^{+}	$H^{+} + Al^{3+}$	SB	NG
	(cmol$_c$ dm^{-3})						(Mg ha^{-1})
Fallow 1	3.75	1.16	0.17	0.09	4.28	5.17	5.45
Fallow 2	2.60	0.67	0.44	0.18	5.60	3.88	4.99
Fallow 3	2.10	0.79	0.18	0.09	4.62	3.16	4.07
Fallow 4	2.03	0.85	0.24	0.10	4.91	3.21	4.53
Fallow 5	3.24	1.61	0.24	0.06	7.64	5.14	7.30
Fallow 6	2.70	1.23	0.15	0.11	5.45	4.18	5.69
Fallow 7	2.88	1.85	0.18	0.30	6.57	5.21	8.93
Fallow 8	2.12	1.17	0.30	0.45	7.21	4.03	7.34
Polyculture 1	3.10	1.34	0.10	0.10	4.44	4.65	5.19
Polyculture 2	2.26	0.78	0.17	0.19	5.01	3.40	4.36
Polyculture 3	3.06	1.24	0.15	0.39	4.71	4.83	6.82

Continuation Table 2

Polyculture 4	2.44	0.95	0.16	0.09	4.49	3.63	4.57
Polyculture 5	1.67	0.72	0.65	0.19	6.90	3.23	6.00
Polyculture 6	3.16	2.25	0.14	0.06	4.56	5.62	9.42
Polyculture 7	1.64	1.05	0.20	0.09	6.34	2.98	5.13
Polyculture 8	4.32	2.88	0.05	0.50	4.33	7.75	1.32
Turnip + oat 1	2.65	1.80	0.08	0.07	5.72	4.60	7.48
Turnip + oat 2	2.40	1.57	0.16	0.30	6.61	4.43	7.80
Turnip + oat 3	2.47	1.10	0.25	0.53	5.60	4.35	7.21
Turnip + oat 4	2.85	1.42	0.18	0.22	4.87	4.67	7.00
Turnip + oat 5	2.72	1.64	0.13	0.03	4.61	4.52	9.92
Turnip + oat 6	2.79	1.42	0.26	0.27	5.43	4.74	7.45
Turnip + oat 7	2.58	0.77	0.34	0.22	6.09	3.91	5.10
Turnip + oat 8	3.21	1.30	0.15	0.49	4.26	5.14	7.43

The agricultural gypsum used contained 22% CaO and 14% S-SO_4^{2-}. Recommendation of gypsum requirement was based on the increase of Ca^{2+} saturation to 60% in the ECEC in the subsoil layer (0.2 - 0.4 m), when it is less than 54% (Caires; Guimarães, 2018), according to formula (1). From the variable rate among subplots, gypsum doses varied from 4.37 to 9.42 Mg ha^{-1}, considering a precision agriculture system structure.

$$GR(Mg\ ha^{-1}) = \left(0.6 * ECEC - Ca^{2+}\right) * 6.4 \tag{1}$$

Were, GR is the Gypsum Requirement for soybean culture, ECEC is the Effective Cation Exchange Capacity ($Ca^{2+} + Mg^{2+} + K^{+} + Al^{3+}$) (cmol$_c$ dm^{-3}) and Ca^{2+}, is the Calcium (cmol$_c$ dm^{-3}).

Approximately 20 days after gypsum application, soybean (*Glycine max* (L.) Merrill) cultivar TMG IPRO 7061 was sown in November. Seeds received an industrial treatment and were co-inoculated at sowing with *Bradyrhizobium* and *Azospirillum* bacteria. Base fertilization was applied with 250 Mg ha^{-3} of the formulated fertilizer NPK 4-14-8 in the seed furrow. For that, a seeder-fertilizer Semeato® SHM11/13 with a kit for a honeycombed disc structured with five rows was used. It was adjusted to deposit nine seeds per row meter, at 3.5 cm depth, with a between-row spacing of 0.45 m.

Evaluations

Chlorophyll content and yield components were evaluated for soybeans. The chlorophyll content was evaluated by the Soil Plant Analysis Development (SPAD) index, carried out from five plants in the net area of each subplot. SPAD was performed on the leaflets of the third leaf (from the apex to the base), between 9 and 11 am in the phenological stage of full flowering (R1) and grain filling (R5.5) (Fehr *et al*., 1971).

A portable chlorophyllometer (model ClorofiLOG, CFL1030, Falker) was used to read the SPAD index. Knowing that chlorophyll absorbs light at some wavelengths, in this device, the measurement units are estimated by the differential reading of the amount of light transmitted by the leaf in three wavelength regions (635, 660, and 880 nm).

The yield components of soybean were evaluated in five plants per subplot at full maturity stage (R8) (Fehr *et al*., 1971), and were evaluated for plant height, number of pods, mass of one thousand grains, and grain yield. Yield data were adjusted to 13% moisture and converted to Mg ha^{-1}. The mass of a thousand grains was evaluated from three samples of 100 grains from each subplot and weighed with a precision scale. The results were expressed in grams.

Soil sampling was carried out in April 2020, nine and five months after liming and gypsum application, respectively, using an auger for the four evaluated layers (0.05, 0.15, 0.25 and 0.35 m). Soil was collected, oven-dried, milled, and sieved in a 2-mm mesh. Chemical analyses were performed at the Soil and Plant Nutrition Laboratory of UNICENTRO to quantify pH ($CaCl_2$), Al^{3+}, $H^{+}+Al^{3+}$, Ca^{2+}, Mg^{2+} (cmol$_c$ dm^{-3}) and S-SO_4^{2-}(mg dm^{-3}) content. Nutrient quantification was performed by the methodology employed by Teixeira *et al*. (2017), using pH in $CaCl_2$ at 1:2.5; $H^{+}+Al^{3+}$, by Shoemaker- McLean and Pratt (SMP) buffer; and Ca^{2+} and Mg^{2+}, in KCl. From the results, base saturation (V%) and saturation of calcium and magnesium in the ECEC were calculated to compare the recommended doses between the different methods.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) and Tukey's test to compare means at 5% and 10% significance levels, using SISVAR (Ferreira, 2011).

RESULTS AND DISCUSSION

Soil chemical attributes

The soil pH ($CaCl_2$) differs between acidity managements in the 0-0.05 m layer (Figure 3-A), in which, the doses of total lime (calcitic + dolomitic) associated or not with gypsum, increased soil pH (4.8 for lime and 4.9 for lime + gypsum) in relation to the area without correction (4.5). For Pauletti and Motta (2019), the ideal pH range in $CaCl_2$ occurs between 5.0 and 5.5 for soybean. This value was achieved with lime associated with gypsum in the 0.35 m layer. It is worth noting that the increases in pH values occur nine months after its application. It is known that lime applied to the surface takes longer to reach the subsurface precisely because it has low mobility in the soil (Joris *et al*., 2016). Furthermore, the cover crops oats + forage turnip and fallow also raised the soil pH to 5.0 in the 0.35 m layer, within the range recommended by Pauletti and Motta (2019). Different plant residues produce organic acids that can alter soil pH (Carmo; Lima; Silva, 2016).

Nine and five months after the application of the lime and gypsum mixture, respectively, the reduction of exchangeable acidity caused by aluminum occurs only in the 0.05 m layer (Figure 3-C), with no significant differences among the other layers. Although gypsum is highly mobile in the soil, a high volume of rainfall is required for a reaction to occur, allowing for the leaching of Al^{3+} and an increase in base saturation in the subsurface (Barros *et al*., 2005; Deus *et al*., 2020). The low precipitation in the area (<400 mm) (Figure 01) during the experiment likely influenced these values, as with less water volume, there were fewer reactions in the soil. Regarding cover crops, there were no differences among the treatments (Figure 3-D).

Potential acidity followed the same behavior as exchangeable acidity, with a difference only in the 0.05 m layer (Figure 3-E). For cover crops, the use of oat + forage turnip reduced potential acidity in the 0.15 m layer compared to polyculture (Figure 3-F). This result can be explained by the anions formed during organic matter decomposition, which neutralized the hydrogen (Gurmessa, 2021).

The acidity management with lime and lime + gypsum at variable rates increase soil Ca^{2+} levels in the 0.05 m layer (Figure 4-A). However, for layer 0.15 m the acidity management with lime does not show differences in relation to the treatment without correction, confirming that the lime applied alone as a corrective does not increase the Ca^{2+} contents in the deeper layers (Esper Neto *et al*., 2019). Associated with gypsum, lime was more effective in increasing Ca^{2+} contents in the 0.15 m layer. These results reinforce that gypsum increases calcium concentration in the soil subsurface (Inagaki *et al*., 2016) even five months after its application.

The soil acidity management with lime and lime + gypsum elevate Mg^{2+} contents in the 0.05 m and 0.25 m layer (Figure 4-C), with the most pronounced value for lime in combination with gypsum, added to the soil five months after liming. Zambrosi, Alleoni and Caires (2007) evidenced the greater presence of Mg^{2+} in deeper soil layers (0.4 - 0.8 m), as they observed that the free form of Mg^{2+} occurred in higher proportion compared to its association with organic and inorganic anions. They also attributed this occurrence to the inorganic anion $S\text{-}SO_4^{2-}$, which showed greater affinity for Mg and facilitated Mg leaching.

For cover crops, oat + forage turnip were found to accumulate more Mg^{2+} in the 0.05 m layer than polyculture and fallow has the same Mg^{2+} content as both treatments in the 0.05 m layer (Figure 4-D). Pissinati, Moreira and Santoro (2016) reported in their findings that forage turnip has a greater capacity to make Mg available on the soil surface, which may explain this result**.**

The liming and lime + gypsum correction did not change the sulfur levels in the different layers (Figures 4-E and 4-F). There was an increase in sulfur content at depth, with no difference between treatments.

In soils with high organic matter content, sulfate can be reduced and remain immobilized. In addition, previous liming favored its leaching due to the increase in ECEC (Vitti *et al*., 2018). The low rainfall (Figure 1) also contributed to the low solubilization of gypsum.

It can be seen that in the 0.15 m layer, magnesium content only increase due to gypsum in fallow (Figure 5-A). Lime stood out compared to unamended soil in areas with oat + forage turnip or polyculture cultivation. Likewise, lime application led to higher soil magnesium content in areas with oat + forage turnip than fallow. This increase is explained by the reduction in soil acidity, favoring the mineralization of organic matter from oat residues, releasing nutrients (Wisniewski; Holtz, 1997).

The efficiency of gypsum in the area under fallow was demonstrated by the increase in calcium content in the 0.35 m layer (Figure 5-C). Moreover, magnesium levels increase by using lime in oat + forage turnip (Figure 5-B). As for the second layer, Mg^{2+} content was raised by liming and gypsum application in fallow. The best

Figure 3 - Values of pH ($CaCl_2$), exchangeable aluminum (Al^{3+}) and potential acidity ($H^+ + Al^{3+}$) in the soil, according to acidity management (A, B, E) and cover crops (B, D, F). ns: not significant; means followed by the same letters do not differ from each other by Tukey's test ($P < 0.05$)

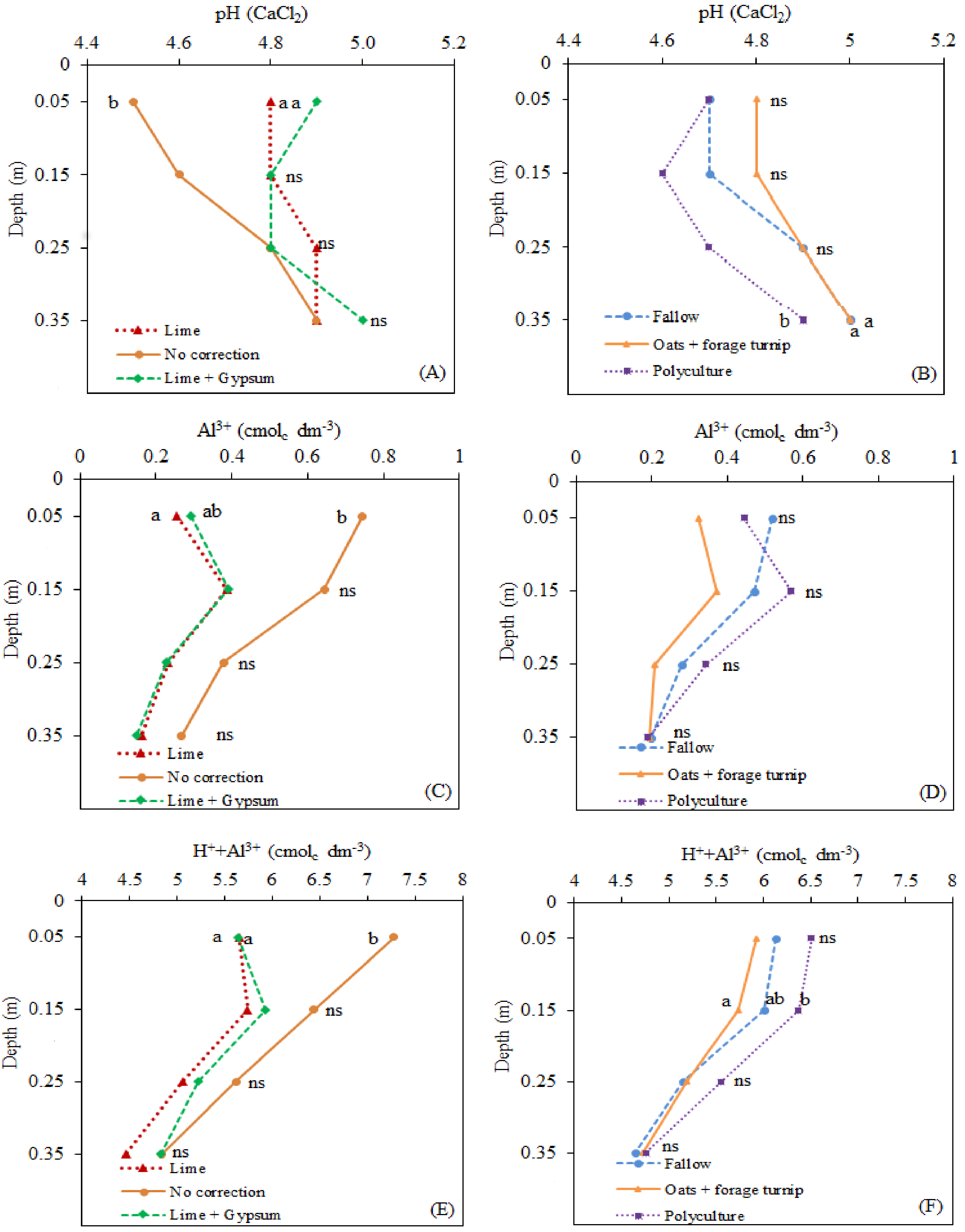
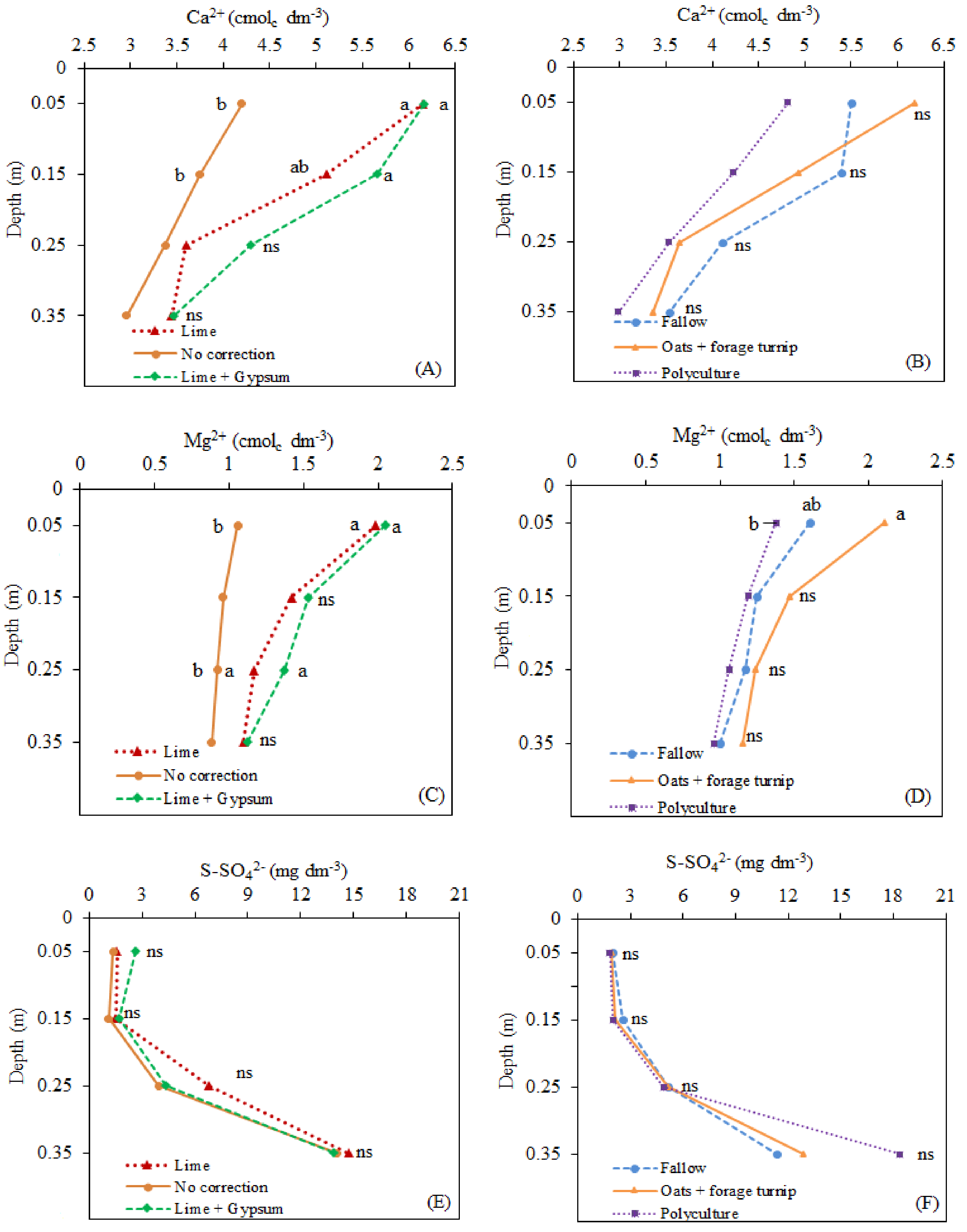


Figure 4 - Calcium (Ca^{2+}), magnesium (Mg^{2+}) and sulfur ($S\text{-}SO_4^{2-}$), contents in the soil, according to acidity management (A, C, E) and cover crops (B, D, F). ns: not significant; means followed by the same letters do not differ from each other by Tukey's test ($P < 0.05$)



results found for fallow regarding acidity management are justifiable, as cover crops absorb considerable amounts of Ca^{2+} and Mg^{2+}, accumulating them in dry matter and temporarily reducing their availability in the soil (Alves; Souza, 2008; Borkert *et al*., 2003).

Nine and five months after lime and gypsum application, respectively and with a total rainfall of 770 mm in this period (Figure 1), the soil base saturation (V%) showed values 16.7 and 15.8% higher for lime and lime + gypsum, respectively, than in the area without correction, for 0 - 0.1 m layer (Figure 6-A). V% increases in depths as of 0.2 m by liming can take four years (Joris *et al*., 2016) or two years with precipitation of 1600 mm (Rodrighero; Barth; Caires, 2015). For cover crops, the oat + forage turnip treatment increases soil base saturation in the 0 - 0.1 m layer compared to polycultive (Figure 6-B), without differentiating from fallow.

Calcium and magnesium saturation in ECEC increased after nine and five months with the application of lime and lime + gypsum, respectively, only in the 0.05 m layer (Figure 6-C and 6-E), with no differences in the other layers, in relation to the uncorrected area. Results also obtained by Caires *et al*. (2004), who observed an increase in calcium saturation up to 0.1 m with the use of lime and gypsum. Additionally, the results show that the mixture of lime types is essential to adjust Ca^{2+} and Mg^{2+} amounts (Pauletti; Motta, 2019). Similarly, Zandoná *et al*. (2015) obtained an increase in calcium, magnesium, and cation exchange capacity in the first layer of an Oxisol (0 - 0.1 m) after nine months of lime and gypsum applied after winter wheat cultivation.

For cover crops, there was no change in calcium saturation in ECEC (Figure 6-D). Whereas magnesium saturation was higher with the use of oat + forage turnip compared to polyculture (Figure 6-F) due to magnesium increase, mainly by forage turnip (Pissinati; Moreira; Santoro, 2016).

Chlorophyll index and yield components of soybean

Soybean chlorophyll index (SPAD) only differed in stage R5.5 (grain filling) (Figure 7-B). Regarding acidity management, liming led to superior chlorophyll A index compared with the uncorrected treatment, but equal values were reached in lime with gypsum. The gypsum also caused no change in the SPAD index of soybean (Santos *et al*., 2019). For cover crops, there was greater chlorophyll A and B activity in grain filling with the use of polyculture compared to oat + forage turnip (Figure 7-B).

The yield components of soybean: plant height (A), number of pods per plant (B), thousand-grain mass (C), and soybean yield (D) in the 2019/2020 crop are shown in Figure 8.

Figure 5 - Interactions for exchangeable base content (Ca^{2+} and Mg^{2+}) and exchangeable Al^{3+} in different soil layers among cover crops and soil acidity management. Means followed by the same lowercase letters do not differ among cover crops for each acidity management, and means followed by the same uppercase letters do not differ among acidity managements for each cover crop by Tukey's test (P < 0.05)

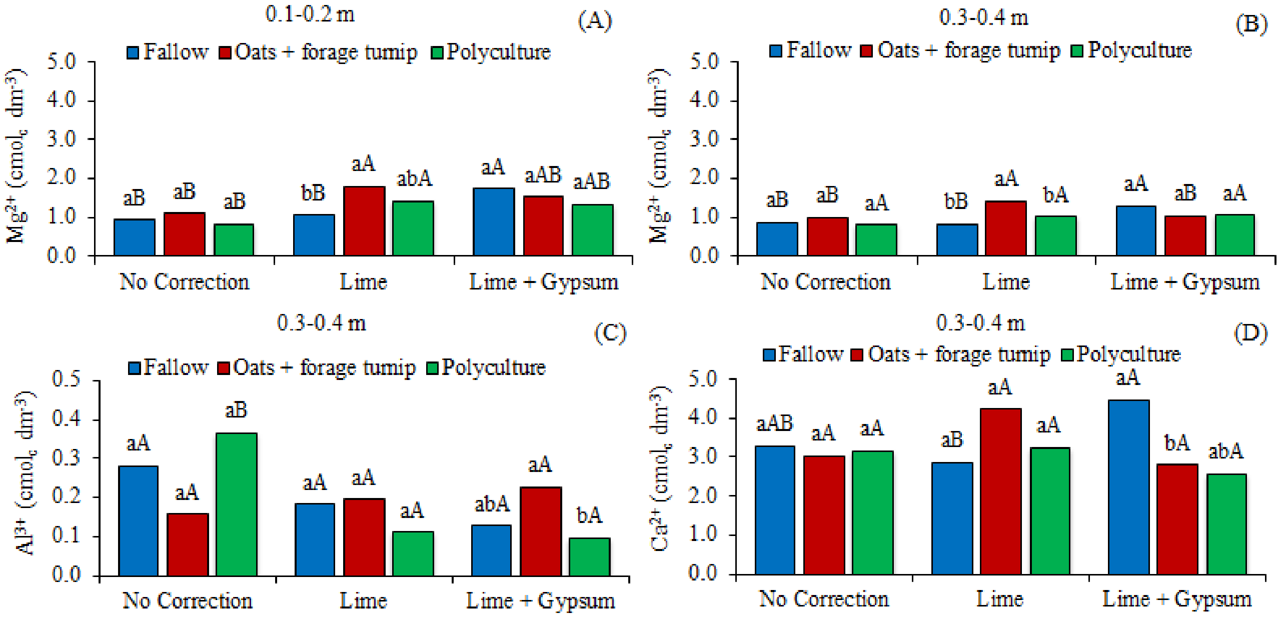
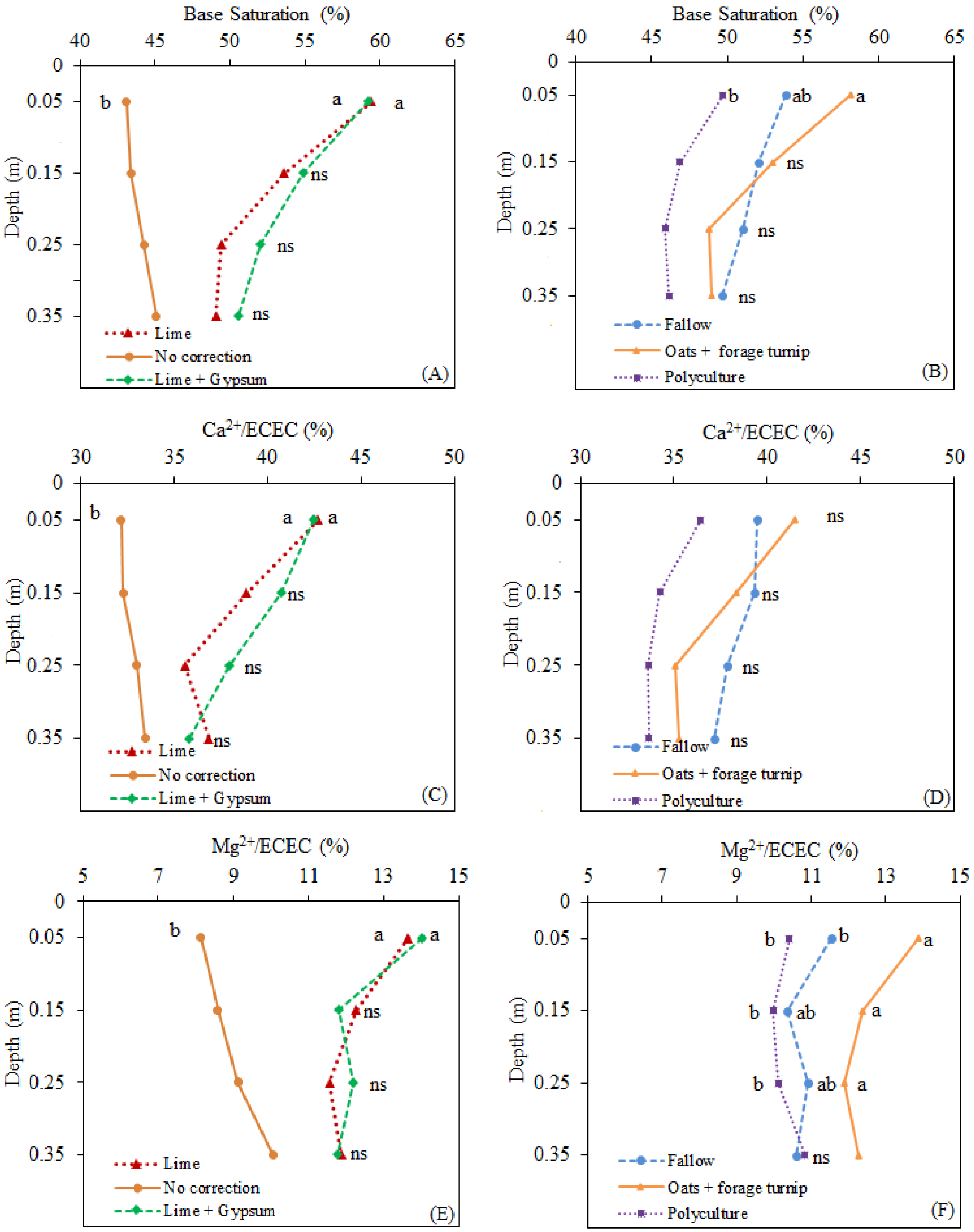


Figure 6 - Base saturation (%), Ca^{2+}/ECEC (%), and Mg^{2+}/ECEC (%) saturation according to acidity management (A, C, E) and cover crops (B, D, F). ns: not significant; means followed by the same letters do not differ by Tukey's test ($P < 0.05$)



The plant height responded significantly to liming, with or without the addition of gypsum (Figure 8-A). The development of the aerial part has a high correlation with the root system, and vice-versa (Goss, 1973). Therefore, this height increase is probably due to the increased availability of calcium, which acts in the development of the root system (Taiz *et al*., 2017). As a result, deeper roots explore a larger area in the soil profile, benefiting nutrient absorption (Santos *et al*., 2019; Schenfert *et al*., 2020), Even more so as the precipitation levels did not reach the maximum expected during the vegetative period (Figure 2).

Figure 7 - SPAD index of chlorophyll A and B in soybean phenological stages R1 (A) and R5.5 (B) according to acidity management and cover crops. Means followed by the same letters do not differ for each chlorophyll type by Tukey's test ($P < 0.05$) within each factor

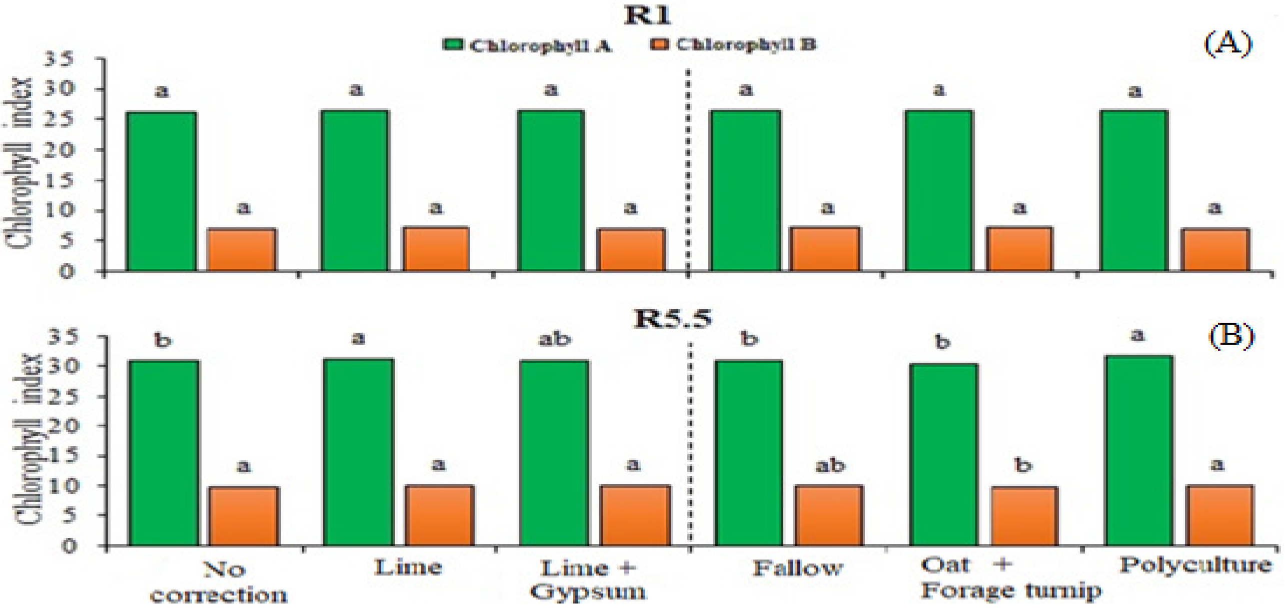
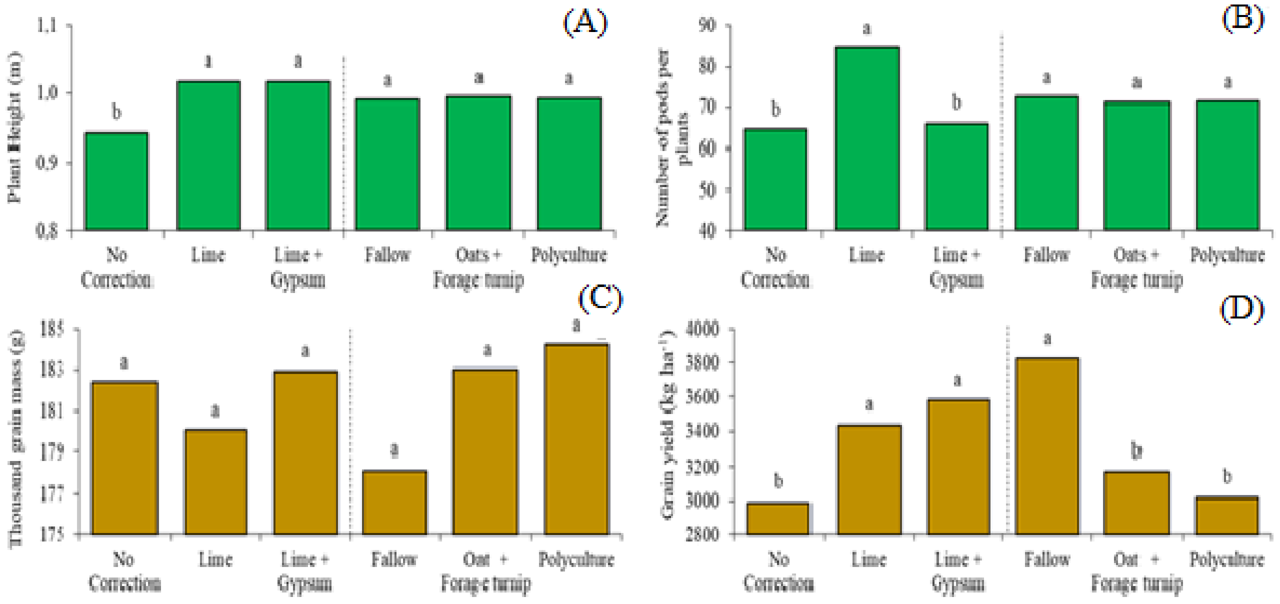


Figure 8 - Plant height (A), number of pods per plant (B), thousand grain mass (C), and soybean grain yield per plant (D) in the 2019/2020 harvest



The number of pods per plant was higher with the use of lime compared to the association of lime with gypsum and no correction (Figure 8-B). The cover crops had no effects on plant height, number of pods, and thousand-grain mass.

Grain yields soybean were higher with the use of lime and lime + gypsum compared to the uncorrected area. Some authors (Fois *et al*., 2018) observed the absence of soybean response to gypsum application due to the lack of water deficit, which was not the case in this study. From November to the end of January, there was a total precipitation of 341 mm (Figure 2), failing to meet the water requirements for soybean cultivation for maximum production, which ranges between 450 to 800 mm per season (Embrapa Soja, 2006).

It is worth noting that rainfall greater than 400 mm and five months are required for the effective solubilization of gypsum and greater soybean yield responses. This methodology proved to be economically viable with liming in the first soybean harvest, increasing yield and profitability per management unit.

Application efficiency of lime and gypsum at variable rates per management unit targeting specific sites of soil acidity with an increase in calcium and magnesium were critical in improving the soil chemical attributes and soybean cultivation.

CONCLUSIONS

1. The cover crops oat + forage turnip and fallow favored the reduction of soil acidity in the 0.35 m layer to the range considered ideal (pH = 5.0) for soybean cultivation;
2. Oats + forage turnip accumulate more Mg^{2+} and increase base saturation in the 0.05 m layer compared to fallow and polyculture, as well as reduce potential acidity in the 0.15 m layer compared to polyculture;
3. When associated with gypsum, lime increased the Ca^{2+} levels in the 0.15 m layer and the Mg^{2+} levels in the 0.15 m and 0.35 m layers.

ACKNOWLEDGMENTS

We acknowledge funding from the Paraná State Araucária Foundation (Fundação Araucária, Brazil), the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil), Finance Code 001, the National Council for Scientific and Technological Development (CNPq, Brazil), and from Paraná Science and Technology, the Higher Education Superintendence (SETI/PR), and the Rural Apprenticeship Service (Serviço Nacional de Aprendizagem Rural – SENAR).

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