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Phosphate fertilization strategies and placement effects on grain crop yields in subtropical no-till Oxisols

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ABSTRACT: Subtropical Oxisols have a high phosphate adsorption capacity and consequently lower phosphorus (P) availability. Therefore, correct management of phosphate fertilization in grain crop rotations is essential to increase the P-use efficiency and minimize potential environmental impacts. This study aimed to evaluate, in soils with medium and high initial P level, fertilization strategies (crop and system fertilization) and placement's effects (banded P and broadcast) on soil available P, crop yield, and P use efficiency. Two field trials were installed on an Oxisol (Humic Hapludox – Latossolos) cultivated with a crop rotation with corn or soybean in the summer, and cereals in the winter. Crop yield, P use efficiency, and soil available P in the 0.00-0.10 and 0.10-0.20 m layers were evaluated during eight growing seasons. Three years of phosphate fertilization increased the P content of the 0.00-0.20 m layer above the critical level (8 mg dm^{-3}) in the soil with medium initial P and maintained the P status above the critical level in the soil with high initial P. The P-rich environment in the 0.00-0.10 m soil layer was sufficient to support high-yield grain crops with low response to fertilization strategies and placement. However, four years of banded P fertilization on high initial P soil resulted in a greater increase in P content in the 0.10-0.20 m layer compared to broadcast P. In the field trial with medium initial available P content, there was a greater response to phosphate fertilization, leading to a significant increase in grain yields when compared to the control treatment with no P, especially for barley (50 % increase). Over four years of evaluation, banded P, regardless of the fertilization strategy (crop or system), proved effective in increasing crop yield (for one crop of black oat and three crops of corn) and P use efficiency (one crop of corn). System fertilization in a high P export environment should be adopted only in soils with available P content above the critical level and after at least four years of using diverse winter cover crops (grass + legume). Otherwise, P fertilization at every sowing (crop fertilization) remains more appropriate for intense grain production systems.

Keywords: phosphate fertilization, P availability, no-till, nutrient management, crop production, phosphorus placement.

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INTRODUCTION

Subtropical soils have a high content of Fe and Al oxides in the clay fraction due to their advanced state of weathering, which determines high phosphorus (P) adsorption capacity (Fink et al., 2016). There is naturally low P availability in these soils, as the chemical bond between phosphate and oxides involves great energy and specificity. Therefore, phosphate fertilization is mandatory to increase P levels above the critical level in grain production systems involving soybeans, corn, and winter cereals, thus ensuring mineral nutrition and expression of the maximum productive crop potential (Hopkins and Hansen, 2019).

Phosphate fertilizer management must consider the rate, type of fertilizer, placement, and time of application (Roberts, 2007). The first two factors have been widely explored in different regions of the world (Volf and Rosolem, 2021; Huang et al., 2023). However, the timing and P placement have not received the same attention. Regarding the temporality of phosphate fertilization, two main strategies stand out (Guera et al., 2020; Guera and da Fonseca, 2021). The first one is the crop fertilization, with the application of fertilizer when sowing each crop and aiming for maximum economic return per unit of nutrient applied (Fontoura et al., 2015). The second one is the system fertilization, where fertilizer is applied in a single annual dose to maintain the nutrient availability status (Farias et al., 2020). In the latter case, it is necessary to consider the cycling and export of nutrients, taking as a reference the crop with higher P requirements, and also considering the lower temperatures in the winter months that can limit the P diffusion into the soil (Vieira et al., 2015).

In Southern Brazil, system fertilization is usually performed when implementing winter crops, and the P rate used is calculated to meet the demand of both winter and summer crops grown over a year. Thus, the implementation of the summer crop is done without the application of fertilizers, which increases the operational performance (Guera and Fonseca, 2022). The system fertilization strategy have been investigated in crop-livestock integration systems, and the findings indicate a greater physical soil quality (Simões et al., 2023) and better energy use efficiency in the production system, per unit of nutrient applied, such as P (Farias et al., 2020; Alves et al., 2022). However, crop-livestock integration systems are characterized by low nutrient exports when compared to the intense agroecosystems with grain crops in the winter and the summer. Therefore, system fertilization in the context of high P export becomes a gap in research and needs to be further explored in studies.

Another aspect that can influence the availability and phosphate fertilizer efficiency is the P placement, whether broadcast or banded. Since P is an element with low mobility in the soil, it tends to accumulate in the soil region where it was applied (Nunes et al., 2020), and this is enhanced in soils cultivated under conservation systems such as no-tillage, where the fertilizer is not mixed into the soil through plowing. Broadcast application increases P content in the first five centimeters of the soil and the formation of a strong P available gradient (Tiecher et al., 2023). The P accumulation in the first centimeters of the soil increases the potential loss of P through runoff, causing economic damage and negatively impacting the environment through surface water eutrophication (Reichert et al., 2019). Studies have shown that P banded results in greater absorption and concentration of P in the grains when compared to broadcast fertilization (Hansel et al., 2017), in addition to an increase 3.7 % in crop yield, including soybeans, corn, and wheat (Nkebiwe et al., 2016). Furthermore, the banded P reduces P contact with the soil, resulting in a smaller volume of fertilized soil compared to the broadcast placement and, consequently, greater P availability, in addition to mitigating the P gradient in depth (Nunes et al., 2011).

Both the strategy and the P placement are affected by the initial P soil availability. In soils with P content below the critical level (“Low” and “Medium” available P), crop fertilization and banded P is generally more efficient than system fertilization and broadcast P on the soil surface (Mallarino et al., 2009; Vieira et al., 2015), due to the strong P drain that the soil mineral matrix exerts in strongly weathered soils (Volf and Rosolem, 2021). On the other hand, in soils with built fertility (available P above the critical level), there may be an increase in the agronomic efficiency of phosphate fertilizers with system fertilization, in both P placements, as long as most of the phosphate binding sites are already saturated in the soil mineral matrix (Resende et al., 2016; Oliveira et al., 2020; Yuan et al., 2020; Gotz et al., 2023).

In the present study, the effect of the fertilization strategy (system and crop fertilization) and P placement (broadcast and banded P) were evaluated in a subtropical Oxisols presenting medium and high initial available P levels on the crop yield, P use efficiency, and available P content in the soil. The hypothesis is that in soil with P level below the critical level, the banded phosphate fertilization applied at the sowing of each crop will promote greater crop productivity, P use efficiency, and available P content in the soil, compared to broadcast P and system fertilization. On the other hand, it is expected that in soils with available P levels above the critical level, the fertilization strategy (system or crop) and the P placement (banded or broadcast) will have little or no effect on crop yields.

MATERIALS AND METHODS

Site description

Two field trials were conducted in the Center-South of Paraná State, Southern Brazil. The climate is classified as humid subtropical, Cfb type (Köeppen classification system), with altitude ranging from 800 to 1,200 m. Average annual temperature is 17 °C, ranging from 21°C in the summer to 13 °C in the winter. The average annual precipitation is 1,921 mm, and it is well distributed throughout the year, with no dry season and frequent frosts (Fontoura et al., 2015). The soils in both field trials are classified as Oxisols (Humic Hapludox) (Soil Survey Staff, 2022), which correponds to Latossolo Bruno alumínico, according to Brazilian Soil Classification System (Santos et al., 2013). The texture varies from clayey to very clayey. In the clay fraction, the predominant minerals are kaolinite, iron oxides (goethite and hematite), and aluminum oxides (gibbsite). Both field trials were carried out for four years in areas under no-tillage for more than 20 years, presenting Medium (Candói site) and High (Pinhão site) available P levels in the soil. The interpretation of available P levels in the soil extracted by Mehlich-1 followed the recommendations of Vieira et al. (2015) for the Center-South region of Paraná: Low P <4 mg dm^{-3}; medium P: 4–8 mg dm^{-3}; high P: 8–16 mg dm^{-3}; and very high >16 mg dm^{-3}. Some soil characteristics of both field trials are presented in table 1. The monthly rainfall and temperature of the field trials from 2019 to 2023 are shown in figure 1.

Table 1. Characterization of the 0.00-0.20 m soil layer before the installation of medium initial P (Candói) and high initial P (Pinhão) trials, State of Paraná, Southern Brazil

Soil properties	Medium initial P (Candói, PR)	High initial P (Pinhão, PR)
Clay (g kg^{-1})[(1)]	>600	>600
pH($CaCl_2$)[(2)]	5.2	5.6
Total organic carbon (g dm^{-3})[(3)]	38	34
Cation exchange capacity (cmol$_c$ dm^{-3})[(4)]	17.5	11.9
Exchangeable Al (cmol$_c$ dm^{-3})[(5)]	0.0	0.0
Exchangeable Ca+Mg (cmol$_c$ dm^{-3})[(5)]	11.3	7.0
Available K (cmol$_c$ dm^{-3})[(6)]	0.2	0.4
Available P (mg dm^{-3})[(6)]	4.9	15.9
Saturation by Ca+Mg+K (%)[(7)]	65	62

[(1)] Pipette method; [(2)] pH($CaCl_2$) (0.01 mol L^{-1}), relation 1:2.5; [(3)] Walkley-Black method ($K_2Cr_2O_2$ 0.5 mol L^{-1}); [(4)] Sum of Ca+Mg+K+ (H+Al). [(5)] Extracted by KCl 1 mol L^{-1}; [(6)] Extracted by Mehlich-1 solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}); [(7)] (Ca+Mg+K/CEC$_{pH\ 7.0}$) × 100.

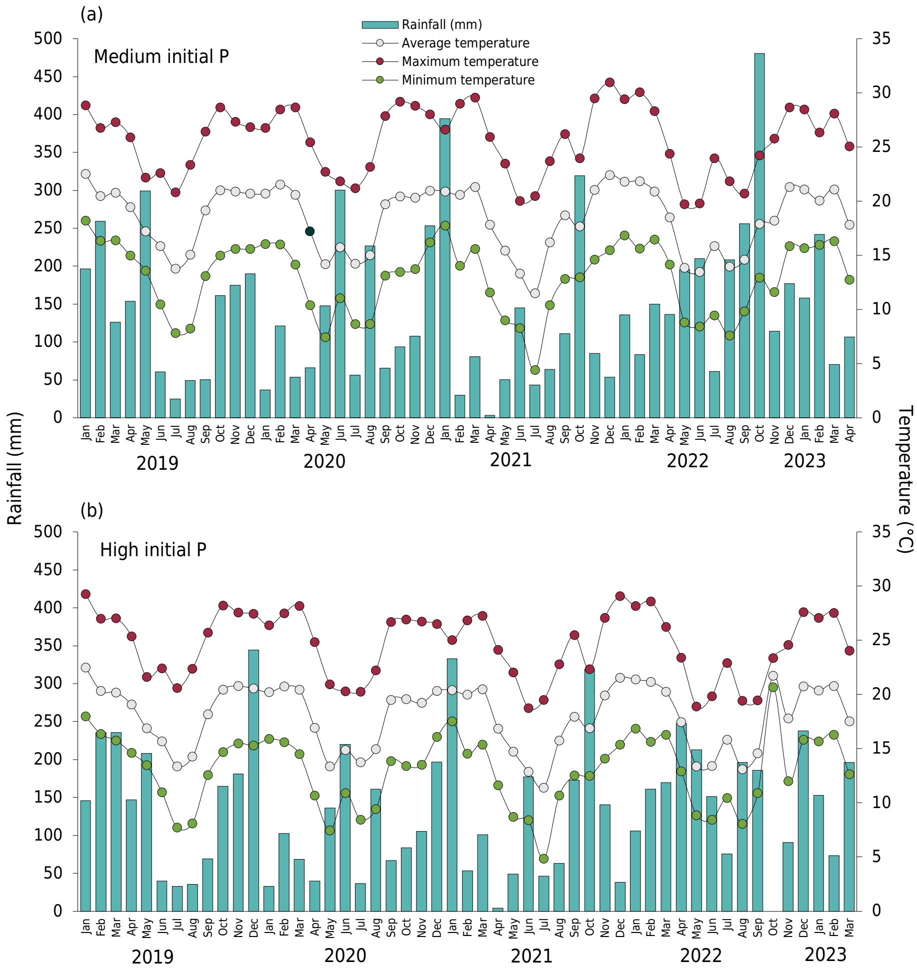

Figure 1. Air temperature (minimum, mean and maximum) and rainfall monthly averages in the field trials of medium (a – Candói, PR) and high (b – Pinhão, PR) initial P conditions in the study 2019-2023. In the South Hemisphere, winter cereals are grown from June to October, soybean from November to March, and corn from September to February.

Experimental design and treatments

The field trials were installed in the winter of 2019. The treatments included two factors: (i) fertilization strategy and (ii) P placement, and one additional treatment with no P (control). In total, five treatments were arranged in randomized blocks with three (medium initial P site) and four (high initial P site) field replications, with plots of 32 and 35 m^2, respectively.

Phosphorus rates were calculated according to current recommendations for the Center-South region of Paraná (Table 2; Fontoura et al., 2015). The fertilization strategy treatments were: (i) crop fertilization, which consisted of applying half (50 %) the annual P rate to the winter crops, and half (50 %) to the summer crops, and (ii) system fertilization, where the full annual P rate (100 %) was applied in the winter crops. The P placement treatments were: (i) banded P, with a row spacing of 0.17 m in the winter crops and 0.40 m in the summer crops, and (ii) broadcast P on the soil surface. The additional control treatment did not receive phosphate fertilizer, but received fertilizer with N and K in doses equal to all treatments.

Crop rotations and phosphate fertilization

In this study, four agricultural years were evaluated, and the same crop rotation was implemented in all treatments each site. In the field trial with medium initial P, black oat (*Avena strigosa* Schreb, 3 seasons), vetch (*Vicia sativa*, 1 season), and barley

(*Hordeum vulgare* L., 1 season) were grown in the winter while soybeans (*Glycine max* (L.), 3 seasons) and corn (*Zea mays L.*, 1 season) were grown in the summer. In the field trial with high initial P, black oat (*Avena strigosa* Schreb, 3 seasons), radish (*Raphanus sativus* L., 1 season), and barley (*Hordeum vulgare* L., 1 season) were grown in the winter while soybean (3 seasons) and corn (1 season) were grown in the summer (Table 2). The total P rate applied over the four years evaluated was 317 and 186 kg ha^{-1} of P in the field trials with medium (Candói) and high (Pinhão) initial P, respectively, using triple superphosphate (TSP) as P source (Table 2).

Plant evaluations and performance indexes

Black oat was evaluated for dry matter yield at the beginning of grain filling and expressed in Mg ha^{-1}. Soybean, corn, and barley crops were evaluated for grain yield at 130 g kg^{-1} moisture and also expressed in Mg ha^{-1}. Phosphorus export via grains was estimated using the yield of each crop and the P content in the grains. For barley, the P content in the grain used was 3.0 kg Mg^{-1}, which was obtained from a local database of the Agrária Foundation for Agricultural Research. For corn, the P content in the grain used was 2.2 kg Mg^{-1}, which was the average content obtained on 36 observations from (Sena, 2010) and 41 from Duarte et al. (2019). For soybean, the P content in the grain used was 5.5 kg Mg^{-1}, obtained from a meta-analysis of nutrient content in soybeans in Brazil (Filippi et al., 2021). From the yield and P export data via grains, the Partial Phosphorus Balance (PPB) was calculated as an efficiency index that expresses how much nutrient is being removed from the system when compared to how much is being applied (Dobermann, 2007) (Equation 1).

$$\textit{Partial Phosphorus Balance}\ (\%) = \frac{\textit{Cummulative P remove by grain}\ (kg\ ha^{-1})}{\textit{Cummulative of P applied}\ (kg\ ha^{-1})} \times 100 \qquad \text{Eq. 1}$$

Table 2. Crop rotation from 2019 to 2023 in both field trials and the amount of P applied according to the initial P condition in Oxisols under no-tillage, State of Paraná, Southern Brazil

Period	Year	Medium initial P (Candói, PR)			High initial P (Pinhão, PR)		
		Crop	P rate: Crop fertilization	P rate: System fertilization	Crop	P rate: Crop fertilization	P rate: System fertilization
			kg ha^{-1}			kg ha^{-1}	
1st year	Winter 2019	Black oat	44	83	Black oat	22	50
	Summer 2019/2020	Soybean	39	0	Soybean	28	0
2nd year	Winter 2020	Barley	44	83	Black oat	11	68
	Summer 2020/2021	Soybean	39	0	Corn	57	0
3rd year	Winter 2021	Black oat	44	83	Fodder radish/ Barley	31	68
	Summer 2021/2022	Soybean	39	0	Soybean	37	0
4th year	Winter 2022	Black oat/ Vetch	17	67	Black oat	0	0
	Summer 2022/2023	Corn	50	0	Soybean	0	0
Total			317	317		186	186

Soil sampling and evaluations

Soil samples were taken from the 0.00-0.10 and 0.10-0.20 m layers after harvesting summer crops in 2019/2020, 2021/2022, and 2022/2023, corresponding to the first, third, and fourth years of evaluation of the field trials. The samples were air-dried, ground, sieved to 2 mm, and analyzed for P available by Mehlich-1 (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) (Mehlich, 1953), following the procedure described in (Tedesco et al., 1995).

Statistical analysis

Statistical analysis of the data consisted of checking the normality of the data with the Shapiro-Wilk test, for homogeneity of variances the Bartlett test and analysis of variance (ANOVA). When a statistical difference was found ($p<0.05$), the means were compared using the Tukey test ($p<0.05$). For each initial P condition, the data were organized for analysis of variance (ANOVA) considering the factors "fertilization strategy" and "placement", as well as their interaction (Figure 2), and the control as an additional treatment. For crop yields data, the effects included in the statistical model were fertilization strategy (system or crop fertilization) and placement (banded or broadcast P). For soil available P data, the soil layer (0.00-0.10 and 0.10-0.20 m) was considered as a third factor in the ANOVA. These effects and their interactions were used as fixed effects, and the block as a random effect. Mixed models (lme) for each variable were tested and chosen using Akaike's Information Criterion (AIC). Furthermore, the available P content in the soil in each layer and the crop yield of the control treatment were compared with the average of the treatments that received P application for each comparison, using the Wilcoxon Signed-Rank test ($p<0.05$) (non-parametric). The partial phosphorus balance (PPB) was presented with standard error bars. All analyses were performed using RStudio software version 4.2.0.

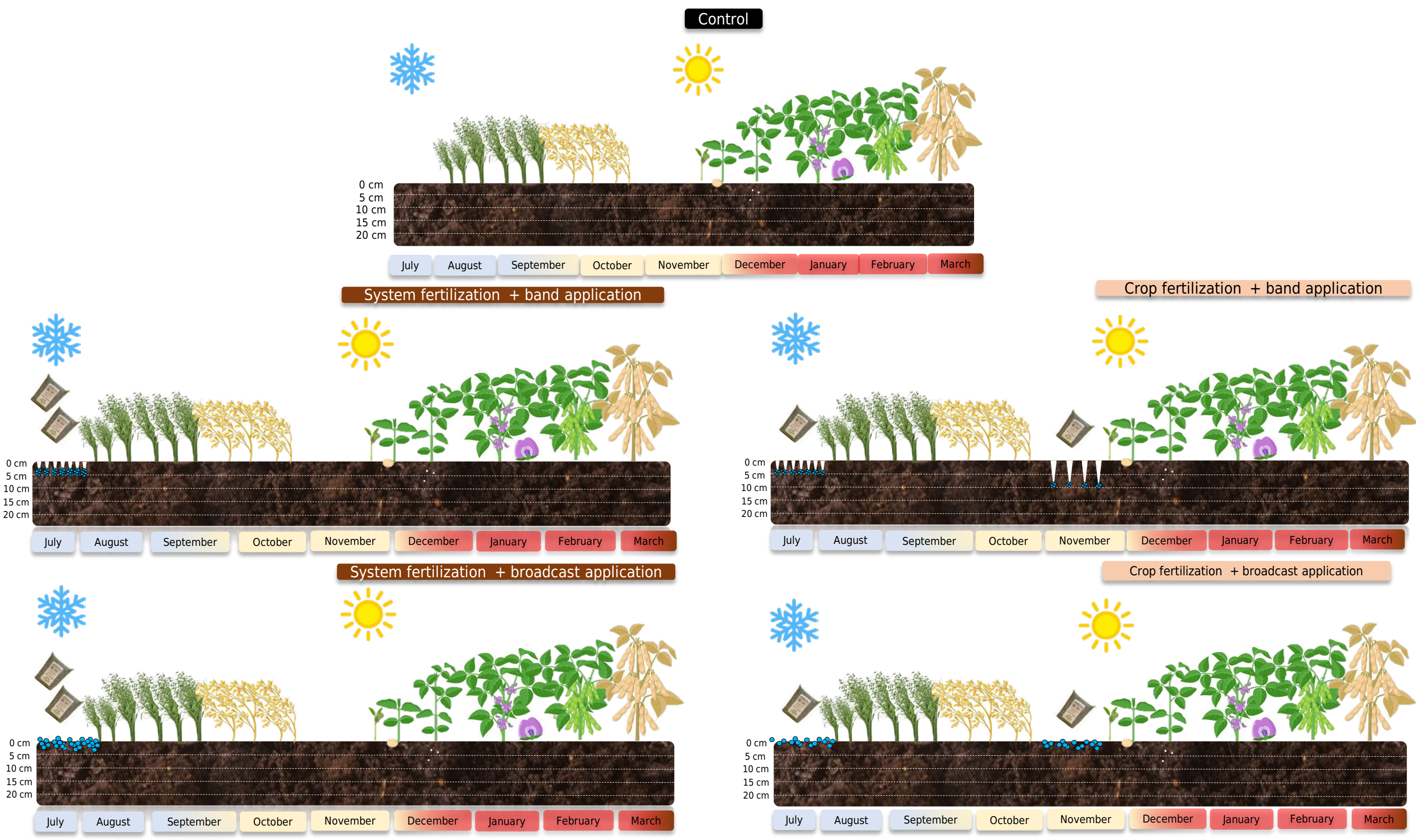

Figure 2. Treatments involving the factors fertilization strategy and P placement installed in trials with medium initial P (Candói) and high initial P (Pinhão), State of Paraná, Southern Brazil.

RESULTS AND DISCUSSION

Evolution of the available P in the diagnostic soil layer over time

In the field trial with medium initial P (Candói site), neither the fertilizer placement (broadcast or banded P) nor the fertilization strategy (crop or system fertilization) affected the available P content in any of the three soil evaluations (2020, 2022, and 2023) (Table 3). When using the diagnostic layer (0.00-0.20 m), it is possible to verify that the average of the fertilized treatments increased the available P status above the critical P level (8 mg dm^{-3}) shortly after the second soil sampling (2022), and maintaining the high P level status until 2023 (Figure 3). On the other hand, the control treatment remained with soil available P level below the critical threshold (8 mg dm^{-3}), ranging from 5.2 to 7.0 mg dm^{-3} in the three soil samplings performed.

In the field trial with high initial P (Pinhão site), the average content of available P in the 0.00-0.20 m soil layer for the fertilized treatments was always above the critical threshold (8 mg dm^{-3}). On the other hand, the available P content in the control treatment with no P fertilization decreased over time, reaching 5.0 mg dm^{-3} in 2023.

Combined results from both sites indicate that the phosphate fertilizer recommendation for the Center-South region of Paraná State is adequate (Foutoura et al., 2015; Vieira et al., 2015), since it maintained an adequate soil P status in the field trial with high initial P content and increased P availability in the field trial that initially had P content below the critical threshold.

Table 3. Significance of the effects of experimental factors (fertilization strategy [crop and system] and placement [band and broadcast]) and their interactions on P availability in the soil and crop yield of the field trials with medium and high initial available P in the soil, as a result of analysis of variance (ANOVA)

Variables	Fertilization strategy (FS)	Placement (P)	Depth (D)	FS × P	FS × D	P × D	FS × P × D
Medium initial P (Candói, PR)							
Soil available P in 2020	ns	ns	***	ns	ns	ns	ns
Soil available P in 2022	ns	ns	***	ns	ns	ns	ns
Soil available P in 2023	ns	ns	***	ns	ns	ns	ns
Black oat DM 2019	ns	ns	-	***	-	-	-
Soybean yield 2019/2020	ns	ns	-	ns	-	-	-
Barley yield 2019	ns	ns	-	ns	-	-	-
Soybean yield 2020/2021	ns	ns	-	ns	-	-	-
Soybean yield 2021/2022	ns	ns	-	ns	-	-	-
Corn yield 2022/2023	ns	ns	-	*	-	-	-
High initial P (Pinhão, PR)							
Soil available P in 2020	ns	ns	***	ns	ns	ns	ns
Soil available P in 2022	ns	ns	***	ns	ns	ns	ns
Soil available P in 2023	ns	ns	***	*	ns	ns	ns
Black oat DM 2019	ns	*	-	ns	-	-	-
Soybean yield 2019/2020	ns	ns	-	ns	-	-	-
Corn yield 2020/2021	***	***	-	*	-	-	-
Barley yield 2021	ns	ns	-	ns	-	-	-
Soybean yield 2021/2022	ns	ns	-	ns	-	-	-
Soybean yield 2022/2023	ns	ns	-	ns	-	-	-

DM: dry matter. * Significant at p<0.05. ** Significant at p<0.01. *** Significant at p<0.001. ns : not significant.

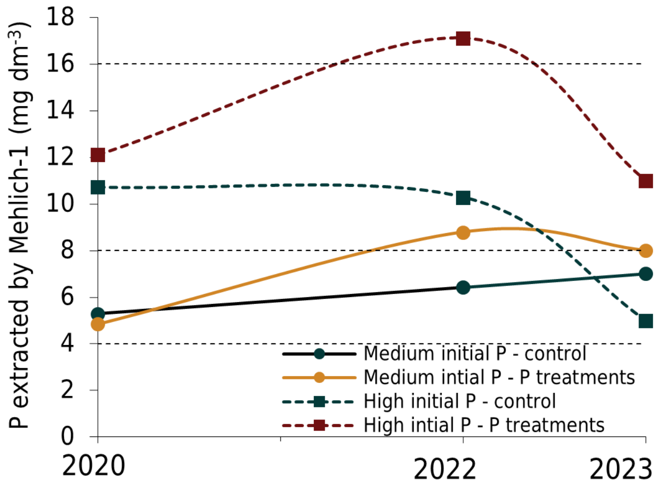

Figure 3. Available P content in the soil in the 0.00-0.20 m layers after the first (2020), third (2022), and fourth (2023) year of conducting the experiments under medium (a) and high (b) initial P. Values are the average of two fertilization strategies and two placements, in addition to the control (no P) (n = 15 in soil with Medium initial P; n = 20 in soil with high initial P).

Evolution of the available P content in-depth and its effect on crop yields

Available P content was affected by the soil layer in all sampling periods, and it was always higher in the 0.00-0.10 m than in the 0.10-0.20 m soil layer. In the field trial with medium initial P, the treatments receiving phosphate fertilizer increased the available P content in the 0.00-0.10 m layer over time and reached approximately twice the critical level in 2022 and 2023 (14.5 and 14.0 mg dm^{-3}) (Figure 4a). However, in the 0.10-0.20 m layer, the available P content ranged from only 24 to 39 % of the critical threshold (1.9 to 3.1 mg dm^{-3}). In the field trial with high initial P, the available P content in the 0.00-0.10 m layer was 2.4 to 3.2 times greater than the critical threshold (19.3 to 26.0 mg dm^{-3}) (Figure 4b), while in the 0.10-0.20 m layer, it ranged from 4.9 to 8.2 mg dm^{-3}, classified as a medium to high available P level.

Results demonstrated that regardless of the fertilization strategy, placement, and initial conditions of available P in the soil, there was a gradient of P in the soil that was intensified over the years of phosphate fertilization (Table 3 and Figure 4). In long-term no-till fields, fertilizer and crop residues are deposited on the topsoil layer, enriching the first centimeters of soils with available P (Hansel et al., 2017; Nunes et al., 2021). Our results corroborate with studies that found the greatest accumulation of P in the 0.00-0.10 m layer when compared to the 0.10-0.20 m layer regardless of the fertilization strategies (Amorim, 2020) and P placement (Bellinaso et al., 2021; Gotz et al., 2023).

Only in the fourth year of P fertilization (2023) in the field trial with high initial P was possible to verify the effectiveness of banding P to increase the P available content in-depth. The banded P resulted in a higher soil available P content than broadcast P in the 0.10-0.20 m layer (5.7 and 3.3 mg dm^{-3}, respectively, corresponding to 71 and 41 % of the critical level) (Table 3 and Figure 4c). Both banded and broadcast P fertilization have different impacts, most noticeable in soil layers where the fertilizer is applied (i.e., 0.00-0.10 m for broadcast and 0.10-0.20 m for banded P). This difference intensifies after years of fertilization, leading to the accumulation of P in the topsoil in broadcast P treatments, and the mitigation of the intense gradient in-depth in banded P treatments (Nunes et al., 2011, 2021). The greater P availability in depth can promote root growth at deeper soil layers and improve crops resilience to drought (Hansel et al., 2017).

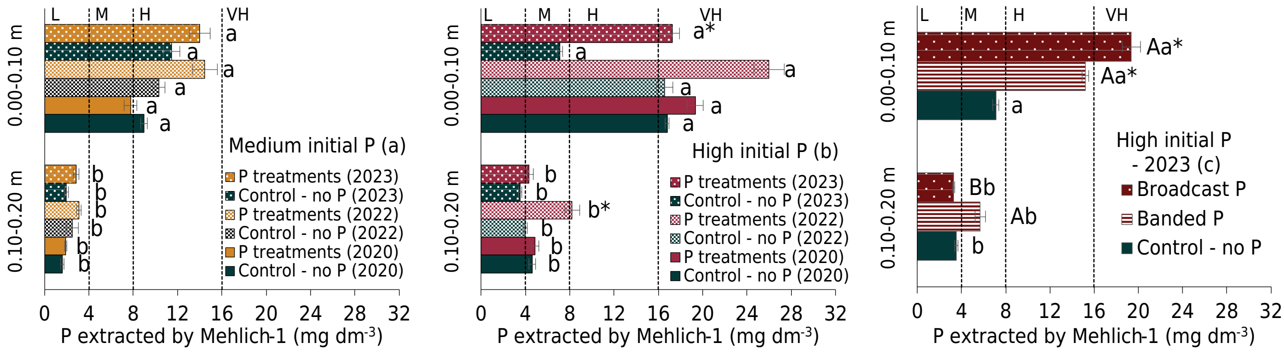

Figure 4. Available P content in the soil in the 0.00-0.10 and 0.10-0.20 m layers after the first (2020), third (2022) and fourth (2023) year of conducting the experiments under medium (a) and high (b) initial P. Available P content by P placement (banded P or broadcast) in the 0.00-0.10 and 0.10-0.20 m soil layers after four years of phosphate fertilization (2023) on high initial P soil (c). Values are the average of two fertilization strategies and two placements, in addition to the control (no P) (n = 15 in soil with Medium initial P, n = 20 in soil with high initial P). Means between layers followed by the same letter are not statistically different according to the Tukey test ($p<0.05$). Means in the same layer followed by (*) are statistically different from the control, compared by the Wilcoxon Signed-Rank test ($p<0.05$). L: low; M: medium; H: high; VH: very high.

Both field trials demonstrate that the 0.00-0.10 m layer is an environment rich in available P and suitable for crop growth and development. As a result, in the field trials with medium and high initial P, respectively, only three and four of the six grain crop seasons evaluated in each site demonstrated a significant difference in yield between treatments with and without P application. For these crops, the average grain yield increase in the P treatments compared to the control was 36 ± 18 % and 13 ± 11 % for the field trials with medium and high initial P content, respectively. These results corroborate that there is a greater response to phosphate fertilization in soils with lower P availability (Yu et al., 2021). In the field trial with medium initial P, barley yield in the 2020 season (one year after the start of the experiment) almost doubled in the treatments receiving P when compared to the control. Barley is known to be more demanding on soil fertility, especially P (Yu et al., 2021; Tiecher et al., 2023). Furthermore, the lower temperatures of the winter months in the Brazilian subtropics restrict the diffusion process of phosphate from the soil to the plant roots, and therefore, the winter cereals generally have a higher critical level of soil available P when compared to the summer crops (Vieira et al., 2015; Yu et al., 2021).

Although higher temperatures in the summer may favor the diffusion of P in the soil, among the six grain crop seasons evaluated in each field trial, three soybean seasons and two corn seasons responded to P fertilizer compared to the control. This might have resulted from the uneven distribution of P in the top 0.20 m of soil. Therefore, even if the top 0.10 m of soil has a high concentration of available P, this layer is also more prone to water loss. Plants must therefore rely on P from deeper layers, but below 0.10 m, the P availability is lower. The significant evapotranspiration and soil moisture reduction, even for a few days, may limit the P diffusion and, as a result, the plant uptake, even while the topsoil contains an adequate P content or even twice the critical level (Mariotte et al., 2020). The strong P gradient in the soil under no-tillage could even be better visualized when using more stratified layers (i.e., layers every 0.05 m), as found by Bellinaso et al. (2021).

Placement and fertilization strategies effects on grain yield and P use efficiency

In the field trial with medium initial P, the black oat dry matter yield (2019) increased with banded P when compared to broadcast P (4.6 Mg ha^{-1} *vs* 3.9 Mg ha^{-1}) in the system fertilization strategy, but it was not affected by the placement of P in the crop fertilization strategy (Table 3 and Figure 5a). Furthermore, in banded P treatments, there was a higher black oat dry matter yield in system fertilization compared to crop fertilization (4.6 *vs* 4.0 Mg ha^{-1}). Crops subjected to soil conditions below the critical level of P obtain a greater yield response when compared to high soil fertility conditions (Fontoura et al., 2015; CQFS-RS/SC, 2016). The greater response in black oat yield under system fertilization is due to the difference in the P rate applied in this first evaluation season of the experiment (Table 3) compared to treatments under crop fertilization. Furthermore, black oat is a winter cereal that is very responsive to fertilization, especially when the P is banded, due to the greater proximity of the fertilizer granules to the seed (Fontoura et al., 2015; Freiling et al., 2022).

In the 2022/2023 corn season of the field trial with medium initial P, there was no difference in yield between the fertilization strategies (crop or system fertilization) (Figure 5a). However, when using the system fertilization strategy, corn yield increased by 4 % in banded P (16.9 Mg ha^{-1}) compared to broadcast P (16.2 Mg ha^{-1}). After four years of crop rotation, these results demonstrated that corn was benefited from the combination of system fertilization and banded P. Although corn did not receive P fertilization at sowing in these treatments (Table 3), the greatest response of corn may be linked to the previous crop, which was an intercropping of black oat + vetch. Therefore, corn possibly produced more in the treatment with system fertilization and banded P due to a greater yield of black oat and vetch residues. These cover crops are responsive to P fertilizer, as was evidenced in this study for the first black oat season. The high input of black oat residues cycles the P applied and favors the next crop cultivated (Calegari et al., 2013; Tiecher et al., 2017) and promotes an increase in the N supply through vetch residues for corn (equivalent to 40 kg ha^{-1}) (Fontoura and Bayer, 2009). In addition to enhancing P mineralization with vetch crop due to greater production of acid phosphatase (Tiecher et al., 2012; Rheinheimer et al., 2019).

In the field trial with high initial P, the corn yield (2020/2021) increased by about 1.7 Mg ha^{-1} in the treatment with banded P and crop fertilization when compared to the treatments with broadcast P and system fertilization, regardless of the P placement (Figure 5b). Furthermore, in the crop fertilization strategy, the banded P (9.7 Mg ha^{-1}) increased corn yield by 2.2 Mg ha^{-1} compared to broadcast application (7.5 Mg ha^{-1}) (Figure 5b). In this case, it appears that in a situation of less diversification in the use of cover crops (only grasses) and less crop rotation time, crop fertilization and banded P stands out even in an environment reached in available P (above the critical level). Indeed, crops grown in highly fertile soils are less affected by the P placement methods (Resende et al., 2016; Yuan et al., 2020). However, Quinn et al. (2020) found that banded P increased corn yield by 5.2 % even under these conditions. The synergy of absorbing nutrients such as N, P, and K concentrated in a smaller soil volume may favor an increase in crop yield. It should also be considered that corn has a more limited root system than soybeans during the initial development stages, being affected by the planting date and soil temperature at that time. Therefore, there is a greater probability of response of corn even in soils with high available P content (Schröder et al., 1996; Bittman et al., 2006).

Despite the short evaluation period and the limited set of crop seasons evaluated in this study, among the summer crops, soybean was less responsive to fertilization strategies (crop or system) and placement (banded or broadcast P) compared to corn. Soybean is a species that can develop even in adverse conditions (chemical and/or physical limitations), and with good water availability in the first soil centimeters, the chance of responding to P placement is low (Hansel et al., 2017; Bellinaso et al., 2021).

Partial phosphorus balance (PPB) was different between the field trials, although little affected by the fertilization strategy and P placement (Figure 6). Phosphorus export via grains ranged from 34 to 73 % (Figure 6a), considering all crops in the field trial with medium initial P. The PPB for soybeans and barley in the field trial with medium initial P (Figure 6a) was close to the Brazilian average (50 %) of the ten main crops grown during 2000 and 2016 (Pavinato et al., 2020). Barley presented the lowest P use efficiency values when grown under a more limiting soil P condition. These results agree with the meta-analysis by (Yu et al., 2021), which found that barley has a lower P-use efficiency index than corn, wheat, and other cereals.

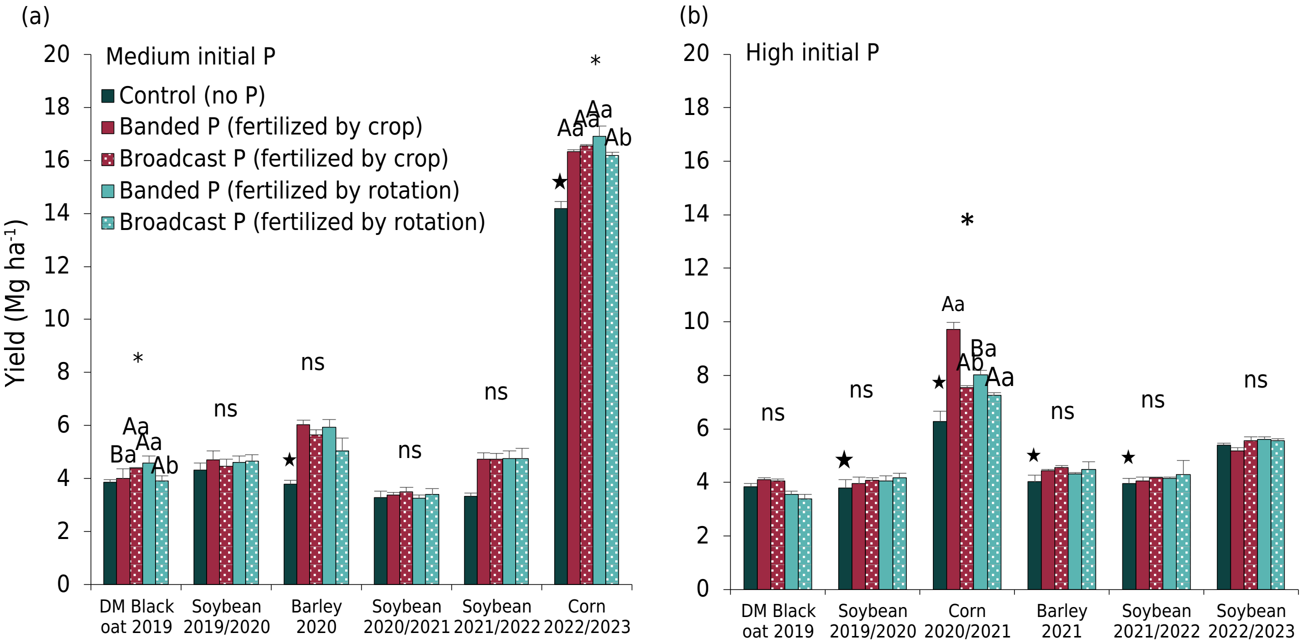

Figure 5. Crop yield over the four years of experiment (2019-2023) under different phosphate fertilizer management (fertilization strategy × placement): in medium (a) and high (b) initial P. Means followed by the same letter are not statistically different according to the Tukey test (p<0.05). ns: not significant. Capital letters compare fertilization strategies (crop and system) within each placement (banded and broadcast P); Lowercase letters compare the placement (banded and broadcast P) in each fertilization strategy (crop and system). * Significant at p<0.05; ** Significant at p<0.01; *** Significant at p<0.001; ns: not significant. ★: Control average (without P) statistically different from the average of treatments that received P application by the Wilcoxon Signed-Rank test (p<0.05).

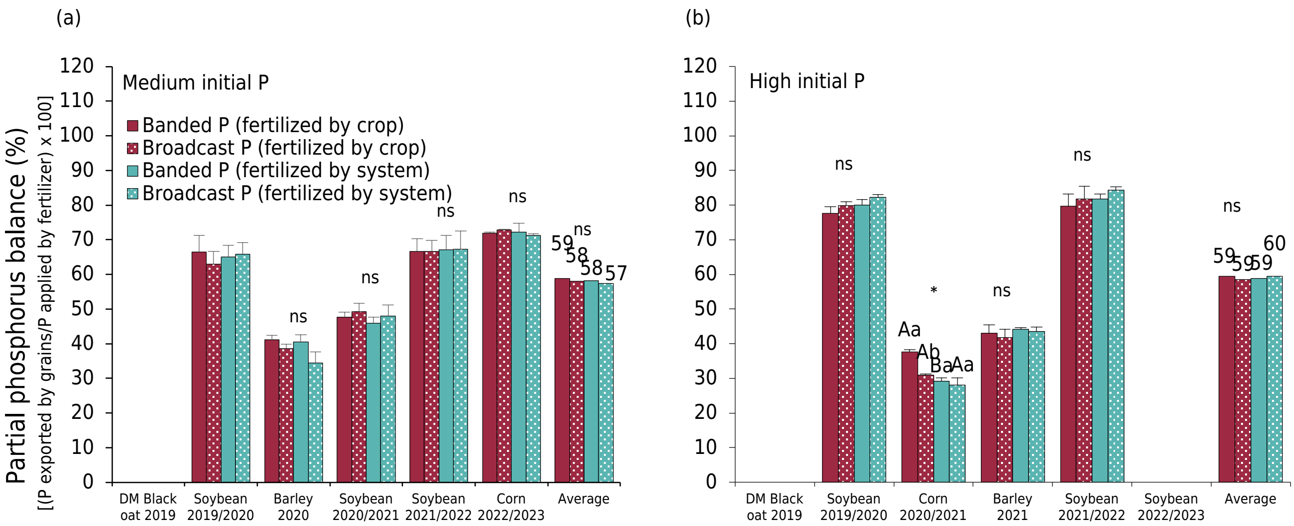

Figure 6. Partial phosphorus balance [(P exported by grains and P applied ratio) × 100] of the crops grown in medium (a) and high initial P (b) in a Brazilian subtropical Oxisol. Means followed by the same letter are not statistically different according to the Tukey test (p<0.05). ns: not significant. Capital letters compare fertilization strategies (crop and system) within each placement (banded and broadcast P); Lowercase letters compare to the placement (banded and broadcast P) in each fertilization strategy (crop and system). * Significant at p<0.05; ** Significant at p<0.01; *** Significant at p<0.001; ns: not significant; DM: Dry matter.

In field trial with high initial P, the PPB ranged from 28 to 84 % (Figure 6b). The PPB was only affected by the fertilization strategy, P placement, and the interaction of both factors in the 2020/2021 corn season. In this case, crop fertilization combined with banded P promoted the highest PPB, probably due to the higher P export and synergy of absorption of nutrients in a smaller soil volume (Quinn et al., 2020).

Phosphorus sources (Nunes et al., 2021; Oliveira et al., 2022), intercropping and crop rotation (Rodrigues et al., 2021; Zhou et al., 2021), soil acidity management (Bellinaso et al., 2021; Tiecher et al., 2023), among other topics, have all been investigated in the course of advances in research on increasing P use efficiency. However, the initial availability of P also affects how efficiently P is used, and our investigation verified this impact by showing increases in P export in soybean in the field trial with a high initial P of up to 20 % (Figure 6b). The higher fertilizer rates required in soils with P levels below or close to the critical level, as well as in the field trial with medium initial P (Table 2) result in lower P use efficiency indexes (Yu et al., 2021; Zhou et al., 2021). It should also be considered that crops grown in the soil with high initial P, in addition to receiving lower P rates via fertilizer (Table 2), there is a greater contribution of P via soil due to the lower buffering capacity of the soil in this condition (Barrow and Debnath, 2014).

CONCLUSIONS

Banded P at the sowing line of corn combined with crop fertilization when the soil presents P content above the critical level proved to be more effective in increasing yield and P use efficiency when compared to broadcast fertilization.

System fertilization for intensive grain production systems should only be used in soils with P content above the critical level. Winter cover crops, such as black oats and vetch, can increase the system fertilization efficiency, as they promote greater yield of plant biomass and P cycling, thus benefiting the following summer crop. However, in soils with P content below the critical level, applying P fertilizer at every sowing (crop fertilization) is the most appropriate strategy to increase P use efficiency in intensive grain production systems.

A gradient of P in-depth was found in both study sites, with little or no effect of the treatments over the four years of evaluations to mitigate the low content of Pin in the 0.10-0.20 m layer. However, in the fourth year of banded P in the field trial with high initial P, the P content in the 0.10-0.20 m soil layer reached 71 % of the critical level, compared to only 41 % with broadcast P. In all seasons evaluated, the high P content in the top 10 centimeters of the soil proved to be sufficient to maintain high crop yields.

DATA AVAILABILITY

The data will be provided upon request.

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