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Phosphorus and silicon fertilizer rates effects on dynamics of soil phosphorus fractions in oxisol under common bean cultivation

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The purpose of this research was to evaluate the effects of P and Si fertilizer rates in dynamic of P fractions in clay soil under greenhouse. The research was carried out in a Dystroferric Red Latosol of a very loamy texture from Lavras city, Minas Gerais State, Brazil. The experimental design was entirely randomized, arranged in 4 × 3 factorial design, with four repetitions. The treatments included four inorganic fertilizer P rates (0, 110, 330 and 560 mg dm^{-3}) and three Si rates (0, 110, 330 and 560 mg dm^{-3}). The preview application of Si fertilizer did not contribute to decrease P desorption. Possibly, the silicate has lower affinity with the bound sites of adsorption than phosphates. The effects of inorganic fertilizer P were higher in increasing the moderately labile and labile P inorganic fractions. Among the organic P fractions, the NaHCO$_3$-Po fraction was the only one that contributes to plant nutrition. The Hedley sequential phosphorus fractionation promoted information about different pools where P was accumulated in the soil after common bean cultivation. The highest amount of P was obtained in stable P fraction, followed by moderately labile and labile P fraction. The moderately labile P fraction decreased after common bean cultivation possibly due to the time of P contact in the soil and redistribution to stable P fraction. The labile form was the lowest P pool in soil; nevertheless the increase in fertilizer P rates increases the amount of P content in labile fraction.

Key words: P fertilizer, Si fertilizer, nutrients interaction, *Phaseolus vulgaris*.

INTRODUCTION

Most Brazilian soils are characterized as low natural fertility due to high weathering through soil formation.

Phosphorus (P) is the most limited nutrient for crop production in highly weathering soil in tropical climate

(Daroub et al., 2003). The P distributions in soil are presented in organic and inorganic P fractions, which combined to define the total soil P (Hedley et al., 1982; Alovisi et al., 2011).

The highly weathering soil shows high capacity of P adsorption and results in small available P in soil solution (Guedes et al., 2012, 2016). The P supply is quite important in early stage of plant growth and the P supply is affected by many factors in the soil, as example: P fertilizer rates, soil mineralogy, cropping systems, and other environment conditions (Grant et al., 2004). Opposing to the other nutrients, the P fertilizer might be applied in overdose in most occasions to saturate the adsorptions sites in soil to remain enough P supply for plant growth (Furtini Neto et al., 2001). The recommendation of P fertilizer is directly related to soil mineralogy, due to P capacity in adsorption in Fe/Al oxy-hydroxides (Wang et al., 2015), as the case of inner sphere complexes formation (Fe^{3+}–O– P), and surface bound in Fe–OH groups (Kim et al., 2011).

Furthermore, the clay composition affects the capacity of P adsorption in soil (Tokura et al., 2002). The adequate offer of P to crops in highly weathering soil is always a challenge, due to complexity in P interactions. The interactions of phosphate (P) ions may form complex minerals in association with cations (Ca, Al, and Fe) (Hinsinger, 2001). The link between P and Fe speciation affects the P concentration in soil (Sundman et al., 2016), as the case of maximum P adsorption capacity correlated with clay, sand, silt, soil organic matter, base saturation, and pH (Pinto et al., 2013). Thus, the knowledge of P interactions in soil and its availability associated with the possibility of reverse P adsorption is quite important to improve P fertilizer recommendation in cropping systems.

The possibility to use another fertilizer source to improve the availability of P in soil solution may be profitable. The silicon (Si) has been studied as a possibility to improve P availability in soil solution due to similarity of silicate anion ($H_3SiO_4^-$) with phosphate ($H_2PO_4^-$). Lee and Kim (2007) reported silicate as a competitor of phosphate and its possibility to exchange phosphate from adsorption sites, resulting in increasing availability of phosphate in soil solution. The Si is present in solid phase of the soil in many types of clay and other mineral compounds, but in highly weathering soil as the case of oxisols its content in soil solution is limited (Guedes et al., 2016).

The possibility to increase Si content in soil solution seems to be a profitable alternative to reduce P adsorption and consequently increases P availability. As observed by Cartes et al. (2015), the presence of Si in solution showed slight reduction in capacity of P sorption. Nevertheless, many unknown factors about Si and P adsorption are still necessary to disclose, as the case of environment factors, soil physical-chemical reactions, soil mineralogy, and Si-P interactions (Alovisi et al., 2014). Thus, the knowledge of nature and P forms distribution in soil may offer important information to the process of evaluation and P availability.

The sequential P fractionation may contribute to identify the P forms retention in soil and its capacity of P supply to soil solution. The sequential P fractionation proposed by Hedley et al. (1982) allows having information about P availability in short and long-term through the P fractionation with different extractor from the weakest to the strongest extractor. These extractors allow the removing of P from solid soil phase and possibility to determine labile, moderately labile, and stable P forms. The purpose of this research was to evaluate the effects of P and Si fertilizer rates in dynamic of P fractions in clay soil under greenhouse.

MATERIALS AND METHODS

Location and soil description

The research was carried out in a soil with a very loamy texture and clay mineralogy constituted mainly by Al/Fe oxy-hydroxides, classified according to Santos et al. (2013) as Dystroferric Red Latosol (LVdf). The greenhouse location was the campus of Universidade Federal de Lavras located in the city of Lavras, State of Minas Gerais, Brazil (approximately 21°13'46.54''S and 44°58'26.30''W, average altitude 932 m above sea level).

Soil properties evaluations

The soil was collected in 0 to 20 cm depth under native vegetation of Brazilian Cerrado biome. After collection, the soil was air-dried, broke up and passed through a 5 mm sieve for the greenhouse experiments. A portion of the samples was passed through a 2 mm sieve and then subjected to physical, chemical and mineralogical analyses. The physical analysis involved the determination of the granulometric fractions of the air-dried soil (ADS) using the pipette method (Day, 1965).

The chemical analyses included the pH, sorption complex, organic C, macronutrients and micronutrients content. The availability of P was evaluated using the Mehlich-1 extractor (Claessen, 1997) and ion-exchange resin (Raij and Feitosa, 1980). The free Fe oxy-hydroxides from the clay fraction were obtained by dissolution with dithionite-citratebicarbonate (Fed) (Mehra and Jackson, 1960). The less crystalline Fe oxy-hydroxides of the clay fraction was obtained with ammonium oxalate acid (FeO) according to Schwertman et al. (1986), and the iron and aluminium oxy-hydroxides by ADS sulphuric attack were determined according to Claessen (1997).

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Table 1. Chemical, physical and mineralogical soil properties.

Soil properties	%
pH_{H2O}	4.8
Al^{+3} ($cmol_c$ dm^{-3})	1.1
Ca^{+2} ($cmol_c$ dm^{-3})	0.4
Mg^{2+} ($cmol_c$ dm^{-3})	0.2
K^{+} (mg dm^{-3})	30
$H^{+} + Al^{3+}$ ($cmol_c$ dm^{-3})	9.5
Mehlich1-P (mg dm^{-3})	1.1
Resin-P (mg dm^{-3})	12.9
SB ($cmol_c$ dm^{-3})	0.7
Effective CEC ($cmol_c.dm^{-3}$)	1.7
CEC to pH 7.0 ($cmol_{c.}$ dm^{-3})	10.2
BS (%)	7
m (%)	61
SOM (dag kg^{-1})	3.9
Si (mg dm^{-3})	6.2
B (mg dm^{-3})	0.4
Cu (mg dm^{-3})	2.1
Fe (mg dm^{-3})	73.1
Mn (mg dm^{-3})	11.4
Zn (mg dm^{-3})	0.1
Coarse sand (g kg^{-1})	110
Thin sand (g kg^{-1})	60
Silt (g kg^{-1})	110
Clay (g kg^{-1})	720
SiO_2 (g kg^{-1})	153
Al_2O_3 (g kg^{-1})	262
Fe_2O_3 (g kg^{-1})	237
TiO_2 (g kg^{-1})	202
P_2O_5 (g kg^{-1})	1.4
Fe_d (g kg^{-1})	138.8
Fe_o (g kg^{-1})	2.8
Ct (g kg^{-1})	160
Gb (g kg^{-1})	310

CEC: Cation exchange capacity; total acidity pH 7.0 ($H+ +Al^{3+}$); Exchangeable (KCl 1 mol L^{-1}) Ca^{2+}, Mg^{2+} and Al^{3+}; BS: Base Saturation=(Σ cations/CEC)×100.

In the free clay, the gibbsite and kaolinite contents were quantified using differential thermal analysis. The determination of the soluble Si in the soils was conducted according to the method proposed by McKeaque and Cline (1963). The results of the physical, chemical and mineralogical characterization of the studied soil before the application of the treatments are presented in Table 1.

Experimental design and treatments implementation

The experimental design used was entirely random, arranged in a 4 × 3 factorial, with four repetitions, with amount of 48 experimental units. The treatments included four P rates (0, 110, 330 and 560 mg dm^{-3}) and four Si rates (0, 110, 330 and 560 mg dm^{-3}). The P fertilizer rates were defined by the remaining P (Alvarez et al., 2000). Vases with a soil capacity of 3 dm^3 were filled with 2.7 dm^3 of soil.

The soil samples were then subjected to three sequential incubations for a period of 30 days each under humidity conditions equivalent to 60% of the total pore volume (TPV) occupied by water (Freire et al., 1980), which was controlled by daily weighing. The three incubations followed this sequence: (1) incubation after dolomitic limestone application, which was through the micropulverised calcined dolomitic limestone (35% CaO and 14% MgO) applied to the soils in sufficient quantity to elevate the value of the base saturation to 70%; (2) incubation after Si application, the silicic acid was applied in the form of H_4SiO_4 (60% SiO_2) at the rates of 0, 110, 330 and 560 mg dm^{-3} of Si, as defined based on the P rates; and (3) incubation after basic fertilization corresponded to the following nutrient contents in the form of salts p.a. in mg dm^{-3} of soil: 100 of N; 150 of K; 62 of S; 0.81 of B; 1.3 of Cu; 5.0 of Zn; 3.6 of Mn; 1.6 of Fe; and 0.15 of Mo.

The nutrients were applied in a solution form and mixed into the soil for a higher uniformity. The sources of nutrients were: K_2SO_4;

Table 2. Soil properties after soil acidity correction, basic fertilizing and treatment applications.

Treatment[1]	pH	K	Ca	Mg	Al	H+Al	CEC	m	BS	Resin-P	Si
		mg dm^{-3}			cmol$_c$ dm^{-3}				%	mg dm^{-3}	
P_0Si_0	5.2	126	3.3	2.1	0.1	4.0	9.8	2.0	59.1	11.2	6.69
P_0Si_{330}	5.2	128	3.4	2.2	0.1	4.0	9.8	2.0	59.4	11.5	19.91
P_0Si_{560}	5.2	123	3.3	2.1	0.1	3.7	9.5	2.0	60.8	11.5	27.79
$P_{110}Si_0$	5.3	130	3.3	2.2	0.1	3.7	9.9	1.0	62.2	24.5	6.65
$P_{110}Si_{330}$	5.2	121	3.3	2.2	0.1	4.3	10.2	2.0	57.5	27.8	20.62
$P_{110}Si_{560}$	5.1	124	3.4	2.0	0.2	4.5	10.3	3.0	56.3	25.4	27.29
$P_{330}Si_0$	5.3	129	3.1	2.1	0.1	4.2	9.7	2.3	57.2	81.8	7.99
$P_{330} Si_{330}$	5.1	134	3.4	2.2	0.1	5.0	11.0	2.0	54.3	83.4	22.92
$P_{330}Si_{560}$	5.2	131	3.3	2.0	0.1	4.5	10.2	2.0	55.8	81.0	25.37
$P_{560}Si_0$	5.3	129	3.3	2.2	0.1	4.7	10.5	2.0	55.4	126.1	13.90
$P_{560}Si_{330}$	5.1	135	3.4	2.4	0.1	5.6	11.7	2.0	52.1	131.4	18.78
$P_{560}Si_{560}$	5.1	135	3.4	2.1	0.1	5.4	11.2	2.0	51.8	127.8	25.25

[1]The rates of P and Si are in mg dm^{-3}. CEC: Cation exchange capacity; total acidity pH 7.0 (H+ +Al^{3+}); Exchangeable (KCl 1 mol L^{-1}) Ca^{2+}, Mg^{2+} and Al^{3+}; BS: Base Saturation=(Σcations/CEC) × 100.

(NH_4)$_2HPO_4$; NH_4NO_3; KH_2PO_4; H_3PO_4; $MnSO_4.2H_2O$; $CuSO_4.5H_2O$; (NH_4)$6MO7O24.4H_2O$; $ZnSO_4.7H_2O$; $FeSO_4.7H_2O$; and H_3BO_3. After the incubation period of the soils with the treatments in the greenhouse, soil subsamples of each experimental unit (vases) were collected for the analytical determinations (Table 2).

Planting was performed 30 days after the last incubation. Five common bean seeds per vase were sown. After 20 days, the plants were thinned, leaving two plants per vase. The vases were maintained with the humidity at 60% of the TPV (Freire et al., 1980) through the daily weighing of the vases and the addition of deionized water. The cultivar of the common bean plant used was ESAL 168. Topdressing fertilization with N and K were conducted according to the growth of the plants. The treatments received 200 and 170 mg dm^{-3} of N and K, respectively, parceled out in seven applications, in addition to the application of 20 mg of sulphur.

Plant and measurement

The first mature leaves at the tip of the common bean plant branch were collected at the onset of flowering (Malavolta et al., 1997) from each vase and the whole plants were harvested at the physiological maturation of the grains by cutting the plants at ground level. The vegetable matter was dried in a forced-air oven at a temperature between 65 and 70°C and ground in Willey-type mill. The total P content was determined through the mineralisation with nitric-perchloric digestion (Malavolta et al., 1997) and the extracts were measured using colorimetry (Braga and Defelipo, 1974). The aerial part dry matter (APDM) and grains dry matter (GDM) were determined in the plants harvested at the end of the growth cycle. The P accumulated in the aerial part was calculated by multiplying the APDM value by the content of P and dividing this value by 1,000.

Phosphorus fractionation in the soil

The phosphorus fractionation in soil was carried before and after the common bean cultivation, the collection of samples were carried out in each experimental units to analytical determinations and for Hedley sequential Po (P organic) and Pi (P inorganic) fractionations

(resin-Pi, NaHCO$_3$-Po, NaHCO$_3$-Pi, NaOH 0.1M-Po, NaOH 0.1M-Pi, NaOH 0.5M-Po, NaOH 0.5M-Pi, HCl-Pi, and residual-Pi), following the methodology of Hedley et al. (1982). The P forms were determined as follow: labile P forms (resin-Pi, NaHCO$_3$-Po, and NaHCO$_3$-Pi), moderately labile (NaOH 0.1M-Po, NaOH 0.1M-Pi, NaOH 0.5M-Po, and NaOH 0.5M-Pi), and stable P fractions (HCl-Pi, and residual-Pi).

Statistical analysis

The variables evaluated in the experiment were submitted to the analysis of variance (ANOVA) by the F-test (P≤0.01) using the SISVAR statistical analyses software. In the case of significant (P≤0.01) difference in Si and P fertilizer rates, the polynomial equation was adjusted. Simple Pearson's correlations were applied between P forms, soil organic and inorganic P fractions with APDM, DMG, and P-APDM.

RESULTS AND DISCUSSION

Soil inorganic phosphorus (Pi) fractions

The variables (P and Si fertilizer rates) showed significant interactions in the results of Pi fractions in the soil. Inorganic P in NaOH 0.5M, residual-Pi and HCl-Pi even with significant effects of the interactions did not adjust any equation to the data. The labile inorganic P fractions, NaHCO$_3$-Pi, HCl-Pi and resin-Pi were the lower soil P fractions, which were expected due to high weathering in Oxisol (Table 3).

The NaOH 0.1M-Pi and NaOH 0.5M-P$_i$ considered moderately labile for plants showed higher concentration in comparison to labile fraction, as well as observed by Tiessen et al. (1984). These results confirmed the presence of Fe/Al oxy-hydroxides, as goethite and gibbsite, and clay mineralogy composed by kaolinite

Table 3. Soil inorganic P fractions after common bean cultivated.

Treatment[1]	Inorganic P fractions (mg dm^{-3})				
	Resin-Pi (%)	NaHCO$_3$-Pi (%)	NaOH 0.1 M-Pi (%)	NaOH 0.5 M-Pi (%)	HCl-Pi (%)
P$_0$Si$_0$	2.7 (+69)	23.5 (+91)	63.5 (+22)	90.6 (+17)	5.1 (+87)
P$_0$Si$_{330}$	1.7 (+17)	15.8 (+90)	59.3 (+17)	96.0 (+26)	2.4 (+70)
P$_0$Si$_{560}$	1.6 (+46)	9.4 (+85)	58.5 (+25)	99.7 (+30)	2.2 (+80)
P$_{110}$Si$_0$	4.4 (-9)	6.0 (-6)	109.0 (+15)	114.7 (+25)	2.4 (+26)
P$_{110}$Si$_{330}$	5.3 (+19)	6.3 (-16)	100.8 (+17)	105.3 (+18)	3.0 (+29)
P$_{110}$Si$_{560}$	4.3 (-43)	5.6 (-21)	101.1 (+4)	105.1 (+19)	3.0 (+33)
P$_{330}$Si$_0$	19.4 (-39)	28.0 (-6)	190.8 (-3)	133.2 (+22)	4.3 (+40)
P$_{330}$ Si$_{330}$	16.2 (-52)	30.5 (-13)	185.9 (-6)	129.1 (+18)	3.6 (+23)
P$_{330}$Si$_{560}$	26.3 (-22)	26.5 (-13)	182.7 (-7)	133.9 (+21)	9.1 (+73)
P$_{560}$Si$_0$	71.2 (+13)	51.4 (-15)	215.3 (-11)	145.9 (+11)	6.4 (+41)
P$_{560}$Si$_{330}$	70.3 (+7)	57.8 (-11)	227.5 (-5)	138.1 (+9)	5.6 (+31)
P$_{560}$Si$_{560}$	79.3 (-3)	62.0 (-8)	173.4 (-38)	143.2 (+14)	7.8 (+53)
CV.(%)	9.33	3.26	7.70	22.26	13.52
Soil form native vegetation	1.68	1.13	40.42	2.83	25.05

[1]The rates of Si and P-fertiliser applications are in mg dm^{-3}. Values between parentheses indicate percentage of decreasing (-) or increasing (+) in the P fractions after the common bean cultivation.

(Table 1), may result in high capacity of generated bond highly energetic with P. Thus, the NaOH 0.1M-P$_i$ and NaOH 0.5M-P$_i$ fractions act as sink for the P fertilizer in soil. Furthermore, the absence of P fertilizer and the 110 kg P$_2$O$_5$ ha^{-1} showed the lowest resin-P due to majority uptake and exportation by common bean plant and low replacement of the Pi uptake to the soil solution.

The rates of P fertilizer increased the availability of Pi in the labile (resin-P and NaHCO$_3$-Pi) and moderately labile fractions (NaOH 0.1M-P$_i$) (Figure 1); these results indicated that the application of P fertilizer saturated the adsorption site of P, as it was observed by Conte et al. (2003). The rates of silicate fertilizer increased the availability of Pi before the cultivation of common bean. Possibly, the Si fertilizer applied increased the availability of Pi due to decreasing of bond energy of phosphate to soil colloids (Carvalho et al., 2001). The labile (resin-Pi and NaHCO$_3$-Pi) and moderately labile fractions (NaOH 0.1M-P$_i$) decreased after common bean cultivated (Figure 1), which may reassure the increase in P availability and uptake by common bean plant with the application of Si fertilizer, which was more evident in the treatments with higher rates of P fertilizer (Table 3). The uptake of P by common bean from resin-Pi and NaHCO$_3$-Pi fractions ensure the lability of these Pi fractions (Figure 1), as well as attained by Hedley et al. (1982).

As reported by Lilienfein et al. (2000), the effects of P uptake by plant in short-time are more evident in labile and moderately labile P fractions. In relation to NaOH 0.1M-Pi and NaOH 0.5M-Pi, moderately labile fractions, this comprises the P bound in Fe/Al oxy-hydroxides, the content of both fractions increased with the increment of P fertilizer rates. These increase in moderately labile

fractions indicated that these fractions accumulate the excess of P fertilizer applied. As reported by Tokura et al. (2011), the moderately labile fractions (NaOH 0.1M-Pi and NaOH 0.5M-Pi) act as sink of P in the soil, majority in the soils with high content of Fe and Al oxy-hydroxides.

The highest content of NaOH 0.5M-Pi after common bean cultivated may be associated with more time of contact between Pi from fertilizer applied and Fe/Al oxy-hydroxides in the soil. The soil of the experiment had high content of Fe/Al oxy-hydroxides (Table 1); these oxides pursue high capacity of P immobilization forming complex of high energy and hard reversibility (Tokura et al., 2002, 2011). Nevertheless, these moderately labile fractions may show lability, working as a factor of the buffer amount of soil P (Rheinheimer et al., 2000).

The decrease of NaOH 0.1M-P$_i$ after common bean cultivated suggested this fraction as the major buffer amount of the labile fractions, which may replace the P in soil solution after plant uptake extract. This fact may be reassured by the significant and positive correlation of NaOH 0.1M-P$_i$ with aerial part dry matter (APDM), grain dry matter (GDM) and phosphorus accumulated in P-APDM (Table 4). The content of P extracted with HCl showed little modifications with the application of P fertilizer (Table 3), indicating little amount of P from fertilizer accumulates in the stable P fraction (HCl-P). The HCl extract preferably the P bound in Ca, however, in Oxisol due to weathering the Ca exchangeable tend to be small, resulting in small content of P bound with Ca. Nevertheless, the cultivation of common bean increased the content of P extracted by HCl, indicating that a small part of the P fertilizer accumulated in HCl-P fraction, which did not contribute to common bean nutrition as
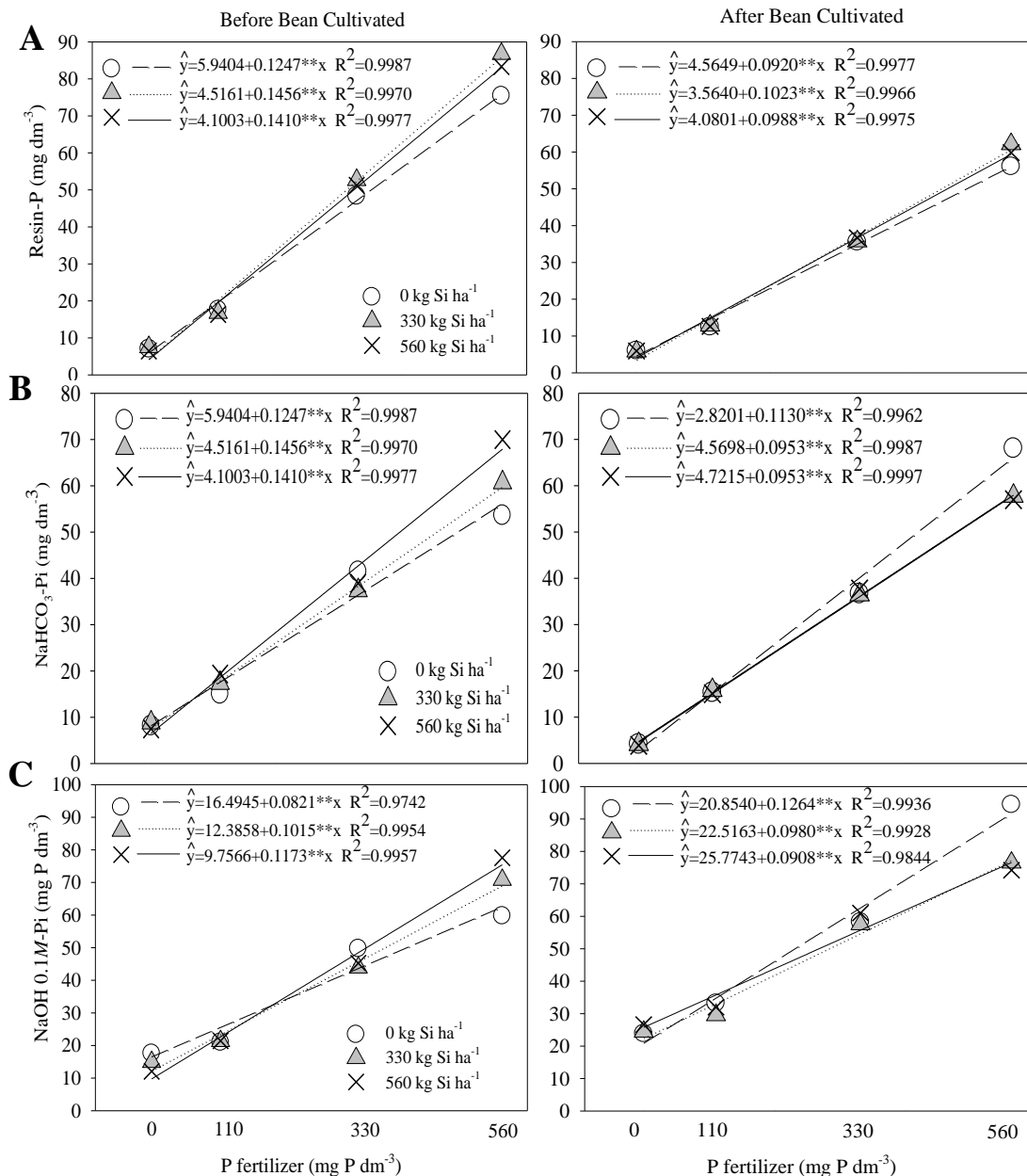
Before Bean Cultivated   After Bean Cultivated

Figure 1. Soil inorganic P fractions affected by P and Si fertilizer rates under common bean cultivation.

observed in Table 4, due to absence of correlation with APDM, GDM and phosphorus in the P-APDM.

Comparing the soil P content extracted to HCl before and after common bean cultivation, decrease in HCl-P content after common bean cultivation was observed (Table 3). Possibly, the decrease may be associated with common bean uptake of Ca and P through the plant cycle, which may favored the dissolution of Ca phosphates. As reported by Novais et al. (2007), soil with higher cations exchange capacity (CEC) and higher soil organic matter may increase the capacity of Ca sink, thus favours the dissolutions of Ca phosphates.

Soil organic P fractions

The treatments (Si and P fertilizer rates) evaluated showed significant (p<0.01) interactions. The data of NaOH 0.5M-Po fraction did not adjust regression equations even with the significant effect of P fertilizer rates. The NaOH 0.1M-Po fraction predominates organic P fractions, in accordance with Cassagne and Remaury (2000). Before or after common bean cultivation, the Po decreased with the increase in P fertilizer rates (Figure 2).

The reduction may be due to higher organic matter

Table 4. Person´s correlations between P fractions and forms with the dry matter aerial part (DMAP), grain dry matter (GDM), P accumulate in DMAP (P-DMAP).

P fractions and forms	DMAP	GDM	P-DMAP
Resin-Pi	0.92**	0.94**	0.83**
NaHCO$_3$-Pi	0.92**	0.94**	0.84**
NaHCO$_3$-Po	0.50**	0.56**	0.50**
NaOH 0.1M-Pi	0.90**	0.92**	0.83**
NaOH 0.1M-Po	-0.57**	-0.55**	-0.43**
NaOH 0.5M-Pi	0.53**	0.60**	0.57**
NaOH 0.5M-Po	0.02^{ns}	-0.01^{ns}	0.14^{ns}
HCl-Pi	-0.16^{ns}	-0.13^{ns}	-0.06^{ns}
Residual-Pi	-0.28n^s	-0.21^{ns}	-0.21^{ns}
Labile-P[1]	0.92**	0.94**	0.84**
Moderately labile-P[2]	0.64**	0.63**	0.69**
Stable-P[3]	-0.30^{ns}	-0.23^{ns}	-0.23^{ns}

**Significant at 1% of probability. *Significant at 5% of probability. NS: No-significant. [1]Labile P forms (resin-Pi, NaHCO$_3$-Po, and NaHCO$_3$-Pi), [2]moderately labile (NaOH 0.1M-Po, NaOH 0.1M-Pi, NaOH 0.5M-Po, and NaOH 0.5M-Pi), and [3]stable P fractions (HCl-Pi, and residual-Pi).
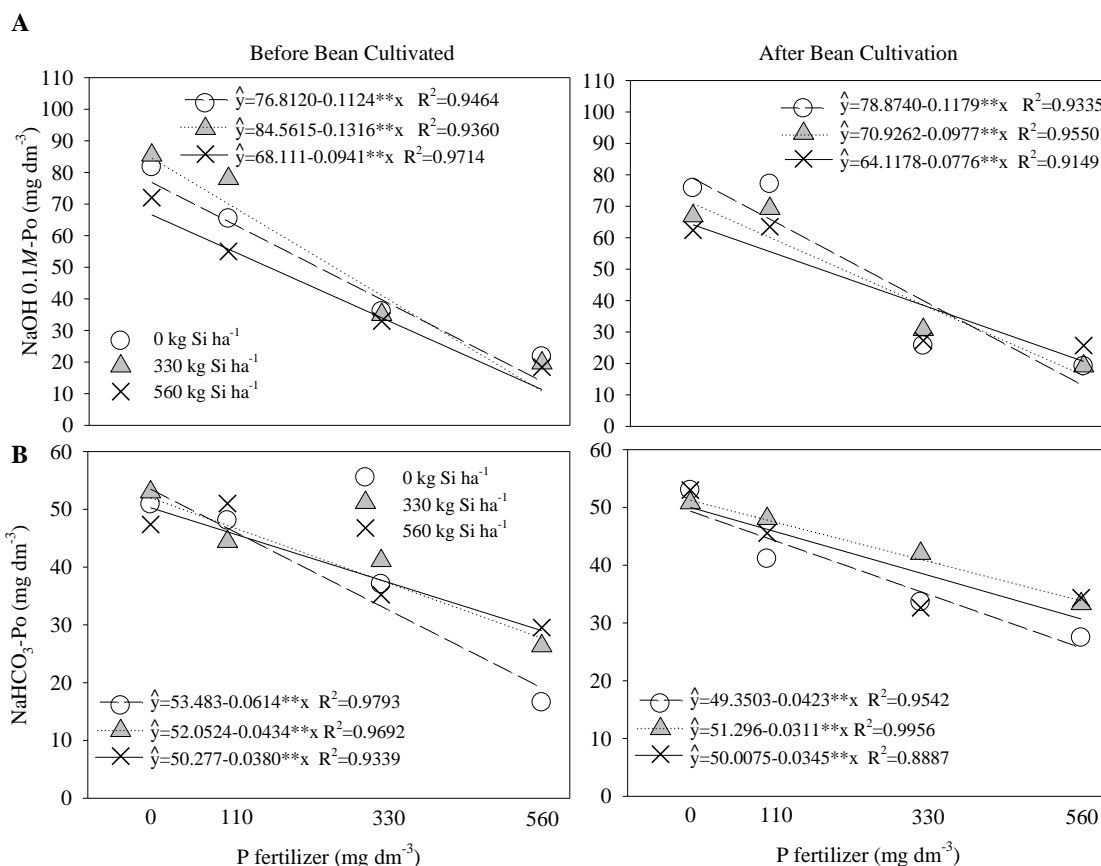

Figure 2. Soil organic P fractions affected by P and Si fertilizer under common bean cultivation.

mineralization promoted by increase in P content and uptake of P by plants (Araújo et al., 1993; Tokura et al., 2011). The decrease in Po fractions was higher than Pi fractions (Table 3). This can occur because of the

Table 5. Soil organic P fractions after common bean cultivated.

Treatment[1]	Po fractions		
	NaHCO$_3$-Po	NaOH 0.1 M-P$_o$	NaOH 0.5 M-P$_o$
	mg dm^{-3}		
P$_0$Si$_0$	16.7 (-76)	54.2 (-18)	7.0 (-78)
P$_0$Si$_{330}$	22.6 (-60)	59.1 (-28)	4.8 (-86)
P$_0$Si$_{560}$	17.2 (-60)	55.7 (+37)	8.8 (-64)
P$_{110}$Si$_0$	21.9 (-21)	43.5 (-61)	10.9 (-74)
P$_{110}$Si$_{330}$	17.1 (-18)	48.8 (-60)	8.9 (-78)
P$_{110}$Si$_{560}$	13.3 (-2)	60.6 (-43)	12.6 (-63)
P$_{330}$Si$_0$	7.9 (-25)	14.8 (-86)	13.3 (-65)
P$_{330}$ Si$_{330}$	9.7 (-57)	24.0 (-72)	12.3 (-74)
P$_{330}$Si$_{560}$	11.1 (-64)	22.5 (-74)	11.6 (-80)
P$_{560}$Si$_0$	4.5 (-81)	94.3 (-37)	9.9 (-92)
P$_{560}$Si$_{330}$	3.3 (-87)	53.2 (-64)	7.6 (-85)
P$_{560}$Si$_{560}$	1.9 (-92)	102.80 (-4)	18.9 (-63)
C.V. (%)	14.12	11.96	10.40
Soil form native vegetation	48.81	183.84	69.20

[1]The rates of Si and P-fertilizer applications are in mg dm^{-3}. Values between parentheses indicate percentage of decreasing (-) or increasing (+) in the P fractions after the common bean cultivation.

association of Po accumulation with the increase in soil organic matter; what did not occur during the experimental time. Besides, the NaHCO3-Po fractions are related to the organic compounds of easy decomposition, which sustains and is regulator by microbial biomass of soil (Lourente et al., 2016). Seybold et al. (1999) reported that transformation of Pi to Po in clay soils is more difficult than sand soil, due to higher activity of adsorptions site in clay soils conferring to clay soil lower resilience than sand soil. This performance was observed in the results (Tables 3 and 4), which resulted in higher proportion of Pi fractions than Po fractions. As reported by Kämpf and Curi (2000), the organic compounds imply an inhibitor effect in the crystallization process of Fe/Al oxy-hydroxides favoring the formation of microcrystalline forms with high specific surface.

The specific surface has the capacity of P adsorption, but many organic compounds are concurrent with orthophosphates by the adsorptions sites (Lopez-Hernandez et al., 1986; Guedes et al., 2016). Tokura et al. (2002) reported lower P desorption in the mineral soil fraction with the increase of weathering process which compensated the increase of soil organic matter participation in supply P for plants uptake. Thus, the Po fractions may have relevant participation as source of P for plants uptake, through the release of P from mineralization of Po (Novais and Smyth, 1999; Cunha et al., 2007).

Even though the reactions of precipitation and P adsorption which regulates retention and releases P in the soil; generally, these reactions act with great intensity and fast, the mineralization remains of the organic compounds of P and also contributes to the remains in the medium-term and long-term of the levels of labile P in the soil available for plants (Novais et al., 2007). The negative and significant results of correlation between the NaOH 0.1M-Po and APDM, GDM and phosphorus in APDM (Table 4), indicate these fractions buffer the labile P fractions in soil, once the decrease in NaOH 0.1M-Po after the common bean cultivation (Table 5). All the Po fractions decreased its content, even in the treatment with absence of P fertilizer (Table 5). Thus, the P bound in soil organic matter compounds can be considered the major quantity factor of P in no fertilizer soil. While in soil P fertilizer, the balance of P in solution remained by both Po and Pi fractions.

Phosphorus forms in the soil

The moderately labile and stable forms of P were predominant (Table 6), which is in accordance with the fact of the magnitude of P adsorption depending on quantity of constituents with capacity of adsorption molecules in soil. Oxisols tend to prime the Pi fractions bound to mineral fractions with high energy and the inorganic forms stabilized physically and chemically (Rheinheimer et al., 2008).

The results indicate that the application of P fertilizer accumulated majority in moderately labile and stable P fractions. The P forms in the soil were affected after common bean cultivation. The decrease of P after common bean cultivation occurred in the labile and moderately labile P fractions (Figure 3). The reduction of

Table 6. Soil phosphorus forms after common bean cultivated.

Treatment[1]	P forms		
	Labile P[2]	Moderately labile P[3]	Stable P[4]
	mg dm^{-3}		
P_0Si_0	42.9 (-41)	215.4 (-3)	443.0 (+14)
P_0Si_{330}	40.1 (-33)	219.2 (-7)	459.0 (+19)
P_0Si_{560}	28.3 (-37)	222.8 (+22)	431.6 (+11)
$P_{110}Si_0$	32.3 (-17)	278.0 (-16)	439.7 (+10)
$P_{110}Si_{330}$	28.7 (-6)	263.8 (-21)	439.2 (+6)
$P_{110}Si_{560}$	23.3 (-18)	279.4 (-13)	405.3 (+7)
$P_{330}Si_0$	55.4 (-23)	352.1 (-21)	432.86 (+5)
$P_{330}Si_{330}$	56.3 (-38)	351.3 (-20)	444.1 (+7)
$P_{330}Si_{560}$	63.9 (-33)	350.7 (-21)	423.6 (+1)
$P_{560}Si_0$	127.1 (-13)	465.4 (-29)	417.4 (-0.4)
$P_{560}Si_{330}$	131.4 (-15)	426.4 (-24)	421.8 (+11)
$P_{560}Si_{560}$	143.3 (-17)	438.3 (-22)	418.1 (+18)
C.V. (%)	7.56	4.36	17.36
Soil from native vegetation	51.62	296.29	186.72

[1]The rates of Si and P-fertilizer applications are in mg dm^{-3}. [2]Labile P forms (resin-P, NaHCO$_3$-Po, and NaHCO$_3$-Pi), [3]moderately labile (NaOH 0.1M-Po, NaOH 0.1M-Pi, NaOH 0.5M-Po, and NaOH 0.5M-Pi), and [4]stable P fractions (HCl-Pi, and residual-Pi). Values between parentheses indicate percentage of decreasing (-) or increasing (+) in the P fractions after the common bean cultivation.
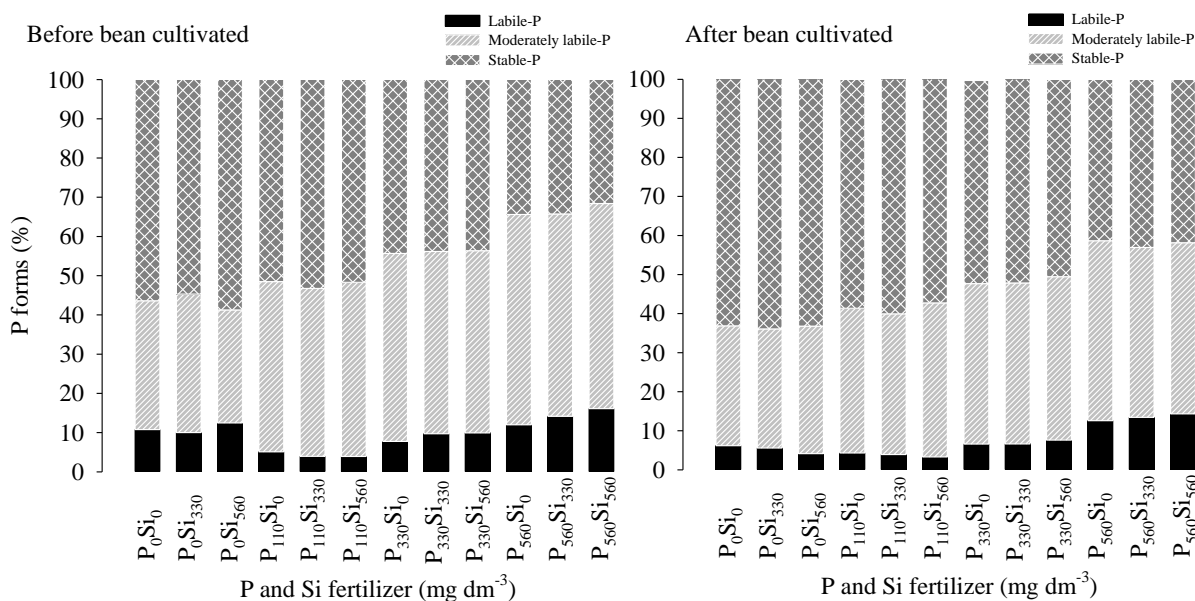

Figure 3. Effects of Si and P-fertilization on soil P fractions before and after common bean cultivated. [1]Labile P forms (resin-Pi, NaHCO$_3$-Po, and NaHCO$_3$-Pi), [2]moderately labile (NaOH 0.1M-Po, NaOH 0.1M-Pi, NaOH 0.5M-Po, and NaOH 0.5M-Pi), and [3]stable P fractions (HCl-Pi, and residual-Pi).

P is the consequence of the plant uptake due to the positive correlation between the labile and moderately labile P fraction with the APDM, GDM and P accumulated in the aerial part (Table 4). As reported by Rheinheimer et al. (2000) and Alovisi et al. (2011), the moderately labile P fraction is dynamic and participates in the availability of P for plant nutrition once moderately labile fraction decreased its participation in total P in soil through time. On the other hand, increment occurred in stable P forms (Figure 3); this P form did not contribute to common bean nutrition as observed by the absence of correlation between stable P forms with APDM, GDM,

and P accumulated in P-APDM (Table 4).

Generally, the P fertilizer applied was slowly redistributed to moderately labile and stable P forms in the soil due to the reactions with clay-minerals and Fe/Al oxy-hydroxides in the soil. As reported by Novais and Smyth (1999), the contact of P in soil with clay-minerals and Fe/Al oxy-hydroxides through time results in formation of inter sphere complex with high energy of bound. The Si fertilizer affected little quantity the alteration in P forms (Table 6). The preview application of Si fertilizer did not contribute to decrease P fixation. Possibly, the silicate has lower affinity with the bound sites of adsorption than phosphates. Carvalho et al. (2001) observed in soil less weathering higher effects of Si in desorption of P than in soil more weathering as the case of Oxisol.

The moderately labile and stable P forms showed higher amount of P (Figure 3), which is related to high amount of Fe/Al oxy-hydroxides in the soil. The total content of P after common bean cultivation was higher than in the soil without P fertilizer. Basically, the highest amount of total P is due to the exportation by grain to be less than the amount of P fertilizer applied. The increase in total P content may affect some soil chemical as: the natural balance among P forms in soil, its relations with the other nutrients, the microbial biomass, and the rate transfer among environments (Sharpley et al., 1995).

Conclusions

The preview application of Si fertilizer did not contribute to decrease desorption of P in soil. Possibly, the silicate has lower affinity with the bound sites of adsorption than phosphates. The P fertilizer applied increase majority the moderate labile P fraction followed by labile P fraction. Among the organic P fractions, the $NaHCO_3$-Po fraction was the only one that contributed to the plant nutrition. The Hedley sequential fractionation promoted information about different pools where P was accumulated in the soil after common bean cultivation. The highest amount of P was obtained in stable P fraction, followed by moderately labile and labile P fraction. The moderately labile P fraction decreased after common bean cultivation possibly due to the contact time and redistribution to stable P fraction. The labile form was the lowest P pool in soil; nevertheless, the increase in P fertilizer rates increases the amount of P in labile fraction.

Conflict of interests

The authors have not declared any conflict of interests.

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