



DOI: <http://dx.doi.org/10.1590/1807-1929/agriambi.v24n11p735-740>

Maize yield influenced by the residual effects of sedimentary phosphates in high-calcium soil

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ABSTRACT: It was evaluated the residual effects of sedimentary phosphates associated with the annual application of phosphate on maize grown in Inceptisol soil with a high exchangeable calcium concentration and pH value of 6.0. The experiment was conducted based on a completely randomized block design with strip-split plots. The main plots were treated with Bayóvar rock phosphate, Itafós rock phosphate, or triple superphosphate, while the control received no additional phosphate. The phosphate sources were applied by broadcasting and incorporated in the soil two years prior to the current study at 200 kg of P_2O_5 ha⁻¹, with no tillage in subsequent years. In the sub-plots, phosphate doses of 0, 60, and 120 kg of P_2O_5 ha⁻¹ year⁻¹, as triple superphosphate, were applied at the base of the sowing furrows. Leaf phosphorus (P), grain yield, and soil P by ion exchange resin were evaluated. Differences were observed between the leaf P among the plots treated with phosphate sources and the control plot, which declined from 2013 to 2015. In 2013 and 2014, rock phosphate residuals influenced the grain yield when there was no annual application of phosphate. In 2015, grain yields in rock phosphate treatments without annual phosphate application were not superior to those in the control treatment and did not differ significantly from the plots receiving triple superphosphate. Furthermore, it was found that the soil P content extracted by ion exchange resin was higher in the Itafós treatment; however, for this source, the correlation between soil P and grain yield was relatively weak.

Key words: *Zea mays* L., phosphate fertilizer, phosphorus, ion exchange resin

Produtividade de milho influenciada pelo efeito residual de fosfatos sedimentares em solo alto em cálcio

RESUMO: Avaliou-se o efeito residual de fosfatos sedimentares associado a doses anuais de fósforo em milho cultivado em um Cambissolo com elevado teor de cálcio trocável e pH 6,0. O delineamento experimental foi em blocos casualizados com parcelas subdivididas em faixa. As parcelas principais foram o fosfato de rocha de Bayóvar, o fosfato de rocha Itafós, o superfosfato triplo e um tratamento controle, sem aplicação de fosfatos. Estas fontes foram aplicadas a lanço e incorporadas no solo dois anos antes do presente estudo, com dose equivalente a 200 kg de P_2O_5 ha⁻¹ e não houve preparo de solo nos anos subsequentes. Nas subparcelas, foram aplicadas as doses de 0, 60 e 120 kg de P_2O_5 ha⁻¹ ano⁻¹ através de superfosfato triplo no fundo do sulco de semeadura. O teor foliar de P, a produtividade de grãos e fósforo no solo pela resina de troca iônica foram avaliados. As diferenças na concentração de fósforo foliar entre os tratamentos com as fontes fosfatadas e o tratamento controle reduziram de 2013 a 2015. Em 2013 e 2014, os efeitos residuais dos fosfatos de rocha influenciaram a produtividade quando não houve aplicação anual de fósforo. Em 2015, a produtividade nos tratamentos com os fosfatos de rocha não foi superior ao controle, mas também não diferiu significativamente do superfosfato triplo. O teor residual de P no solo, extraído pelo método da resina, foi maior no tratamento com Itafós, entretanto, para esta fonte, a correlação entre o teor de P no solo e a produtividade foi fraca.

Palavras-chave: *Zea mays* L., fertilizante fosfatado, fósforo, resina de troca iônica



INTRODUCTION

Broadcast and incorporated application of rock phosphates can be used to enhance soil phosphorus (P) availability and reduce the doses of phosphate applied annually to crops as soluble fertilizer (Novais et al., 2007; Sousa et al., 2009). However, few studies have evaluated the suitability of this fertilization technique for annual crops (Vasconcellos et al., 1986; Lange et al., 2016).

Owing to their higher solubility, sedimentary rock phosphates are more suitable for direct application to soils than igneous phosphates (Rajan et al., 2004). In many cases, their efficiency is similar to that of soluble phosphate sources during the year of their application (Husnain et al., 2014; Duarte et al., 2015; Nakamura et al., 2013, 2016).

In the Brazilian Northeast, Souza et al. (2014) observed that broadcast and incorporated applications of sedimentary phosphates to an Inceptisol soil (with an exchangeable Ca^{2+} equal to $13.5 \text{ cmol}_c \text{ dm}^{-3}$ and pH value of 6.0) reduced the triple superphosphate dose required at maize sowing for two years after their application. In general, a high exchangeable calcium concentration and pH value greater than 5.5 are potentially unfavorable to rock phosphate dissolution (Chien & Menon, 1995; Junio et al., 2013).

Rock phosphates can often have residual effects on crops years after their initial application. Their lower solubility compared to soluble phosphate sources, such as superphosphates and ammonium phosphates, protect P from the soil reactions that typically reduce their availability for plants (Resende et al., 2006).

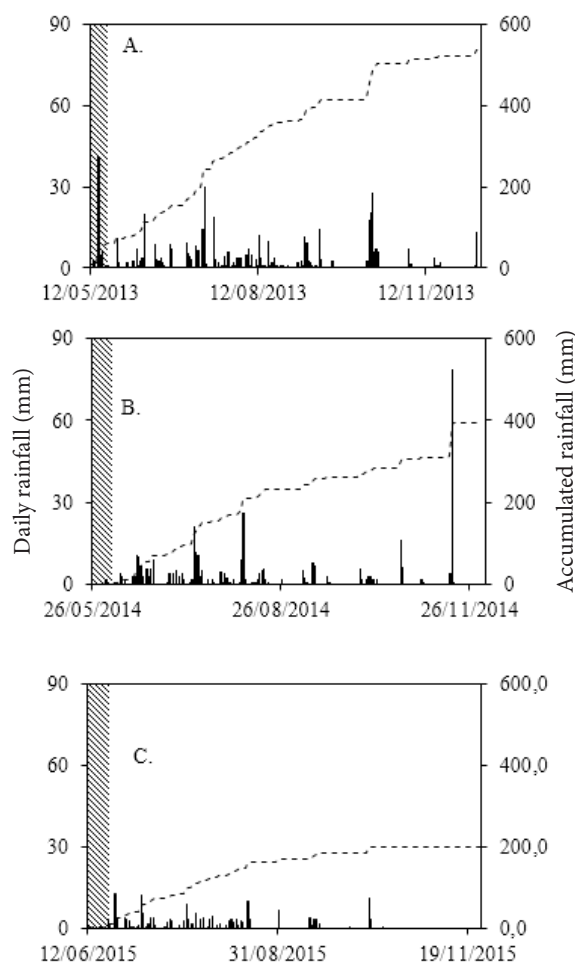
The objective of this study was to evaluate the residual effects of the broadcast and incorporated application of Bayóvar and Itafós sedimentary phosphates associated with the annual application of phosphate fertilizer on maize yield in an Inceptisol with high calcium concentration.

MATERIAL AND METHODS

The experiment was established in 2011 and Souza et al. (2014) previously presented initial results obtained from 2011 to 2012. In this paper, we present data collected from 2013 to 2015.

The experiment was conducted in an area characterized by an Inceptisol soil at the Embrapa Experimental Station in Frei Paulo municipality in the state of Sergipe, Brazil (coordinates $10^\circ 36.159' \text{ S}$, $37^\circ 38.198' \text{ W}$). According to the Köppen's classification, the climate of the region is classified as As, with an annual average temperature of 24°C . Rainfall during maize cycle in 2013, 2014 and 2015 is shown in Figure 1.

Prior to commencing the experiment, soil samples were collected from 0-0.20 m depth. The composition of the soil in terms of particle size was: sand 226.2 g kg^{-1} , silt 420.6 g kg^{-1} , and clay 353.2 g kg^{-1} . The characteristics of the soil based on chemical analyses were: pH (H_2O), 6.0; organic matter, 17.2 g dm^{-3} ; P (Mehlich-1), $< 1.39 \text{ mg dm}^{-3}$; Ca^{2+} , $13.5 \text{ cmol}_c \text{ dm}^{-3}$; Mg^{2+} , $1.7 \text{ cmol}_c \text{ dm}^{-3}$; K^+ , $0.32 \text{ cmol}_c \text{ dm}^{-3}$; Na^+ , $0.30 \text{ cmol}_c \text{ dm}^{-3}$; H+Al, $2.03 \text{ cmol}_c \text{ dm}^{-3}$; Al^{3+} , $0.09 \text{ cmol}_c \text{ dm}^{-3}$; cation exchange



¹The hatched area represents the days before sowing

Figure 1. Daily and accumulated rainfall in 2013 (A), 2014 (B), and 2015 (C) from 10 days prior sowing to the date of maize harvest, at the Embrapa Experimental Station, Frei Paulo, SE, Brazil¹

capacity, $17.8 \text{ cmol}_c \text{ dm}^{-3}$; and base saturation, 88.8% (Souza et al., 2014).

A randomized block design was used with strip-split plots and four repetitions as the experimental design. For the main plots, Bayóvar rock phosphate, Itafós rock phosphate, and triple superphosphate (TSP - standard source) were applied through broadcasting and incorporated into the soil. A plot to which no phosphate was applied served as control. The amount of P_2O_5 applied in the main plots was 200 kg ha^{-1} , based on the total P_2O_5 contents of the fertilizers. Information regarding total P_2O_5 and the 2% citric acid solubility of the sources was previously presented by Souza et al. (2014).

Sub-plots were treated with TSP at doses of 0, 60, and $120 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ year}^{-1}$ which was applied at the base of the sowing furrows. The sub-plots were set up with five rows of 7 m each in length, spaced at intervals of 0.80 m. In each of the three years of the study, maize plants were sown at a density of $62,500 \text{ plants ha}^{-1}$.

During the first year (2011), the soil was tilled and the phosphate fertilizers were broadcast and incorporated into the soil on April 19. In 2013, the maize hybrid AG 7088 PRO2 (Agrocere) was sown on May 22; in 2014, AG 7088 PRO (Agrocere) was sown on June 5; in 2015, 2B-433 (Dow Agrosiences) was sown on June 22.

At 65, 69, and 66 days after sowing in 2013, 2014, and 2015, respectively, leaf samples were collected at the female flowering stage. The whole leaf below and opposite to the ear was collected from all plants in the plots for leaf P analysis.

The leaf material was cleaned, dried, ground, and digested using a mixture of nitric and perchloric acids. The concentration of P in solution was measured using molecular spectrometry after color development (Silva, 2009).

Soil samples were collected at depths from 0 to 0.20 m in plots without annual P fertilization at 138, 82, and 137 days after sowing in 2013, 2014, and 2015, respectively. Each bulk sample consisted of six sub-samples collected between the rows in each sub-plot. These samples were subjected to available P analysis based on extraction using ion exchange resins (Silva, 2009). In all the years, maize was harvested when the grain moisture was approximately 13%.

The normality and homogeneity of variance of the data were tested by Shapiro-Wilk and Hartley tests. These showed that the soil P data were not normally distributed ($p \leq 0.05$) with non-homogeneous variance ($p \leq 0.01$). After $\log(x)$ transformation, Hartley and Shapiro-Wilk tests verified the normality and homogeneity of the variance of the data, which were subsequently subjected to analysis of variance, followed by a comparison of means using the Tukey test ($p \leq 0.05$). Soil P data were analyzed considering time effect (split plot in time).

Linear correlation analyses of the relationships between soil P and corn variables (leaf P and grain yield) were performed to determine the accuracy of the ion exchange resin method in the rock phosphate treatments. Statistical analyses were performed using Sisvar statistical software (Ferreira, 2011).

RESULTS AND DISCUSSION

Over the period from 2013 to 2015, there was an annual reduction in the accumulated rainfall during the maize cycle, not only in terms of volume but also with respect to frequency (Figure 1). In 2015, the lowest accumulated rainfall during the growing season (191 mm) was associated with a pronounced reduction in yield (30%) compared with that in 2014.

According to Andrade et al. (2015), maize requires an accumulated rainfall of 380-550 mm during the growing season. Water deficits have been shown to reduce nutrient uptake, photosynthesis, plant growth, and yield (Efeoglu et al., 2009).

The variance analysis for grain yield and leaf P content are shown in Table 1. In all the years, there was a significant interaction between broadcast and incorporated phosphate application and annually applied phosphate doses for grain yield ($p \leq 0.05$) (Table 1). In 2013, the leaf P concentration was affected by broadcast and incorporated phosphate application ($p \leq 0.01$) and annual application of phosphate doses ($p \leq 0.01$) independently, whereas in 2014 and 2015, it was significantly influenced by annual application of phosphate doses ($p \leq 0.01$).

Grain yield was only influenced by broadcast and incorporated phosphate application in treatments without P at sowing (Table 2). We suspect that the application of 60 and 120 kg of P_2O_5 ha⁻¹ year⁻¹ since 2011 increased the available soil P content in rows to a level that promoted the maximum productivity under these conditions. In these treatments, the maize yield was greater than 9000, 8000, and 5000 kg ha⁻¹ in 2013, 2014, and 2015, respectively.

Table 1. Summary of the analysis of variance in grain yield and leaf phosphorus (P) concentration in 2013, 2014, and 2015¹

Source of variation	DF	2013 (third year)		2014 (fourth year)		2015 (fifth year)	
		Grain yield	Leaf P	Grain yield	Leaf P	Grain yield	Leaf P
Mean squares							
Blocks	3	4,094,278.65	0.28	2,174,244.07	0.03	5,242,029.09	0.06
BIPA	3	4,841,962.92 ^{ns}	1.38 ^{**}	2,519,615.91 ^{ns}	0.12 ^{ns}	3,668,297.24 ^{ns}	0.06 ^{ns}
Error (a)	9	1,743,513.28	0.07	1,674,578.49	0.08	2,692,400.93	0.07
AD	2	50,910,320.49 ^{**}	7.95 ^{**}	58,704,641.14 ^{**}	3.54 ^{**}	50,743,320.96 ^{**}	7.71 ^{**}
Error (b)	6	1,310,496.58	0.08	2,684,479.93	0.06	1,480,062.53	0.08
BIPA × AD	6	4,219,362.63 ^{**}	0.04 ^{ns}	1,561,995.81 ^{**}	0.12 ^{ns}	1,150,698.70 [*]	0.01 ^{ns}
Error (c)	18	815,820.38	0.03	193,248.78	0.05	298,547.99	0.05
Overall mean		8875 kg ha ⁻¹	2.65 g kg ⁻¹	8235 kg ha ⁻¹	2.05 g kg ⁻¹	5750 kg ha ⁻¹	2.08 g kg ⁻¹
CV a (%)		14.88	9.75	15.71	14.09	28.54	12.92
CV b (%)		12.90	10.84	19.90	11.83	21.16	13.46
CV c (%)		10.18	6.37	5.34	11.12	9.50	11.48

¹BIPA - Broadcast and incorporated phosphate application; AD - Annual phosphate doses; DF - Degrees of freedom; ^{ns}, ^{*}, and ^{**} - Not significant and significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

Table 2. Effect of broadcast and incorporated phosphate sources on maize yield (grain) from the third (2013) to the fifth year (2015)¹

Broadcast and incorporated phosphate application	2013 (Third year)			2014 (Fourth year)			2015 (Fifth year)		
	Annual doses (kg of P_2O_5 ha ⁻¹)								
	0	60	120	0	60	120	0	60	120
Grain yield (kg ha ⁻¹)									
Triple superphosphate	8235 a	10376	9337	6859 a	9518	9352	4400 a	7018	6587
BSRP	8321 a	10414	9688	6575 a	9302	9329	4306 ab	6427	7434
IARP	5960 b	9868	9953	6323 a	9303	9583	3895 ab	7038	7132
Control	4775 b	9569	10001	4351 b	8784	9541	2216 b	5896	6652

¹Means followed by the same lowercase letter in columns are not significantly different at $p \leq 0.05$, as determined using the Tukey test; BSRP - Bayóvar-Sechura rock phosphate; IARP - Itafós-Arraias rock phosphate

In 2013, when no annual doses of phosphate were applied, the broadcast and incorporated application of triple superphosphate and Bayóvar rock phosphate promoted higher grain yields than Itafós and the control (Table 2). This was consistent with the solubility pattern of these sources (Chien et al., 2011; Souza et al., 2014) and the obtention of adequate rainfall for maize production recorded in that year (Figure 1A).

In 2014, broadcast and incorporated phosphate application increased the grain yield when annual phosphate doses were not applied, although no significant differences among the sources were observed (Table 2). According to Resende et al. (2006), differences among phosphate sources characterized by different solubilities diminish over time. The slow solubilization of rock phosphate particles and the more intense soil P fixation and exportation by crops in the triple superphosphate treatment may have contributed to the similarity of responses after four years (2011-2014) of the experiment (Novais et al., 2007).

In 2015, only broadcast and incorporated application of triple superphosphate produced higher grain yields than the control when no annual doses of phosphate were applied (Table 2). Here, it is conceivable that low rainfall in this year affected the dissolution of rock phosphates (Figure 1C). Adequate soil moisture favors the removal of Ca, P, and bases from rock phosphate particle surfaces, enhancing their dissolution (Rajan et al., 1996; Kumari & Phogat, 2008).

The differences between the leaf P of corn treated with phosphate sources and that of the control also decreased from 2013 to 2015 (Table 3).

In 2013, leaf P concentrations were higher in all treatments with broadcast and incorporated phosphate compared with the control (Table 3). However, differences in leaf P among treatments with different phosphate sources were only detected when no annual phosphate doses were applied; these differences were related to the solubility of the sources.

Annual P fertilization (60 and 120 kg of P_2O_5 ha⁻¹ year⁻¹) increased leaf P content to a level where there were no significant differences in the leaf P content in response to the different sources. These results indicate that applying phosphate annually could reduce crop dependence on the residual P derived from broadcast and incorporated applications. Vasconcellos et al. (1986) and Souza et al. (2014) obtained similar results.

In 2014, broadcast and incorporated phosphate application had no significant influence on leaf P when phosphate was applied at doses of 0 and 120 kg P_2O_5 ha⁻¹ year⁻¹ (Table 3).

Only the Bayóvar treatment increased the leaf P concentration relative to that of the control at an annual dose of 60 kg P_2O_5 ha⁻¹. Annual P fertilization at this dosage may have influenced plant development and the capacity of plants to absorb P from Bayóvar particles owing to their intermediary solubility compared to triple superphosphate and Itafós rock phosphate (Souza et al., 2014).

In 2015, we detected no differences among phosphate sources and the control with respect to leaf P concentrations (Table 3). In addition to the annual P fertilization effect, it is conceivable that low rainfall in 2015 (Figure 1C) may have affected the solubilization of P forms in the soil, including rock phosphate particles. In addition, P diffusion to the roots can be affected by reduced soil moisture (He & Dijkstra, 2014).

In the absence of annual P fertilization, the residual effects of rock phosphates increased grain yields compared with the control plot until 2014 (Table 2). In 2014, the yield increments in these treatments were equivalent to 50.16% (Bayóvar) and 44.48% (Itafós) of the increments with the application of 60 of P_2O_5 ha⁻¹ year⁻¹ in the control treatment.

It is important to emphasize that, since 2013, the potential yield of maize was attained in response to the annual application of phosphate at the dose of 60 kg P_2O_5 ha⁻¹ year⁻¹. These results thus indicate that the application of lower amounts of phosphate at sowing in the rock phosphates treatments are sufficient to realize the yield potential compared with the control, even after three years of its application.

The high exchangeable calcium concentration of the soil did not prevent the use of sedimentary rock phosphates in our study. In this regard, rainfall is probably an important contributory factor, given that the effects of rock phosphates were more pronounced in years with higher rainfall than in years with lower rainfall (Figure 1 and Table 2). As previously indicated, soil moisture favors the removal of dissolution products from the rock phosphate particles, enhancing their dissolution.

In this respect, however, it is important to emphasize that plants can also affect rock phosphate dissolution through absorbing P and Ca²⁺ and liberating H⁺ and organic acids (Kumari & Phogat, 2008; Novais et al., 2017). In addition, rhizosphere microorganisms contribute to the solubilization of P from rock phosphates, thereby facilitating its plant uptake (Hamdali et al., 2008).

Soil P, determined by the ion exchange resin extraction, was influenced by broadcast and incorporated phosphate application ($p \leq 0.01$). Tukey test analysis indicated that in

Table 3. Effect of broadcast and incorporated phosphate application and annual phosphate doses on leaf phosphorus concentrations from 2013 to 2015¹

Broadcast and incorporated phosphate application	2013 (Third year)			2014 (Fourth year)			2015 (Fifth year)		
	Annual doses (kg of P_2O_5 ha ⁻¹)								
	0	60	120	0	60	120	0	60	120
Triple superphosphate	2.19 a	2.98 a	3.35 a	1.69	2.26 ab	2.54	1.41	2.19	2.82
BSRP	2.11 ab	3.26 a	3.45 a	1.53	2.47 a	2.27	1.36	2.18	2.82
IARP	1.79 b	2.88 a	3.27 a	1.42	2.16 ab	2.48	1.45	2.18	2.67
Control	1.37 c	2.35 b	2.80 b	1.47	1.87 b	2.45	1.20	2.08	2.65

¹Means followed by the same lowercase letter in columns are not significantly different at $p \leq 0.05$, as determined by the Tukey test; BSRP - Bayóvar-Sechura rock phosphate; IARP - Itafós-Arrais rock phosphate

all the years, the soil P content in plots treated with Itafós was higher than in the control plot and had the highest values obtained in the experiment, thereby indicating overestimation (Table 4). In the Bayóvar treatment, resin-extracted P was higher than in the control in 2014, whereas in the triple superphosphate treatment, soil P did not exceed that recorded in the control.

The analysis of the relationships between maize variables (grain yield and leaf P) and different phosphate sources indicated that these sources influenced the performance of the ion exchange resin method (Table 5). For sedimentary phosphates, resin-extracted P and grain yield were relatively weakly correlated and the correlations between resin P and leaf P were non-significant. In contrast, the resin-extracted P and maize variables for triple superphosphate were significantly correlated ($p < 0.01$).

Ion exchange resin method, also known as mixed resin, is used as an extractor in routine soil analyses in Brazil. It is well adapted for use in a diversity of soils and situations, given that the extraction is based on non-destructive cation-anion exchange (Silva & Raij, 1999; Farias et al., 2009; Schindwein et al., 2011; Freitas et al., 2013).

However, according to Freitas et al. (2013), the use of cation exchange resin may result in the excess extraction of Ca^{2+} from the soil, which can promote rock phosphate solubilization. As a result, short-term P availability can be overestimated, and sedimentary phosphates appear to be more susceptible to this effect than igneous phosphates owing to their higher solubility (Sousa et al., 2009).

Our finding that the Pearson and angular coefficients for the relationships between soil P and grain yield were lower

Table 4. Residual soil phosphorus (P) extracted using ion exchange resin for P sources applied by broadcasting and incorporation in the soil¹

Treatments	2013	2014	2015
	Resin P (mg dm ⁻³)		
Triple superphosphate	15.75 ab	13.00 ab	10.25 b
BSRP	16.00 ab	19.00 a	15.25 ab
IARP	24.25 a	30.25 a	36.25 a
Control treatment	9.75 b	7.75 b	6.50 b
CV (%)	13.47		

¹The data obtained from the treatments without annual phosphate doses were analyzed considering the time effect (split plot in time); Tukey's test was performed using log (x)-transformed data; The coefficient of variation (CV) values presented relate to the transformed data; The original mean soil P values are presented in the Table; Means followed by the same lowercase letter in columns are not significantly different at $p \leq 0.05$, as determined by the Tukey test; BSRP - Bayóvar-Sechura rock phosphate; IARP - Itafós-Arraias rock phosphate

Table 5. Linear regression and Pearson correlation coefficients for grain yield and leaf phosphorus (P) as a function of soil P extracted using ion exchange resin for different P sources¹

Sources ²	Equations	r	X min	X max
Triple Superphosphate	$Y_{\text{grain yield}} = 359.05x + 1369.4$ $Y_{\text{leaf P}} = 0.0501x + 1.0306$	0.75** 0.61**		25
Bayóvar	$Y_{\text{grain yield}} = 232.7x + 2211.2$ $Y_{\text{leaf P}} = 0.0211x + 1.2466$	0.64** 0.37 ^{ns}	4	27
Itafós	$Y_{\text{grain yield}} = 51.858x + 3759.3$ $Y_{\text{leaf P}} = 0.0053x + 1.35$	0.48* 0.36 ^{ns}		79

¹Soil P, grain yield and leaf P data from the treatments without annual phosphate doses; Only data from the third to the fifth year of the experiment are considered; ²All the treatments in which P sources were broadcast and incorporated in the soil were grouped with the control (n = 24); ^{ns}, * and ** Not significant and significant at $p \leq 0.05$ and $p \leq 0.01$, as determined by a t-test, respectively

for Itafós than Bayóvar (Table 5) can probably be attributed to the lower solubility of Itafós, which results in deposition of larger amounts of insolubilized particles in the soil. Thus, the anion exchange resin could recover higher quantities of P from these particles that are not available in the short term because of the excessive extraction of Ca by the cation exchange resin.

CONCLUSIONS

1. Rock phosphates influenced maize grain yield even four years after their initial application but only in treatments without the annual addition of soluble phosphate fertilizer.
2. High grain yields were obtained when the broadcast and incorporated application of rock phosphates was supplemented with an annual phosphate application of 60 and 120 kg P_2O_5 ha⁻¹ year⁻¹ during the period from 2013 to 2015.
3. Differences in the leaf P concentration among the maize grown in the plots treated with phosphate sources and that grown in the control plot declined from 2013 to 2015.
4. The residual soil P concentration, extracted using an ion exchange resin, was higher in plots treated with Itafós, although a weaker correlation was observed between soil P and maize grain yield for this source.

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