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Liming and grazing intensities effects on soil mineral nitrogen throughout the pasture cycle in a subtropical integrated crop-livestock system

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ABSTRACT: Grazing intensity is a preponderant factor for the success of integrated crop-livestock systems (ICLS). Management of grazing intensity impacts soil organic matter (SOM) dynamics, soil reacidification process, and amount and quality of residues added to the ICLS. Consequently, the soil mineral nitrogen (N) forms may present different behavior throughout the pasture cycle, because they are directed linked to SOM and soil acidity dynamics. This study aimed to evaluate the impact of grazing intensities and liming in the temporal variation of acidity and mineral N forms in soil surface (0.00-0.20 m) and subsurface (0.20-0.40 m), throughout the pasture cycle of an ICLS under an Oxisol in the Brazilian subtropics. The study was performed 11 years after the beginning of the field experiment, characterized by the cattle grazing in a winter pasture of oat + ryegrass during the winter and soybean cropping during the summer. The experimental design is randomized block with three replicates, where the grazing intensities are in the plots and liming is the subplots. The grazing intensities were defined as grazing sward height management, being 0.10, 0.20-0.30, and 0.40 m defined as intensive (IG), moderate (MG) and light grazing (LG), respectively. We evaluated the soil ammonium ($N\text{-}NH_4^+$), nitrate ($N\text{-}NO_3^-$), mineral N and pH at 45, 70, 156 and 192 days after pasture sowing (DAPS). Our results showed that grazing intensities only affected the soil pH at the end of pasture cycle, with MG presenting higher pH than IG and LG, regardless of liming. A decrease of soil N mineral stocks was observed throughout the pasture cycle in all managements, due to the decrease of soil $N\text{-}NO_3^-$ stocks in the surface and subsurface layers and of $N\text{-}NH_4^+$ only in the surface layer. The influence of grazing intensities was only observed for N mineral forms in limed areas before the beginning of grazing. At 45 DAPS, MG and LG presented the highest and the lowest $N\text{-}NH_4^+$, respectively. At 70 DAPS, the behavior was inverse, and LG presented the highest $N\text{-}NO_3^-$ stock and the MG and IG the lowest $N\text{-}NO_3^-$ stocks. With such results, it is possible to conclude that there is an influence of grazing intensity and liming in the temporal variation of soil pH and mineral N forms in ICLS and this may be utilized for improvements in N fertilizer management, mainly before the starting of winter grazing.

Keywords: ammonium, nitrate, no-tillage, Oxisol, soil acidity.

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INTRODUCTION

Integrated crop-livestock systems (ICLS) are conservationist production systems that aim to maximize animal and plant productions with economic and environmental sustainability (Moraes et al., 2014). In Brazil, approximately 11.5 million hectares are occupied by different arrangements of ICLS. The subtropical region is responsible for 44 % of this area (Skorupa and Manzatto, 2019). In the crop phase, commonly adopted in the summer period, the ICLS of the Brazilian subtropical region is characterized by irrigated rice (*Oryza sativa*), soybean (*Glycine max*) and/or corn (*Zea mays*). In the livestock phase, commonly adopted in the winter period, the main plant species utilized are forage grasses, as oats (*Avena* sp.) and annual ryegrass (*Lolium multiflorum*) (Carvalho et al., 2006).

These forage grasses are of great importance for the ICLS in Brazilian subtropics, since they produce high amounts of pasture with great quality in relatively low temperatures, being tolerant to the frosts that commonly occur in autumn and winter. The total production of dry matter (DM) that these plant species can produce is about 10 Mg ha^{-1} with adequate management. In addition, the concentration of total digestible nutrients can reach more than 80 % and provide a great animal performance (Fontaneli et al., 2016). However, a relevant factor for the success of ICLS is the grazing intensity management of the livestock phase, which determines the amount of available forage for the animal: higher grazing intensities will provide lower forage availability and vice versa. According to Carvalho et al. (2010a), the management of grazing intensity impacts nutrient cycling, animal production, and the amount of plant residue for soil covering. In addition, this also constitutes one of the main challenges for the increase of the ICLS area in Southern Brazil. There are paradigms linked to the consumption of forage material that would otherwise cover the soil and the potential soil compaction by animal trampling (Carvalho et al., 2021), i.e., both are linked to the grazing intensity of the livestock phase.

Intensive (or high) grazing intensities also result in higher animal stocking and higher live weight (LW) gain per area. However, it also results in lower pasture DM production, lower individual LW gain (Carvalho et al., 2010b), and lower plant residue on the soil surface. Silva et al. (2014) evaluated the effect of grazing intensities on soil carbon (C) balance after ten years of ICLS's adoption in Brazilian subtropics, managed with a pasture of oat and annual ryegrass and bovine grazing in the winter season and soybean in the summer season. They demonstrated that intensive grazing (0.10 m of sward height management) results in a negative soil C balance. Thus, intensive grazing intensities is a potential C emitting for the atmosphere, decreasing the soil C stock and the soil organic matter (SOM) contents (Assmann et al., 2014).

The SOM is a stock and source of nutrients, such as nitrogen (N), phosphorus (P) and sulfur (S). According to Novais et al. (2007), 95 % of soil N is organic, and only 5 % is inorganic. Assmann et al. (2014) also evaluated the effect of different grazing intensities in a subtropical ICLS in southern Brazil, verifying that the soil N stock decreased under intensive grazing in the 0.00-0.40 m layer after nine years, mainly due to the decrease of SOM. This effect is associated with the low plant residue amounts linked to nitrogen losses in the soil surface, as ammonia volatilization and surface runoff due to the less soil water permeability under intensive grazing (Haynes and Williams, 1993; Assmann et al., 2014). Therefore, since the grazing intensity adopted in the ICLS influences the soil C and N stock and SOM contents, our hypothesis is that grazing intensity also will influence N mineralization and the predominant forms of inorganic and mineral N. In the context of ICLS, the study of soil N dynamics is important to define pasture management more efficient in the use efficiency of N applied via fertilizers, minimizing losses for the environment. However, studies with such issues are still scarce.

Ammonium (NH_4^+) and the nitrate (NO_3^-) are the major forms of mineral N in the soils. In subtropical and well aerated soils, the NH_4^+ is the main N product from SOM mineralization, and tends to be transformed into NO_3^- by soil microorganisms (Monteiro et al., 2014). The pH is one of the major regulatory factors in the transformations of soil N forms. For this reason, the liming may be a strategy for mitigating N losses in the soil. The soil acidity correction through liming increases its cation exchange capacity (CEC) in soils with variable charges (CEC dependent on SOM) and consequently the NH_4^+ adsorption (Tasca et al., 2011), probably reducing potential losses due to NO_3^- leaching. It is well-recognized that under ICLS the soil acidity dynamics is different because the corrective effect of surface liming can reach deeper soil layers (Martins et al., 2014) and the reacidification rate is lower (Martins et al., 2016), as compared to only cropping systems. However, studies that linked this different soil acidity dynamic with the soil mineral N dynamics, concerning its stocks and predominant forms, are still scarce.

We hypothesized that moderate grazing intensities associated with soil liming may have higher soil mineral N stocks ($N\text{-}NO_3^- + N\text{-}NH_4^+$) as compared to intensive grazing intensity and absence of liming. To verify this hypothesis, this study aimed to evaluate the effect of different grazing intensities and liming in the temporal variation of soil acidity and N mineral stocks in the surface (0.00-0.20 m) and subsurface (0.20-0.40 m) of an Oxisol, throughout the pasture cycle (livestock season) of a long-term ICLS (soybean-beef cattle) in Brazilian subtropics.

MATERIALS AND METHODS

This study was carried out in an experiment established in 2001, located in São Miguel das Missões County, Rio Grande do Sul State, Brazil, in Espinilho Farm (29° 03’ 10” S latitude, 53° 50’ 44” W longitude) (Figure 1). The average altitude is 465 m and the climate is classified as subtropical with a warm humid summer (Cfa), according to Köppen classification system (Kottek et al., 2006). The average annual temperature is 19 °C, and the average annual precipitation is 1,850 mm. The soil is a red Oxisol, deep, well drained, and with clayey texture (540, 270, and 190 g kg^{-1} of clay, silt, and sand, respectively). The soil chemical properties in 0.00-0.20 m soil layer at the beginning of

Figure 1. Location of the experimental area in the county of São Miguel das Missões, Rio Grande do Sul State, Southern Brazil.

the experiment (November 2000) were: pH(H_2O) (1:1 ratio) of 4.7, SOM (Walkley-Black) of 32 g kg^{-1}, exchangeable calcium (Ca^{2+}) (KCl 1 mol L^{-1}) of 48 $mmol_c$ kg^{-1}, exchangeable magnesium (Mg^{2+}) (KCl 1 mol L^{-1}) of 16 $mmol_c$ kg^{-1}, exchangeable aluminum (Al^{3+}) (KCl 1 mol L^{-1}) of 4 $mmol_c$ kg^{-1}, potential acidity (H+Al, via SMP index) of 96 $mmol_c$ kg^{-1}, available phosphorous (P) (Mehlich-1) of 8 mg kg^{-1}, available potassium (K) (Mehlich-1) of 126 mg kg^{-1}, base saturation of 41 % and Al saturation of 10 %. The cattle grazing began in June 2001 in a black oat (*Avena strigosa*) + Italian ryegrass mixed winter pasture. The ICLS consisted of grazing cycles from May-June to November (winter season) and soybean cropping from November-December to March-April (summer season).

Treatments consisted of grazing intensities during the winter season, which were determined by the sward management height, in plots ranging from 0.8 to 3.6 ha. Sward management heights were 0.10, 0.20, 0.30, and 0.40 m with an additional reference treatment (non-grazed), organized in a randomized block design with three replications. For this study, intensive grazing (IG – 0.10 m of sward management height), moderate grazing (MG - average of 0.20 and 0.30 m of sward management height) and light grazing (LG – 0.40 m of sward management height) were used. Pasture heights were controlled every 14 days by the Sward stick method (Barthram, 1986), which consists of a graduated stick measuring system with a “marker” that slides up and down until the first forage leaf blade is reached. In each plot, approximately 100 randomized readings (points) were conducted. The average sward height resulted from managing the grazing intensity (stocks) by adding or removing steers from each plot as required.

After the first grazing cycle and the implantation of the first soybean cycle (November 2001), 4.5 Mg ha^{-1} of lime was applied to the soil surface of the entire experimental area [relative neutralizing power (RNP) = 62 %]. In May 2010, a new superficial application of the limestone was carried out, aiming to increase the pH of the soil to 5.5 in the 0.00-0.10 m layer (CQFS-RS/SC, 2004), with a rate of 3.6 Mg ha^{-1} (RNP = 74 %). This application was performed in half of the plots, and from this application, the experimental design was considered a randomized block with split plots. The fertilization consisted of the N supply in pasture and P and K supply in soybeans, expecting yields between 4.0 and 7.0 Mg ha^{-1} of dry matter for pasture and 4.0 Mg ha^{-1} of grains for soybeans (CQFS-RS/SC, 2004). More details concerning the long-term data are available in table 1 and Martins et al. (2015).

The current study was performed in the winter season of 2012: eleven years after the experiment implantation and two years after the lime application in subplots. In this year, the pasture sowing was performed on April 24th, with 50 and 25 kg ha^{-1} of black oat and ryegrass seeds, respectively. In this year, the fertilization time changed, and all the fertilizers started to be applied in the winter season. Therefore, 60 kg ha^{-1} of P_2O_5 ha and 60 kg ha^{-1} of K_2O were applied in the pasture sowing (CQFS-RS/SC, 2004), in the

Table 1. Average sward height, average herbage mass (HM), average daily herbage accumulation rate (DHA), total herbage production (THP), residual biomass on soil surface at the end of the stocking period (Residue) in mixed black oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pastures and soybean yield of a long-term (12 years) integrated crop–livestock system under no-till in Brazilian subtropics

Variable	Treatment				
	Intensive grazing	Moderate grazing	Light grazing	Mean	RMSE(1)
Sward height (cm)	12.1±0.84	25.5±0.60	37.8±0.84	25.2	4.85
HM (kg DM ha^{-1})	1375.6±111.80	2552.2±79.05	3481.6±113.74	2481.8	612.36
DHA (kg DM ha^{-1} day^{-1})	41.4±2.52	43.4±1.80	48.7±2.57	44.2	13.83
THP (kg DM ha^{-1})	5933.8±392.51	6761.1±272.67	7314.8±385.67	6697.6	2076.30
Residue (kg DM ha^{-1})	1377.4±245.19	3853.9±169.09	5555.2±245.19	3663.6	1095.84
Soybean yield (kg ha^{-1})(2)	2549.3±226.59	2468±160.22	2720.6±226.59	2551.9	1177.38

(1) Root mean square error. ns: not significant. (2) Relationship soybean yield/soybean residue = 1:1.

forms of triple superphosphate and potassium chloride, respectively. The N fertilization has been performed in 30 and 60 days after the pasture sowing (DAPS), with 60 and 80 kg ha^{-1} of N, respectively, broadcast applied as urea. The grazing started in 70 DAPS, when the pasture reached the average height of 0.30 m and a DM of 2.2 Mg ha^{-1}, with animals weighing 212 kg, on average. The winter grazing period was 130 days (200 DAPS).

The soil sampling was performed in 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m layers four times during the pasture season (45, 70, 156, and 192 DAPS). The soil pH(H_2O) (1:1 ratio) was determined in all soil layers. For evaluation of N mineral forms, layers of soil surface (0.00-0.20 m) and subsurface (0.20-0.40 m) were used to determine the contents (mg kg^{-1}) of NH_4^+ and NO_3^- (Kjeldahl method). The forms of mineral N were converted into N stock (kg ha^{-1}) through conversion by soil density (1.32 and 1.35 kg dm^{-3} in layers 0.00-0.20 and 0.20-0.40 m). For N determination, the field soil moisture was preserved and determined, with the soil samples being maintained at 4 °C up to 14 days until the KCl extraction. The other steps in pH and N analyses were those described in Tedesco et al. (1995).

The results obtained were submitted to analysis of variance (ANOVA) and, when significant ($p<0.05$), the means were compared by Tukey's test at 5 % significance. The statistical model was a mixed-model. The model considered the grazing intensities (IG, MG and LG), liming application (no-liming and liming), soil sampling times (45, 70, 156, and 192 DAPS) and soil layers (0.00-0.20 and 0.20-0.40 m for N mineral forms, and 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m for soil pH) as fixed factors and the blocks as random factor. In addition, the significance of the relationship between soil pH and soil mineral N forms was evaluated using Pearson's correlation coefficients (r) at the 5 % level. All statistical analyses were performed in the R program.

RESULTS

The results from ANOVA are presented in table 2. The soil pH presented a significant effect for grazing intensity and liming, with both presenting significant interaction also

Table 2. Significance of the effects of experimental factors and their interactions in mineral nitrogen forms and pH in integrated crop-livestock system experiment in Southern Brazil, as resulting from analysis of variance (ANOVA)

Variable	NH_4^+	NO_3^-	Mineral N	pH
G(1)	ns	ns	ns	ns
A(2)	ns	ns	ns	**
S(3)	***	***	***	***
L(4)	***	***	***	***
G × A	ns	ns	ns	ns
G × S	*	***	*	**
A × S	ns	**	**	*
G × L	ns	ns	ns	ns
A × L	*	ns	ns	***
S × L	**	***	***	ns
G × A × S	*	**	**	ns
G × A × L	ns	ns	ns	ns
G × L × S	ns	*	ns	ns
A × L × S	ns	ns	ns	ns
G × A × S × L	ns	ns	ns	ns

(1) Grazing intensity. (2) Liming. (3) Sampling time. (4) Soil layer. * significant at $p<0.05$. ** significant at $p<0.01$. *** significant at $p<0.001$. ns: not significant.

with sampling time throughout the pasture cycle. Regarding the effect of soil layer on pH, only the interaction with liming was significant (Table 2). The forms of soil mineral N presented triple interaction among the grazing intensity, the liming and the sampling time, and double interaction with the soil layer and sampling time. Specifically for $N\text{-}NH_4^+$, also the interaction between liming and soil layer was significant (Table 2). Due to these significances among sources of variation and evaluated soil variables, the results are presented in the following manner.

Effects on soil pH

The grazing intensities did not influence the soil pH in each sampling time throughout the pasture cycle. The pH values vary from 4.6 to 5.1, regardless of soil layer and liming (Figure 2a). However, the only grazing intensity that did not show variation throughout the pasture cycle was the MG, which maintained an average pH value of 5.0. The grazing intensities of IG and LG presented a pH decrease from the beginning to the ending of the pasture cycle, when they presented pH values of 4.6 and 4.7, respectively (Figure 2a).

Regarding the liming effects (Figure 2b), independent of grazing intensity and soil layer, the soil pH was similar to the 156 DAPS for limed and non-limed areas, averaging 5.1 and 4.9, respectively. At the end of the pasture cycle (192 DAPS), a decrease of 0.2 and 0.4 units in soil pH was observed for limed and non-limed areas, respectively (Figure 2b). The average soil pH values without liming were similar to those with liming only in the 156 DAPS. Limed areas presented higher soil pH as compared to non-limed areas, and these differences were of 0.2, 0.2 and 0.3 units in the 45, 70 and 192 DAPS, respectively (Figure 2b).

Soil pH was also affected in different soil layers, regardless of grazing intensity and sampling time (Figure 3). The limed area presented higher pH (5.5) than the non-limed area (4.9) only in the soil surface layer (0.00-0.05 m). Finally, the limed areas presented a higher soil pH values stratification among soil layers, with differences being observed in all evaluated soil layers and values varying from 4.6 to 5.5. In non-limed areas, there was no difference between the pH values from the soil surface up to 0.20 m depth, with the values averaging 4.9. The difference in these

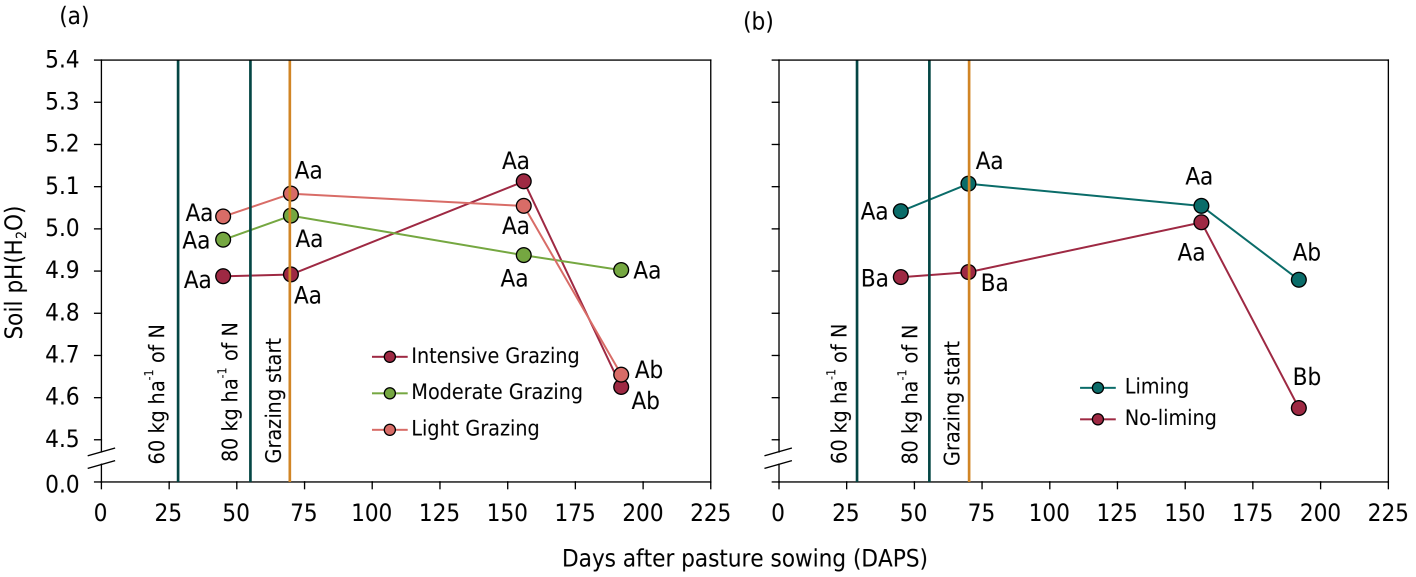

Figure 2. Soil pH (average of 0.00-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.40 m layers) affected by grazing intensities (a) and liming (b) – application was in May 2010, during the pasture winter season of a no-till integrated crop-livestock system in an Oxisol of Brazilian subtropics. Tukey test ($p<0.05$): the uppercase letters compare grazing intensities (a) or lime application (b) within each soil sampling time and the lowercase letters compare soil sampling time within each grazing intensity (a) or lime application (b). The blue line is the N application.

areas occurred only in the deeper evaluated soil layer (0.20-0.40 m), where the soil pH value was 4.6 (Figure 3).

Effects on soil mineral N forms

Soil N-NH_4^+ stocks throughout the pasture cycle did not differ between limed and non-limed areas (Figures 4a, 4b, 4c and 4d), and the average of three first sampling times (45, 70 and 156 DAPS) was 66 % higher than that observed at 192 DAPS. However, 79 and 58 % more N-NH_4^+ were observed in the MG in limed areas and at 45 DAPS, as compared to LG and IG, respectively (Figure 4a). With liming and at 45 DAPS, the MG presented a soil N-NH_4^+ stock that was 95 % higher than the other sampling times. On the other hand, the LG presented similar soil N-NH_4^+ stocks during the whole pasture cycle, which was 26 kg N ha^{-1}.

Regarding N-NO_3^-, the MG and IG presented a higher soil stock in the first period (45 DAPS), which was 327 % higher than the other sampling times (Figure 4a). For the LG, the N-NO_3^- stock with liming was similar between 45 and 70 DAPS (Figures 4a and 4b) (38 kg ha^{-1} of N), decreasing to only 9 kg ha^{-1} of N in 156 and 192 DAPS (Figures 4c and 4d). At 70 DAPS, in this same scenario, the soil N-NO_3^- stocks were 216 and 247 % higher than the MG and IG, respectively, and was 140 % higher than the non-limed areas (Figure 4b).

Concerning the soil mineral N stocks in different layers (Figure 5), a higher N-NH_4^+ stock was observed in the surface layer (0.00-0.20 m) than in the subsurface layer (0.20-0.40 m) throughout the whole pasture cycle and regardless of grazing intensity and liming. The difference between soil layers was, on average, 22 kg ha^{-1} of N (Figure 5). The surface soil layer (0.00-0.20 m) presented a gradual decrease in the N-NH_4^+ stocks throughout the pasture cycle (Figure 6a). In this soil layer, the N-NH_4^+ stock at 192 DAPS was 50 % of the N-NH_4^+ stock at 192 DAPS. On the other hand, in the subsurface soil layer (0.20-0.40 m),

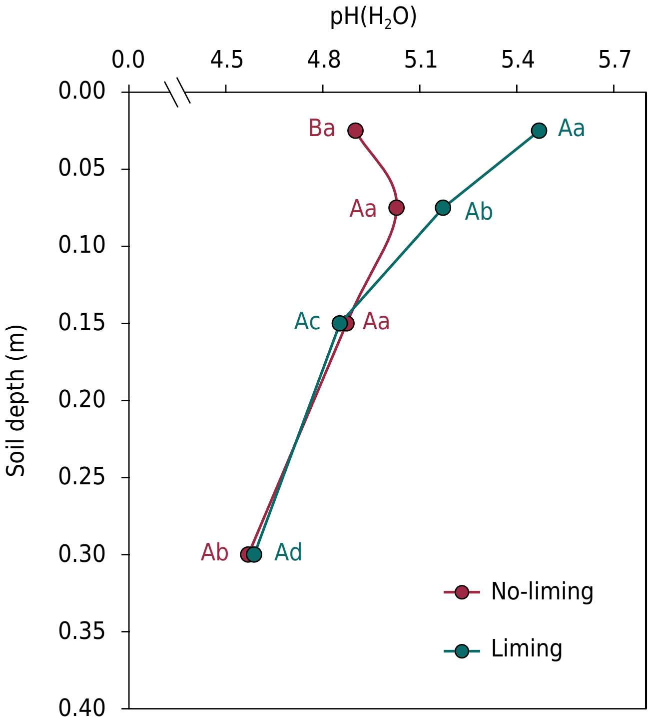

Figure 3. Soil pH (average of different grazing intensities and soil sampling times during the pasture winter season) affected by lime application in a no-till integrated crop-livestock system in an Oxisol of Brazilian subtropics. Tukey test ($p<0.05$): the uppercase letters compare the lime application within each soil layer for soil pH, and the lowercase letters compare the soil layer within each lime application.

the N-NH_4^+ stocks did not present variation throughout the pasture cycle (Figure 6a), with an average amount of 15 kg ha^{-1} of N. In addition, in this soil layer, the non-limed areas presented an N-NH_4^+ stock 37 % higher than the limed areas (Figure 5).

For soil N-NO_3^- stocks, we observed that surface and subsurface layers presented a gradual decrease in the amounts during the pasture cycle, regardless of grazing intensity

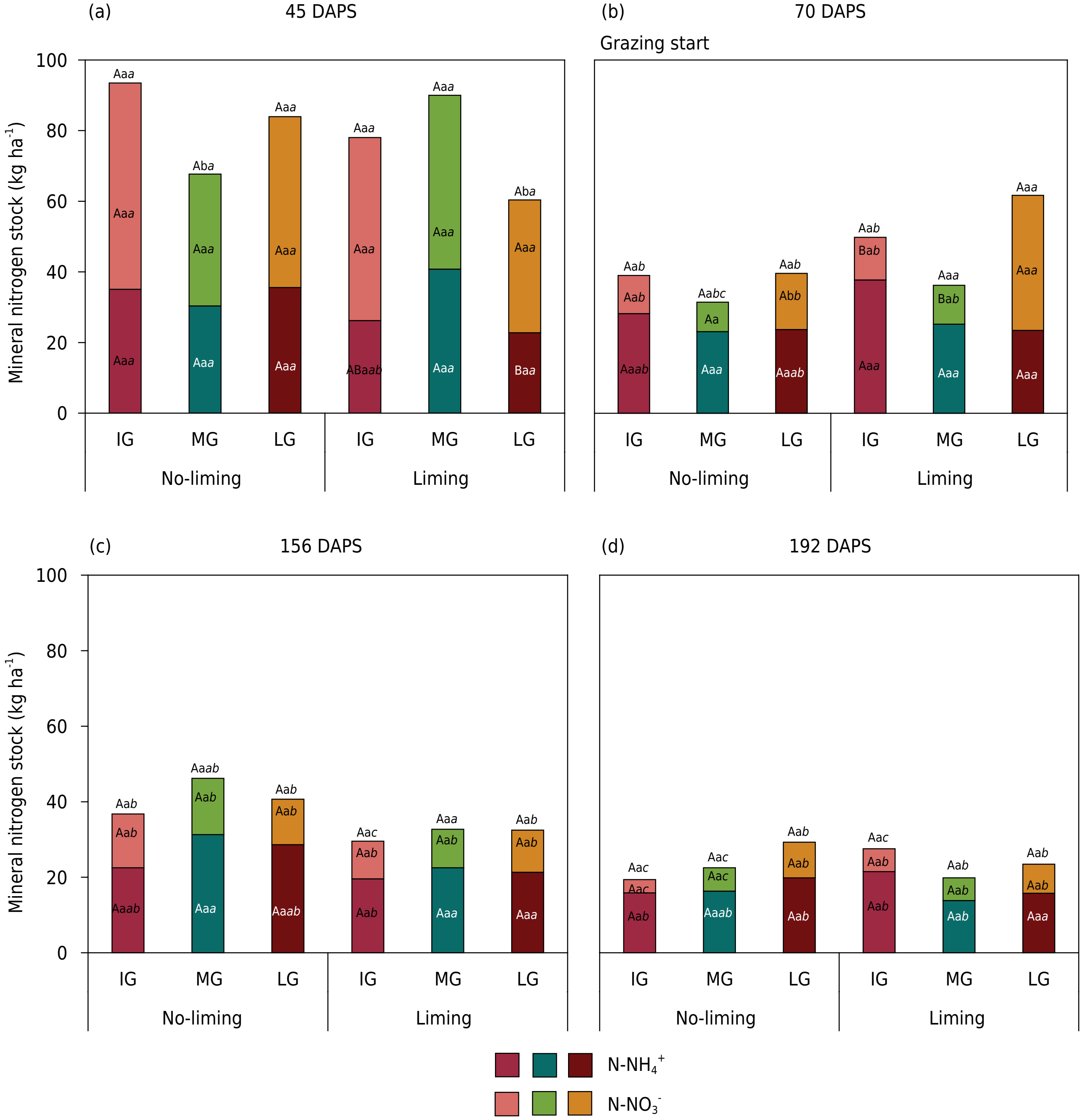

Figure 4. Soil mineral nitrogen forms (average of 0.00-0.20 and 0.20-0.40 m layers) affected by different grazing intensities (IG – intensive grazing, MG – moderate grazing and LG – light grazing) and lime application in different sampling times (DAPS – days after pasture sowing) during the pasture winter season of a no-till integrated crop-livestock system in an Oxisol of Brazilian subtropics. Tukey test ($p<0.05$): the uppercase letters compare the grazing intensities within each lime application and soil sampling time for each mineral nitrogen forms, the lowercase letters compare the lime application within each grazing intensities and soil sampling time for each mineral nitrogen forms and the italic and lowercase letters compare the soils sampling time within each grazing intensities and lime application for each mineral nitrogen form.

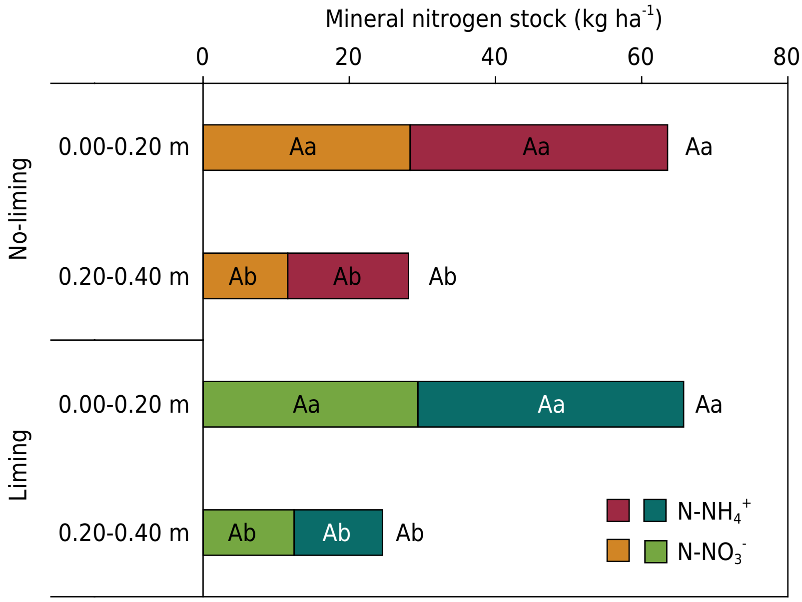

Figure 5. Soil mineral nitrogen forms (average of different grazing intensities and soil sampling times during the pasture winter season) affected by the lime application and soil layers in a no-till integrated crop-livestock system in an Oxisol of Brazilian subtropics. Tukey test ($p<0.05$): the uppercase letters compare the lime application within the soil layer for each mineral nitrogen form. The lowercase letters compare the soil layer within lime application for each mineral nitrogen form.

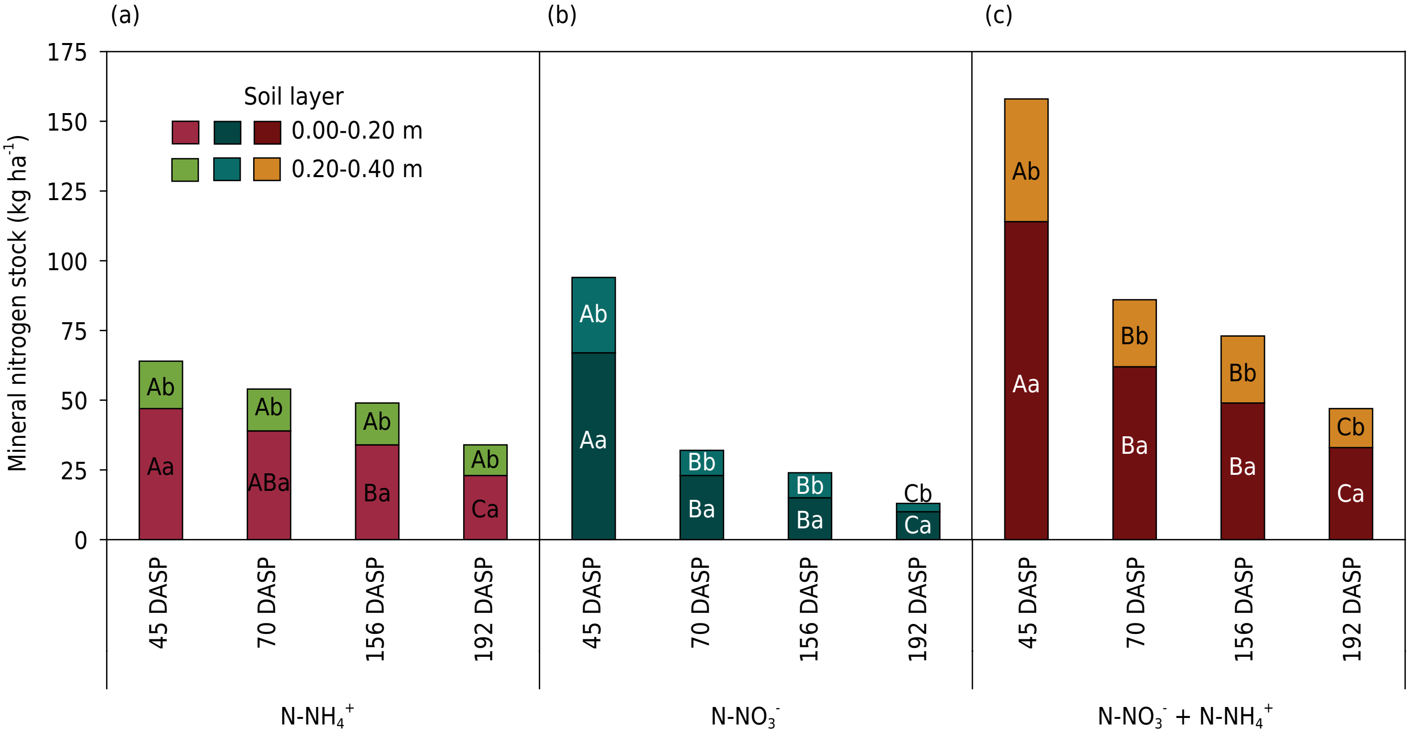

Figure 6. Soil mineral nitrogen forms (average of different grazing intensities and lime application) affected by soil layer and sampling time (DAPS – days after pasture sowing) during the pasture winter season in a no-till integrated crop-livestock system in an Oxisol of Brazilian subtropics. Tukey test ($p<0.05$): the uppercase letters compare soil sampling time within each soil layer, and the lowercase letters compare soil layer within each soil sampling time.

and liming (Figure 6b). The difference observed from 45 DAPS to 192 DAPS was 57 and 24 kg ha^{-1} of N in the soil surface (0.00-0.20 m) and subsurface layer (0.20-0.40 m), respectively. In addition, the surface layer presented a soil N-NO$_3^-$ stock that was 17 kg ha^{-1} of N higher than the subsurface layer, and the liming did not influence the N-NO$_3^-$ stocks in any of the soil layers (Figure 5).

Effects on soil mineral N amounts

The total mineral N (N-NO_3^- + N-NH_4^+) was affected by liming only in the LG at 45 and 70 DAPS, regardless of soil layers (Figures 4a and 4b). In this grazing intensity, the non-limed area presented 39 % more mineral N stock at the 45 DAPS (Figure 4a) and 56 % less mineral N stock at 70 DAPS (Figure 4b), as compared to limed areas. There were no differences among grazing intensities in each soil sampling time, regardless of soil layer evaluated, presenting the average of 79, 43, 36 and 23 kg ha^{-1} of N at 45, 70, 156 and 192 DAPS, respectively (Figures 4a, 4b, 4c and 4d).

Also, there were no differences among sampling times in the IG limed and non-limed, in the MG limed and in the LG non-limed. These treatments presented higher soil mineral N at 45 DAPS as compared to the other sampling times (Figure 4). The MG non-limed presented a similar soil mineral N at 45, 70, and 156 DAPS, being 32 kg ha^{-1} N higher than the soil mineral N at 192 DAPS. On the other hand, the limed LG treatment presented similarity in soil mineral N at 45 and 70 DAPS, being 53 kg ha^{-1} N higher than the N mineral amounts at 156 and 192 DAPS (Figure 4).

Regarding the soil layers, the soil surface (0.00-0.20 m) presented the mineral N stock higher than the soil subsurface (0.20-0.40 m) in all the evaluated sampling times, regardless of grazing intensity and liming (Figure 6c). The difference between layers decreased along the pasture cycle, with average amounts of 70, 38, 25 and 19 kg ha^{-1} of N at 45, 70, 156, and 192 DAPS, respectively (Figure 6c). The decrease in soil mineral N stock in the first sampling time (45 DAPS) for the average of the first 86 days of animal grazing (70 to 156 DAPS) represented 105 and 83 % for the soil surface and subsurface, respectively. And the difference from the first 86 days of animal grazing up to the end of animal grazing (192 DAPS) represented 68 and 71 % for the soil surface and subsurface, respectively (Figure 6c).

DISCUSSION

Stocks and forms of N mineral throughout the pasture cycle

The ICLS are production systems of great complexity due to the interaction between plant and animal components. The animal insertion strongly impacts soil physical and chemical properties (Carvalho et al., 2015). The animal impact may be highlighted by the temporal variability of attributes with high dynamicity in a short period, as pH (Martins et al., 2016) and the mineral N forms (Sá et al., 2011).

The pH is considered a soil master variable (McBride, 1994) and has great variability throughout the time (Martins et al., 2016). This great variability is due to the interaction of pH with many other soil factors, mainly linked to the C and N cycles (Bolan and Hedley, 2003). Animal grazing influences C and N cycles, increasing the microbial activity (Souza et al., 2010), nutrient cycling (Carvalho et al., 2010a), and residue addition (Assmann et al., 2014). The LG treatment maximizes the SOM accumulation due to the higher plant residue (Assmann et al., 2014). On the other hand, the IG presents a higher addition of animal residue and a higher microbial activity (Souza et al., 2010). Both SOM and microbial activity affect soil acidity, maybe being the reason for the decrease in soil pH values at the end of the pasture cycle in the treatments LG and IG, respectively (Figure 2a).

The different sampling times also highlighted the different dynamics of soil mineral N. Higher mineral N stocks were expected after the leguminous cropping and N fertilization, decreasing along time due to the plant uptake and losses for the environment (Cardoso et al., 2011). After the mineralization of soybean residue, a predominance of N-NO_3^- is expected (Figure 4) due to the fast decomposition of low C/N residues (Sá et al., 2011; Assmann et al., 2015). However, the N-NO_3^- is very mobile in soil, and if it is not uptake by plants, it may be lost by leaching. This process explains the lower mineral N stocks from 45 DAPS, with the exception of LG in limed areas – which lasted until 70 DAPS –probably due to the higher SOM of this treatment (Assmann et al., 2014) (Figure 4).

The absence of difference in soil N-NH_4^+ stocks up to 156 DAPS, the top period for pasture DM production, may be explained as a function of soybean residue mineralization and the beginning of grazing with frequent N cycling due to animal dung and urine (Carvalho et al., 2010b). The decrease of soil N-NH_4^+ stocks after the 156 DAPS may be explained by the reduction in soybean residue mineralization and the lower amount of pasture residue and N cycling. Cardoso et al. (2011) evaluated the variation on soil N-NH_4^+ and N-NO_3^- along a year, with different soil management systems, and found that no-till systems present lower mineralization rates at the end of oat cycle after soybean, corroborating with our results.

Nitrate nitrogen governed the temporal variability of mineral N stocks in the soil layers$^-$ stocks, mainly because the N-NH_4^+ stocks were constant in the soil subsurface (0.20-0.40 m), with lower decrease along time in the soil surface (0.00-0.20 m) (Figure 6). The similarity of soil N-NH_4^+ stocks throughout the pasture cycle is expected because the main source of N-NH_4^+ is the residue mineralization and NH_4^+ is rapidly transformed into NO_3^- by nitrifiers bacteria (Cardoso et al., 2011). On the other hand, the lower variation of N-NH_4^+ stocks in soil surface over time shows the mineralization of organic material deposited on the soil surface during the animal grazing (Figure 6). These results evidenced the necessity of studies on the temporal variability of livestock phase in ICLS to better identify animal effects on soil properties with high dynamicity, such as pH and mineral N stocks.

Role of liming on the soil mineral N forms

The results showed that there is a tendency for limed areas present higher soil mineral N stock (MG at 45 DAPS and LG at 70 DAPS, both with pH of approximately 5.0), mainly in areas with higher SOM (MG and LG as compared to IG) (Assmann et al., 2014). Likewise, there was a positive correlation between soil pH and mineral N in both forms ($p<0.001$). However, a lower correlation coefficient (r-value of 0.28) was observed when relating soil pH and soil mineral N-NO_3^-. The large relationship between soil pH and the mineral N-NH_4^+ content ($r = 0.58$) could be due to the effect of the increased pH has on the mineralization of SOM by the action of microorganisms (Cardoso et al., 2011).

In acid soils already corrected by liming, there is an increase in microbial activity, which is responsible for residue decomposition and nutrient mineralization (Edmeades et al., 1981; León et al., 2017). Borgohain et al. (2019) evaluated the mineralization rate of plant residue affected by liming and by the application of different organic composts, as animal manure, and concluded that there is a maximization of mineralization and nitrification when animal manure application and liming is performed, corroborating with what may occur under ICLS.

Despite the soil total mineral N difference, there were no differences between limed and non-limed areas in the N-NO_3^- and N-NH_4^+ stocks throughout the pasture cycle (Figure 4), contrary to our hypothesis. However, a higher N-NH_4^+ stock was found in soil subsurface (0.20-0.40 m) in non-limed areas (Figure 5). In non-limed areas, a portion of negative charges from solid soil phase is occupied by Al^{3+} and H^+, besides the other basic cations (Ca^{2+}, Mg^{2+} and K^+). Consequently, the soil effective CEC is lower than the effective CEC in limed areas, decreasing the adsorption of basic cations and increasing their mobility in the soil profile (Crusciol et al., 2011). Another factor that may influence the higher N-NH_4^+ stock in soil subsurface in non-limed areas is the impact of low pH in the soil surface in the population of bacteria that oxidize the NH_4^+ (Banning et al., 2015), which are very sensitive to pH changes (Rousk et al., 2010). In this manner, the inefficiency of such bacteria – also called nitrifiers – in addition to the low adsorption of basic cations in non-limed areas and the frequent addition of urea via urine and fertilization may explain the higher N stock in soil subsurface.

CONCLUSIONS

In general, grazing intensity and liming influence the temporal variability of soil pH and mineral N forms in our study, performed in an Oxisol during the livestock phase of an ICLS (soybean-beef cattle) in Brazilian subtropics. The grazing intensity affects pH at the end of the pasture cycle regardless of liming, with moderate grazing presenting higher pH values (5.0) than intensive or light grazing (4.6). In addition, moderate grazing is the only management that does not change its pH value during the livestock phase. A decrease in soil total mineral N stocks along the pasture cycle also occurs, from 158 to 47 kg N ha^{-1} up to 0.40 m soil depth (regardless of management), mainly due to the decrease of N-NO_3^- stocks in the surface and subsurface layers and of N-NH_4^+ only in the surface layer. In non-limed areas, there is no influence of grazing intensities on soil mineral N forms during the pasture cycle. However, variations in N-NH_4^+ and N-NO_3^- occur in limed areas before the beginning of animal grazing, mainly under light grazing intensity. This grazing intensity presents the lowest N-NH_4^+ (23 kg ha^{-1} of N) and the highest N-NO_3^- (38 kg ha^{-1} of N) stocks in the first and second sampling times (45 and 70 days after pasture sowing, respectively). However, no differences in total mineral N stocks were observed in both sampling times. With such results, it is possible to conclude that grazing intensity and liming affect the temporal variation of soil pH and mineral N forms in ICLS, and this info may be utilized for improvements in N fertilizer management, mainly before the starting of winter grazing.

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