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Phosphorus lability in a subtropical Acrisol under long-term integrated crop-livestock system: impacts of grazing management and cropping system

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ABSTRACT: Studies on lability of soil phosphorus (P) under integrated crop-livestock systems (ICLS) are still scarce, especially for deep soil layers (more than 0.20 m depth) and different managements in the crop and livestock phase. Distinct management in these phases may lead to a different distribution of soil P pools according to its lability (labile, moderately labile, less labile and residual) and, consequently, the P availability for plant nutrition. This study aimed to determine the soil P pools, by P fractionation and its distribution in lability classes. In a long-term ICLS experiment of grain and sheep production established in 2003, in Southern Brazil, we sampled in 2017 the 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.26, 0.26-0.30 and 0.30-0.40 m layers of a Red Dystrophic Acrisol (*Argissolo Vermelho distrófico*) under two cropping systems in the summer (soybean/corn rotation and soybean/soybean succession), two grazing intensities (moderate and low) and two methods (continuous and rotational) in winter. Fractionation of P consisted of sequential extractions with anionic exchange resin, $NaHCO_3$ 0.5 mol L^{-1}, NaOH 0.1 mol L^{-1}, HCl 1 mol L^{-1}, and NaOH 0.5 mol L^{-1}. The fractions were grouped in four different pools: labile, moderated labile, less labile and residual P. The soybean/soybean succession increased the labile pool of soil P in the 0.00-0.10 m layer compared to the soybean/corn rotation, regardless of the management of the livestock phase. Meanwhile, the management of the livestock phase also influenced soil P lability, regardless of the management of the crop phase. Low grazing intensity increased the levels of labile soil P in the 0.00-0.05 m layer, in comparison with the moderate grazing intensity and regardless of the grazing method. Grazing methods did not impact the soil P lability or content. The greater soil P availability in the soybean/soybean succession can be attributed to the higher quality (low carbon/nitrogen ratio) of the residue, while in the low grazing intensity to the higher forage dry matter production. Such management benefits nutrient cycling and consequently the P availability to the plants, being important to decrease production costs with the reduction and/or greater use efficiency of phosphate fertilizers.

Keywords: no-tillage, sheep, soybean, corn, fractionation.

INTRODUCTION

Integrated crop-livestock systems (ICLS) are developed to optimize land-use and diversify farm income (Kluthcouski et al., 2000). One of the ICLS models that can be used in areas of grain production in summer, typical of subtropical regions such as Southern Brazil, is the inclusion of grazing (livestock) in the winter period. The winter period is commonly used with cover crops that have a high forage potential (Carvalho et al., 2018, 2021). In this way, the adoption of ICLS under the pillars of conservation agriculture (no-tillage – NT) provides improvements in soil fertility due to the higher carbon (C) input compared to monoculture with conventional tillage, promoting a higher plant dry matter accumulation and an adequate crop rotation (Moore et al., 2000; Freitas, 2005).

The scenario of the southern state of Brazil, Rio Grande do Sul (RS), is a good example of how ICLS can change food production with sustainable intensification in subtropical regions. In RS, approximately 8.1 million hectares are cultivated with cash crops in summer, being soybean and corn the main crops in highlands. However, during winter, only 1.5 million hectares are used to grow small grains (wheat, barley, oats and triticale), while 6.6 million hectares are under fallow or with cover crops (EMATER/RS-ASCAR, 2020a,b). In this context, the areas that remain with cover crops are being underutilized, especially regarding the direct economic return to the farmer. Additionally, areas under fallow can cause physical, chemical, and biological soil degradation (Al-Kaisi and Lal, 2017).

The transition from purely agricultural areas (cropping) to ICLS, with livestock in the winter period, may improve soil quality by greater nutrient cycling, due to the ingestion of pasture by the animal and the deposition of excreta in the same grazing area (Loss et al., 2012). The greater or lesser magnitude of this process depends on pasture management, leading to differences in the utilization of nutrients that are cycling in the system, as well as losses due to leaching or runoff. In the long term, this process may lead to a differentiated need for nutrient inputs in the soil, which should be based on losses and replacement of the amount exported, mainly by grains from the crop phase of the ICLS (Anghinoni et al., 2013). According to Farias et al. (2020), ICLS with well-managed pastures and adequate fertilization strategy that aims greater nutrient use efficiency are a potential and necessary pathway to increase food production and improving land-use sustainability. But simply storing these nutrients in the soil is not the only concern. Their dispersal and forms of accumulation in the soil are also important. Some authors suggest that the amount of excreta accumulated in places of high permanence of animals is affected when they are under rotational grazing (Williams and Haynes, 1990; Wilkinson and Stuedemann, 1992; Johnson, 1993), so that, when animals are stimulated to greater movement in pastures tends to a more uniform excretal distribution (Mathews et al., 1994). In the long term, this may lead to more labile forms of nutrients in the soil.

One of the major controversies encompassing finite nutrient sources occurs especially for phosphorus (P). It is not known for sure how far it will be feasible to extract, transform and distribute these supplies, which are transformed into mineral fertilizers and sold to farmers to enable food production (Pantano et al., 2016). In addition to the amount of P fertilizers per se, the amount of energy and resources needed to produce P fertilizers should also be considered. Thus, we need more efficient managements that reduce losses and improve efficiency in the use of P. Many studies have shown that including ICLS in purely cash crop areas may make these areas more self-sustaining. ICLS can increase P cycling and economic returns, as shown in the studies of Costa et al. (2014) and Assmann et al. (2017).

Phosphorous is a nutrient that has a very specific behavior in the soil: low mobility, low desorption and high adsorption rates to colloids (Parfitt, 1979). Generally, tropical and subtropical soils are highly weathered and have high iron oxides content in the clay fraction, promoting high P adsorption and low availability to plants. This is a problem for the food production system because P is an essential nutrient that plants depend on to complete their cycle (Quirino, 2010). However, P is found in the soil in different forms and lability (Gatiboni et al., 2013). Most routine soil analyses, which serve as a parameter for defining the nutrient rate to be applied as fertilizer, evaluate the most readily available P, or labile P (Tedesco et al., 1995). However, it does not evaluate the less labile pools in the soil, which, although it is not readily available, can act as a source of P to the plants. Crop rotation and grazing management can modify the P cycling and its lability, mainly by grazing intensity and crop rotation (Assmann et al., 2017; Damian et al., 2020). Studies have also shown that plant diversity increases P lability in soils (Tiecher et al., 2012). In addition, the management may influence the dynamics of nutrients in deeper soil layers. Most studies evaluated only surface soil layers (commonly up to 0.20 m), which may limit the comprehension of nutrient dynamics in the soil, as Veloso et al. (2018) showed for soil organic carbon in a long-term no-till system. However, most studies that focus on understanding P dynamics in subtropical ICLS evaluated the soil only up to 0.20 m depth (Costa et al., 2014; Deiss et al., 2020).

In this context, studies on P lability pools in soil in ICLS are still scarce, especially those evaluating the effect of different managements in the crop and livestock phases in soil layers below 0.20 m depth. Based on the current knowledge, our study hypothesizes that crop rotation in the crop phase and the rotational method with moderate intensity in the livestock phase benefit more labile soil P pools in ICLS. This study aimed to evaluate the soil P lability up to 0.40 m depth of an Acrisol under no-till ICLS with long-term grain and sheep production in Southern Brazil, with different managements of the crop phase (crop rotation and succession) and livestock phase (moderate and low grazing intensities and continuous and rotational grazing methods).

MATERIALS AND METHODS

Experimental protocol

The experiment was established in 2003 at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul, located in the municipality of Eldorado do Sul, in the Central Depression Region of the Rio Grande do Sul State, Southern Brazil. Climate is classified as subtropical humid (Cfa) according to the Köppen classification system (Kottek et al., 2006). Since the experiment's beginning, annual rainfall ranged from 1,200 to 2,000 mm. The soil is classified as a typical *Argissolo Vermelho distrófico* (Santos et al., 2013), corresponding to Red Dystrophic Acrisol (IUSS Working Group WRB, 2014). Soil texture in the 0.00-0.30 m soil layer is 155, 238 and 606 g kg^{-1} of clay (<0.002 mm), silt (0.002-0.05 mm) and sand (>0.05 mm), respectively, being classified as a sand-loam soil. Soil chemical properties and the contents of crystalline and amorphous Fe and Al of the experimental area, sampled in June of 2017, are presented in table 1.

The experiment consisted of an ICLS with cash crops in summer and sheep grazing in winter. Experimental area had 4.5 hectares, with 16 plots. The experimental design used was the randomized blocks, with four replications, consisting of a 2 × 2 factorial with subdivided plots. Grazing intensity (moderate and low) and grazing method (continuous and rotational) were the two main factors, with the cropping system (succession and rotation) the subdivided plots.

Grazing intensities were established according to the forage allowance, expressed as kg of dry matter (DM) per 100 kg of animal live weight (LW) per day. In the moderate grazing intensity, forage allowance was 2.5 times the potential of forage intake per sheep. In the low grazing intensity, the forage allowance was 5.0 times the potential of forage

Table 1. Soil properties in the experimental area of long-term no-till integrated crop-livestock (grains and sheep) system in an Acrisol of Southern Brazil

Soil chemical property	Soil layer				
	0.00-0.05 m	0.05-0.10 m	0.10-0.20 m	0.20-0.30 m	0.30-0.40 m
Ca^{2+} ($cmol_c\ dm^{-3}$)[(1)]	1.3	0.8	0.9	1.4	1.4
Mg^{2+} ($cmol_c\ dm^{-3}$)[(1)]	0.7	0.4	0.4	0.6	0.7
Al^{3+} ($cmol_c\ dm^{-3}$)[(1)]	1.2	1.4	1.4	1.3	1.3
P ($mg\ dm^{-3}$)[(2)]	95	94	46	17	12
K ($mg\ dm^{-3}$)[(2)]	84	69	68	66	65
OM (%)	2.9	1.5	1.1	1.0	1.0
pH(H_2O)	3.9	3.8	4.0	4.2	4.3
SMP index	5.4	5.4	5.6	5.6	5.6
H+Al ($cmol_c\ dm^{-3}$)	10.2	10.2	8.9	8.7	8.7
CEC_{pH7} ($cmol_c\ dm^{-3}$)	12.3	11.6	10.4	10.9	11.0
V (%)	18	12	14	20	21
m (%)	36	52	49	39	37
Fe_d[(3)] ($g\ kg^{-1}$)	7.6	7.2	7.4	8.1	8.4
Al_d[(3)] ($g\ kg^{-1}$)	1.7	1.6	1.6	1.9	2.0
Fe_o[(4)] ($g\ kg^{-1}$)	3.1	3.2	3.0	2.3	2.2
Al_o[(4)] ($g\ kg^{-1}$)	1.9	1.9	2.1	2.5	2.7

[(1)] Extracted with KCl 1.0 mol L^{-1}. [(2)] Extracted with Mehlich-1 solution. [(3)] Extraction performed by the citrate-dithio-bicarbonate method. [(4)] Extraction performed by the ammonium acid oxalate method.

intake per sheep. The forage intake potential of sheep is 4.0 kg of DM per 100 kg of LW (Primary Industries Standing Committee, 2019). Therefore, forage supply was 10 and 20 % of LW, for moderate and low grazing intensity, respectively. Detailed information about the experiment's conduction can be found in the studies by Arnuti (2018) and Alves et al. (2020). Average amount of nutrients applied each year was 150, 28, and 50 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively. More information about the applied nutrients can be found in Alves et al. (2019).

Soil sampling

Soil was sampled in June of 2017, up to a depth of 0.40 m in five layers (0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m) in the 32 plots, totaling 160 samples. Samples were collected with a cutting shovel up to 0.20 m depth, and with an auger from 0.20-0.40 m depth. In each subplot, three subsamples were collected to compose a sample. Collected soil samples were dried in a forced air circulation oven at 45 °C, milled into a 2 mm sieve, and stored in plastic pots. In the summer before this soil sampling, soybean was grown in the treatment of the soybean/corn cropping system.

Evaluation of phosphorus lability

Soil P lability was performed through P fractionation using the method proposed by Hedley et al. (1982) with the modifications suggested by Condron and Goh (1989). Fractionation consisted of successive extractions with anionic exchange resin, $NaHCO_3$ 0.5 mol L^{-1} (labile P), NaOH 0.1 mol L^{-1} and HCl 1 mol L^{-1} (moderately labile), and NaOH 0.5 mol L^{-1} (P less labile), and digestion and extraction with H_2SO_4 + H_2O_2 + $MgCl_2$ (residual P). Fractions were grouped in four different pools: Labile P, labile organic and inorganic P; Moderately labile P, inorganic P chemosorbed to Al or Fe oxides; Less labile P, inorganic P bonded to calcium phosphate; and Residual P, the remainder of the soil P.

Statistical analysis

Statistical analysis of the data consisted of the Shapiro-Wilk test to verify the normality, Bartlett test to verify the homogeneity of variances, and the analysis of variance (ANOVA). When statistical significance was reached ($p<0.05$), the means were compared by the Tukey multiple comparison test ($p<0.05$). The statistical model used in ANOVA was as follows: $Y_{ijklm} = \mu + B_i + M_j + I_k + M_jI_k + \text{error a (ijk)} + S_l + M_jS_l + I_kS_l + M_jI_kS_l + \text{error b (ijkl)} + C_m + M_jC_m + I_kC_m + S_lC_m + M_jI_kC_m + M_jS_lC_m + I_kS_lC_m + M_jI_kS_lC_m + \text{error c (ijklm)}$; in which: μ is the overall average; B is the blocks (I = 1, 2, 3, 4); M is the grazing method (j = 1, 2); I is the grazing intensity (k = 1, 2); S is the cropping system (l = 1,2); C is the soil layer (m = 1, 2, 3, 4, 5), and error is the experimental error. Statistical analyses were performed with SAS and SISVAR software. Principal Component Analysis (PCA) was performed using the factoextra package from R (v.4.1.1). Data was centered or normalized before the computation of the factor scores.

RESULTS

Labile soil P pool ranged from 3 to 135 mg kg^{-1}, with an average of 53 mg kg^{-1}. The moderately labile soil P pool ranged from 28 to 221 mg kg^{-1}, with an average of 98 mg kg^{-1}. The less labile soil P pool ranged from 9 to 44 mg kg^{-1}, with an average of 25 mg kg^{-1}. Residual soil P pool ranged from 10 to 394 mg kg^{-1}, with an average of 128 mg kg^{-1}. Total soil P pools ranged from 72 to 653 mg kg^{-1}, with an average of 304 mg kg^{-1} (Figure 1).

ANOVA was performed for each class of soil P lability, and the result is presented in table 2. Results demonstrated that the cropping systems impact soil P lability independently of the management of the livestock phase (grazing intensities and grazing methods) and vice-versa. Thus, the results obtained in our study will be presented in

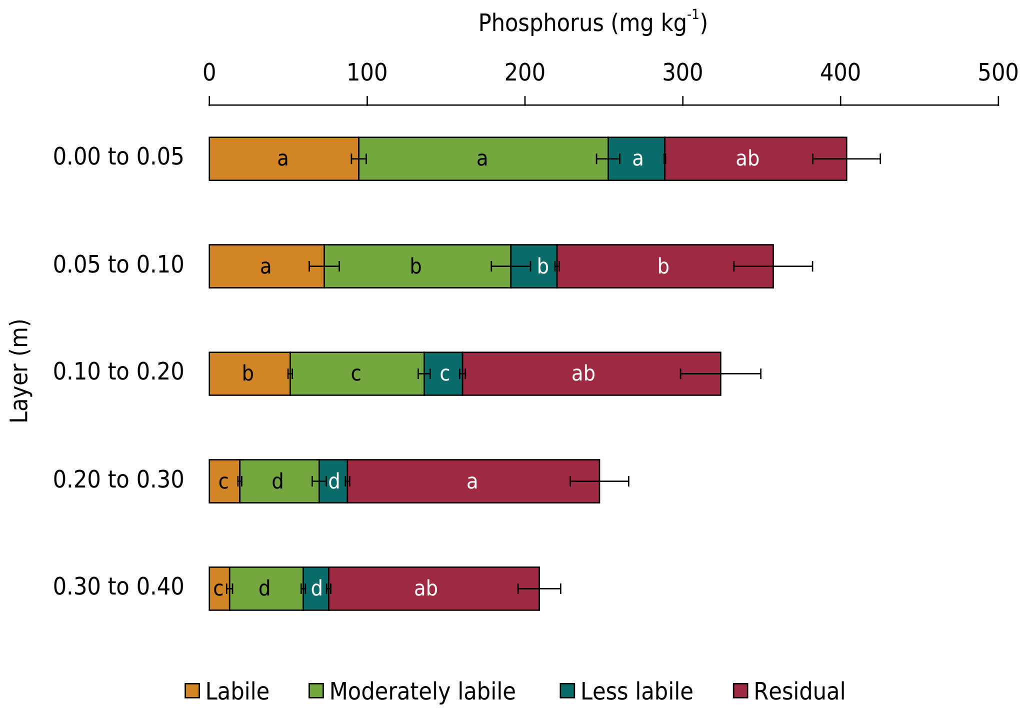

Figure 1. Soil phosphorus pools in different soil layers, regardless of cropping system (monoculture soybean/soybean and rotation soybean/corn) and grazing management (rotational and continuous methods and moderate and low intensities), in a long-term no-till integrated crop-livestock (grains and sheep) system in an Acrisol of Southern Brazil. Lowercase letters differentiate layers (Tukey test, $p<0.05$) within each phosphorus pool. Bars represent the standard deviation of the mean.

two sub-items. The first will deal with the effect of cropping system management on soil P lability, regardless of livestock phase management. And the second will deal with the effect of livestock phase management on soil P lability, regardless of cropping system management.

Effect of cropping system management on soil phosphorus lability

The effect of summer cropping systems was independent of grazing intensity or grazing method for all soil P labilities. The soybean/soybean succession presented higher levels of labile and moderately labile soil P pools in the surface layers (0.00-0.10 m) compared to the soybean/corn rotation. For labile soil P, the highest levels were observed in 0.00-0.05 and 0.05-0.10 m soil layers, being 12 and 22 % higher in succession than in crop rotation, respectively (Figure 2a). Moderately labile soil P also presented higher levels in 0.00-0.05 and 0.05-0.10 m layers, being 12.3 and 9.3 % higher in succession as compared to crop rotation, respectively (Figure 2b).

No difference was observed between the cropping systems along the soil profile for the less labile and residual soil P. The less labile soil P ranged from 30.3 to 43.7 and 9.0 to 23.3 mg kg^{-1} in 0.00-0.05 and 0.30-0.40 m soil layer, respectively (Figure 2c); and the residual soil P ranged from 34.1 to 191.6 and 46.9 to 196.1 mg kg^{-1} in 0.00-0.05 and 0.30-0.40 m soil layer respectively (Figure 2d).

Effect of grazing intensities and methods on soil phosphorus lability

The effect of grazing intensities and grazing methods in the ICLS was independent of cropping system management for all soil P labilities. The ANOVA performed for labile and moderately labile soil P pools presented interaction between grazing intensities and grazing methods. Continuous grazing method with low grazing intensity had higher levels of labile P pool in the 0.05-0.10 m soil layer compared to the other management

Table 2. Significance of the sources of variation for each pool of soil phosphorus, as a result of analysis of variance (ANOVA, $p<0.05$), in a long-term no-till integrated crop-livestock (grains and sheep) system in an Acrisol of Southern Brazil

Sources of variation	Soil phosphorus pool				
	Labile	Moderately labile	Less labile	Residual	Total
Grazing method (GM)	ns	ns	ns	ns	ns
Grazing intensity (GI)	ns	ns	ns	ns	ns
Cropping system (CS)	ns	0.030	ns	ns	ns
Soil layer (SL)	<0.001	<0.001	0.041	ns	<0.001
GM*GI	ns	ns	ns	ns	ns
GM*CS	ns	ns	ns	ns	ns
GM*SL	ns	ns	ns	ns	ns
GI*CS	ns	ns	ns	ns	ns
GI*SL	ns	ns	ns	ns	ns
CS*SL	0.011	0.015	ns	ns	ns
GM*GI*SL	ns	0.050	ns	ns	ns
GM*GI*CS	ns	ns	ns	ns	ns
GM*CS*SL	ns	ns	ns	ns	ns
GI*CS*SL	ns	ns	ns	ns	ns
GM*GI*CS*SL	ns	ns	ns	0.015	0.032

ns: not significant.

of the livestock phase. Labile soil P pool in the 0.05-0.10 m soil layer for low grazing intensity and rotational grazing method was 95.2 mg kg^{-1}, for low grazing intensity and continuous grazing method was 86.0 mg kg^{-1}, for the moderate grazing intensity and continuous grazing method was 72.8 mg kg^{-1} and for moderate grazing intensity and rotational grazing method was 89.6 mg kg^{-1} (Figure 3a).

Regarding the moderately labile soil P pool, the treatment with continuous grazing method and low grazing intensity presented the highest levels in the 0.05-0.10 m soil layer compared to the other combination of management of the livestock phase. The P pool for low grazing intensity and rotational grazing method was 134.0 mg kg^{-1}, and for low grazing intensity and continuous grazing method was 147.4 mg kg^{-1}. For the moderate grazing intensity and in the continuous and rotational grazing method was 118.3 and 140.2 mg kg^{-1}, respectively (Figure 3b).

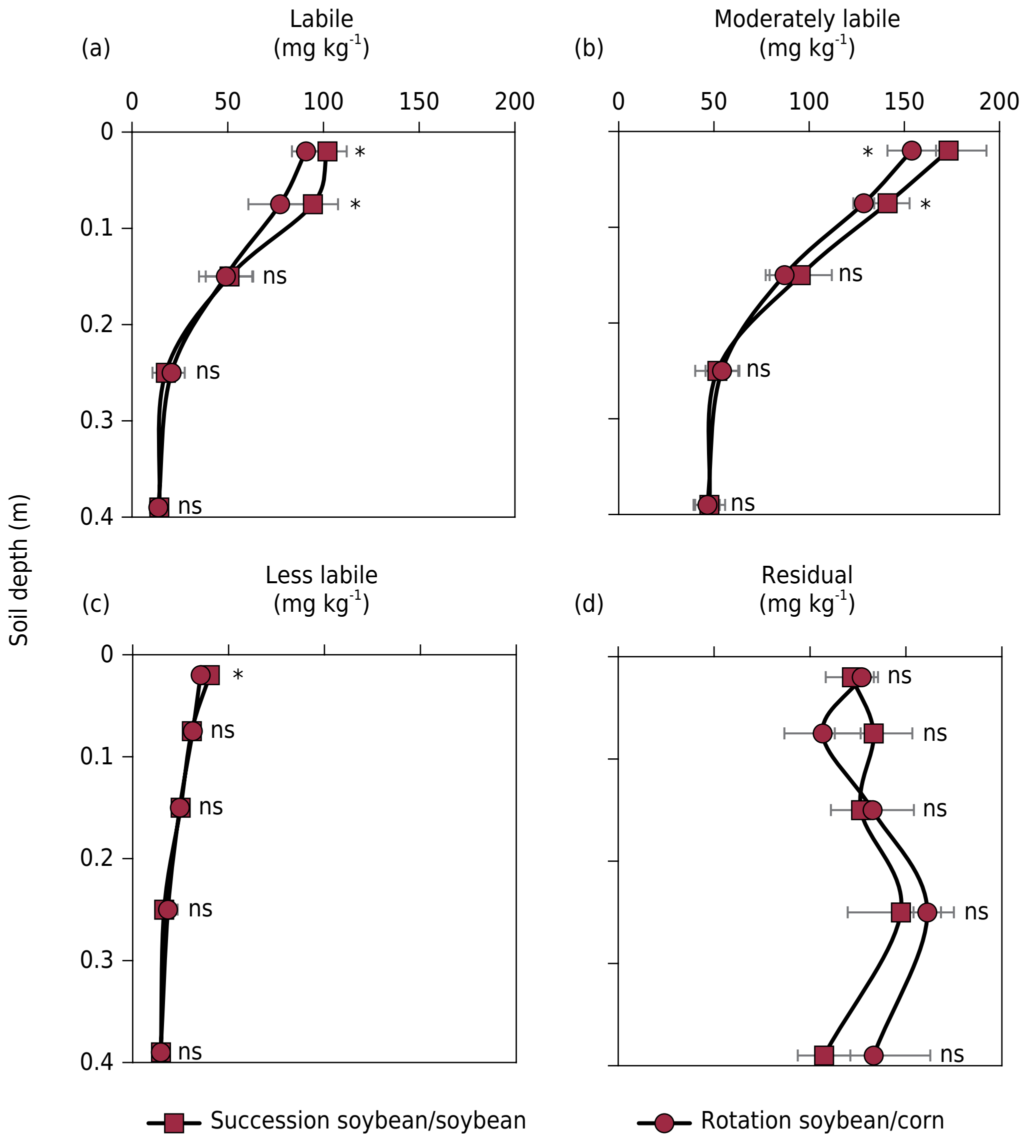

Figure 2. Labile (a), moderately labile (b), less labile (c) and residual (d) phosphorus pools in different soil layers, affected by the crop phase management (cropping system), independently of livestock phase management (grazing intensity and grazing method), in a long-term no-till integrated crop-livestock (grains and sheep) system in an Acrisol of Southern Brazil. Tukey test ($p<0.05$). ns: no significant difference; *: significant difference within each soil layer. Bars represent the standard deviation of the mean.

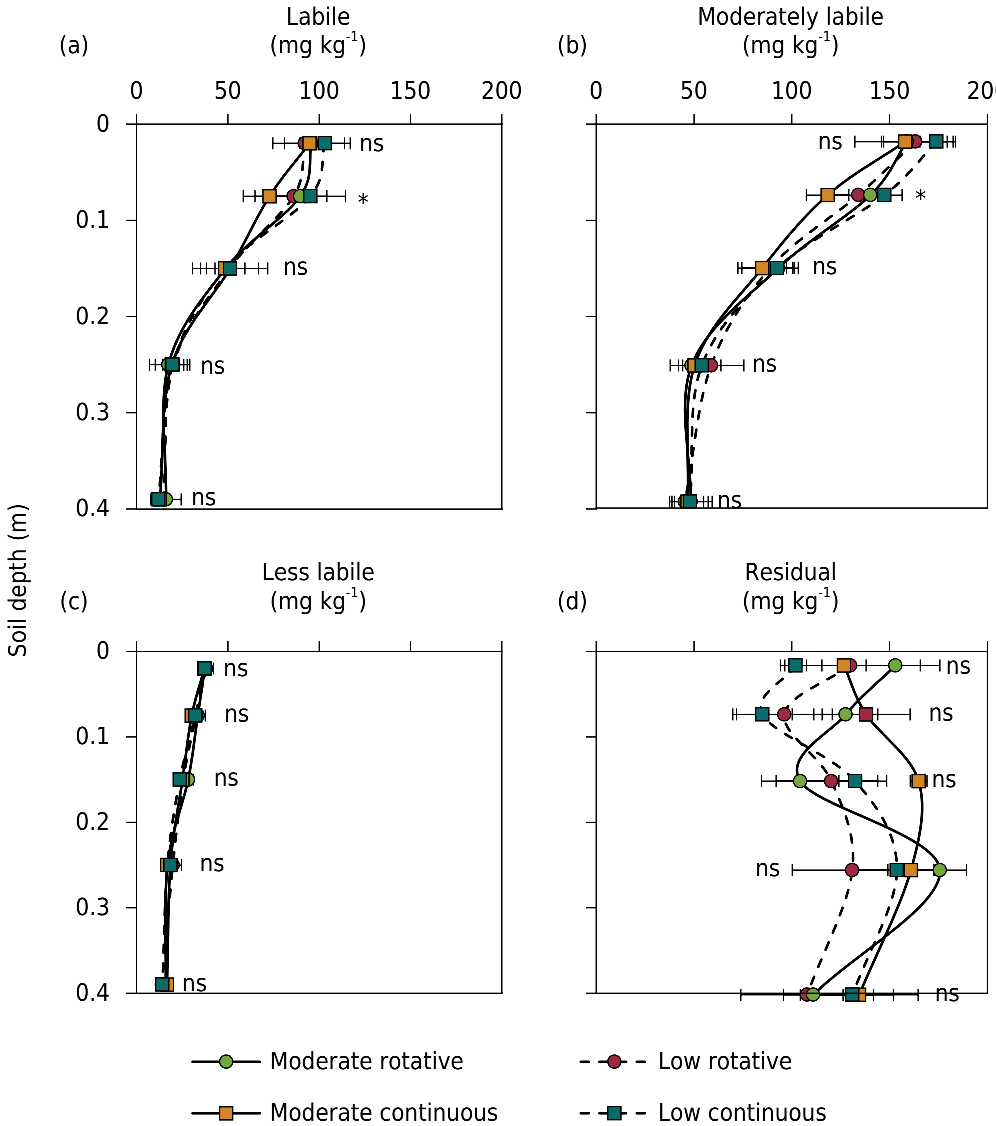

Figure 3. Labile (a), moderately labile (b), less labile (c) and residual (d) phosphorus pools in different soil layers, affected by livestock phase management (grazing intensity and grazing method), independently of crop phase management (cropping system), in a long-term no-till integrated crop-livestock (grains and sheep) system in an Acrisol of Southern Brazil. Tukey test ($p<0.05$). ns: not significant difference. *: significant difference within each soil layer. Bar represents the standard deviation of the mean.

Less labile and residual P did not differ among grazing intensities or grazing methods. In the 0.00-0.10 m layer, where the other soil P pool labilities were modified, the contents of the less labile P pool ranged from 29.2 to 36.9 mg kg^{-1} (Figure 3c) and the residual P pool ranged from 84.5 to 151.9 mg kg^{-1} (Figure 3d).

Relationship of soil phosphorus lability with the cropping system and grazing intensities and methods

According to the PCA analysis, the cropping system, grazing intensity and method were related to the P pools measured according to its lability in different soil layers. The PCA analysis extracted two principal components, which explain 98.5 % of the soil P lability. The corresponding map is displayed in figure 4.

Labile, moderated labile and less labile P pools were highly correlated and associated with soil layer of 0.00-0.05 m, showing that most changes in such P pools occurred in this layer due to differentiated cropping system management and grazing intensities and

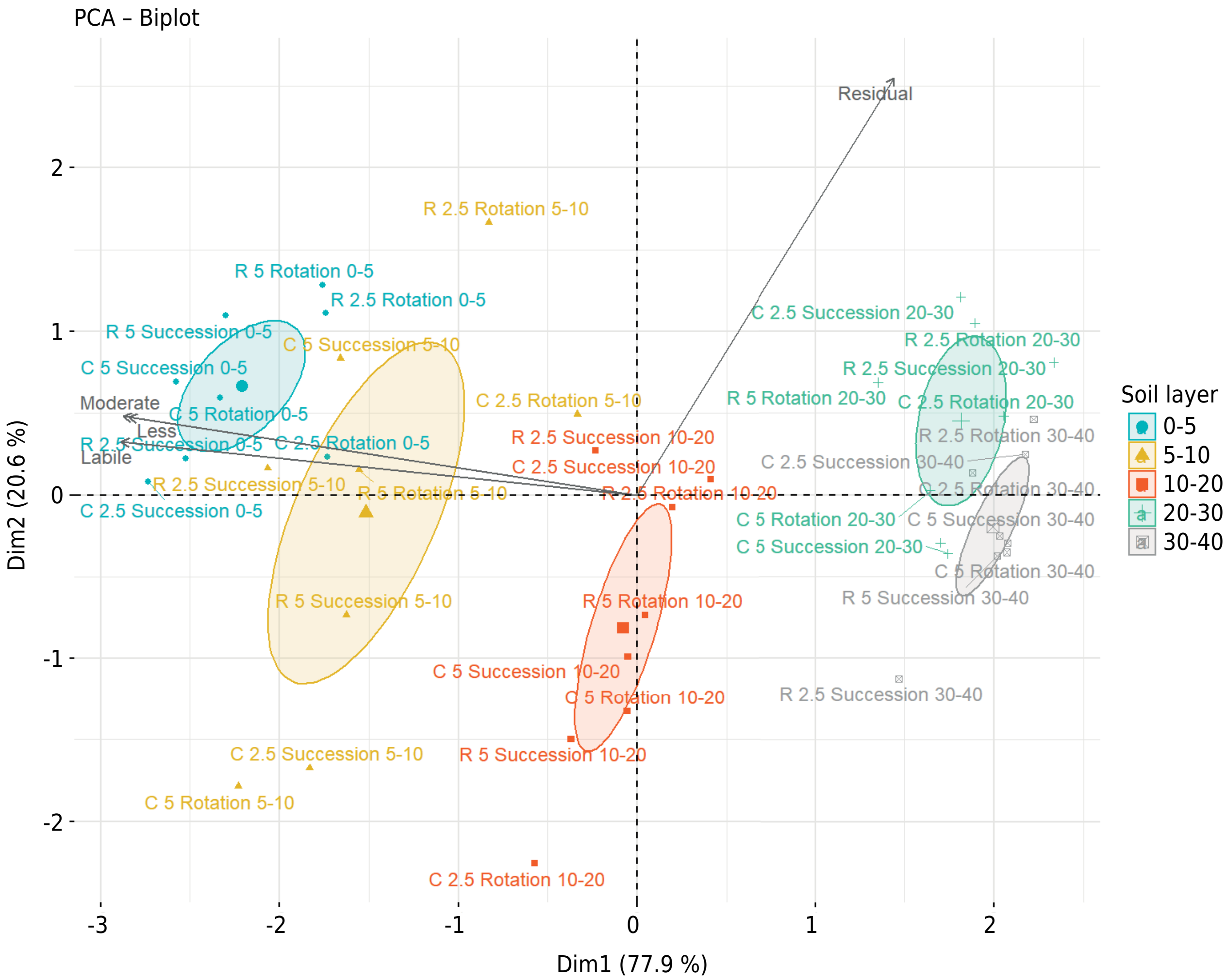

Figure 4. Principal component analysis of phosphorus (P) pools (labile, moderately labile, less labile and residual) in different soil layers (0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.40 m) submitted to cropping systems (soybean/soybean succession and soybean/corn rotation), grazing intensities (moderate and low) and grazing methods (rotational and continuous) in a long-term no-till integrated crop-livestock (grains and sheep) system in an Acrisol of Southern Brazil. Individual colors differed by groups (soil layers). Components 1 and 2 explain 98.5 % of the total variance. R: rotational method; C: continuous method; 2.5: moderate grazing intensity; 5: low grazing intensity.

methods of the evaluated ICLS. Soil layers of 0.20-0.30 and 0.30-0.40 m were positive correlated to the residual P pool, which was not affected by evaluated management. The intermediate soil layers (0.05-0.10 m and 0.10-0.20 m) were not correlated with no P pool evaluated.

DISCUSSION

All P lability pools decreased in concentration along the soil profile, from the top 0.00-0.10 m layer to the subsurface layers (0.10-0.40 m) (Figure 1). Only the residual P pool presented higher contents pools in the subsurface layers (0.10-0.40 m). The highest soil P levels in the 0.00-0.10 m layer occurred for the moderately labile pool (299 mg kg^{-1}) and the lowest level occurred for the less labile pool (67 mg kg^{-1}), on average of all treatments (Figure 1). In areas under NT, higher soil P pools are commonly found in the surface layers compared to the subsurface layers, as obtained in the PCA analysis (Figure 4). This occurs mainly due to the low P mobility in soil and, therefore, its permanence close to where it was applied as fertilizer (Rheinheimer and Anghinoni, 2001). In addition, the P uptake from deeper layers and its deposition as crop residue on the soil surface, further increases the vertical concentration gradient

(Schlindwein and Anghinoni, 2000; Loss et al., 2012). Also, the low contents of Fe and Al oxides and clay fraction of the studied Acrisol (Table 1) are probably the reasons for higher P contents in labile and moderately labile pools than in less labile and residual pools. Besides that, Rheinheimer and Anghinoni (2003) show that in no-till, the majority of P pools accumulated in the moderately labile pool, probably by the residue's lower decomposition rate.

The most important result concerning the cropping system management in the ICLS is the occurrence of higher pools of labile and moderately labile soil P under soybean/soybean succession, compared to soybean/corn rotation (Figures 2a and 2b). The possible explanation for that is linked to the amount and quality of residue addition in the different treatments. Alves et al. (2020) evaluated the soil C stocks in the same experiment and sampling time, verifying that the soybean/soybean monoculture presented higher soil C stocks in the 0.00-0.30 m layer (45 Mg ha^{-1}), compared to the soybean/corn rotation (39 Mg ha^{-1}). According to the authors, this occurs due the higher quality (low C:N ratio) of the soybean residues since the higher N content of the straw favors the soil C accumulation (Veloso et al., 2019; Alves et al., 2020). Soil OM, besides being a source of P for soil solution, can act in the blockage of P adsorption sites (Afif et al., 1995), increasing the levels of labile P. Thus, the highest accumulation of labile and moderately labile P (Figures 2a and 2b) verified in the soybean/soybean succession compared with soybean/corn rotation may be related to the quality of the residue added to the soil.

This similar result of less labile and residual P between succession and crop rotation may be related to equal P input via fertilization in those two treatments (Alves et al., 2019). In addition, low grain yields were observed in the experiment over the years (average of 2.2 and 4.8 Mg ha^{-1}, for soybean and corn, respectively) (Alves et al., 2020). Thus, it is estimated that the export of P by grains was similar in both cases since the exported amounts of P per ton of soybean grains are higher than that exported by corn (13.4 and 16.7 kg ha^{-1} in the average of years, respectively) (CQFS-RS/SC, 2016).

It was not possible to affirm that the grazing method influences the soil P lability because the difference depends on the grazing intensity. It was expected that the rotational grazing method would present higher levels of labile soil P pool due to the more homogeneous distribution of excretes in the grazing area. The same is valid for grazing intensities since there was no increase or decrease in soil P lability when the grazing intensities effects were isolated. This also refuses the initial hypothesis because it was assumed that a higher grazing intensity would result in a greater volume of excretes. As the excretes have P in more readily available forms, a higher soil P lability in moderate grazing intensity was expected in relation to the low grazing intensity.

The highest P contents in the most labile pools verified in the management with continuous grazing method and in low grazing intensity (Figures 3a and 3b) may be related to the total forage production and amount of plant residue and feces excreta deposited on the soil surface at the end of the grazing cycle. Moojen et al. (2022) evaluated the biomass production of the ryegrass in the same experimental area from 2003 to 2016. The results showed that the continuous grazing method in low grazing intensity presented an annual production of ryegrass higher than in the other treatments of the livestock phase, with 10.2 Mg ha^{-1}. The continuous method with moderated intensity, the rotative method with low intensity and rotative method with moderated intensity had 7.4, 9.0 and 7.5 Mg ha^{-1} of forage production. On the other hand, the plant residue P content decompounds more in labile than recalcitrant fractions (Assmann et al., 2017). This means that the highest production of DM in the continuous method may have resulted in higher P cycling and release at the end of the grazing cycle, increasing the levels of the most labile pools (Figures 3a and 3b) in the uppermost soil layer (up to 0.10 m).

Additionally, more intense grazing decreases soil C stocks (Souza et al., 2009; Assmann et al., 2014), especially by reducing pasture residue amount. This was also verified in this experiment by Alves et al. (2020), showing that soil under low grazing intensity had greater C stock (44 Mg ha^{-1}) compared to moderate grazing (40 Mg ha^{-1}). This result corroborates with our study, where the low grazing intensity presented higher soil P contents in the most labile pools (Figures 3a and 3b). As previously mentioned, OM acts in the blockade of P adsorption sites (Yaghi and Hartikainen, 2013), increasing the contents of labile pools and reducing less labile pools.

CONCLUSIONS

The highest P contents in the 0.00-0.10 m soil layer were found in the moderately labile pool; in the 0.10-0.40 m soil layer, the highest levels are found in the residual P pool, regardless of the management of the cropping system and grazing intensity and method. However, the cropping system and grazing intensity and method impact the soil P pools. Soybean/soybean succession increases the most labile P pools until the 0.00-0.10 m soil layer compared to soybean/corn rotation. The continuous grazing method and the low grazing intensity increase the P lability in the 0.05-0.10 m soil layer.

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