



# Enhancing Wheat and Soybean Yields in a Subtropical Oxisol Through Effective P Fertilization Strategies

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Received: 1 November 2019 / Accepted: 17 March 2020 / Published online: 27 March 2020  
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## Abstract

Phosphorus (P) deficiency limits agricultural production in tropical and subtropical soils, where soil mineralogy is dominated by kaolinite, iron, and aluminum oxides. The aim of this work was to compare two application methods of P, to the soil surface and to the sowing line, to determine the most effective strategy to increase wheat and soybean yields on an oxidic subtropical soil in Brazil under field conditions. Additionally, four inorganic P fertilizers (monoammonium phosphate (MAP); single superphosphate (SS); triple superphosphate (TP); and natural rock phosphate (NP)) in a wheat crop and four different P rates (zero, 0; low, 45; medium, 90; and high, 180 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub>) of TP in a soybean crop were tested after being applied to the soil surface and to the sowing line. A significant increase in yield (54%) was only found when TP was applied to the sowing line in comparison with the soil surface in wheat plants, probably due to its high solubility. However, the application method did not produce a significant effect in soybean yields, probably because this crop has a different P requirement and root distribution pattern than wheat. In the case of P fertilizers applied to the soil surface, higher wheat yields were observed with NP and MAP in comparison with TP. Finally, a linear increase was observed in soybean yields while increasing the P rate, finding significant differences between the plants fertilized with the highest P rate and the non-P-fertilized plants (24% yield increase in the first case). Our results highlight the need for specific P fertilization strategies for the different crops grown on subtropical regions where soil mineralogy curbs P availability.

**Keywords** P fertilizers · P application method · P rate · P adsorption · Plant nutrition

## 1 Introduction

Tropical and subtropical soils mainly are acid soils whose mineralogy is dominated by the presence of clay minerals like kaolinite and iron and aluminum oxides/hydroxides (Kämpf et al. 2012). These factors contribute to the limited availability of certain essential nutrients for plants, for example,

phosphorus (P) that is strongly adsorbed onto the soil mineral surfaces (Johnson and Loeppert 2006; Santos et al. 2008; Fink et al. 2016a). As a result, P deficiency limits plant growth and agricultural production in these areas (Novais et al. 2007; George et al. 2018).

Phosphorus fertilization in soils with a limited P availability is fundamental to enhance plant yield. However, it requires a deep understanding of soil reactions after P addition. Most of the total P added (up to 90%) is quickly adsorbed onto mineral surfaces (fast adsorption, 1 h), and slowly later (Barrow 1983). Williams and Reith (1971) found that only a small fraction of the P applied to the soil remained available 1 year after its application (8–20%) and it was reduced to a lower amount (2.7%) 6 years later. Furthermore, this situation is aggravated in soils with oxidic mineralogy. Fink et al. (2016b) assessed P desorption in subtropical soils incubated for 30 days and observed that soils with a high goethite content desorbed 30% less P than soils with the same Fe oxide contents but with the predominance of hematite.

**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s42729-020-00232-y>) contains supplementary material, which is available to authorized users.

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Phosphorus use efficiency depends on several factors, among others, soil management, the type of fertilizer (source of P, solubility, composition, and richness in P), and the application method (Resende et al. 2006; Motomiya et al. 2004; Zhang et al. 2019). Both factors affect soil P availability and, as a result, crop yield (Montoniya et al. 2004; Silva et al. 2009; Sá et al. 2013; Vieira et al. 2013, 2015; Valadão et al. 2017). The application of P fertilizers to the soil surface is the most common practice, which has a reduced economic cost in comparison with other methods (Olibone and Rosolem 2010) but it is not always the best alternative for plant nutrition and the environment. An inadequate P management is associated with low P diffusion and high adsorption of P on the soil particles, increasing the P concentration in the first centimeters of soil. Consequently, it intensifies the risk of potential P losses and contamination of water bodies (Shigaki et al. 2007; Fischer et al. 2018) and reduces P use efficiency.

In Brazil, soybean and wheat are an important source of incomes for farmers (Oliveira Neto and Santos 2017; Conab 2016) but their yields and grain quality are often limited as they are grown on soils with a reduced P availability (Novais et al. 2007; Pontigo et al. 2018). Furthermore, the world phosphate rock reserves could only provide P for the following 60–90 years (Cordell et al. 2009; Vaccari 2009). Therefore, P fertilization strategies in tropical and subtropical regions should be optimized to enhance the amount of P that is available for the crop.

The aim of this study was to compare two application methods of P, to the soil surface and to the sowing line, to determine the most effective strategy to increase plant yields (wheat and soybean) on an oxidic subtropical soil in Brazil. In line with the main aim, we evaluated four inorganic P fertilizers with different solubility and composition (monoammonium phosphate, single superphosphate, triple superphosphate, and natural phosphate) in a wheat crop, and four different P rates of triple superphosphate (no P fertilization, low, medium, and high) in a soybean crop. Our hypotheses are that the application of P to the sowing line will increase plant yields in comparison with the application to the soil surface because the P granules will be nearer to the plant roots, and that the effect of the four P fertilizers on wheat yields will depend on their solubility and composition, while only the highest P doses applied to the soybean crop will increase its yield in comparison with the non P fertilization as most of the P applied will be adsorbed onto the soil surfaces and only a small portion will be available for plants.

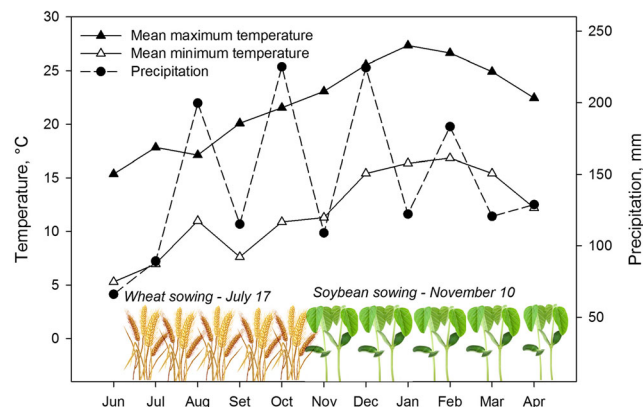
## 2 Materials and Methods

Two field experiments were developed in Palmas, Brazil (26° 30' 43.7" S 51° 59' 0.8" W) in 2016–2017, under Cfb climate (Köppen's classification), with low temperatures in winter and

fair summer (mean annual 22.6 °C), and mean annual precipitation of 2142 mm (IAPAR 2016). During our experiments, although the cumulative precipitation was 1389 mm (Fig. 1), there was a dry period (10 mm) from July 17 (2016) to August 6 (2016). The soil of this experimental area is classified as an Oxisol (Soil Survey Staff 2010). A composite sample from the area used for the field experiments was collected, air-dried for 1 week, and sieved to 2 mm for analysis (in duplicate). The soil used in the two experiments had the following chemical properties (Table 1): organic matter, 40.2 g kg<sup>-1</sup> (by wet oxidation); pH<sub>H2O</sub>, 5.4 (soil:water ratio 1:1); Ca, Mg (exchangeable with KCl), and K (extracted by Mehlich I solution), 4.4, 2.5, and 0.3 cmol<sub>c</sub> kg<sup>-1</sup>, respectively; aluminum and base saturation, 0% and 61%, respectively; and had a medium level of P availability (6.0 mg kg<sup>-1</sup>; by Mehlich I solution), according to CQFS - RS/SC (2004). The soil has 628, 347, and 25 g kg<sup>-1</sup> of clay, silt, and sand, respectively. Regarding Fe oxides, the soil had 77.9 g kg<sup>-1</sup> of Fe extracted with the citrate-bicarbonate-dithionite method (Mehra and Jackson 1960) and 7.3 g kg<sup>-1</sup> of poorly crystalline Fe oxides, extracted with ammonium oxalate in the dark (Schwertmann 1964). In addition, the X-ray diffractometer shows a predominance of kaolinite and goethite, and presence of hematite and gibbsite (Fig. S1).

### 2.1 First Field Experiment: Wheat Crop

Wheat (*Triticum aestivum* cv. Gralha Azul) was sown at 4-cm depth in July 2016 (row spacing of 0.17 m) and harvested in November 2016. The fertilization consisted of 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> (different P fertilizers were used, according to CQFS - RS/SC (2004), 30 kg ha<sup>-1</sup> for soil P correction and 45 kg ha<sup>-1</sup> for wheat maintenance), 60 kg K<sub>2</sub>O ha<sup>-1</sup> as KCl and 60 kg N ha<sup>-1</sup> as urea (33% applied at sowing and 66% at the tillering stage) following regional recommendations (CQFS - RS/SC 2004) for an expected yield of 3 Mg ha<sup>-1</sup>. The P fertilizers were applied using two different application methods, to the soil surface and to the sowing line (allocated at



**Fig. 1** Climate conditions (temperature and precipitation) in the months that wheat and soybean experiments were conducted

**Table 1** Chemical characterization of the soil used for wheat and soybean crops

pH <sub>H<sub>2</sub>O</sub>	Ca cmol <sub>c</sub> kg <sup>-1</sup>	Mg cmol <sub>c</sub> kg <sup>-1</sup>	Al	H + Al	K	CEC	P mg kg <sup>-1</sup>	Al saturation %	Base saturation	Organic matter g kg <sup>-1</sup>
5.4	4.4	2.5	0.0	4.6	0.3	11.8	6.0	0	61	40.2

pH<sub>H<sub>2</sub>O</sub> determined in soil:water ratio 1:1; Ca, Mg, and Al exchangeable with KCl 1 mol L<sup>-1</sup>; K and P extracted by Mehlich I solution; H + Al estimated by SMP solution; organic matter determined by wet oxidation; according to CQFS - RS/SC (2004)

5-cm soil depth and 5 cm at both sides of the seeds), and five different P fertilizers (the most commonly used in Brazil) were compared: no P (control treatment), monoammonium phosphate (MAP; 48% P<sub>2</sub>O<sub>5</sub> soluble in neutral ammonium citrate), single superphosphate (SS; 18% P<sub>2</sub>O<sub>5</sub> soluble in neutral ammonium citrate), triple superphosphate (TP; 41% P<sub>2</sub>O<sub>5</sub> soluble in neutral ammonium citrate), and natural phosphate of rock melted at 1500 °C (NP; 14% P<sub>2</sub>O<sub>5</sub> soluble in citric acid 2%). The N applied with MAP (9% of the total) was subtracted from the N applied with urea in the first application.

The experimental design was a randomized block design with four replications per combination of application method and P fertilizer (2 fertilizer application methods, 5 different P fertilizers, and 4 replications; 40 plots of 1.2 × 1.2 m—1.44 m<sup>2</sup> each).

The following measurements were done at different plant growth stages: plant density was determined 1 week after total germination; tiller number per plant was determined after total tillering; the number of wheat ears was assessed after the anthesis stage; the number of spikelet per ear and grain per ear and thousand grain weight (TGW) were determined after physiologic maturation.

## 2.2 Second Field Experiment: Soybean Crop

The soybean (*Glycine max* cv. TMG 7062) of the second field experiment was sown in November 2016 (row spacing of 0.45 m) at 4-cm soil depth in the adjacent area of the wheat experiment but at a distance of 10 m to avoid the effect of phosphate fertilization applied to the former crop. This crop was harvested in April 2017. The recommended fertilization (CQFS - RS/SC 2004) was 90 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> applied in the form of triple superphosphate (TP) and 80 kg K<sub>2</sub>O ha<sup>-1</sup> as KCl for an expected yield of 4 Mg ha<sup>-1</sup> following recommendations for this province and crop (CQFS - RS/SC 2004). The P fertilizers were applied to the soil surface or to the sowing line (allocated at 5-cm soil depth and 5 cm at both sides of the seeds) at different P<sub>2</sub>O<sub>5</sub> rates: no P, low, medium, and high P rates (0, 45, 90, and 180 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> representing 0, 50, 100, and 200% of the recommended rate). The experimental design was a randomized block design with four replications per combination of application method and P rate (4 P rates, 2 application methods, and 4 replications; 32 plots of 2 × 2 m—4 m<sup>2</sup> each).

After physiologic maturation (April 2017), plant height, height of the first legume, number of legumes, TGW, and crop yield were measured.

## 2.3 Statistical Analysis

The data were subjected to factorial analysis of variance (ANOVA) for each field experiment. When an interaction between the 2 factors occurred, application method, and the five P fertilizers used in the first experiment or the four P rates used in the second one, one-way ANOVAs were developed to study (1) the effect of the application method for each P fertilizer and (2) the effect of each P fertilizer for each application method, independently. These analyses took into account the block design. Means were compared with Tukey's HSD post hoc test. All analyses were done by using Statistix 10 software from Analytical Software (Tallahassee, FL, USA). We considered significant differences when  $p < 0.10$  due to the high variability obtained under field conditions and to minimize the arbitrariness of rejecting or accepting a null hypothesis when  $p$  is near 0.05 (Zar 2010).

## 3 Results

### 3.1 Wheat Experiment: Application Method and P Fertilizers

Table 2 shows plant density (mean value of the experiment, 125.9 ± 2.0) and number of tillers per plant (13.8 ± 0.2), ears per plant (11.2 ± 0.2), spikelets (16.1 ± 0.1), and grains per ear (29.6 ± 0.1) as a function of the application method and the P fertilizer. They were not affected by the two studied factors except the number of ears per plant. Unexpectedly, this variable was significantly higher in wheat plants grown under no P fertilization (13.1) than that in plants which received P as SS and TP (9.7 and 10.3, respectively; Table 2) but it was not significantly reduced for plants fertilized with MAP and NP (11.4 and 11.5, respectively).

In this experiment, a significant interaction between the application method and the P fertilizer occurred for TGW ( $p = 0.0518$ ; Fig. 2a) and yield ( $p = 0.0151$ ; Fig. 2b). The effect of the application of P to the sowing line was limited to an increase in TGW and yield (35.5 ± 0.7 g; 5670 ± 601 kg ha<sup>-1</sup>,

**Table 2** Factorial ANOVAs for the number of plants per square meter and number of tillers, ears, spikelets, and grains per plant (mean  $\pm$  standard error,  $n = 4$ ) as a function of the application method (soil surface and sowing line) and the five different P fertilizers assessed in

the wheat crop. Different letters indicate significant differences between the means according to Tukey's HSD post hoc test. The lack of letters means no significant differences between the different application methods or P fertilizers

Factor	Plants m <sup>-2</sup>	Tiller plant <sup>-1</sup>	Ears plant <sup>-1</sup>	Spikelets ear <sup>-1</sup>	Grains ear <sup>-1</sup>
Application method					
Sowing line	119.2 $\pm$ 7.8	14.0 $\pm$ 0.8	11.6 $\pm$ 0.4	16.0 $\pm$ 0.1	30.1 $\pm$ 1.0
Soil surface	132.5 $\pm$ 7.5	13.5 $\pm$ 0.7	10.8 $\pm$ 0.5	16.1 $\pm$ 0.2	29.0 $\pm$ 0.7
<i>P</i> <sub>application method</sub>	0.2368	0.6817	0.1247	0.7951	0.4166
P fertilizer					
Control (no P)	111.8 $\pm$ 9.5	15.4 $\pm$ 0.4	13.1 $\pm$ 0.8 a	15.6 $\pm$ 0.3	29.6 $\pm$ 1.2
Monoammonium phosphate	116.7 $\pm$ 12.4	15.0 $\pm$ 1.9	11.4 $\pm$ 0.3 ab	16.2 $\pm$ 0.1	29.3 $\pm$ 1.5
Single superphosphate	125.5 $\pm$ 14.1	12.1 $\pm$ 1.0	9.7 $\pm$ 0.7 b	16.2 $\pm$ 0.3	28.6 $\pm$ 1.2
Triple superphosphate	130.4 $\pm$ 11.1	13.3 $\pm$ 0.7	10.3 $\pm$ 0.6 b	16.2 $\pm$ 0.2	30.7 $\pm$ 2.1
Natural phosphate	145.1 $\pm$ 12.7	13.0 $\pm$ 0.9	11.5 $\pm$ 0.3ab	16.2 $\pm$ 0.3	29.6 $\pm$ 1.0
<i>P</i> <sub>fertilizer</sub>	0.3715	0.3028	0.0038	0.3166	0.9169
<i>P</i> <sub>interaction</sub>	0.5931	0.8975	0.4594	0.2256	0.5988

respectively) in comparison with the application to the soil surface (30.1  $\pm$  1.0 g; 3682  $\pm$  585 kg ha<sup>-1</sup>, respectively) when TP was used (Fig. 2a, b). The different P fertilizers did not influence TGW or yield when they were applied to the sowing line but they had a variable effect on TGW after their application to the soil surface. Firstly, wheat plants fertilized with SS had the highest TGW, followed by those fertilized with MAP or NP and no fertilized with P, and then, by the plants fertilized with TP (Fig. 2a). Secondly, significantly higher yields were obtained for plants fertilized with NP and MAP, followed by SS and those non fertilized with P, and, finally, wheat plants fertilized with TP.

### 3.2 Soybean Experiment: Application Method and P Rates

Plant height (average of 72.7  $\pm$  0.9 cm), height of the first legume (average of 17.6  $\pm$  0.3 cm), and number of legumes per plant (average of 65.6  $\pm$  2.9) were not altered by the application method or the P rate (Table 3).

Figure 3 shows the interaction that occurred between the two factors studied in this experiment (application method and P rate) for TGW ( $p = 0.085$ ). Only the highest P rate applied to the sowing line (200% of the recommended) significantly increased the TWG (g) in comparison with the same amount of P applied to the soil surface (185.8  $\pm$  5.6 vs 167.3  $\pm$  4.1) and with the other P rates (185.8  $\pm$  5.6 vs 167.8  $\pm$  4.2, no P; 167.3  $\pm$  0.8, low P; and 167.4  $\pm$  4.0, medium P) applied to the sowing line (Fig. 3). In line with these results, soybean yield was significantly increased by the highest P rate as follows: high P rate (5378 kg ha<sup>-1</sup>), medium P rate (5047 kg ha<sup>-1</sup>), low P rate (4662 kg ha<sup>-1</sup>), and no P (4337 kg ha<sup>-1</sup>; Fig. 4). However, soybean yield was not affected by the application method ( $p =$

0.556). Although significant differences were only found between the non-P-fertilized plants and the plants fertilized with the highest P dose (increase of 24% in yield;  $p < 0.0794$ ), soybean yields were fitted to a straight line ( $R^2 = 0.96$ ,  $p = 0.0197$ ) which means that the addition of P was proportional to the observed increase in yield for this crop.

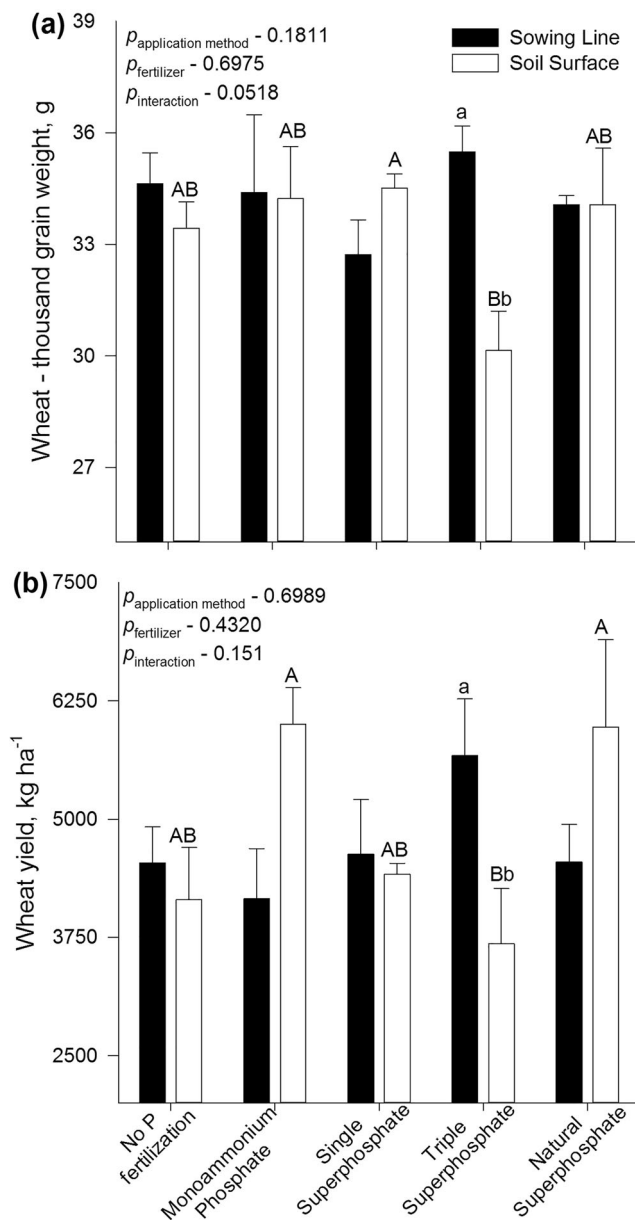
## 4 Discussion

### 4.1 Plant Growth Variables

The main factors that determine plant germination are light, temperature, water, and oxygen availability (Nassif et al. 1998). The low plant density observed in the wheat crop (125.8 plants m<sup>-2</sup>) in comparison with the expected value (300 plants m<sup>-2</sup>; Cunha et al. 2016) is explained because of the scarce rainfall registered during the first 21 days after sowing (10 mm from July 17 to August 06). This low plant density positively affected the number of tillers per plant (total mean value of 13.8), because the tillering stage was extended under these circumstances (Sander et al. 2011). In line with that point, Whaley et al. (2000) observed that the highest interception of solar radiation (up to 90%) occurred with plant densities between 37 and 82 plants m<sup>-2</sup> in comparison with higher plant densities (around 300 plant m<sup>-2</sup>), as an effect of the increase in the number of tillers: low plant density that resulted in a high number of tillers (Gross et al. 2012). It did not occur in the soybean crop that was sown later, and rainfall was considerable to not limit this variable (plant density was like the expected values—25 plant m<sup>-2</sup>).

Previous studies about the influence of P on plant density, number of tillers per plant, spikelets, and grains per ear (wheat





**Fig. 2** Thousand grain weight (a) and yield (b) (mean ± standard error,  $n = 4$ ) of the wheat plants at harvest as a function of the application method (soil surface and sowing line) and P fertilizers used in this study. Different uppercase letters indicate differences ( $p < 0.10$ ) between fertilizers for each application method and different lowercase letters indicate differences ( $p < 0.10$ ) between the application method for the same fertilizer. The lack of letter indicates no significant differences between application methods or P fertilizers

crop) or plant height, height of the first legume, and number of legumes (soybean crop) are contradictories with our results. Our results do not agree with Fioreze et al. (2012), who found a direct increase in tiller emission with the increase of phosphate fertilization in wheat plants (from 8 to 12 tillers per plant when P addition was increased from 150 to 600 mg P kg<sup>-1</sup>). Furthermore, some authors found a positive response to P fertilization (Alam and Jahan 2013; Rahman and Wilson

1977; Oliveira et al. 1984), while others did not find a relationship with the P fertilizer applied (Majeed et al. 2014) regarding the spikelet number per ear.

The height of the first legume is determined by the growth of the first internodes and it is defined in the initial vegetative plant growth stages. Nevertheless, approximately 60% of P is absorbed after the flowering stage (Hammond et al. 1951). Our results showed that the phosphate soil content without the addition of P (6.0 mg dm<sup>-3</sup> extracted by Mehlich I; CQFS-RS/SC 2004) was enough for a proper initial plant growth and it could explain the lack of significant differences in these plant growth parameters.

#### 4.2 Thousand Grain Weight and Yield

The differences in TGW and yield in wheat plants in relation to the different P fertilizers could be partially explained due to their different composition and solubility. For example, SS has around 18% of sulfur (CQFS-RS/SC 2004) and it could be the reason why a significantly higher TGW was found in the plants fertilized to the soil surface with this product. Similar results were described in Tao et al. (2018), who observed that the application of 45 kg ha<sup>-1</sup> of sulfur to a wheat crop increased their TGW and yield up to 34.7% and 30.2%, respectively, in comparison with no sulfur addition. Salvagiotti et al. (2009) also reported an increase in nitrogen uptake and yields (up to 30%) in wheat crops fertilized with 30 kg S ha<sup>-1</sup>. Furthermore, fertilizing with MAP implies the addition of an extra amount of nitrogen to the crop, which could have helped produce the higher yields observed when it was applied to the soil surface in the wheat crop. In addition, MAP had the highest solubility of all P fertilizers used in this field experiment.

Soil mineralogy in strongly weathered soils, including Oxisols as the one used in our study, is dominated by Fe oxides which form strong bonds with phosphate limiting P availability for the crops (Fink et al. 2016a). It is well-known that P solubility and diffusion in soil is low (Fink et al. 2016b) compared with other macronutrients such as N or K. Therefore, P management in these weathered soils is vital in order to obtain a proper plant growth and non-limited yields by P. The application of fertilizers to the sowing line is recommended to enhance higher P concentrations near to the root expansion zone and to improve P uptake for soybean plants, especially in soils with a low P content (Rosolem and Merlin 2014). However, a positive effect of fertilizing with P to the sowing line was only observed for TGW and yield of the wheat plants fertilized with TP, and for TGW of the soybean plants fertilized with the highest P rate of TP in comparison with soil surface fertilized plants. It should be noted that TP is the second fertilizer with the highest solubility (after MAP) of those used in the wheat experiment. Galetto et al. (2014) evaluated P fertilizers with different solubility

**Table 3** Factorial ANOVAs for plant height, height of the first legume, and number of legumes (mean  $\pm$  standard error,  $n = 4$ ) as a function of the application method (soil surface and sowing line) and different P doses assessed in the soybean crop. There are no significant differences between the means according to Tukey's HSD post hoc test

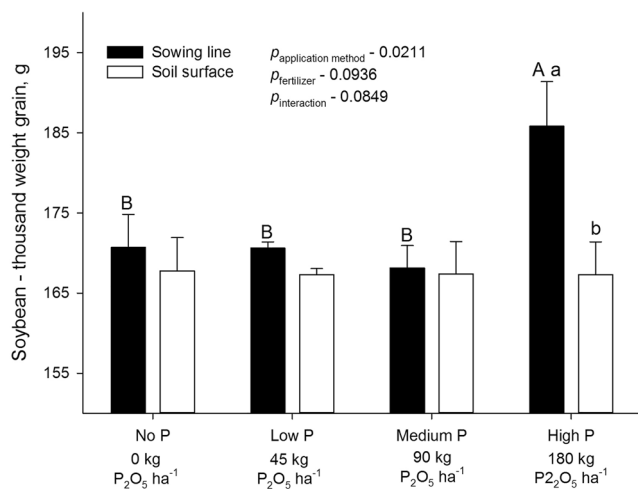
Factor	Plant height (cm)	Height of the first legume (cm)	Legume (number)
Application method			
Sowing line	73.8 $\pm$ 2.3	17.5 $\pm$ 0.6	66.1 $\pm$ 6.5
Soil surface	71.6 $\pm$ 1.2	17.6 $\pm$ 0.5	65.0 $\pm$ 5.4
$P_{\text{application method}}$	0.2163	0.8805	0.8560
P rate			
No P (0 kg ha <sup>-1</sup> )	69.2 $\pm$ 2.5	17.8 $\pm$ 0.7	60.4 $\pm$ 4.3
Low P (45 kg ha <sup>-1</sup> )	73.3 $\pm$ 1.5	17.4 $\pm$ 0.6	61.4 $\pm$ 3.3
Medium P (90 kg ha <sup>-1</sup> )	74.3 $\pm$ 1.1	17.3 $\pm$ 0.5	71.9 $\pm$ 8.8
High P (180 kg ha <sup>-1</sup> )	74.0 $\pm$ 1.9	17.9 $\pm$ 0.5	68.5 $\pm$ 5.8
$P_{\text{fertilizer}}$	0.1769	0.8810	0.4826
$P_{\text{interaction}}$	0.2954	0.1793	0.4739

and found that a positive effect of TP occurred immediately after its application in the first crop, while the effect of water-insoluble P fertilizers (like the NP used here) improved forage and maize yields only after 3 years of continuous application.

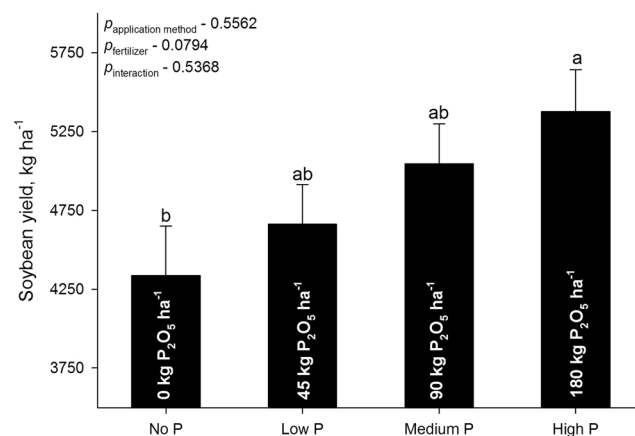
Additionally, Hoang and Marschner (2019) observed that P uptake by wheat plants was lower than the total P mobilized by root exudates in a long-term experiment, indicating that a considerable amount of P added with fertilizers was not available for plants. Thus, P fertilizers with high solubility rapidly increase the P in soil solution and accelerate the P adsorption in the fast stage but decrease the P potential availability. On the other hand, P fertilizers with low solubility (as our NP) do not increase available P in soil solution enough to satisfy plant requirements. Under these conditions, cereals increase the phosphatase acid activity in the soil (Redel et al. 2019) and

become more efficient to uptake P, which could explain our results when NP was applied to the soil surface to the wheat crop.

In these field experiments, it seems that some P fertilizers (wheat crop) applied to the soil surface (NP and MAP) and to the sowing line (only TP) and the different P rates (soybean crop) of TP (applied to the soil surface and to the sowing line together), but especially the highest one, were able to saturate up to a certain point the Fe oxides surfaces of the soil. It resulted in an increase of the availability of P that was reflected in plant yields. It could be because the initial P content of this soil was medium (6.0 mg kg<sup>-1</sup>, near high, according to CQFS - RS/SC (2004)) and the pathways by which P is adsorbed were limited, reducing P adsorption and making possible an increase in P availability (Barrow and Debnath 2014; Barrow et al. 2018). In addition, our results agree with Pauletti et al. (2010), who found that the application method (soil surface or sowing line) was not important for the yield of soybean grown on soil with a considerable soil P content.



**Fig. 3** Thousand grain weight (mean  $\pm$  standard error,  $n = 4$ ) of the soybean grown at harvest as a function of the application method (soil surface and sowing line) and the P rate of triple superphosphate used in this study (no P, low, medium, and high P rates; 0, 50, 100, and 200% of the recommended rate, respectively). Different uppercase letters indicate differences ( $p < 0.10$ ) between fertilizers for each application method and different lowercase letters indicate differences ( $p < 0.10$ ) between the application methods for the same P rate. The lack of letter indicates no significant differences between application methods or P rates



**Fig. 4** Yield (mean  $\pm$  standard error,  $n = 4$ ) of the soybean crop at harvest as a function of the application method (soil surface and sowing line) and the P rate of triple superphosphate used in this study (no P, low, medium, and high P rates; 0, 50, 100, and 200% of the recommended rate, respectively). Different lowercase letters indicate significant differences ( $p < 0.10$ ) between P rates

However, Kamran et al. (2018) assessed the effect of P fertilization (until 200 mg kg<sup>-1</sup>) on soybean growth in acidic soil (pH 4.2 and exchangeable acidity around 6 cmol<sub>c</sub> kg<sup>-1</sup>) and concluded that P fertilization is fundamental to improve physiologic attributes of soybean grown in these soils.

As shown in this study, crops show different responses to P fertilization. Sucunza et al. (2018) assessed the effect of P fertilization in soybean and wheat crops grown on soils with different P contents during 14 years and concluded that wheat was more sensitive to P fertilization than other crops. This higher sensitivity of wheat to P fertilization was also observed by Redel et al. (2019) when they compared this crop with oat and barley. According to these authors, this was related to a higher acid phosphatase activity in the roots of wheat. However, Vieira et al. (2013, 2015) found that a higher soil P content is required for winter crops than for summer crops, especially when they are grown in an oxidic soil as the one used in our field experiments. Finally, Fan et al. (2016) fitted eleven root distribution patterns of temperate crops to a versatile equation and they found that thicker roots are more concentrated in the first centimeters of soil, with this effect being more evident in dicotyledonous plants (including soybean) than that in monocotyledonous plants (including wheat). Therefore, the different sensitivity to P fertilization and the different root distribution patterns could explain the differences observed between our wheat and soybean crops regarding the application method when TP was used.

## 5 Conclusions

Our results show the difficulty of enhancing phosphorus availability and yields of plants grown on a tropical or subtropical Oxisol in which phosphorus availability is curbed by its mineralogy. Although multiple combinations of the different factors were included in this study (application method and phosphorus fertilizers for wheat or phosphorus rates for soybean), plant yields were only increased by a reduced number of them. For wheat, yields were increased up to more than 50% by fertilizing to the sowing line (as we initially hypothesized) with triple superphosphate in comparison with the application of phosphorus to the soil surface or by fertilizing with natural phosphate or monoammonium phosphate to the soil in comparison with triple superphosphate when they were applied to the soil surface. For soybean, the highest phosphorus rate of triple superphosphate increased yields up to 24% independently of the application method.

In this Oxisol, it seems that the strategies that improved crop yields were able to saturate the surface of the iron oxides, probably due to the high solubility of these fertilizers (monoammonium phosphate, triple superphosphate) and to the initial soil phosphorus content. It facilitated an increase in the availability of phosphorus in the soil solution and,

consequently, in crop yields. These results highlight the importance of the design of specific fertilization strategies, considering P fertilizer solubility and composition and P rate, for the different crops in subtropical regions.

**Acknowledgments** This work was supported by the Federal Institute of Paraná [EDITAL PROEPI N° 03/2016].

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