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Corn fertilization with triple superphosphate in a Typic Hapludox soil under the residual effect of alternative phosphorus sources

Adubação do milho com superfosfato triplo em Latossolo Vermelho sob efeito residual de fontes alternativas de fósforo

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ABSTRACT

In variable-charge soils, the use of alternative phosphorus sources may influence further soluble phosphate fertilization. This study aimed to evaluate phosphorus (P) availability for corn plants in response to triple superphosphate fertilization (TSP) in a Typic Hapludox (Oxisol) soil with residual P from alternative sources. The experiment was carried out in a greenhouse under a completely randomized design and 2x4x5 factorial scheme, with four replications. Treatments consisted of five TSP doses (0, 30, 60, 90, and 120 mg dm^{-3} P), and two sequential corn croppings with and without liming; the area was previously grown with *Urochloa* spp. and fertilized with precipitated phosphate-1 (PP1), precipitated phosphate-2 (PP2), natural reactive phosphate (NRP), and TSP at 120 mg dm^{-3}. The P from TSP has its dynamics within the soil-plant system and fertilization efficiency in corn crops altered by the residual effect of P from alternative sources and by soil acidity correctives. The residual effects of PP2 and NRP, dry matter yield and P accumulation in corn were higher for TSP doses above 30 mg dm^{-3}, being greater in the first cropping and in limed soils. Yet for PP2 and NRP residual effects, the highest soil availability of P was registered after the two sequential cropping in both acidity conditions, thus showing an enhanced residual effect.

KEYWORDS: available phosphorus, phosphate residue, soil acidity.

RESUMO

O uso de fontes alternativas na adubação fosfatada em solos de carga variável pode influenciar a adubação com fosfato solúvel. O objetivo do trabalho foi avaliar a eficiência na disponibilidade de fósforo (P) para a cultura do milho em resposta a adubação com superfosfato triplo (TSP) em Latossolo Vermelho sob efeito residual de fontes alternativas de P. O experimento foi conduzido em casa de vegetação em delineamento inteiramente casualizado no esquema fatorial 2x4x5, com quatro repetições. Os tratamentos consistiram de cinco doses de TSP (0, 30, 60, 90 e 120 mg dm^{-3} de P) com dois cultivos sequenciais de milho com calagem e sem calagem, em solo anteriormente adubado com Fosfato precipitado-1 (PP1), Fosfato precipitado-2 (PP2), Fosfato natural reativo (NRP) e TSP na dose de 120 mg dm^{-3} de P e cultivado com *Urochloa*. A dinâmica e a eficiência do fósforo (P) no sistema solo-planta proveniente superfosfato triplo (TSP) na adubação da cultura do milho é alterado pelo efeito residual de fontes alternativas e pelo uso de corretivos no solo. Sob o efeito residual de PP2 e NRP houve maior produção de matéria seca e acúmulo de P nas plantas de milho em doses a partir de 30 mg dm^{-3} de P na forma de TSP, sendo os maiores incrementos no primeiro cultivo e nas condições do solo com calagem. Nos tratamentos sob o efeito residual de PP2 e NRP houveram os maiores teores de P disponível no solo após dois cultivos sequenciais de milho em ambas as condições de manejo da acidez do solo, demonstrando um maior efeito residual.

PALAVRAS-CHAVE: fósforo disponível, resíduo fosfatado, acidez do solo.

INTRODUCTION

Overall, Brazilian soils are naturally variable-charge and phosphorus deficient (BOLAN et al. 2013, BORTOLON et al. 2016). This mineral deficiency is attributed to a high adsorption capacity of soil mineral phase. In addition, P availability for plants grown in acidic and low-activity clay soils depends largely on the degree at which phosphate ions form a complex soluble or are strongly adsorbed by mineral surfaces (SHUAI & ZINATI 2009, CHIEN et al. 2011).

In these soils, adsorption and precipitation reactions control the destination of P from fertilizers (FERNANDES et al. 2015, MONTALVO et al. 2015), mostly adsorption in soil rich in oxides, hydroxides, or iron and aluminum oxyhydroxides (SHUAI & ZINATI 2009, FINK et al. 2016).

Nearly 50% of phosphate fertilizer applied in Brazil are imported (BRASIL 2015), making this country dependent on such input for agriculture. P sources with lower solubility are a great fertilization alternative, and their efficiency may be equal to soluble phosphates in the medium and long-term (RESENDE et al. 2006). These sources are regularly surface-applied in pastures (OLIVEIRA et al. 2014), mainly for *Brachiaria* genus grazing areas (MERLIN et al. 2014).

Unpredictably, this management system can be interrupted due to agribusiness reasons, when prices force farmers to exchange for more profitable crops, such as corn. Besides that, little is known about the use of wastewater from low-reactivity phosphate rocks, and its effects on P availability. In addition, there is lack of information on the dynamics of this nutrient within the soil-plant system for soils further fertilized with soluble phosphate.

Based on the above-mentioned, this study has a hypothesis that the use of alternative sources for tropical forage fertilizations may alter P availability and responses to further corn-crop fertilization with soluble phosphates. The evaluation of P availability under these conditions allows a better understanding of its dynamics within the soil-plant system, besides contributing to an efficient use and management of these sources in agriculture.

Therefore, the objective of this research was to assess P availability and fertilization efficiency for corn plants in response to triple superphosphate fertilization, in a Typic Hapludox (Oxisol) soil with and without liming, under the residual effect of alternative P sources.

MATERIAL AND METHODS

The experiment was conducted in a greenhouse under controlled conditions. The facility is located in the city of Botucatu, SP, Brazil. The evaluated soil was a medium-textured Typic Hapludox (Latossolo Vermelho Distroférrico) (CARVALHO et al. 1983) from a no-tillage native land, fertilizer- and corrective-free. The material was collected within a 0.0-0.2 m depth layer. After collection, these samples were sieved through a 4-mm screen to remove roots, leaves, and clods. Then, polyethylene pots (3.6 L) were filled with 3.2 dm^3 dry soil.

Firstly, *Urochloa brizantha* cv. Marandú (*Urochloa*) was grown using different phosphorus sources: precipitated phosphate-1 (PP1), precipitated phosphate-2 (PP2), natural reactive phosphate (NRP), and triple superphosphate (TSP) - all at a P dose of 120 mg dm^{-3}. Table 1 shows the chemical and physical characteristics of all fertilizers, determined by the official method of the Brazilian Ministry of Agriculture (BRASIL 1983).

Table 1. Chemical and physical characteristics of the phosphorus sources used in fertilization of *Urochloa brizanta* cv. Marandu experiment.

Fertilizer	P_2O_5				Ca^{+2}	Mg^{+2}	K^+	$S\text{-}SO_4^=$	Sieve[1]	
	Total	(AC)	($CNA+H_2O$)	(H_2O)					4mm	1 mm
	-- % ---									
PP1	9.1	2.62	3.53	0	24.8	0.2	0	3.6	100	99
PP2	14.4	5.97	11.68	0	15.0	0.3	0	2.5	88	58
NRP	29.4	6.87	5.77	0	32.6	0.3	0	2.4	100	99
TSP	48	17.04	45.07	37.34	13.1	0.3	0	4.4	75	6.4

PP1: Precipitated phosphate-1; PP2: Precipitated phosphate-2; NRP: Natural reactive phosphate; TSP: Triple superphosphate; CAS: citric acid soluble P_2O_5; NAC + H_2O: P_2O_5 soluble in neutral ammonium citrate + water; H_2O: P_2O_5 - soluble in water; Ca^{+2}: total calcium; Mg^{+2}: total magnesium; K^+: total potassium; $S\text{-}SO_4^-$: total sulfur in sulfate form. (1) Percentage of passing sample through 4 and 1 mm sieves.

Urochloa was grown in soil under two different acidity conditions, one limed to 70% base saturation (V), and another with no liming, i.e. under natural soil conditions (V = 6%).

The experimental design was completely randomized in a 2x4x5 factorial scheme, with four replications. Under this experiment conditions, we evaluated soils under the residual effect or not of liming, and under the residual effect of four P sources (PP1, PP2, NRP, and TSP). After that, five doses of soluble phosphate in triple superphosphate form (TSP) were applied to the soil at five rates (0, 30, 60, 90 and 120 mg dm^{-3} of P), only in the first cropping.

Table 2 discloses the chemical properties of the evaluated soil as described by RAIJ et al. (2001). Sand, silt, and clay contents are 669, 274, and 57 g kg^{-1}, respectively, according to EMBRAPA (1997).

Table 2. Initial attributes in a Typic Hapludox 0.0 to 0.2 m layer used in *Urochloa brizanta* cv. Marandu experiment, and after *Urochloa* experiment with fertilization and alternative phosphorus sources.

Treatment	pH	V	Al^{+3}	H+Al	Ca^{+2}	Mg^{+2}	K^{+}	CTC	P_{resin} (1)	SOM	SD
	$CaCl_2$	%		---------- mmolc dm-3 ---------					mg dm^{-3}	g dm^{-3}	g cm^{-3}
Initial	4.0	6	19	67	3	1	0.3	71	4.0	30	1.2
Chemical attributes of soil after *Urochloa* experiment in limed soil											
PP1	5.2	59	0	29	32	10	0.9	72	84	19	----
PP2	5.6	61	0	22	26	8	0.9	57	84	20	----
NRP	5.3	58	0	30	27	14	1.0	72	45	16	----
TSP	5.0	52	0	35	27	11	0.8	74	34	18	----
Chemical attributes of soil after *Urochloa* experiment in non-limed soil											
PP1	4.0	20	17	88	12	10	0.7	111	45	16	----
PP2	4.4	28	12	72	24	4	0.8	101	44	17	----
NRP	4.1	16	16	82	15	1	0.7	99	32	15	----
TSP	3.9	12	21	100	10	3	0.6	114	33	16	----

CEC = Calculated cation exchange capacity; SOM = Soil Organic Matter; SD = Soil Density; V: Saturation by Bases; Al^{+3}: exchangeable aluminum; Ca^{+2}: exchangeable calcium; Mg^{+2}: exchangeable magnesium; P: extractable phosphorus resin method; K^{+}: extractable potassium. PP1 = Precipitated phosphate-1; PP2 = Precipitated phosphate-2; NRP = Natural reactive phosphate; TSP = Triple superphosphate.

TSP doses were incorporated into the soil in granule formulation. Except for P, the other nutrients were provided at an optimal level to avoid deficiencies of other nutrients. And so, plants received 30 mg dm^{-3} nitrogen (N) via ammonium sulfate, 40 mg dm^{-3} K via KCl, and doses of 0.3, 0.75, 5.0, 7.5 mg dm^{-3} of Cu, Zn, B, and Mn via copper chloride, zinc chloride, boric acid, and manganese chloride, respectively. Micronutrients were surface-applied using a solution 10 days after plant germination. After 15 days of emergence, 60 mg N pot^{-1} was surface-applied as topdressing via liquid urea.

Two corn crops (*Zea* spp.) were sequentially grown for 40 days each, being the first during spring-summer and the second in summer. Three corn plants were sown per pot, being kept under intermittent irrigation to maintain soil moisture near 70% field capacity. The same doses of N, K, and micronutrients were employed in both cropping cycles, being applied via liquid solution 10 days after emergence.

The corn cultivar adopted was 2B587 PW, from Dow AgroSciences, which is an early cycle hybrid. Seeds were previously treated with fungicide (Vitavax Thiram 200 SC; carboxin + thiram) at a dose of 300 mL per 100 kg seeds, and with insecticide (Cruiser 700 WS; thiamethoxam) at 150 g per 100 kg seeds. Dose calculations were based on 1 kg seeds.

For both cycles, corn shoot dry biomass was measured by cutting plants at soil level. The harvested material was dried in a forced air circulation oven at 65 °C for 72 hours, or until reaching a constant weight. Afterwards, sampled were weighed on a digital scale with 2-digit precision. Then, the material was ground in a Wiley mill to a particle size of less than 1 mm, for P total content determinations, as described by MALAVOLTA et al. (1997). The accumulated P amount (mg pot^{-1}) was estimated by multiplying its content in plant shoot (g kg^{-1}) by total dry matter (g pot^{-1}).

After plants were harvested, potting soil was collected, homogenized, and sieved through a 2-mm mesh sieve. Next, the soil was dried in a forced air circulation oven at 40 ˚C for 48 hours, and stored in hermetically sealed containers until analysis. Lastly, P availability was analyzed by the resin method, as described by RAIJ et al. (2001).

The data was submitted to normality and variance homogeneity analyses, transforming when necessary. After parametric assumptions were covered, variance analysis using F test was carried out, considering a completely randomized design in a triple factorial scheme, with treatment effect evaluation and mean comparison performed by Tukey's test ($p \leq 0.05$). In addition, a regression analysis was conducted to investigate the effects of TSP doses.

RESULTS AND DISCUSSION

If compared to non-limed soils, P supply by TSP in limed soils increased shoot dry matter (DM) in both crop cycles (Table 3). Moreover, plant growth was limited in non-limed soil conditions (Table 1). In this

Oxisol, the zero-charge point is 4.4 and, when non-limed, positive charges predominate over negative charges, arising P adsorption to mineral surfaces and decreasing P available for plants.

Table 3. Corn shoot dry biomass (g/pot) in response to increasing doses of triple superphosphate fertilization (TSP) applied to a Typic Hapludox under residual effect of alternative P sources with and without liming.

Fertilizer	P dose (mg dm^{-3})					Regression equation
	0	30	60	90	120	
	....g pot^{-1}					
	Crop 1					
	Limed soil					
PP1	24.1 Cc	25.3 Bbc	26.8 Bab	26.6 Bab	27.3 a	$\hat{y} = 24.4 + 0.03x$ $R^2 = 0.65$
PP2	30.0 A	28.2 A	29.5 A	29.1 A	28.4	$\hat{y} = 29.0$
NRP	27.3 B	28.0 A	28.8 A	27.9 AB	28.0	$\hat{y} = 28.0$
TSP	21.7 Db	25.0 Ba	26.1 Ba	27.6 Aba	26.6 a	$\hat{y} = 21.7 + 0.1x - 0.0007x^2$ $R^2 = 0.82$
	Non-limed soil					
PP1	10.1	10.2	10.8	11.2 B	12.0 B	$\hat{y} = 9.9 + 0.02x$ $R^2 = 0.60$
PP2	10.6	11.9	12.1	14.2 A	14.1 A	$\hat{y} = 10.7 + 0.03x$ $R^2 = 0.66$
NRP	10.1	10.8	12.0	11.9 B	12.4 B	$\hat{y} = 10.3 + 0.02x$ $R^2 = 0.77$
TSP	10.0	10.2	11.3	10.7 B	10.9 B	$\hat{y} = 9.8 + 0.03x - 0.0002x^2$ $R^2 = 0.52$
	Crop 2					
	Limed soil					
PP1	9.5	10.1	10.3	11.5	10.8	$\hat{y} = 10.4$
PP2	10.5	11.1	11.2	11.4	11.4	$\hat{y} = 11.1$
NRP	11.6	11.7	12.4	11.3	11.5	$\hat{y} = 11.7$
TSP	6.9 b	11.9 a	10.7 a	11.0 a	11.1 a	$\hat{y} = 10.3$
	Non-limed soil					
PP1	1.9 b	1.9 Bb	3.2 ab	3.2 ab	4.6 ABa	$\hat{y} = 1.6 + 0.02x$ $R^2 = 0.59$
PP2	2.7 b	4.5 Aab	4.5 ab	5.5 ab	6.5 Aa	$\hat{y} = 3.0 + 0.03x$ $R^2 = 0.70$
NRP	2.1	2.3 B	3.9	3.8	4.2 AB	$\hat{y} = 2.1 + 0.02x$ $R^2 = 0.63$
TSP	1.2	1.7 B	2.0	3.0	2.6 B	$\hat{y} = 1.3 + 0.01x$ $R^2 = 0.52$

Means followed by different letters (lowercase horizontally and uppercase in vertically) stand for differences between treatments, within each management practice by Tukey's test ($p \leq 0.05$). The significance level of regression equations was ** $p \leq 0.01$.

Variable-charge or pH-dependent soils have a varied colloid electric potential, where positive or negative charges may predominate as per soil management (SALAZAR-CAMACHO & VILLALOBOS 2010). Such dynamics have influence on P availability to crops (SHUAI & ZINATTI 2009, BOLAN et al. 2013). Unless soil acidity is corrected, natural or alternative phosphates with increased slow solubility, or at most acidic pH, would have a poor performance. Non-limed soil conditions might somehow favor solubility of alternative sources; however, the most electropositive potential in this soil will strongly retain P by site-specific adsorption.

The plants grown in limed soil under PP2 and NRP residual effect reached the highest DM production (Table 3); yet, these results had no significant difference when compared with those achieved by increasing TSP doses. Both PP1 and TSP sources reached an increasing linear and quadratic effect as TSP doses were raised.

RESENDE et al. (2006) evaluated the application of P sources with variable solubility on a clayey Ultisol (*Argissolo Vermelho Distrófico típico*) with low P availability; they observed similar increases in three different corn cycles when using an NRP source. These authors inferred that, in the mid-term, intermediate solubility sources such as NRP could provide the same benefits to corn grain yield, as do soluble sources, thus the choice will remain a matter of ton price and of its application mode.

Notably, PP2 and NRP increased P content availability expressively, reducing plant responses to TSP fertilization (Table 2). FONTOURA et al. (2010) emphasized that soils with elevated P levels require no phosphate fertilization for yield increments, which is corroborated in our study by DM results of PP2 and NRP sources. Studying a Oxisol (*Latossolo Bruno*) high P availability, the foregoing authors observed no significant effect of two NRPs and TSP on crop productivity. In this study, the DM increases achieved using

PP1 and TSP sources were significantly lower than were those with PP2 and NRP, even in soils with high P content (Table 2).

Crops grown in limed-soils under residual effect of PP1 and TSP had the lowest DM during the first cycle (Table 3). The increasing doses of TSP (60, 90 and 120 mg dm^{-3}) in soil under PP1 residual effect showed an increasing linear behavior with the highest DM yields; and in soil under TSP residual effect, it had a quadratic behavior from P doses of 30 mg dm^{-3}. Since TSP is a soluble source (Table 1), it could have increased P levels in the soil during *Urochloa* cropping, which might had favored this element exportation via forage harvest, thus decreasing its availability and residual effect during the corn cropping. A similar effect was observed for PP1 residual, enlightening the linear DM increases with TSP doses.

In the first cropping, shoot DM differences were detected for corn grown in non-limed soil under PP2 residual, only at TSP doses of 90 and 120 mg P dm^{-3} (Table 3). Inversely, all P doses via TSP showed increasing linear effects for treatments under PP1, PP2, and NRP residual effects, and quadratic for that under TSP residual. On the other hand, DM production during the second cropping was lower if compared to the first in both limed and non-limed soils (Table 3). Limed soil conditions increased corn DM when under TSP residual, at which all P doses differed from dose zero (0 mg dm^{-3}).

Also in the second cropping, a linear effect of P doses on DM production was observed in corn grown in non-limed soils under PP1, PP2, NRP, and TSP residual effects (Table 3). Remarkably, differences among TSP doses were solely noted in treatments under PP1 residual effect, and the highest DM values were reached in soil under PP1 residual at 60, 90, and 120 mg dm^{-3} doses and under PP2 residual, where all doses differed from dose zero (0 mg dm^{-3}). The highest DM production was provided by corn plants grown in soil under PP2 residual at TSP dose of 30 mg P $dm^{-3.}$

Table 4. Phosphorus content (g kg^{-1}) in corn plants as a response to increasing P doses via triple superphosphate fertilization (TSP) in limed and non-limed Typic Hapludox soil under residual effect of alternative P sources.

Fertilizer	P dose (mg dm^{-3})					Regression equation
	0	30	60	90	120	
	......................................g kg^{-1}					
	Crop 1					
	Limed soil					
PP1	1.2	1.1	1.1	1.3	1.3	$\hat{y} = 1.2$
PP2	1.3	1.4	1.4	1.5	1.6	$\hat{y} = 1.4$
NRP	1.3	1.4	1.5	1.6	1.6	$\hat{y} = 1.5$
TSP	1.3	1.2	1.1	1.2	1.4	$\hat{y} = 1.3 - 0.006x + 5.3\ 10^{-5}\ x^2 \quad R^2 = 0.61$
	Non-limed soil					
PP1	1.1 c	1.3 c	2.1 Ab	2.0 b	2.6 Aa	$\hat{y} = 1.1 + 0.01x\ R^2 = 0.87$
PP2	1.2 c	1.4 bc	1.6 Bab	1.8 ab	1.8 Ba	$\hat{y} = 1.3 + 0.005x\ R^2 = 0.75$
NRP	1.2 c	1.4 bc	1.6 Bb	2.0 a	1.9 Ba	$\hat{y} = 1.2 + 0.007x\ R^2 = 0.79$
TSP	1.3 c	1.3 c	1.6 Bb	2.1 a	2.1 Ba	$\hat{y} = 1.2 + 0.008x\ R^2 = 0.80$
	Crop 2					
	Limed soil					
PP1	0.9	0.9	1.0	0.9	1.0	$\hat{y} = 0.9$
PP2	1.0	1.0	1.1	1.1	1.2	$\hat{y} = 1.1$
NRP	1.1	1.1	1.1	1.2	1.2	$\hat{y} = 1.1$
TSP	1.0	0.9	0.9	1.0	0.9	$\hat{y} = 0.9$
	Non-limed soil					
PP1	1.3	1.1	1.2	1.1	1.1	$\hat{y} = 1.2$
PP2	1.2	1.1	1.1	1.1	1.1	$\hat{y} = 1.1$
NRP	1.2	1.2	1.2	1.2	1.2	$\hat{y} = 1.2$
TSP	0.9	1.0	1.2	1.2	1.1	$\hat{y} = 1.1$

Means followed by different letters (lowercase horizontally and uppercase in vertically) stand for differences between treatments, within each management practice by Tukey's test ($p \leq 0.05$). The significance level of regression equations was ** $p \leq 0.01$.

In limed soils, the P content in corn of the first crop had no influence from residual of previously applied alternative sources, regardless of the TSP dose (Table 4). In this first cropping, only TSP residual influenced plant yield in limed soils as P dose was raised.

The elevated P supply to Urochloa plants, coupled with the high P extraction strength by these grasses (FOLONI et al. 2008) may have reduced P availability in the soil (Tables 1 and 2), and thereby enhancing the corn response to TSP doses. By testing different P sources, SOUZA et al. (2014) reported no significant effect when using several doses of TSP on P content in corn during first cropping; conversely, a linear response was observed due to the residual of such fertilization in a second corn cycle.

The P contents in non-limed soil showed no differences among the applied TSP doses for treatments under residual effect (Table 4). Yet for P content in corn plants, the highest values were reached by applying P doses of 60 and 120 mg dm^{-3} for treatments under PP1 residual effect; 90 and 120 mg P dm^{-3} P for those under NRP and TSP residual, respectively; and 120 mg P dm^{-3} for treatments under PP1 residual. Notwithstanding, all these treatments showed an increasing linear behavior as P dose was raised.

Under these soil non-limed conditions, the P content in plant tissues increased since the plants developed little, given the low pH in these treatments. In the second crop, however, these levels varied neither for phosphate sources nor for TSP doses.

Corn shoot P accumulation increased in both crop cycles with phosphate fertilization, and the highest values were reached in limed soils (Table 5). Except for treatments in limed soil under NRP residual effect in the second cycle, the other treatments presented an increasing linear behavior with TSP doses regardless of liming.

Table 5. Phosphorus accumulation in corn shoot dry biomass (mg/pot) as a response to triple superphosphate fertilization (TSP) in Typic Hapludox non-limed and limed soil under residual effect of alternative P sources.

Fertilizer	P dose (mg dm^{-3})					Regression equation
	0	30	60	90	120	
	..................................mg pot^{-1}..					
			Crop 1			
			Limed soil			
PP1	29.6 Bb	28.5 Bb	30.6 Bb	37.0 Ba	36.6 Ba	$\hat{y} = 28 + 08x$ $R^2 = 0.43$
PP2	40.3 A	38.1 A	41.8 A	43.0 A	45.0 A	$\hat{y} = 38 + 0.05x$ $R^2 = 0.28$
NRP	36.2 Ab	39.0 Aab	42.8 Aab	44.5 Aa	45.4 Aa	$\hat{y} = 36.8 + 0.08x$ $R^2 = 0.65$
TSP	27.1 Bb	29.4 Bb	28.9 Bb	32.1 Bab	35.9 Ba	$\hat{y} = 26.6 + 0.07x$ $R^2 = 0.71$
			Non-limed soil			
PP1	11.2 c	13.3 c	22.8 b	22.9 b	28.0 A	$\hat{y} = 10.4 + 0.16x$ $R^2 = 0.90$
PP2	12.8 d	16.9 cd	19.8 bc	23.5 ab	25.6 a	$\hat{y} = 13.3 + 0.11x$ $R^2 = 0.87$
NRP	12.0 c	15.4 bc	19.3 b	23.2 ab	24.7 a	$\hat{y} = 12.3 + 0.11x$ $R^2 = 0.88$
TSP	12.5 b	13.5 b	18.1 a	22.8 a	22.7 a	$\hat{y} = 12.0 + 0.10x$ $R^2 = 0.82$
			Crop 2			
			Limed soil			
PP1	8.8 B	9.0 B	9.9 B	10.6	10.8	$\hat{y} = 8.6 + 0.02x$ $R^2 = 0.27$
PP2	10.7 AB	11.3 AB	12.2 AB	12.9	13.9	$\hat{y} = 10.3 + 0.03x$ $R^2 = 0.58$
NRP	12.4 A	13.1 A	13.5 A	13.2	13.7	$\hat{y} = 13.2$
TSP	6.5 Bb	10.2 ABa	9.4Ba	10.7 a	10.5 a	$\hat{y} = 8.0 + 0.03x$ $R^2 = 0.36$
			Non-limed soil			
PP1	2.5 b	2.1 Bb	3.7 ABab	3.7 Bab	5.0 Aa	$\hat{y} = 2.1 + 0.02x$ $R^2 = 0.38$
PP2	3.1 c	4.9 Aabc	4.3 ABbc	6.1 Aab	7.0 Aa	$\hat{y} = 3.3 + 0.03x$ $R^2 = 0.55$
NRP	2.5 b	2.8 Bb	4.8 Aab	4.5ABab	5.2 Aa	$\hat{y} = 2.5 + 0.02x$ $R^2 = 0.43$
TSP	1.2	1.6 B	2.4 B	3.4 B	2.7 B	$\hat{y} = 1.2 + 0.02x$ $R^2 = 0.54$

Means followed by different letters (lowercase horizontally and uppercase in vertically) stand for differences between treatments, within each management practice by Tukey's test ($p \leq 0.05$). The significance level of regression equations was ** $p \leq 0.01$.

Still regarding P accumulation, the increasing TSP doses only had effect on corn grown in limed soil during the first cultivation, with the highest values under PP2 and NRP residual effects (Table 5). Notwithstanding, there was an effect of TSP doses in both cultivation conditions. The largest accumulations in corn grown in limed soils occurred starting from a P dose of 90 mg dm^{-3} for soils under PP1 and TSP residual; and from a dose of 30 mg P dm^{-3} for that under NRP; but no effect was observed for treatments under PP2 effect. Whereas for plants grown in non-limed soils, the highest accumulations were recorded from a P dose of 90 mg dm^{-3} for PP2 and NRP treatments; from 60 mg P dm^{-3} for TSP; and at 120 mg P dm^{-3} for PP1.

However, these results did not corroborate those obtained by HOROWITZ & MEURER (2003), who achieved a greater P shoot accumulation when testing TSP and two NRP sources, with different grain sizes, in two consecutive corn crop cycles in a Typic Hapludox soil at a pH of 5.5. Lastly, the soil availability and use efficiency of P from TSP can be altered by residual effect of alternative P sources and by liming.

The higher P accumulation in corn plants in treatments under PP2 and NRP residual effect is related to the characteristics of these sources (Table 1). These materials grant greater residual due to a slower P availability to the soil, thus interfering with the response of subsequent phosphate fertilizations. Both PP1 and TSP sources had the same effect, which indicates that the former might have provided P in such a way, favoring *Urochloa* plants absorption and reducing TSP performance for corn fertilization.

The plants grown in limed soil during the second crop showed P accumulation differences when comparing all the applied doses of TSP with dose zero, only for treatments under TSP residual (Table 5). Yet, treatments on non-limed soils showed P accumulation differences, with the highest values in those under PP1 and NRP effects (60, 90, and 120 mg P dm^{-3}) and under PP2 (30, 90, and 120 mg P dm^{-3}). Among the non-limed soil treatments, the highest P accumulations were found in those under PP1, PP2, and NRP residual effects, at P doses of 60 and 120 mg dm^{-3}; in treatments under PP2 and NRP at 90 mg P dm^{-3}; and under PP2 treatment at 30 mg dm^{-3}.

After two cultivations, differences in soil P availability were registered regardless of liming (Table 6). In limed soils, the highest availability was reached by applying TSP doses of 60, 90, and 120 mg P dm^{-3} in treatments under PP2 and NRP residual effect. Yet in non-limed soils, the TSP doses were 90 and 120 mg P dm^{-3} under PP1, PP2, NRP, and TSP residuals. In brief, both soil conditions demonstrated an increasing linear behavior as TSP doses were raised.

Table 6. Soil phosphorus availability (mg dm^{-3}) as a function of triple superphosphate fertilization (TSP) in limed and non-limed Typic Hapludox soils under residual effect of alternative P sources.

Fertilizer	P dose (mg dm^{-3})					Regression equation
	0	30	60	90	120	
	................................mg dm^{-3}..					
				Limed soil		
PP1	12 Cc	25 Bbc	30 Cb	37 Bab	49 Ba	$\hat{y} = 13.3 + 0.3x$ $R^2 = 0.81$
PP2	31 Ab	35 Ab	53Aa	57Aa	59 Aa	$\hat{y} = 31.9 + 0.2x$ $R^2 = 0.71$
NRP	24 ABc	39 Abc	43 Ab	48 Aab	62 Aa	$\hat{y} = 26.6 + 0.3x$ $R^2 = 0.30$
TSP	18 BCc	23 Bbc	36 BCa	31 Bab	39 Ba	$\hat{y} = 19.4 + 0.2x$ $R^2 = 0.60$
				Non-limed soil		
PP1	21Bc	27 Bbc	31Cb	48 a	52 a	$\hat{y} = 19.6 + 0.3x$ $R^2 = 0.74$
PP2	32 Ab	42 Ab	54 Ab	51 ab	65 a	$\hat{y} = 34.3 + 0.2x$ $R^2 = 0.55$
NRP	28 ABc	36 ABbc	48 ABb	42 ab	56 a	$\hat{y} = 29.6 + 0.2x$ $R^2 = 0.62$
TSP	27 ABc	32 ABbc	39 BCbc	41 b	57 a	$\hat{y} = 25.8 + 0.2x$ $R^2 = 0.74$

Means followed by different letters (lowercase horizontally and uppercase in vertically) stand for differences between treatments, within each management practice by Tukey's test ($p \leq 0.05$). The significance level of regression equations was ** $p \leq 0.01$.

Both NRP and PP2 had longer residual effect in limed soils. This is because these sources present higher solubility in acidic conditions (Table 1); the use of corrective agents raises soil pH, decreasing P solubility and increasing its availability together with a greater electronegative potential in the soil. Meanwhile, the higher availability in non-limed soils can be explained by the little development of plants under such acidity status, absorbing less P from soil and generating its accumulation whether fertilized.

CONCLUSION

The dynamics and efficiency in the soil-plant system of phosphorus (P) from triple superphosphate (TSP) used for corn crop fertilization can be altered by residual effect derived from previous applications of alternative P sources and by soil liming.

Under PP2 and NRP residual effects, corn plants increase dry matter output and P accumulation in tissues when TSP doses from 30 mg P dm^{-3} are applied; however, the major increments would be reached in the first crop cycle and in limed soils.

An increased soil P availability was registered in treatments under PP2 and NRP residual effect after two sequential cycles, in both soil acidity conditions; therefore, these sources proved to have a greater residual effect.

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