



Phosphate Fertilizer in Soybean-Wheat Cropping System Under No-Till Management

Adônis Moreira^{1*}, Larissa A. C. Moraes¹ and Rafael Petineli²

¹ Department of Plant Nutrition, Brazilian Agricultural Research Corporation (Embrapa Soja), Londrina, Brazil, ² Department of Crop Science, Londrina State University, Londrina, Brazil

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*Correspondence:

Adônis Moreira
adonis.moreira@embrapa.br

Specialty section:

This article was submitted to
Crop Biology and Sustainability,
a section of the journal
Frontiers in Sustainable Food Systems

Received: 22 May 2020

Accepted: 12 August 2020

Published: 15 October 2020

Citation:

Moreira A, Moraes LAC and Petineli R
(2020) Phosphate Fertilizer in
Soybean-Wheat Cropping System
Under No-Till Management.
Front. Sustain. Food Syst. 4:564586.
doi: 10.3389/fsufs.2020.564586

Improvements in soybean (*Glycine max* [L.] Merrill) and wheat (*Triticum aestivum* L.) yields in cropping systems under no-till management (NTM) in the subtropics have been obtained through advances in phosphorus (P) utilization, cultivar selection, and planting and harvesting strategies. This fact, along with the P application in band application in consolidated planting, has resulted in adequate P utilization efficiency and small depleted soil P levels. The aim of this study was to evaluate the efficiency of P₂O₅ rates and application methods in soybean-wheat cropping under NTM during two growing seasons (2014–2016) in a Typical Eutrothox. Four P₂O₅ rates (0, 30, 60, and 120 kg ha⁻¹) of triple superphosphate (45% P₂O₅) were applied using two application methods (broadcast and band application at sowing) before the soybean and wheat crops were cultivated. Both P application methods resulted in a significant yield response to P₂O₅ rates for the soybean and wheat crops. Under NTM, broadcast P₂O₅ application was more effective than band application in soybean, and maximum grain yields were obtained with 129.3 and 88.1 kg P₂O₅ ha⁻¹, respectively. Maximum wheat grain yields were obtained with 91.8 and 99.7 kg P₂O₅ ha⁻¹ for broadcast and band application, respectively. Except for total P in leaves, nutrient uptake and yield components were not affected by the P application methods and rates. The results suggested that in soils with adequate available P levels of >15 mg kg⁻¹ (Mehlich 1 extractant), the grain yield is equivalent or superior with broadcast P application as compared with band application for both soybean and wheat crops when cultivated in a Typical Eutrothox under subtropical conditions. However, broadcast application is considered more effective for large areas of grain cultivation, where it is necessary to sow crops uniformly within the shortest possible time.

Keywords: *Glycine max*, *Triticum aestivum*, broadcast application, band application, nutritional state of plants, subtropical conditions, Typical Eutrothox

HIGHLIGHTS

- Phosphorus (P) application increased soybean and wheat grain yield independently of application method.
- Broadcast P₂O₅ application in a consolidated no-till management was efficient in making P available to plants.

- The P_2O_5 application methods (broadcast and band application) did not influence the nutritional status of soybean and wheat plants.
- Our study provides a comprehensive survey of the response of application type (broadcast and band application) and P_2O_5 rates in soybean-wheat cropping system in no-till management and provides novel insights to improve the sustainability and quality of P (P_2O_5) fertilization under subtropical conditions.

INTRODUCTION

Most soils in Brazil are deficient in phosphorus (P). Associated crop plant P deficiencies are more evident in grain crops, and result in reduced plant size, low pod insertion height, and small ears (Sfredo, 2008). In no-till management (NTM), crop rotation and/or cropping system in tropical and subtropical climates became viable only with the development of technologies to increase the use efficiency of fertilizers and correctives in different soil types in these regions. In these places, the use of large amounts of fertilizer, combined with the absence of abundant reserves of phosphate rocks of sedimentary origin and the need to maximize the time between one cultivation and the next, justifies studies to investigate optimization of phosphate fertilizer use efficiency in agriculture.

Crop rotation is feasible for several crops as it provides continuous soil protection, a good amount of soil organic matter (SOM), and nutrient accumulation which are of fundamental importance for maintaining high yields over the years. No-till management involves the implantation of crops in unturned soil and their protection by cover with straw residues. In NTM, the soil is not de-structured; however, this approach is restricted to band application (Fidelis et al., 2003).

The management of phosphate fertilizer influences the availability of nutrients in the soil and in the plants (Hansel, 2019). The application method can change the speed and capacity of the fertilizer to react in the soil, which in turn can change the solubilization and P availability for the plant, influencing the use efficiency (Lacerda et al., 2015). Fertilizer application must be planned from a long-term perspective, since the cost of fertilization and the responses in productivity are subject to many uncertainties and may vary from year to year (Fixen and Halvorson, 1991; Resende et al., 2006). Among the systems adopted, there are controversies about the ways of supplying the soil with adequate P levels since soluble phosphates, while promptly making P available, have shown good results in different application forms (Borges and Mallarino, 2003).

The use of soybean (*Glycine max* [L.] Merrill) and wheat (*Triticum aestivum* L.) in a single cropping system is common in southern Brazil. Both crops benefit from this management system: the higher soil fertility requirement for wheat cultivation results in greater soil nutrient uptake in the straw, mainly P, and contributes to a reduction of fertilization needed for soybean crops, while wheat and other cereals benefit from the provision of significant amounts of N, P, and K left by soybean crop residues (Stainer et al., 2000; Rossi et al., 2013).

There are controversies about the efficiency of P_2O_5 application in relation to the method used (broadcast or band application) and the appropriate rate. Therefore, the objective of this study was to determine if the method and rate of P_2O_5 application has an influence on soil fertility, grain yield (GY), yield components, and nutritional status of soybean and wheat crops grown under subtropical conditions in a Kaolinitic Typical Eutrorthox.

MATERIALS AND METHODS

Site and Experimental Design

The experiment was carried out in the field under rainfed conditions in an NTM (operational for 10 years). The study was conducted across two growing seasons (2014–2015 and 2015–2016) in the same field rotation located in Londrina, Paraná State, in southern Brazil ($23^{\circ} 23' 30''$ LS and $51^{\circ} 11' 05''$ LW) (Figure 1). The soil, classified as a loamy (710 g kg^{-1} clay) Kaolinitic Typical Eutrorthox (USDA, soil taxonomy classification), had the following chemical properties (determined at a depth of 0–0.1 m) prior to soybean cultivation: pH (CaCl_2) = 4.9, soil organic matter (SOM) = 31.3 g kg^{-1} , P (Mehlich 1 extractant) = 3.7 mg kg^{-1} , P (Resin extractant) = 9.1 mg kg^{-1} , potassium (K^+) (Mehlich 1) = $0.7 \text{ cmol}_c \text{ kg}^{-1}$, calcium (Ca^{2+}) (KCl, 1.0 mol L^{-1}) = $5.1 \text{ cmol}_c \text{ kg}^{-1}$, magnesium (Mg^{2+}) (KCl, 1.0 mol L^{-1}) = $1.9 \text{ cmol}_c \text{ kg}^{-1}$, sulfur (S-SO_4^{2-}) = 79.1 mg kg^{-1} , aluminum (Al^{3+}) = $0.1 \text{ cmol}_c \text{ kg}^{-1}$, potential acidity ($\text{H}+\text{Al}$) = $3.8 \text{ cmol}_c \text{ kg}^{-1}$, cation exchange capacity (CEC) = $11.5 \text{ cmol}_c \text{ kg}^{-1}$, base saturation (V) = 67%, boron (B) available = 0.6 mg kg^{-1} , copper (Cu) available (DTPA-TEA) = 18.3 mg kg^{-1} , iron (Fe) available (DTPA-TEA) = 101.6 mg kg^{-1} , manganese (Mn) available (DTPA-TEA) = 173.8 mg kg^{-1} , and zinc (Zn) available (DTPA-TEA) = 7.9 mg kg^{-1} . The region has a humid subtropical climate (Köppen classification: Cfa) and sequential water balance and temperature (Figure 2) in the soybean and wheat crop seasons (2014–2016) according to Thornthwaite and Mather (1955).

The experiment was set up as a randomized block design in a 2×4 factorial scheme [two application methods (broadcast, total area of plot, and band application together with the seed) and four P_2O_5 rates (0, 30, 60, and 120 kg ha^{-1} , equivalent to 0, 13.1, 26.2, and 52.4 kg ha^{-1} of P)] in a split-plot arrangement (growing season), with four replicates. For the first cultivation, the soybean cv. 'M5947 IPRO' crop was grown in plots of $4.0 \times 8.0 \text{ m}$ with a row spacing of 0.5 m. After each soybean crop, wheat cv. 'Pardela' was cultivated in succession with a spacing of 0.175 m to quantify the residual effects of phosphate application to the soybean crop. Phytosanitary treatments and weed control of the soybean and wheat crops were carried out according to the recommendations described in TPS (2013) and ITTT (2011).

The micronutrients (B, Cu, Fe, Mn, and Zn) were applied in the form of salts mixed with 2.0 Mg ha^{-1} of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). In the second cultivation, fertilization of the soybean crop was based on soil chemical analysis sampled after the first wheat crop and carried out according to

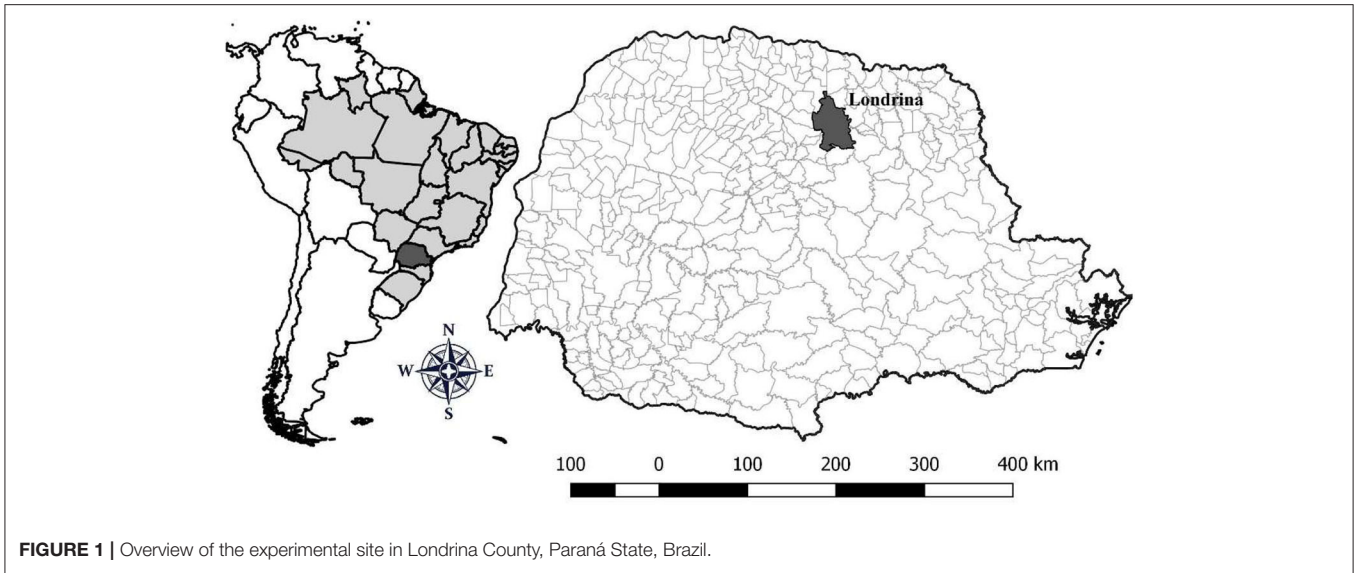


FIGURE 1 | Overview of the experimental site in Londrina County, Paraná State, Brazil.

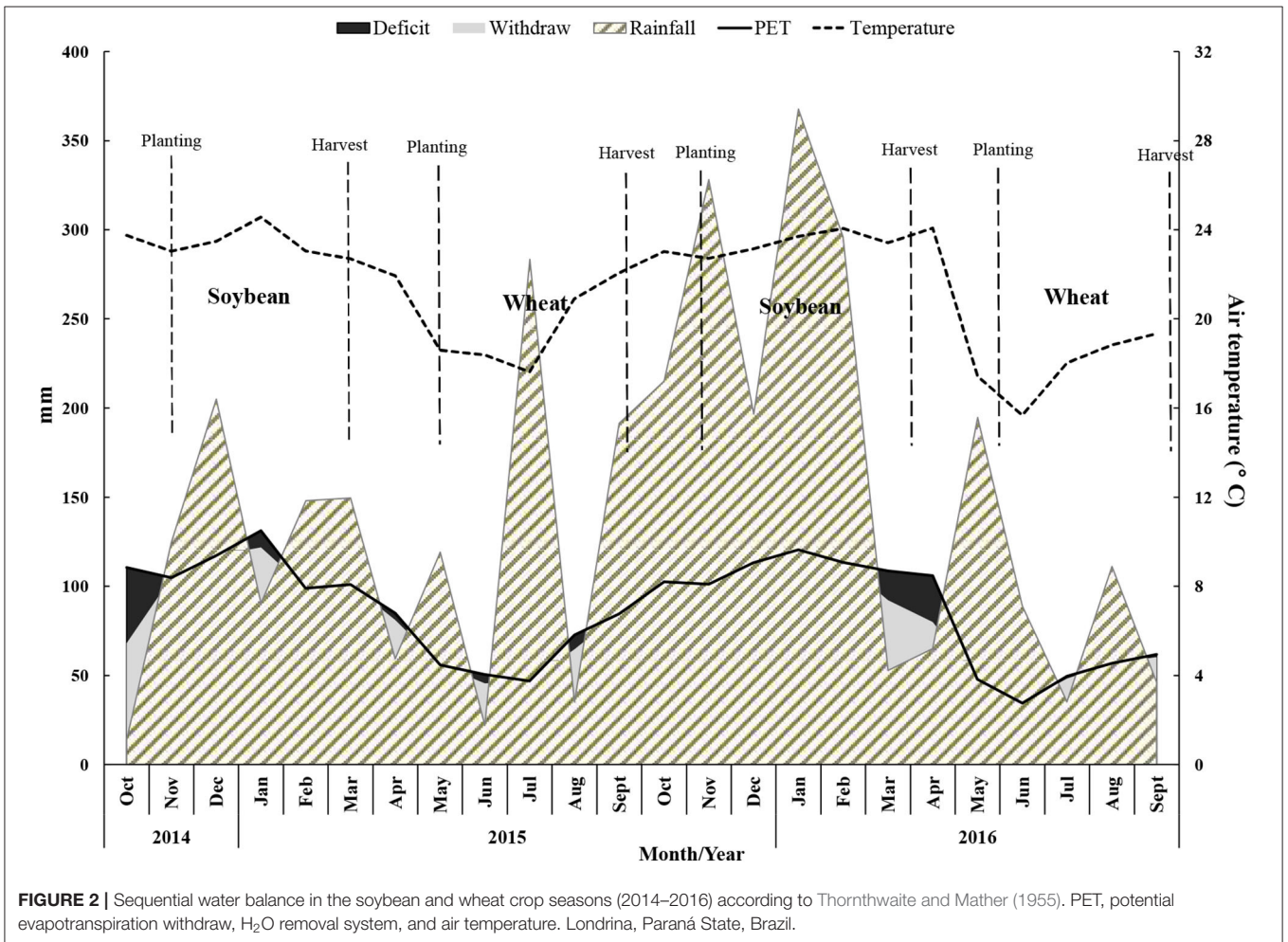


FIGURE 2 | Sequential water balance in the soybean and wheat crop seasons (2014–2016) according to Thornthwaite and Mather (1955). PET, potential evapotranspiration withdrawal, H₂O removal system, and air temperature. Londrina, Paraná State, Brazil.

Moreira et al. (2019b). In both soybean cultivations, seeds were inoculated with *Bradyrhizobium elkanii* SEMIA 587 and SEMIA 5019 (4.0×10^9 viable cells g^{-1}) and treated with a solution

containing 20 $g\ ha^{-1}$ of molybdenum (Mo), 2.0 $g\ ha^{-1}$ of cobalt (Co), and 10 $g\ ha^{-1}$ of nickel (Ni). For the second soybean crop, in addition to the P₂O₅ treatments, the experimental area

received 183 kg ha⁻¹ of potassium chloride [KCl (60% K₂O)] (Moreira et al., 2019b). In both cultivations, the wheat crop received 180 kg ha⁻¹ of urea (45% N) in sowing.

Evaluation of the Experiments

At the R2 reproductive stage, leaves 3 and 4 were collected at random from the apex of 30 plants to determine the nutritional status and chlorophyll level of the plants with hand-held chlorophyll meters (SPAD-502, Minolta, Japan) of the plants, afterwards, the data were transformed in chlorophyll contents (mg cm⁻²) using the equation $y = 16.033 + (7.5774 \times \text{SPAD})$ using the equation $y = 16.033 + (7.5774 \times \text{SPAD})$ (Moreira et al., 2020). The leaves were collected and dried under forced ventilation oven at 65 ± 5 °C until constant weight. The total N was extracted by sulfuric digestion and determined by the micro-Kjeldahl method (Nelson and Sommers, 1972). The total P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentrations were extracted by digestion in a nitric-perchloric solution. The total P concentration was determined by spectrophotometry with molybdenum blue and the S concentration by turbidimetry. The total K, Ca, Mg, Cu, Fe, Mn, and Zn concentrations were analyzed by atomic absorption spectrophotometry, according to the methods described by Malavolta et al. (1997). Soil chemical analyses (pH, C, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) were carried out according to the methodologies described in Teixeira et al. (2017).

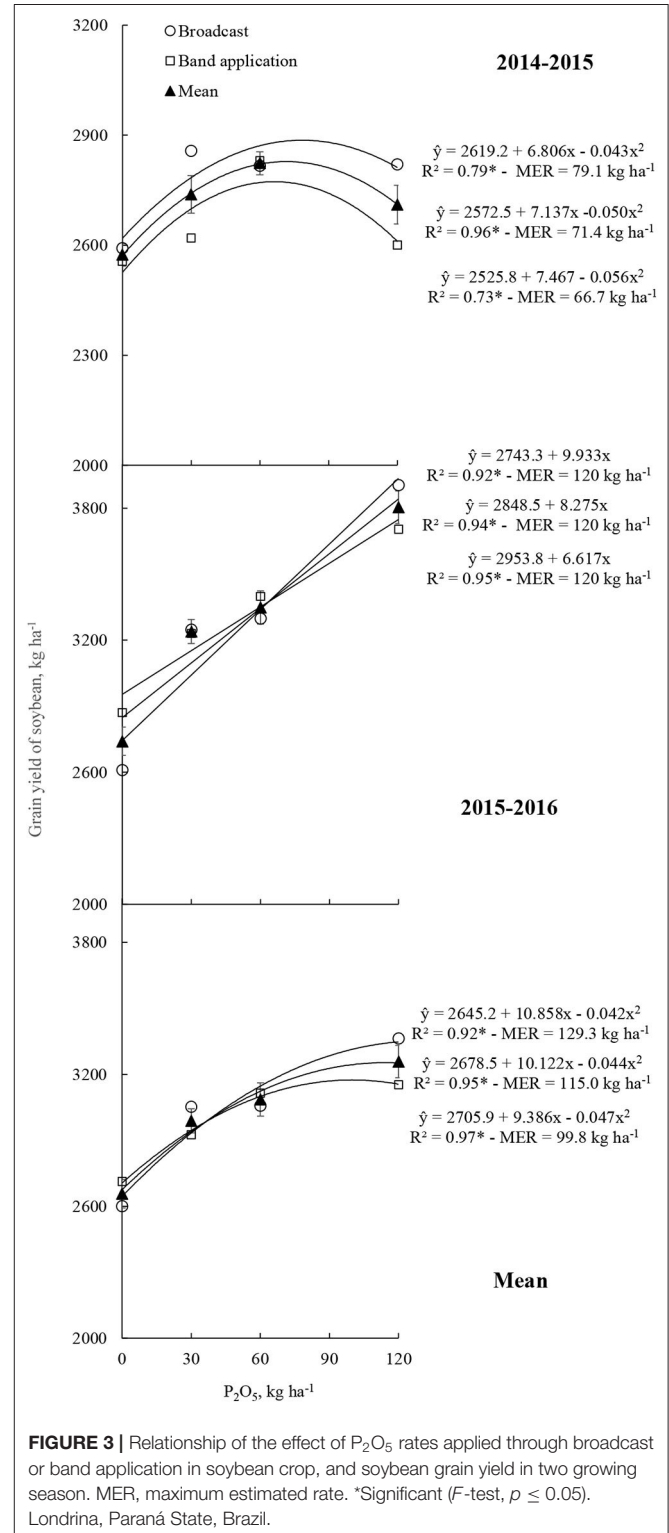
At the R6 growth stage (Fehr et al., 1971), 30 soybean plants were collected from the four central rows in each plot to determine the number of pods (NP), number of grains per pod (NGP), and plant height (PH). Soybean grain yield (GY) and 100 grain mass (R8 stage) were determined from an area of 3.0 × 7.0 m, leaving a 0.5-m border on all sides of each plot.

For the wheat crop, at the 10.1 stage, leaves were collected from 30 plants at random within each treatment to determine the nutritional status (N, P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn—as per Malavolta et al., 1997), and chlorophyll level (SPAD-502, Minolta, Japan), and transformed with the equation described by Uddling et al. (2007). The GY, PH, hectoliter volume (HV), number of spikelet (NS), number of spikelets per clump (NSC), and 1000 grain mass were quantified. At the end of the crop cycle (harvest), soils were sampled from each treatment at a depth of 0–0.1 m to quantify available P with Mehlich 1 and resin extractants as described by Teixeira et al. (2017).

Statistical Analysis

Normality of the distribution of the traits was tested via Shapiro–Wilk’s normality test (Shapiro and Wilk, 1965), testing the null hypothesis that the sample belongs to a population with normal distribution with the statistic X ($0 < X < 1$); if X is equal to 1, the data perfectly fit normal distribution, whereas small values of X are evidence of deviations from normality. The value of the statistic and the associated p -value were obtained; if this p -value was less than the nominal value of significance $p \leq 0.05$, the null hypothesis of normality was rejected. Normality of residuals was examined using the UNIVARIATE procedure ($p \leq 0.05$). Squared and absolute values of residuals were examined with Levene’s Test to confirm homogeneity of variances ($p \leq 0.05$). After the

normality test, the treatment variance data (soybean and wheat) were subjected to analysis of variance (ANOVA) and F -test using the standard least squares procedure of JMP by SAS. Regression and Pearson product-moment correlations were derived using



the REG procedure of SAS to investigate the relation between P₂O₅ rates with grain yield (GY), yield components, nutrient concentrations, and chlorophyll level of soybean and wheat, and the regression equations for GY were chosen according to the best fit of the points within the curve. Where there was interaction of treatments × growing seasons (*p* ≤ 0.05), the data were separated for each growing season.

RESULTS AND DISCUSSION

There was an interaction of P₂O₅ rate and application method on GY for both the soybean (Figure 3) and wheat (Figure 4) crops. In the two growing seasons, the yield of soybeans responded to the P₂O₅ application with a quadratic effect in the first and a linear effect in the second cultivation cycle. In addition, the results from the GY regression analysis under the effect of P₂O₅ rates indicated that, when grown in a Typic Eutrorthox, the broadcast application for the soybean crop showed an average value for the two harvests that was 5.4% higher for the maximum estimated rate (MER) of 99.8 kg ha⁻¹ of P₂O₅ for the band application at sowing method and 129.3 kg ha⁻¹ for the broadcast method with a MER of 115.0 kg ha⁻¹ for the mean of the two application methods (Figure 2). These values are beyond the official recommendation for yield 3.0 to 4.0 Mg ha⁻¹ (Moreira et al., 2019b). The wheat crop GY also increased with increasing P₂O₅ rates, but there was no effect of the application method (Figure 4). However, there was less yield in the second crop, probably due to less rain at the beginning of flowering (Figure 2). The mean GY of the two crops varied from 2,975.5 kg ha⁻¹ for the MER of 91.8 kg ha⁻¹ of P₂O₅ applied using the band application method to 2,977.7 kg ha⁻¹ for the MER of 99.7 kg ha⁻¹ of P₂O₅ applied using the broadcast approach.

Similar results reflecting the positive effects of P₂O₅ rates on GY of soybeans and wheat have been reported by Moreira et al. (2014) and Blue et al. (1990). Regarding the P₂O₅ rates and the two application methods, Heckman and Kamprath (1992) and Borges and Mallarino (2000) obtained positive responses in soybean GY with an increase in P rates application in the soil with both application methods. The band application or broadcast method showed no difference, even with available P levels in the soil within ranges considered low and very low (Moreira et al., 2019b). A low soil P level was a characteristic of the present study, where the average P content available in the soil before planting was 3.7 mg kg⁻¹ (determined using the Mehlich 1 extractant). In a cultivation study carried out under “Cerrado” conditions, in a Typical Oxisol with a clayey texture and low P concentration, Broch and Chueiri (2005) obtained similar soybean yields when applying P fertilizer using the broadcast or the band application method. Regarding yield components, only the chlorophyll levels and number of grains per plant (NGP) in soybean crop and the number of spikelets (NS), and chlorophyll levels in wheat were significantly influenced by the P₂O₅ rates (Table 1). Fageria et al. (2011, 2013) reported that in phosphate fertilization studies, the NGP and NS have a greater influence in increasing GY as compared with other yield components, while P in the plants

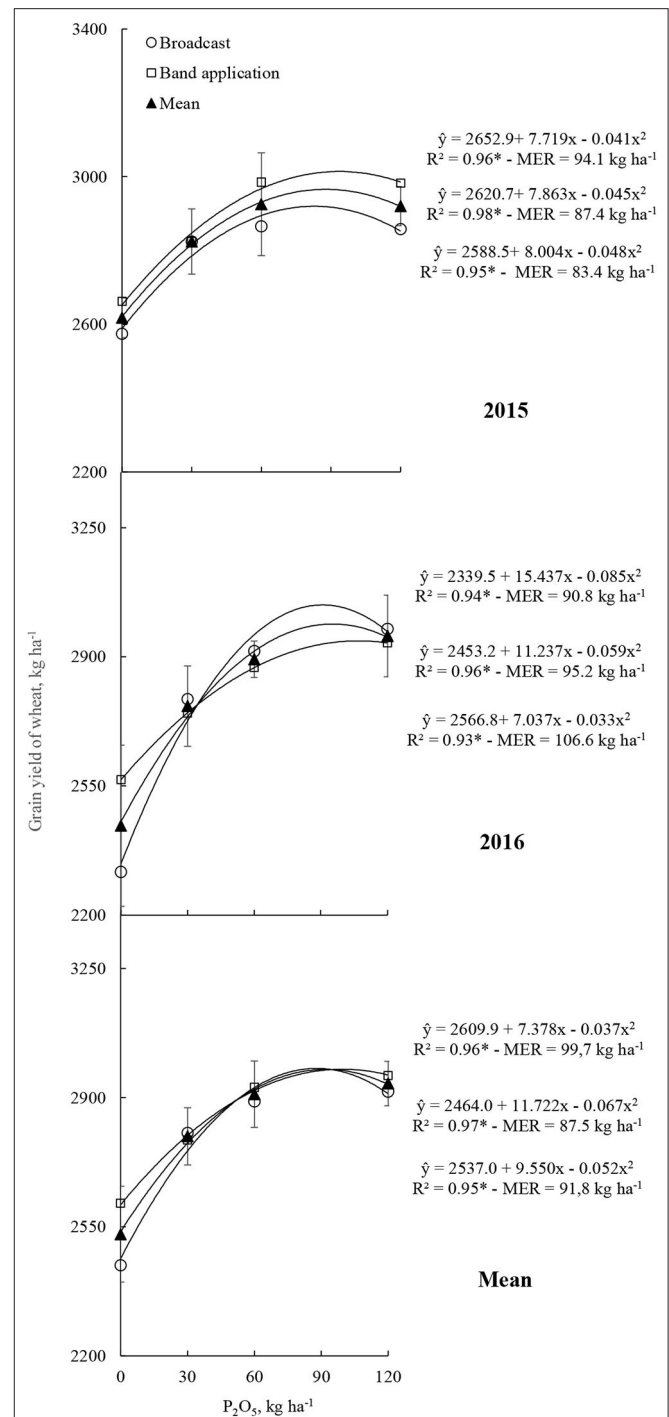


FIGURE 4 | Relationship of the residual effect of P₂O₅ rates applied through broadcast or band application in soybean crop and wheat grain yield in two growing seasons. MER, maximum estimated rate. *Significant (*F*-test, *p* ≤ 0.05). Londrina, Paraná State, Brazil.

acts directly as an energy donor in the process of photosynthesis (Malavolta et al., 1997).

Studies by Anghinoni (1992) and Sousa et al. (2002) have shown that rates higher than 100 kg ha⁻¹ of P₂O₅ can be applied

TABLE 1 | Yield components and chlorophyll level as influenced by P₂O₅ rates, under broadcast and band application, on the average of two growing seasons of a soybean–wheat cropping system, Londrina, Paraná State, Brazil.

P ₂ O ₅ rates (kg ha ⁻¹)	Soybean						Wheat					
	Chlorophyll	100 grains	Height	NPP	NGP	NGP/NPP	Chlorophyll	1000 grains	Height	Spikelet	SC	HV
	mg m ⁻²	G	Cm	n	n		mg m ⁻²	g	cm	n	n	kg
BROADCAST												
0	246.1 ± 5.5	11.2 ± 0.9	56.4 ± 13.7	41.5 ± 15.2	103.5 ± 38.3	2.5 ± 0.2	340.3 ± 28.5	29.8 ± 0.7	81.2 ± 4.8	44.5 ± 1.7	34.8 ± 3.1	78.2 ± 0.8
30	248.5 ± 11.6	12.4 ± 0.7	60.4 ± 5.3	52.1 ± 10.8	129.3 ± 25.1	2.5 ± 0.1	346.5 ± 11.4	30.0 ± 0.6	78.8 ± 2.9	46.3 ± 3.6	36.0 ± 2.7	79.0 ± 0.5
60	248.7 ± 8.1	11.8 ± 0.5	62.7 ± 6.4	54.3 ± 9.0	137.9 ± 16.8	2.5 ± 0.2	349.5 ± 17.8	32.4 ± 0.9	80.6 ± 7.7	47.8 ± 3.0	30.0 ± 2.2	78.4 ± 0.7
120	253.8 ± 9.6	12.5 ± 1.1	65.0 ± 16.4	47.9 ± 12.5	121.2 ± 34.0	2.5 ± 0.2	361.9 ± 17.7	29.6 ± 0.6	79.9 ± 3.0	48.0 ± 2.6	31.5 ± 3.3	78.1 ± 0.3
Mean	249.3	12.0	61.1	49.0	123.0	2.5	349.6	30.5	80.1	46.7	33.1	78.4
BAND APPLICATION												
0	240.9 ± 13.0	12.0 ± 0.6	52.3 ± 4.1	46.5 ± 5.1	113.7 ± 13.3	2.4 ± 0.2	341.3 ± 29.8	30.3 ± 0.4	76.7 ± 6.1	42.5 ± 3.0	29.3 ± 2.9	78.8 ± 0.7
30	246.2 ± 10.8	11.8 ± 0.2	60.8 ± 4.6	49.7 ± 3.8	117.3 ± 11.7	2.4 ± 0.2	347.1 ± 25.0	29.8 ± 1.1	80.0 ± 3.0	46.3 ± 3.6	38.0 ± 3.4	78.5 ± 1.2
60	247.7 ± 5.1	12.3 ± 0.6	61.7 ± 4.6	53.2 ± 8.0	125.7 ± 17.2	2.4 ± 0.1	358.9 ± 19.5	29.8 ± 0.4	79.7 ± 4.9	46.8 ± 3.5	30.5 ± 1.8	78.4 ± 2.3
120	248.3 ± 13.8	12.1 ± 0.8	67.5 ± 4.3	51.4 ± 9.8	122.5 ± 22.2	2.4 ± 0.2	364.1 ± 27.3	29.8 ± 0.8	78.7 ± 1.3	47.0 ± 5.4	34.0 ± 2.6	78.7 ± 5.3
Mean	245.8	12.1	60.6	50.2	119.8	2.4	352.9	29.9	78.8	45.7	33.0	78.6
MEAN												
0	243.5 ± 9.3	11.6 ± 0.8	54.4 ± 8.9	44.0 ± 10.2	110.4 ± 25.0	2.5 ± 0.2	340.8 ± 27.8	30.1 ± 0.6	79.0 ± 5.5	43.5 ± 2.4	32.1 ± 3.0	78.5 ± 0.8
30	247.4 ± 11.2	12.1 ± 0.5	60.6 ± 5.0	50.9 ± 7.3	123.3 ± 18.4	2.5 ± 0.2	346.8 ± 18.2	29.9 ± 0.9	79.4 ± 3.0	46.3 ± 3.6	37.0 ± 3.1	78.8 ± 0.9
60	248.2 ± 6.6	12.1 ± 0.6	62.2 ± 5.5	53.8 ± 8.5	131.8 ± 17.0	2.5 ± 0.2	354.2 ± 18.7	31.1 ± 0.7	80.2 ± 6.3	47.3 ± 3.3	30.3 ± 2.0	78.4 ± 1.5
120	251.1 ± 11.7	12.3 ± 1.0	66.3 ± 10.4	50.0 ± 11.2	121.8 ± 28.1	2.5 ± 0.2	363.0 ± 22.5	29.7 ± 0.7	79.3 ± 2.2	47.5 ± 3.4	32.8 ± 2.5	78.4 ± 2.8
Mean	247.6	12.0	60.9	49.6	122.6	2.5	351.2	30.2	79.5	46.2	33.1	78.5
F-TEST												
AM	ns	Ns	Ns	ns	ns	Ns	ns	ns	ns	ns	ns	ns
P ₂ O ₅ rates	*	Ns	Ns	ns	*	Ns	*	ns	ns	*	ns	ns
AM × P ₂ O ₅ rates	ns	Ns	Ns	ns	ns	Ns	ns	ns	ns	ns	ns	ns
CV (%)	3.9	6.0	12.2	18.8	18.0	8.0	6.2	2.4	5.3	6.9	8.0	1.9

*Significant (*F*-test, $p \leq 0.05$); ns, non-significant (*F*-test, $p > 0.05$); AM, application method; CV, coefficient of variation; SD, standard deviation; SC, spikelets per clump; NPP, number of pods per plant; NGP, number of grains per plant; HV, hectoliter volume.

using the broadcast method without influencing the GY. Resende et al. (2006) and Borges and Mallarino (2003) investigated P sources, P rates, and application methods in corn (*Zea mays* L.) and soybean crop and observed that fertilization by broadcast and/or band application with soluble P sources yielded similar productivity. Prado et al. (2001) point out that in soils with a low P concentration, the adsorption of this nutrient is maximized when the phosphate fertilizer is applied as a broadcast with incorporation. This application methods lead to a greater contact of the P with the solid phase of the soil and, at the same time, the P contact with the plant root system is reduced. According to Lana et al. (2003), where there is non-incorporation of fertilizer in the soil, P fertilization can reduce losses due to fixation, being provisionally adsorbed on SOM, which becomes available to plants after mineralization (Anderson, 1980) and provides greater root development in the topsoil (Barber, 1995). Another factor to be highlighted is that in NTM, characterized by greater SOM accumulation in the upper layers of the soil, the restrictive effect described by Novais and Smyth (1999) was not observed. This restrictive effect is that more weathered tropical soils with high fixation power represent a drain preferential of P, and the

broadcast application of P₂O₅ proves inadequate to meet plant demands. Although the results of the present study indicate better plant responses with broadcast application of P₂O₅, it is worth mentioning that due to the slope of the land and excessive rain (runoff effect), the band application at sowing method can reduce fertilizer losses by laminar leaching (Borges and Mallarino, 2003).

In this study, the available P levels in the soil under soybean and wheat crops showed linear increases in Mehlich 1 (P-M1) and ion exchange resin (P-RE) in relation to P₂O₅ rates (Table 2). In Brazil, these two methods are considered official; however, the interpretations must be in accordance with the corresponding calibrations made in each region of the country. The P-M1 extractant available P-values were lower than the P-RE values extracted until 5.7 times as much available P as that of P-M1, a result similar to that observed by Moreira and Malavolta (2001). In addition, both had a high correlation coefficient (soybean: y (P-RE) = 6.628 + 3.202 (P-M1), $r = 0.90$, and wheat: y (P-RE) = 1.127 + 4.264 (P-M1), $r = 0.86$, $p \leq 0.05$). These results confirm the findings of Moreira et al. (1997) and Moreira and Malavolta (2001) for these two extractants, indicating that both

TABLE 2 | Phosphorus availability in the soil with Mehlich 1 and resin extractants after a soybean-wheat cropping system due to the P₂O₅ rates and application method (AM) (broadcast and band application), Londrina, Paraná State, Brazil.

P ₂ O ₅ rates (kg ha ⁻¹)	Soybean				Wheat			
	2014–2015		2015–2016		2015		2016	
	Mehlich 1 mg kg ⁻¹	Resin mg kg ⁻¹	Mehlich 1 mg kg ⁻¹	Resin mg kg ⁻¹	Mehlich 1 mg kg ⁻¹	Resin mg kg ⁻¹	Mehlich 1 mg kg ⁻¹	Resin mg kg ⁻¹
BROADCAST								
0	4.4 ± 0.4	9.1 ± 0.7	4.2 ± 0.3	8.8 ± 0.5	4.4 ± 0.8	17.7 ± 1.8	4.1 ± 0.5	13.5 ± 1.5
30	5.1 ± 0.4	12.5 ± 1.7	4.7 ± 0.4	13.3 ± 2.3	4.5 ± 0.3	19.0 ± 0.4	4.7 ± 0.6	19.7 ± 1.0
60	6.2 ± 0.6	14.0 ± 2.2	5.8 ± 0.5	13.3 ± 1.0	5.3 ± 0.2	21.7 ± 0.7	6.2 ± 0.3	23.9 ± 1.7
120	6.9 ± 0.4	23.4 ± 2.1	6.8 ± 0.4	23.8 ± 0.8	6.7 ± 1.3	25.4 ± 3.4	7.1 ± 0.9	27.4 ± 2.5
Mean	5.7	14.8	5.4	14.8	5.2	21.0	5.5	21.1
BAND APPLICATION								
0	3.5 ± 0.3	8.4 ± 1.4	3.6 ± 0.2	8.8 ± 1.0	4.3 ± 0.3	18.0 ± 0.5	3.9 ± 0.4	15.8 ± 1.1
30	4.1 ± 0.5	11.0 ± 3.5	4.2 ± 0.4	11.3 ± 3.6	5.1 ± 0.2	20.8 ± 0.4	5.3 ± 0.5	17.6 ± 1.9
60	5.5 ± 0.9	18.9 ± 4.2	5.4 ± 0.8	18.5 ± 3.4	6.0 ± 0.3	23.9 ± 0.8	6.1 ± 0.4	21.4 ± 2.4
120	6.0 ± 1.0	19.1 ± 5.3	5.8 ± 0.9	17.8 ± 6.2	7.7 ± 1.2	28.9 ± 2.7	7.6 ± 0.7	24.7 ± 1.9
Mean	4.8	14.3	4.8	14.1	5.8	22.9	5.7	19.9
MEAN								
0	4.0 ± 0.4	8.8 ± 1.1	3.9 ± 0.3	8.8 ± 0.8	4.4 ± 0.6	17.9 ± 1.2	4.0 ± 0.5	14.7 ± 1.3
30	4.6 ± 0.5	11.8 ± 2.6	4.5 ± 0.4	12.3 ± 3.0	4.8 ± 0.3	19.9 ± 0.4	5.0 ± 0.6	18.7 ± 1.5
60	5.9 ± 0.8	16.5 ± 3.2	5.6 ± 0.7	15.9 ± 2.2	5.7 ± 0.3	22.8 ± 0.8	6.2 ± 0.4	22.7 ± 2.1
120	6.5 ± 0.7	21.2 ± 3.7	6.3 ± 0.7	20.8 ± 3.5	7.2 ± 1.3	27.2 ± 3.1	7.4 ± 0.8	26.1 ± 2.2
Mean	5.3	14.6	5.1	14.5	5.5	23.0	5.7	21.0
F-TEST								
AM	*	ns	ns	Ns	ns	ns	ns	Ns
Rates (R)	*	*	*	*	*	*	*	*
AM × R	ns	ns	ns	Ns	ns	ns	ns	Ns
CV%	13.9	19.5	12.8	17.9	13.9	6.5	12.2	8.9

*Significant (F-test, $p \leq 0.05$); ns, non-significant (F-test, $p > 0.05$); AM, application method; Rates, P₂O₅ rates; CV, coefficient of variation; SD, standard deviation.

TABLE 3 | Leaf N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentrations as influenced by P₂O₅ rates, with two application methods (AM) (broadcast or band application), on the average of two growing seasons of soybean crops, Londrina, Paraná State, Brazil.

P ₂ O ₅ rates (kg ha ⁻¹)	N g kg ⁻¹	P g kg ⁻¹	K g kg ⁻¹	Ca g kg ⁻¹	Mg g kg ⁻¹	S g kg ⁻¹	B Mg kg ⁻¹	Cu Mg kg ⁻¹	Fe mg kg ⁻¹	Mn Mg kg ⁻¹	Zn mg kg ⁻¹
BROADCAST											
0	36.4 ± 3.8	2.6 ± 0.3	20.8 ± 2.7	8.5 ± 0.4	2.8 ± 0.2	1.7 ± 0.3	54.4 ± 5.7	8.2 ± 0.7	103.8 ± 14.2	133.5 ± 23.2	56.3 ± 7.3
30	37.1 ± 2.0	2.8 ± 0.3	21.2 ± 2.1	8.2 ± 0.3	2.8 ± 0.2	1.8 ± 0.2	48.7 ± 7.5	8.1 ± 0.8	118.4 ± 25.8	126.3 ± 16.8	49.2 ± 2.8
60	35.8 ± 1.8	3.0 ± 0.3	20.7 ± 1.0	8.0 ± 0.4	2.8 ± 0.2	1.9 ± 0.2	42.5 ± 6.8	7.9 ± 0.6	124.1 ± 37.9	132.8 ± 22.4	52.3 ± 4.4
120	34.3 ± 4.6	3.7 ± 0.4	21.3 ± 3.0	8.2 ± 0.2	2.7 ± 0.1	1.8 ± 0.1	45.9 ± 11.0	8.1 ± 0.9	128.8 ± 43.4	128.4 ± 27.3	49.0 ± 3.1
Mean	35.9	3.0	21.0	8.2	2.8	1.8	47.9	8.1	118.8	130.3	51.7
T8BAND APPLICATION											
0	34.7 ± 2.8	2.9 ± 0.1	21.2 ± 2.2	7.7 ± 0.5	2.8 ± 0.2	1.9 ± 0.2	44.5 ± 4.9	8.1 ± 0.1	109.8 ± 12.4	121.0 ± 8.8	50.4 ± 3.3
30	35.0 ± 2.9	3.1 ± 0.2	21.3 ± 2.4	8.1 ± 0.5	2.9 ± 0.3	1.9 ± 0.2	59.9 ± 9.8	7.7 ± 0.3	98.0 ± 19.0	124.7 ± 9.8	51.5 ± 1.9
60	35.8 ± 2.8	3.2 ± 0.4	21.8 ± 1.4	7.9 ± 0.4	2.9 ± 0.2	2.0 ± ± 0.2	53.4 ± 7.2	7.7 ± 0.6	104.3 ± 9.4	124.1 ± 12.3	49.3 ± 1.8
120	37.4 ± 2.8	3.4 ± 0.3	21.8 ± 2.4	8.2 ± 0.6	3.0 ± 0.3	2.5 ± 0.2	49.6 ± 5.0	8.3 ± 0.4	127.8 ± 42.3	128.2 ± 8.7	54.4 ± 5.4
Mean	35.7	3.2	21.5	8.0	2.9	2.1	51.9	8.0	110.0	124.5	51.4
MEAN											
0	35.5 ± 3.3	2.7 ± 0.2	21.0 ± 2.5	8.1 ± 0.5	2.8 ± 0.2	1.8 ± 0.3	49.5 ± 5.3	8.1 ± 0.4	106.8 ± 13.3	127.3 ± 16.0	53.4 ± 5.3
30	36.1 ± 2.5	3.0 ± 0.3	21.2 ± 2.3	8.1 ± 0.4	2.9 ± 0.3	1.8 ± 0.2	54.3 ± 8.7	7.9 ± 0.6	108.2 ± 22.4	125.5 ± 13.3	50.3 ± 2.4
60	35.8 ± 2.3	3.1 ± 0.4	21.3 ± 1.2	8.0 ± 0.4	2.8 ± 0.2	1.9 ± 0.2	47.9 ± 7.0	7.8 ± 0.6	114.2 ± 23.7	128.4 ± 17.4	50.8 ± 3.1
120	35.8 ± 3.4	3.5 ± 0.4	21.6 ± 2.7	8.2 ± 0.4	2.8 ± 0.2	2.1 ± 0.2	47.8 ± 8.0	8.2 ± 0.7	128.3 ± 42.9	128.3 ± 18.0	51.7 ± 3.7
Mean	35.8	3.1	21.3	8.1	2.8	1.9	50.0	8.2	114.4	127.4	51.6
F-TEST											
AM	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
P ₂ O ₅ rates	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
AM × P ₂ O ₅ rates	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	7.9	12.5	9.3	5.4	7.4	14.9	17.0	7.0	23.5	12.0	8.5

*Significant (*F*-test, $p \leq 0.05$); ns, non-significant (*F*-test, $p > 0.05$); AM, application method; CV, coefficient of variation; SD, standard deviation.

TABLE 4 | Leaf N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentrations as influenced by the P₂O₅ rates, with two application methods (AM) (broadcast or band application), on the average of two growing seasons of wheat crops, Londrina, Paraná State, Brazil.

P ₂ O ₅ rates (kg ha ⁻¹)	N g kg ⁻¹	P g kg ⁻¹	K g kg ⁻¹	Ca g kg ⁻¹	Mg g kg ⁻¹	S g kg ⁻¹	B mg kg ⁻¹	Cu mg kg ⁻¹	Fe mg kg ⁻¹	Mn mg kg ⁻¹	Zn mg kg ⁻¹
BROADCAST											
T2 0	29.7 ± 6.4	1.9 ± 0.2	23.5 ± 2.7	3.5 ± 1.2	2.1 ± 0.4	3.5 ± 0.4	25.6 ± 2.1	8.7 ± 1.1	119.6 ± 23.3	142.0 ± 35.4	35.5 ± 3.7
30	30.9 ± 6.3	2.3 ± 0.2	23.5 ± 1.1	5.1 ± 1.2	2.0 ± 0.2	3.6 ± 0.4	37.6 ± 2.7	8.2 ± 0.8	125.8 ± 47.5	151.8 ± 23.8	34.4 ± 2.1
60	29.9 ± 8.3	2.4 ± 0.1	22.5 ± 1.5	5.9 ± 0.7	1.8 ± 0.2	3.8 ± 0.3	27.3 ± 3.2	8.0 ± 0.9	123.1 ± 18.5	165.3 ± 22.6	31.8 ± 4.8
120	31.1 ± 5.8	2.7 ± 0.1	23.9 ± 1.5	4.4 ± 1.1	2.1 ± 0.3	3.9 ± 0.1	35.8 ± 2.8	8.0 ± 1.2	136.3 ± 27.5	176.2 ± 29.2	31.4 ± 1.3
Mean	30.4	2.3	23.4	4.7	2.0	3.7	31.6	8.2	126.2	158.8	33.3
BAND APPLICATION											
0	31.2 ± 2.2	2.1 ± 0.1	21.4 ± 1.6	7.4 ± 2.5	2.1 ± 0.3	3.6 ± 0.2	33.8 ± 2.5	8.8 ± 0.5	147.2 ± 49.7	171.6 ± 18.0	33.4 ± 4.1
30	30.3 ± 5.5	2.4 ± 0.1	18.8 ± 2.2	6.1 ± 0.9	2.0 ± 0.3	4.0 ± 0.5	37.5 ± 1.9	8.1 ± 0.8	137.3 ± 40.4	161.4 ± 13.0	32.9 ± 3.1
60	30.6 ± 6.6	2.5 ± 0.1	21.6 ± 2.2	5.6 ± 2.6	2.1 ± 0.2	3.6 ± 0.4	28.5 ± 2.4	8.7 ± 0.7	165.9 ± 41.6	157.7 ± 12.1	32.7 ± 1.4
120	24.1 ± 3.4	2.7 ± 0.1	20.6 ± 4.3	4.9 ± 1.4	2.0 ± 0.2	4.0 ± 0.1	38.3 ± 2.2	8.6 ± 0.6	161.3 ± 43.6	174.6 ± 20.8	32.6 ± 3.7
Mean	29.1	2.4	20.6	6.0	2.1	3.8	34.5	8.6	152.9	166.3	32.9
MEAN											
0	30.5 ± 4.3	2.0 ± 0.2	22.5 ± 2.2	5.5 ± 1.9	2.1 ± 0.4	3.5 ± 0.3	29.7 ± 2.3	8.7 ± 0.8	133.4 ± 36.5	156.8 ± 26.7	34.5 ± 3.9
30	30.6 ± 5.9	2.3 ± 0.2	21.1 ± 1.7	5.6 ± 1.1	2.0 ± 0.3	3.8 ± 0.5	37.6 ± 2.3	8.1 ± 0.8	131.6 ± 44.0	156.6 ± 18.4	33.7 ± 2.6
60	30.3 ± 7.5	2.5 ± 0.1	22.0 ± 1.9	5.7 ± 1.7	1.9 ± 0.2	3.7 ± 0.3	27.9 ± 2.8	8.3 ± 0.8	144.5 ± 30.1	161.5 ± 17.4	33.3 ± 3.1
120	27.6 ± 4.6	2.7 ± 0.1	22.2 ± 2.9	4.7 ± 1.3	2.1 ± 0.3	3.9 ± 0.1	37.0 ± 2.5	8.3 ± 0.9	148.8 ± 35.6	175.4 ± 25.0	32.0 ± 2.5
Mean	30.0	2.4	22.0	5.4	2.1	3.8	33.1	8.4	139.6	162.6	33.1
F-TEST											
AM	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
P ₂ O ₅ rates	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
AM × P ₂ O ₅ rates	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	18.6	8.3	9.9	27.8	14.3	7.9	7.5	10.7	26.2	13.4	9.1

*Significant (F-test, $p < 0.05$); ns, non-significant (F-test, $p > 0.05$); AM, application method; CV, coefficient of variation; SD, standard deviation.

are efficient ways of quantifying P availability in the soil. The P available with the Resin method increased from the first to second crop in wheat (Table 2), possibly due to the positive effect of the applied gypsum recovering the P in depth, and the greater sensitivity of extractant in quantifying the availability of nutrient in the soil.

There was a significant relationship between application methods and soybean leaf P, Ca, and S concentrations. Band application at a rate of 120 kg ha⁻¹ of P₂O₅ resulted in a higher foliar P concentration than for the other rate treatments. However, it did not differ significantly from the broadcast application at the same rate (Table 3). The both methods types, the P-M1 and P-RE were well correlated with foliar P concentration for both species ($r = 0.65^*$ and $r = 0.56^*$, for soybean; $r = 0.58^*$ and $r = 0.56^*$, for wheat, respectively, $p \leq 0.05$), that is, the relationship between P-M1 and foliar P concentration was better than that of P-RE and foliar P concentration. Similar results were obtained by Antonangelo et al. (2019) with P rates in the same edaphoclimatic conditions. For K, there was no statistical difference; however, it was observed that P₂O₅ application using the band application method at a rate of 120 kg ha⁻¹ resulted in a 7.0% higher K concentration in soybean leaves in comparison with application using the broadcast method. Probably, there must have been an increase in root volume in depth with the P application in the band application with a consequent increase in the K concentration in the plant. The foliar Ca concentration showed a linear effect ($y = 8.120 + 0.004x$, $R^2 = 0.68$, $p \leq 0.05$) only in the application to the broadcast, possibly due to the P source used that contained 12–14% Ca (Ribeiro et al., 1999). For leaf Mg, B, Cu, Fe, Mn, and Zn concentrations, there were no significant differences between treatments (Table 3). Rosa et al. (2015), in studies on P₂O₅ rates and application methods in soybean crop, observed that the broadcast approach was more effective at increasing the P, K, Ca, S, Mn, and Zn concentrations in the leaves than the band application method. Despite this variability, the foliar nutrient levels found in this study are within the ranges considered by Urano et al. (2006) as adequate in soybean crop. In this study, the negative P × Zn interaction was not observed in the uptake of these nutrients by plants as described by Malavolta et al. (1997) and verified by Moreira et al. (2006) in alfalfa (*Medicago sativa* L.) crop. Regarding the foliar nutrient concentrations of the wheat crop (Table 4), the only significant effect was of residual P₂O₅ rates on the P concentration ($y = 2.080 + 0.006x$, $R^2 = 0.77$, $p \leq 0.05$). The leaf N, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentrations in wheat were not influenced by growing season and treatments, and were close to the concentrations according

with Malavolta et al. (1997) and obtained by Moreira et al. (2019a) in a study on the soybean-wheat intercropping system with Cu rates cultivated under the same soil and climate conditions.

CONCLUSIONS

Fertilization with a soluble phosphate source (triple superphosphate) in a soybean-wheat cropping system under NTM and subtropical conditions increased the productivity of soybeans and wheat over two growing seasons, regardless of the application method used (broadcast or band application). Given the similarity in soybean and wheat yield responses observed in this study, it is advised that the cost-benefit ratio for selecting the best method of P₂O₅ application should largely be determined by the difference in application costs and the relief of the area to be cultivated. The MER obtained for the mean of the two application methods are beyond the official recommendation for yield 3.0–4.0 Mg ha⁻¹. The soybean and wheat foliar P concentrations and the soil available P at a 0–0.1 m depth (determined using P-M1 and P-RE) were, for the most part, influenced by the P₂O₅ rates and not by the P application methods. Available P in the soil extracted by P-M1 and P-RE was highly correlated, with P-RE extracting until 5.7 times as much available P as P-M1.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because no requests to access the datasets should be directed to Adônis Moreira, adonis.moreira@embrapa.br.

AUTHOR CONTRIBUTIONS

AM: conducting the experiment, data tabulation, statistical analysis, and text writing. LM: conducting the experiment, and text writing. RP: conducting the experiment, and data tabulation. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

To the staff of Soil Fertility and Microbiology of Embrapa Soja for conducting the field experiments, the Santa Rita Laboratory for soil and plant analysis, and to the National Council of Technological and Scientific Development (CNPq) for providing scholarships to the first author.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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