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SOILS

The management of phosphate fertilization affects soil phosphorus and yield of autumn/winter crops

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ABSTRACT. In soils with adequate levels of fertility, it is possible to manage phosphate fertilization aiming at the grain production system, instead of each isolated crop. The objective was to evaluate the effects of the management of phosphate fertilization, place and time, on the soil and leaf P content, and crop yield in grain production systems. An experiment was conducted at the farm level in the municipality of Nazareno, state of Minas Gerais, Brazil, for four years on soil with adequate level of fertility. The treatments consisted of the management of phosphate fertilization by broadcast or furrow and dose for each crop or for the production system (spring/summer and autumn/winter crops), being: Control = without phosphate fertilization; Conventional = phosphate fertilization in the furrow in each crop; BTP = phosphate fertilization of the grain production system to broadcast; TPS = phosphate fertilization of the grain production system in the furrow of the spring/summer crop; TPW = phosphate fertilization of the grain production system in the furrow of the autumn/winter crop. Soil P content was evaluated in the third year of implantation, and the crops yield every season crop (maize, soybean, common bean and wheat). The P content in the leaves of maize and soybeans were evaluated in the spring/summer crops. The application of the total dose of phosphate fertilization for both crops in the sowing furrow of the spring/summer or autumn/winter crops (TPS and TPW) promoted operational advantages and increased soil P content in the 0-0.20 m layer, without reducing the yield of the spring/summer crops. Leaf P content was not affected. The Conventional management (phosphate fertilization in the furrow in each crop) provide greater yield of common beans and wheat during autumn/winter crops, which are more subject to water restriction due to less rainfall, even without increasing the soil P content.

Keywords: phosphorus placement; broadcast phosphate fertilization; crop system fertilization; efficient use of fertilizers.

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Introduction

Currently, grain production systems with annual crops in Brazil have been grown two or more crops a year, on soils with adequate or high levels of nutrients. In most Brazilian regions where more than one crop is grown per year, the succession of crops with soybeans in the spring/summer and maize or wheat in the autumn/winter is the most important. In regions of higher altitude, with greater thermal amplitudes, favorable to the cultivation of maize in spring/summer, common beans have been cultivated in succession (autumn/winter); which also makes it possible in some cases to grow winter cereals in a third crops, after common beans, due to the shorter cycle of this crop.

In some studies, the low response of soybean to phosphorus fertilization in soils with adequate levels or high availability of phosphorus (P) has been documented (Lacerda, Resende, Furtini Neto, Hickmann, & Conceição, 2015). Thus, in these situations, flexibility in the management of phosphate fertilization could be considered (Lacerda et al., 2015; Nunes, Sousa, Goedert, & Vivaldi, 2011; Pavinato & Ceretta, 2004; Prochnow et al., 2017; Resende et al., 2006; Santos et al., 2012; Sousa, Nunes, Rein, & Santos Júnior, 2016), and the application can be made only to replace the quantities of the nutrient exported by the crops.

Another way of making fertilization with P more flexible is to manage the fertilization of the grain production system and no longer the isolated crop, as reported in the Brazilian recommendation bulletins (Comissão de Fertilidade do Solo do Estado de Minas Gerais, 1999; van Raij, Cantarella, Quaggio, & Furlani, 1996). In this situation, one could think of fertilizing only the most demanding crop in the grain production system (Altmann, 2012). In the case of systems with soybean/maize or soybean/wheat, maize and wheat would be fertilized, to the detriment of soybean (Caires, Sharr, Joris, Haliski, & Bini, 2017; Pavinato & Ceretta, 2004; Prochnow et al., 2017). In this case, the quantities of nutrients exported by the two crops in the system could be applied, based on yield expectations. There would also be the possibility of thinking about the application of the nutrient in broadcast or buried ("P planting"), before the spring/summer or autumn/winter crop, seeking to improve the operational and logistical performance in the field.

Some authors have discussed the possibility of applying phosphate fertilizers in autumn/winter crop to the detriment of spring/summer crop, based on some works already carried out (Caires et al., 2017; Pavinato & Ceretta, 2004). If the phosphate fertilizer could be transferred to the autumn/winter crop, there would be greater agility in the implementation of the spring/summer crop, with better use of machinery and labor, in addition to lower costs with fertilizers and transportation.

In rainfed crops in Brazil, water stress has a strong impact on crop yields and fertilization efficiency. Therefore, it is important that the studies contemplate various crops and environmental conditions. This is because the availability of P to plants can be strongly affected by soil moisture, as the nutrient is preferably transported by diffusion, which depends on water (Marschner, 2012). Studies on the management of phosphate fertilization aiming at the grain production system are scarce in Brazil and are restricted to the South region (Caires et al., 2017; Pavinato & Ceretta, 2004), therefore, studies in other regions are important to consolidate the results and assist farmers in decision making.

Thus, the objective of this study was to evaluate the effects of the management of phosphate fertilization, place and time, on the soil and leaf P content, and crop yield.

Material and methods

Location and characterization of the area

The experiment was set up in October 2015 on the Santa Helena Farm at 21°15'40" S and 44°30'30" W, at 1,020 m AMSL in the municipality of Nazareno, state of Minas Gerais, Brazil. The area had been managed for 15 years under no-tillage (NT). Climate is type Cwa (Köppen classification), with cold and dry winters and hot and humid summers. Mean annual rainfall and temperature are 1,300 mm and 19.7°C, respectively. The study site and much of Brazil have spring/summer with suitable rainfall and autumn/winter with low rainfall, with water restriction being a problem for autumn/winter crops. The rainfall data and sowing and harvesting time from the 2015/2016 crop season to the 2017/2018 crop season are show in Figure 1. The rainfall data were obtained from the weather station present on the farm.

The soil was classified as a Typic Hapludox according to Soil Taxonomy (Soil Survey Staff, 2014) or "Latossolo Vermelho Amarelo Distrófico típico" according to Brazilian Soil Classification System (Santos et al., 2018) with clayey texture (520 g kg^{-1} of clay). The soil chemical properties prior to the experiment are described in Table 1. According to Sousa et al. (2016), the mean levels of nutrients were close to those considered adequate to maintain high crop yields.

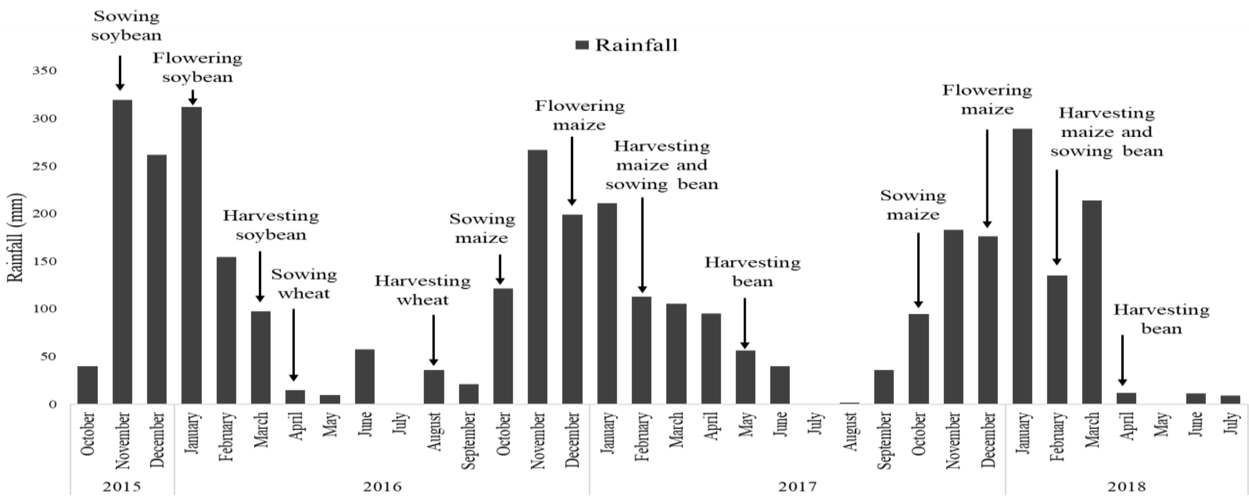

Figure 1. Rainfall data for the 2015/2016, 2016/2017 and 2017/2018 crop seasons and sowing periods, summer crop flowering and harvest.

Table 1. Soil chemical properties prior to the experiment.

Depth	pH	K^+	P*	P**	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	t	T	BS
m	-	--- mg dm^{-3} ---			-------------- $cmol_c$ dm^{-3} --------------						%
0.00-0.10	6.1	106	5.8	30	2.7	0.6	0.0	2.4	3.5	5.9	60
0.10-0.20	5.5	101	5.1	25	1.5	0.4	0.0	4.1	2.2	6.3	37
0.00-0.20	6.0	109	5.2	30	2.1	0.5	0.0	2.6	2.8	5.5	52

pH in water; * P = Mehlich-1; ** P = ionic exchange resin; t = effective cation exchange capacity; T = potential cation exchange capacity; BS = base saturation.

Experimental design

The experiment was conducted in strips with five treatments and five replications. The strips were set up with dimensions of 18 m width and 150 m length (2,700 m²) and subdivided into five experimental plots of 540 m². The treatments consisted of different managements of phosphorus fertilization, considering technological level on the farm's production system.

The treatments were: without application of phosphate fertilizer (Control); application of phosphate fertilizer in the planting furrow in each crop, spring/summer and autumn/winter, as is traditional on the farm (Conventional); application of phosphate fertilizer to broadcast, 20 days before sowing the spring/summer crop, with the total dose for the spring/summer and autumn/winter crops (BTP); application of phosphate fertilizer in the planting furrow 20 days before sowing the spring/summer crop, with the total dose for spring/summer and autumn/winter crops (TPS); application of phosphate fertilizer in the planting furrow 20 days before sowing autumn/winter crop, with the total dose for autumn/winter and spring/summer crops (TPW) (Table 2). The dose and source of phosphate fertilizer used in spring/summer and autumn/winter crops was the same recommended and used by the farm.

Table 2. Sequence of crops, cultivars/hybrids, dose and sources of P_2O_5, and P management in the experimental area.

Crop Season	Season	Crop	Cultivars/Hybrids	P_2O_5 (kg ha^{-1})	Sources	P management P_2O_5 (kg ha^{-1})
2015/2016	S/S	Soybean	NS 7000 IRPO	54	MAP	Control = 0 Conventional = 54 BTP = 162 TPS = 162 TPW = 0
2016	A/W	Wheat	BRS 264	108	MAP	Control = 0 Conventional = 108 BTP = 0 TPS = 0 TPW = 162
2016/2017	S/S	Corn	DKB 230 PRO3	81	MAP	Control = 0 Conventional = 81 BTP = 162 TPS = 162 TPW = 0
2017	A/W	Common Bean	Ouro da Mata	81	MAP	Control = 0 Conventional = 81 BTP = 0 TPS = 0 TPW = 162
2017/2018	S/S	Corn	DKB 230 PRO3	92	09:43:00	Control = 0 Conventional = 92 BTP = 158 TPS = 158 TPW = 0
2018	A/W	Common Bean	Ouro da Mata	66	09:43:00	Control = 0 Conventional = 66 BTP = 0 TPS = 0 TPW = 158

S/S = spring/summer; A/W = autumn/winter; MAP = mono ammonium phosphate; Control = without phosphate fertilization; Conventional = phosphate fertilization in the furrow in each crop; BTP = phosphate fertilization of the grain production system to broadcast; TPS = phosphate fertilization of the grain production system in the furrow of the spring/summer crop; TPW = phosphate fertilization of the grain production system in the furrow of the autumn/winter crop.

The following sequence of crops were implemented: 2015/2016 crop season, soybean in the spring/summer and wheat in the autumn/winter; 2016/2017 and 2017/2018 crop seasons, maize in spring/summer and common beans in autumn/winter. All crops were grown under rainfed conditions. Table 2 describes the sequence of crops, cultivars/hybrids, dose and source of P_2O_5 and management of phosphorus fertilizer with the respective doses of P_2O_5 in each crop season in the experimental area. The management of pests, diseases and weeds, choice of cultivars/hybrids, and nitrogen and potassium fertilization were the same as those adopted by the farm. The dose of nitrogen fertilization applied was corrected by subtracting the amount already contained in the phosphate fertilizer. The supply of K was applied by broadcast before sowing.

Sampling and analysis of leaves and soil

Reference leaves were collected from the summer crops (maize and soybean) for nutritional analysis; 10 leaves were collected from each plot. The reference leaf was the opposite leaf below the ear for maize and the third trifoliate leaf with a petiole counting from the apical meristem for soybean. Both samplings were performed during flowering (stage R1), as recommended by Malavolta, Vitti, and Oliveira (1997). The leaf P content was analyzed according to the methodology described by Silva (1999).

Soil sampling for chemical analysis was carried out at the end of the 2017/2018 crop season; five subsamples were randomly collected per experimental plot at the depths of 0-0.10, 0.10-0.20 and 0.20-0.40 m, which mixed and formed a sample. The soil P content extracted by anion exchange resin was analyzed according to the methodology described by Silva (1999).

Crop yield

To estimate crop yield, the grain from three plant rows (length of 5 m) was sampled at random in the center of the experimental plots. The estimated yield was corrected to 13% grain moisture and extrapolated to an area of the one hectare.

Data analysis

Data on soil and leaf P content, and crop yield were subjected to an analysis of variance (ANOVA), and the means were compared using the Tukey test ($p < 0.05$). Pearson correlation between soil P content and leaf P content was conducted. All analyzes were performed using the R software (R Development Core Team, 2019).

Results and discussion

Soil phosphorus content

Before the implementation of the experiment, soil P levels were considered medium (16-40 mg dm^{-3}) according to van Raij (2011) and high (21-35 mg dm^{-3}) according to Sousa et al. (2016) for annual crops (Table 1). From 2015 to 2018, the area was cultivated with six crops and, at the end, the soil P levels increased in the 0-0.10 m layer for the P managements that applied the total dose of phosphate fertilizer in the seeding furrow (TPS and TPW) (Figure 2). TPS and TPW had higher soil P content compared to Control, Conventional and BTP in the layers 0-0.10 m and 0.10-0.20 m, whereas 0.20-0.40 m was only higher than BTP.

The application of the total dose of phosphate fertilizer, for the production system (spring/summer and autumn/winter crops), in the seeding furrow (located) reduced the fertilizer-soil contact in relation to the application for each crop (Conventional) and total broadcast application (BTP). The greater soil-fertilizer contact and consequently less P availability with broadcast application is already well consolidated in the literature, especially in tropical soils due to increased P adsorption (Campos, Antonangelo, & Alleoni, 2016; Hanyabui et al., 2020; Prado, Fernandes, & Roque, 2001; Prochnow et al., 2017; Rheinheimer, Gatiboni, & Kaminski, 2008; Sousa et al., 2016). The application of phosphate fertilizer in each crop (Conventional) increases the contact-fertilizer in relation to the application of the total dose for two crops because two mobilizations of the soil are made in the planting furrow. Higher residual P content in the soil with the splitting of phosphate fertilizer has been observed when the initial levels of P are low (Resende et al., 2006). There is a lack of studies on phosphate fertilizer-soil contact with full doses and divided into soils with adequate levels of P.

Thus, the application of phosphate fertilizer aimed at the grain production system (spring/summer and autumn/winter crop) proved to be a more efficient option for the producer, since it increased the soil P levels and improved the operational logistics of sowing, since makes it possible to choose which crop the fertilizer will be applied to (Pavinato & Ceretta, 2004). The application of P to the autumn/winter crop row instead of the spring/summer crop row results in advantages regarding the rapidity of spring/summer crop sowing operations, which could help avoid late sowing and the subsequent crop yield restrictions (Caires et al., 2017; Pavinato & Ceretta, 2004).

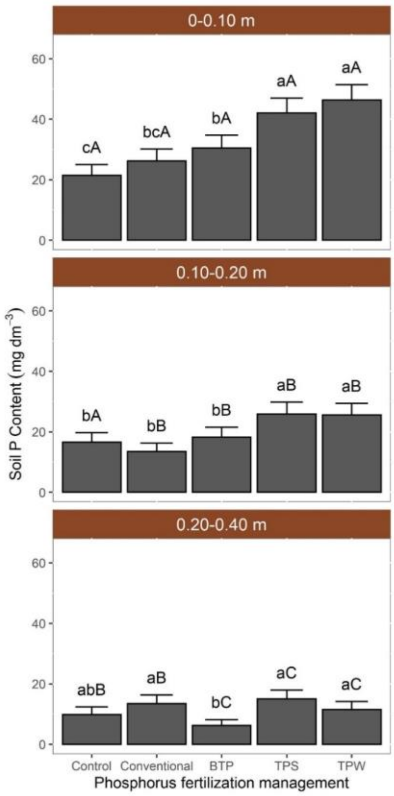

Figure 2. Soil P content, extracted by anion exchange resin, in three soil layers depending on the management of phosphate fertilization. Means followed by equal lowercase letters do not differ for the management of phosphate fertilization and mean followed by equal uppercase letters do not differ for soil layers, by the Tukey's test, at 5% probability. Control = without phosphate fertilization; Conventional = phosphate fertilization in the furrow in each crop; BTP = phosphate fertilization of the grain production system to broadcast; TPS = phosphate fertilization of the grain production system in the furrow of the spring/summer crop; TPW = phosphate fertilization of the grain production system in the furrow of the autumn/winter crop.

In all treatments, except the control which had no P application, the highest levels of P were observed in the 0-10 cm layer compared with the 10-20 cm layer (Figure 2). Soil management with minimal mobilization and ways of applying phosphate fertilizers increase the accumulation of P on the soil surface over time, creating the problem of nutrient stratification (Barbosa, Arruda, Brod, & Pereira, 2015; Cade-Menun et al., 2015; Costa et al., 2009; Nunes et al., 2011; Scheiner & Lavado, 1998; Smith, Huang, & Haney, 2017; Sousa et al., 2016). Phosphorous accumulation in the 0-10 cm layer occurred because the sowing of grains (spring/summer crop) deposited the fertilizer up to a maximum depth of 0.10 m (Denardin et al., 2008), whereas for autumn/winter crops, the fertilizer effectively reaches depths of up to 0.05 m, in addition to the low mobility of P in the soil (Marschner, 2012; Rheinheimer & Anghinoni, 2001; Rheinheimer et al., 2008). Therefore, although fertilization in the furrow is the method most recommended in the literature because it allows a better distribution of P in the surface layer and promotes distribution of the root system, it is also enabling P accumulation in the surface layer (Prochnow et al., 2017), which may have been intensified here by fertilization of the production system (TPS and TPW). The P accumulation in the surface layer can be observed in both the application of P in the furrow and by broadcast (Nunes et al., 2011; Sousa et al., 2016).

Leaf phosphorus content

The leaf P contents of soybean (2015/2016) and maize (2016/2017 and 2017/2018) did not differ between treatments, indicating that they were not altered by the management of phosphate fertilization (Table 3). During the three crops season, the leaf P content of the summer crops were at levels considered suitable for soybeans (2.5 to 5.0 g kg^{-1}) and maize (2.0 to 4.0 g kg^{-1}) according to Cantarella, van Raij, and Camargo (1996). In the studies by Barreto and Fernandes (2002), the application of phosphate fertilizer by broadcasting increased the leaf P content of maize, in soil that initially had very low levels of P, compared to the application in the planting furrow. This difference can possibly be explained by the low initial levels of P in the soil, different from this study.

Table 3. Leaf P content in the spring/summer (2015/2016, 2016/2017 and 2017/2018) crop seasons.

Treatments	Leaf P content (g kg^{-1})		
	2015/2016	2016/2017	2017/2018
	Soybean	Maize	Maize
Control	3.4 a	2.1 a	2.8 a
Conventional	3.1 a	2.2 a	2.7 a
BTP	3.5 a	2.3 a	2.5 a
TPS	3.1 a	2.1 a	2.7 a
TPW	3.0 a	2.1 a	2.6 a

Means followed by the same letter in the column are not significantly different based on the Tukey test ($p < 0.05$). Control = without phosphate fertilization; Conventional = phosphate fertilization in the furrow in each crop; BTP = phosphate fertilization of the grain production system to broadcast; TPS = phosphate fertilization of the grain production system in the furrow of the spring/summer crop; TPW = phosphate fertilization of the grain production system in the furrow of the autumn/winter crop.

There was no correlation between the P levels of the different soil layers (0-10, 10-20 and 20-40 cm) and the leaf P levels in soybeans and maize (Data not shown). Usually, the lack of correlation between the levels of a given nutrient in the soil and its leaf concentration suggests that the method is not suitable for assessing the availability of the nutrient (van Raij, 1998). However, for there to be a correlation, both must have been affected by the treatments; this was not observed, especially for leaf concentrations (Table 3), as P soil levels were already adequate (Table 1) regardless of treatment. In addition, the P resin extractor is the one that best correlates of plant index of bioavailability and the soil P content (van Raij, 1998).

Crop yield

The response of crops yield to P fertilization management was different for spring/summer and autumn/winter crops. Crop yields were only affected by P fertilization management for autumn/winter crops. In spring/summer crops there was no difference even for control (Table 5).

The highest wheat (2016) and common bean (2017) yield were observed with conventional P application, i.e. application to the planting furrow at the time of sowing each crop. In autumn/winter crops is when water restriction normally occurs for crop development (Figure 1), which possibly influenced the response of the crops to the P fertilization management (Prochnow et al., 2017). It should be noted that for good use efficiency of P by plants, there must be an adequate water supply because P transport from the soil solution to the roots occurs by diffusion, which is dependent on soil moisture (Marschner, 2012). It is possible that when the nutrient is applied in the planting furrow and, parceled out for each crop, during a period of water restriction, its supply is favored due to the shorter distance between the root system and the nutrient deposition site. In addition, wheat has a root system with less soil water extract capacity than maize and soybeans (Cabelguenne & Debaeke, 1998).

Table 5. Grain yield of soybean, wheat, maize and common beans from the 2015/2016 crop season to the 2017/2018 crop season.

Treatments	Yield (Mg ha^{-1})						
	soybean	wheat	maize	Common beans	maize	Common beans	accumulate
	2015/2016	2016	2016/2017	2017	2017/2018	2018	2015/2018
Control	4.39 a	1.93 c	14.79 a	2.52 b	11.94 a	2.00 a	37.56 a
Conventional	4.16 a	2.93 a	15.65 a	3.01 a	11.61 a	2.57 a	39.90 a
BTP	4.22 a	2.13 bc	16.32 a	2.77 ab	12.06 a	2.44 a	39.95 a
TPS	4.37 a	2.28 abc	14.47 a	2.64 b	11.61 a	2.13 a	37.54 a
TPW	4.41 a	2.72 ab	14.71 a	2.58 b	12.36 a	2.36 a	39.26 a

Means followed by the same letter in the column are not significantly different based on the Tukey test ($p < 0.05$). Control = without phosphate fertilization; Conventional = phosphate fertilization in the furrow in each crop; BTP = phosphate fertilization of the grain production system to broadcast; TPS = phosphate fertilization of the grain production system in the furrow of the spring/summer crop; TPW = phosphate fertilization of the grain production system in the furrow of the autumn/winter crop.

TPS had the same effect as the Control on the yield of autumn/winter crops. In this P fertilization management, all fertilizer from spring/summer and autumn/winter crops is applied to the furrow 20 days before spring/summer crop, reducing the efficiency of fertilization for autumn/winter crop for two reasons:

application time up to sowing and distance from the application site to the row sowing, since the planting furrow for autumn/winter cultivation does not coincide with the furrow for fertilizer application. The application of all P fertilization in the autumn/winter crop (TPW) did not differ from TPS, being greater than the control only for wheat. Phosphate fertilization by broadcast promoted similar yield to other treatments (Table 5). The accumulated crops yield (2015 to 2018) did not differ between the management of phosphate fertilization.

The lack of response in spring/summer crop yield as a function of the P fertilization management was expected due to the adequate soil P level and water supply for crops. When soils have a nutrient content equal to or above the critical level, they are sufficient to obtain 80-90% of the potential crop yield in the absence of fertilization (Sousa et al., 2016) and regardless of the form of fertilizer application. Thus, nutrients are applied only to replenish the quantities taken up by crops and not to increase soil levels and crop yield (Pauletti, Serrat, Motta, Favaretto, & dos Anjos, 2010). Some studies have shown that in soils with an adequate level of nutrients there is no response in yield of annual crops to phosphate fertilization (Lacerda et al., 2015; Nunes et al., 2011; Pavinato & Ceretta, 2004; Sousa et al., 2016; Zancanaro et al., 2018). These results corroborate the crop yield data obtained in the present study.

Therefore, even though the total dose of phosphate fertilization in the furrow (TPS and TPW) increased the soil P levels over three crops season, it was the conventional management (phosphate fertilization in the furrow in each crop) that promoted higher yields for the crops of autumn/winter.

Conclusion

The management of phosphate fertilization with the application of the total dose for both crops in the sowing furrow of the spring/summer or autumn/winter crops promotes operational advantages and increase of soil P content in the 0-0.20 m layer, without reducing the yield of the spring/summer crops. Leaf P content was not affected by the management of phosphate fertilization. The management of phosphate fertilization influences the crops yield more subject to water restriction (autumn/winter crops), when conventional management (phosphate fertilization in the furrow in each crop) provides greater yield of common beans and wheat.

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