

Dynamic of Phosphorus Fractions in Typic Quartzipsamment Soil Cropped With Bean

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Abstract

Phosphorus is the most limited nutrient in Brazilian soils for plant growth, resulted of low availability and poor P content in bedrock. The aim of the study was to evaluate the dynamic of P fractions in a sand soil typical Quartzipsamment cropped with common bean under the effects of P and Si-fertilizer rates. The research was carried out in a soil with sand texture and clay mineralogy constituted mainly by kaolinite, classified as Neossolo Quartzarênico Órtico típico (RQo). 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). The experimental design used was entirely random, arranged in a 4 × 3 factorial design, with four repetitions, with amount of 48 experimental units. The treatments included four P rates (0, 80, 240 and 410 mg dm⁻³) and four Si rates (0, 240 and 410 mg dm⁻³). Phosphorus fractions in soil are little affected by Si-fertilizer rates. P uptakes by bean plants are correlated to the labile and moderately labile fractions. P-fertilizer rates increment majority the stable P fraction in soil and in lower proportion the labile and moderately labile P fractions in soil. Po-NaHCO₃ is the only that contributes to bean plant nutrition.

Keywords: P and Si-fertilizer, P fractionation, *Phaseolus vulgaris*

1. Introduction

Brazilian soil is composed basically by soil with natural low fertility, and among these soils, great amount are composed by typic quartzipsamment soil, considered as low crop production potential due to intrinsic features: sand granulometry, low nutrient availability and high drainage (Albuquerque, Almeida, Gatiboni, & Eltz, 2011).

Among the chemical elements, the highest constraints for crop production are imposed by phosphorus (P) limitation. P adsorption complexity and higher affinity with soil mineral components impact on nutrient availability for plants uptake. P distribution in soil is present in net crystalline of some soil mineral until more stable fractions as organic matter, which compose the total P fractions in soil that is constituted of organic and inorganic fractions. These organic and inorganic P fractions in soil are present under dynamic balance (Alovisi et al., 2016).

P adsorption is directly correlated with clay content in soil due to capacity of P adsorption in broken face of silicate clay as well as iron (Fe) and aluminum (Al) oxi-hydroxide. Furthermore, mineralogical composition of soil shows important role in soil P adsorption, which is justified by the bind energy between P and each mineralogical soil fraction (Tokura et al., 2011). Kaolinite is the major silicate mineral in expressive amount in soil highly weathering, goethite and hematite area the major Fe oxide, and gibbsite is considered the only Al oxide in highly weathering soil (Fontes, Camargo, & Sposito, 2001).

Beside the mineralogical composition of the soil, phosphate adsorption is related to the presence of anions competition for the same adsorption site in soil solution (Brait, 2008). Researches related to concentration of silicate in soil solution can promote alteration in the characteristic of phosphate adsorption in soil, resulting in decreasing the intensity of P adsorption turn P more available for plant uptake (Menegale, Castro, & Mancuso, 2015). Thus, knowledge about ionic interaction and P forms distribution in soil can offer relevant information of P dynamic in soil and plant, improving the evaluation process of soil availability (Tokura et al., 2011; Alovisei et al., 2016). The knowledge of P dynamic can help in guide soil fertilizer recommendation for crops and the possible silicate affects can contribute for increasing P availability and possible decreasing P fertilizer rates.

P distribution can be estimated by fractionation method, based on extractors with different extractions. The most used method was proposed by Hedley, Stewart, and Chauhan. (1982), which allows to obtain information about P availability in short-term and long-term, by means of P content determination with many degrees of availability using extractor sequencing of lower to higher extraction strength, resulting in removing P from the more available to the less available form.

The aim of the study was to evaluate the dynamic of P fractions in a sand soil typical Quartzipsamment cropped with common bean under the effects of P and Si-fertilizer rates.

2. Materials and methods

2.1 Location and Soil Description

The research was carried out in a soil with sand texture and clay mineralogy constituted mainly by kaolinite, classified according to Santos et al. (2013) as Neossolo Quartzarênico Órtico típico (RQo) [Quartzipsamment (Soil Taxonomy)]. 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).

2.2 Soil Properties Evaluations

The soil was collected in 0-20 cm depth under native vegetation of Brazilian Cerrado biome, located in city of Itutinga, state of Minas Gerais, Brazil. After collection, the soil was air-dried, brokes 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).

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

In the free clay, gibbsite and kaolinite contents were quantified using differential thermal analysis. Soluble Si in the soils was determined 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 on Table 1.

2.3 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, 80, 240 and 410 mg dm⁻³) and four Si rates (0, 240 and 410 mg dm⁻³). The P fertilizer rates were defined by the remaining P (Alvarez, Novais, Dias, & Oliveira, 2000). Vases with a soil capacity of 3 dm³ were filled with 2.7 dm³ 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, Ribeiro, Bahia, Lopes, & Aquino, 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 H₄SiO₄ (60% SiO₂) at the rates of 0, 110 and 410 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 ; $(\text{NH}_4)_2\text{HPO}_4$; NH_4NO_3 ; KH_2PO_4 ; H_3PO_4 ; $\text{MnSO}_4 \cdot 2\text{H}_2\text{O}$; $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$; $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$; $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$; $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 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 done 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.

Table 1. Chemical, physical and mineralogical soil properties

Soil properties	Quartzipsamment
$\text{pH}_{\text{H}_2\text{O}}$	5.0
Al^{3+} ($\text{cmol}_c \text{ dm}^{-3}$)	0.9
Ca^{+2} ($\text{cmol}_c \text{ dm}^{-3}$)	0.4
Mg^{2+} ($\text{cmol}_c \text{ dm}^{-3}$)	0.1
K^+ (mg dm^{-3})	23.0
$\text{H}^+ + \text{Al}^{3+}$ ($\text{cmol}_c \text{ dm}^{-3}$)	4.5
Mehlich1-P (mg dm^{-3})	6.8
Resin-P (mg dm^{-3})	5.4
SB ($\text{cmol}_c \text{ dm}^{-3}$)	0.6
Effective CEC ($\text{cmol}_c \text{ dm}^{-3}$)	1.5
CEC to pH 7.0 ($\text{cmol}_c \text{ dm}^{-3}$)	5.1
BS (%)	12.0
m (%)	60.0
OM (dag kg^{-1})	1.7
Si (mg dm^{-3})	1.3
B (mg dm^{-3})	0.3
Cu (mg dm^{-3})	1.0
Fe (mg dm^{-3})	60.2
Mn (mg dm^{-3})	6.4
Zn (mg dm^{-3})	0.1
Coarse sand (g kg^{-1})	470.0
Thin sand (g kg^{-1})	460.0
Silt (g kg^{-1})	10.0
Clay (g kg^{-1})	60.0
SiO_2 (g kg^{-1})	31.0
Al_2O_3 (g kg^{-1})	36.0
Fe_2O_3 (g kg^{-1})	11.0
TiO_2 (g kg^{-1})	5.0
P_2O_5 (g kg^{-1})	0.0
Fe_d (g kg^{-1})	2.0
Fe_o (g kg^{-1})	0.1
Ct (g kg^{-1})	778.0
Gb (g kg^{-1})	59.0

Note. CEC: Cation Exchange Capacity; total acidity pH 7.0 ($\text{H}^+ + \text{Al}^{3+}$); Exchangeable (KCl 1 mol L^{-1}) Ca^{2+} , Mg^{2+} and Al^{3+} ; BS: Base Saturation = $(\sum \text{cations}/\text{CEC}) \times 100$; Ct: kaolinite; Gb: Gibbsite.

2.4 Plant Material and Measurement

The first mature leaves at the tip of the common bean plant branch were collected at the onset of flowering (Malavolta, Vitti, & Oliveira, 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 & 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.

2.5 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, NaHCO₃-Po, NaHCO₃-Pi, NaOH 0.1 M-Po, NaOH 0.1 M-Pi, NaOH 0.5 M-Po, NaOH 0.5 M-Pi, HCl-Pi, and residual-Pi), following methodology of Hedley et al. (1982). The P forms were determined as follow: labile P forms (resin-Pi, NaHCO₃-Po, and NaHCO₃-Pi), moderately labile (NaOH 0.1 M-Po, NaOH 0.1 M-Pi, NaOH 0.5 M-Po, and NaOH 0.5 M-Pi), and stable P fractions (HCl-Pi, and residual-Pi).

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

Treatments 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 ₀ Si ₀	5.4	119	1.9	1.1	0.2	2.4	5.7	4.7	58.1	13.9	2.63
P ₀ Si ₂₄₀	5.4	118	2.0	1.0	0.1	2.3	5.7	4.0	59.4	13.6	6.67
P ₀ Si ₄₁₀	5.3	121	1.8	1.3	0.2	2.4	5.8	6.0	58.7	14.2	8.00
P ₈₀ Si ₀	5.4	117	1.8	1.2	0.2	0.4	5.7	6.0	58.1	27.5	2.63
P ₈₀ Si ₂₄₀	5.2	117	1.8	1.2	0.2	0.5	5.7	6.0	56.0	27.2	6.35
P ₈₀ Si ₄₁₀	5.3	114	1.8	1.0	0.2	2.6	5.6	6.0	53.5	28.8	8.60
P ₂₄₀ Si ₀	5.3	112	1.7	1.2	0.2	2.7	5.8	5.0	53.2	73.4	2.84
P ₂₄₀ Si ₂₄₀	5.1	113	1.7	1.1	0.2	2.9	6.0	6.0	51.7	73.3	6.11
P ₂₄₀ Si ₄₁₀	5.1	122	1.9	0.9	0.2	3.0	6.1	6.0	50.9	76.0	6.45
P ₄₁₀ Si ₀	5.2	112	1.8	1.1	0.2	2.9	6.1	6.0	52.1	113.4	3.89
P ₄₁₀ Si ₂₄₀	5.2	111	1.6	1.2	0.2	3.0	6.2	5.0	51.2	113.7	6.84
P ₄₁₀ Si ₄₁₀	5.2	114	1.8	1.2	0.1	3.2	6.5	3.0	50.7	124.4	5.82

Note. ¹ The rates of P and Si are in mg dm⁻³. CEC: Cation Exchange Capacity; total acidity pH 7.0 (H⁺ + Al³⁺); Exchangeable (KCl 1 mol L⁻¹) Ca²⁺, Mg²⁺ and Al³⁺; BS: Base Saturation = (Σcations/CEC) × 100; Si: silicon.

2.6 Statistical Analysis

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

3. Results and Discussion

3.1 Soil Inorganic Phosphorus (Pi) Fractions

Significant interactions ($P < 0.01$) were observed among the three factors in study for inorganic P in soil. Phosphorus fertilizer increased P content extracted by anionic exchange resin (Pi-resin), NaHCO₃ (Pi-NaHCO₃) and NaOH 0.1 (Pi_NaOH 0.1) (Table 3), which showed higher accumulation of Pi in fraction Pi_NaOH 0.1, indicating the excess of P-fertilizer can be accumulated in this fraction. These results confirm that Fe and Al oxides as goethite and gibbsite, and kaolinite promote higher bind capacity with P, than this fraction acts as sink of Pi applied.

Bean cropping decreased the labile fractions (P-resin and Pi- NaHCO₃) in the most treatments assessed (Table 3), confirmed the lability of these fractions (Hedley et al., 1982). As reported by Lilienfein et al. (2000), the influence of crop cultivation is more affected in higher available Pi fractions.

The Pi-NaOH 0.1 fraction increased after cultivating bean, indicating that this fraction does not contribute for bean uptakes and nutrition (Table 3), which can be considered low available to plants and its availability depends on soil chemical properties. The Pi-NaOH 0.5 fraction was the majority buffering of the labile fractions, and lower clay content explain the generalized reduction of Pi-NaOH 0.5 fraction, which is the most labile fraction observed. As observed by Santos et al. (2008) and Alovizi et al. (2016), the lower labile fraction participated in P supply for plants, proved by its decreasing in total P through time of P-fertilizer.

Silic (Si) fertilizer promoted higher P availability for plant uptakes under lower P-fertilizer rates, consequently decreased Pi-NaOH 0.5 fraction (Table 3). The increment in P availability due to Si-fertilizer resulted in a positive correlation between Pi-NaOH 0.5 fractions with dry matter of area part (DMAP), grain dry matter (GDM) and P accumulate in DMAP (P-DMAP) (Table 4). Possibly the mechanism of silicate in improving P availability can be associated with its capacity of Pi desorption in solid soil surface (Prado & Fernandes, 2001). The Si-fertilizer may be increased the availability of P due to lower linked energy of phosphate with inorganic colloids, resulting in decreasing the P- NaOH 0.5 fraction (Table 3). As reported by Lopes (1984), the efficiency of Si in increasing P availability in soil is associated with blocking or saturation of adsorption sites by silicate anion.

Table 3. Soil inorganic P fractions after common bean cultivated

	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	5.9 (-8%)	4.1 (-49%)	23.6 (+25%)	2.1 (-2%)	4.4 (+78%)
P ₀ Si ₂₄₀	6.5 (-14%)	4.1 (-54%)	24.4 (+38%)	2.0 (-51%)	3.1 (+67%)
P ₀ Si ₄₁₀	5.8 (-2%)	3.8 (-50%)	26.7 (+55%)	2.3 (-45%)	3.1(+59%)
P ₈₀ Si ₀	12.5 (-2%)	15.2 (+0.4%)	33.1 (+37%)	2.2 (-26%)	3.8 (+60%)
P ₈₀ Si ₂₄₀	12.5 (-29%)	15.8 (-9%)	29.9 (+29%)	1.6 (-72%)	3.2 (+49%)
P ₈₀ Si ₄₁₀	12.9 (-22%)	15.1 (-22%)	31.8 (+33%)	4.4 (-63%)	2.5 (+55%)
P ₂₄₀ Si ₀	36.4 (-28%)	36.7 (-12%)	58.2 (+15%)	2.8 (-11%)	2.5 (+18%)
P ₂₄₀ Si ₂₄₀	35.6 (-26%)	36.7 (-2%)	57.2 (+23%)	3.2 (-2%)	2.8 (+25%)
P ₂₄₀ Si ₄₁₀	35.2 (-33%)	38.1 (-3%)	60.8 (+26%)	5.4 (-34%)	2.9 (+5%)
P ₄₁₀ Si ₀	59.6 (-28%)	68.3 (+22%)	94.8 (+37%)	5.6 (-64%)	3.2 (+21%)
P ₄₁₀ Si ₂₄₀	56.2 (-25%)	57.9 (-5%)	76.9 (+7%)	4.1 (-44%)	3.9 (+45%)
P ₄₁₀ Si ₄₁₀	62.1 (-29%)	56.8 (-19%)	74.5 (-5%)	3.3 (-5%)	3.3 (+20%)
CV(%)	7.67	6.53	7.14	4.06	14.85
Soil form native vegetation	5.22	5.33	15.64	2.88	1.41

Note. 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.

Small amount of P-fertilizer was extracted in HCl (P-HCl) fraction (Table 3), indicating lower quantity of P-fertilizer accumulated in this fraction. Due to soil acidity showed in this soil, resulting in lower content of P-HCl fraction which is associated with lower Ca content and P-Ca (Walker & Syers, 1976). The P-Ca turned available to plants uptakes if soil pH decreases, or decreasing of P or Ca in soil solution (Smiley, 1974). However, increasing of P-HCl content was observed after bean cultivation, indicating that one part of P-fertilizer accumulated which suggested a new formation of Ca phosphate secondary resulted of *in situ* formation of Ca and P available, as well as Tiecher, Rheinheimer, and Calegari (2012). On the other hand, when Si-fertilizer was applied without P-fertilizer, the increment in P-HCl was observed (Table 3). Possibly the application of Si-fertilizer decreased P uptake and controlled the mineralization of P-HCl through the decreasing of Ca activity.

P-fertilizer rates increased Pi availability in higher labile fraction (P-resin and Pi- NaHCO₃) and moderated labile fraction (Pi-NaOH 0.1) (Figure 1), which is due to a process of P saturation sites (Conte, Anghinoni, & Rheinheimer, 2003). The predominant sand fraction resulted in higher availability of Pi fractions in labile fraction due to low adsorption of P. The increasing in Si-fertilizer rates resulted in higher Pi fractions in P-resin and Pi- NaHCO₃ before bean cultivation (Figure 1). Si-fertilizer application can increase the availability of P due to decrease the bound link energy of phosphate with inorganic colloids.

After bean cultivation was possible to observe reduction of P-resin and Pi-NaHCO₃ (Figure 1), this fact reinforces the higher availability of Pi uptake by bean plants with application of Si-fertilizer in soil, which was more evident with higher increment of Pi (Table 3). As reported by Lopes (1984), the efficiency of Si in

increasing Pi availability of soil is not into the anions exchange capacity by phosphate in soil, but by saturation or blocking of adsorption sites of P by silicates anions.

3.2 Soil Organic Phosphorus (Po) Fractions

The interaction effects ($p < 0.01$) were observed among three factors in study (bean cultivation, P-fertilizer and Si-fertilizer rates). The Po-NaOH 0.1 and Po-NaOH 0.5 fractions was predominant in Po extracted (Table 4), as well as observed by Cassagne and Remaury (2000).

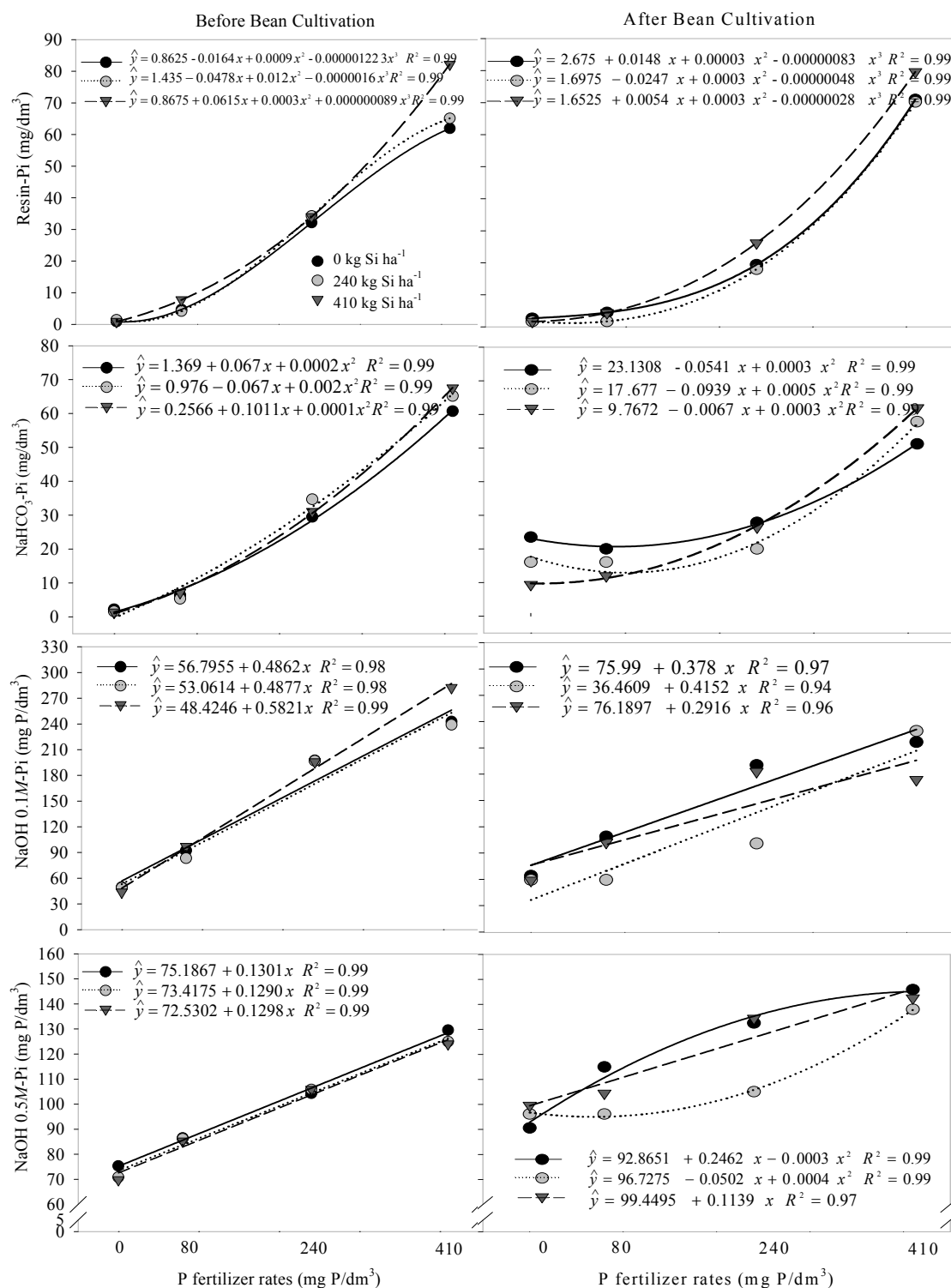


Figure 1. Soil inorganic P fractions affected by P and Si fertilizer rates under common bean cultivation

Table 4. Soil organic P fractions after common bean cultivated

Treatments 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	21.8 (-73%)	51.2 (-0.2%)	61.6 (+56%)
P ₀ Si ₂₄₀	19.0 (-75%)	33.0 (-38%)	27.7 (-35%)
P ₀ Si ₄₁₀	19.4 (-77%)	45.1 (-5%)	27.5 (-51%)
P ₈₀ Si ₀	19.0 (-71%)	50.9 (+5%)	51.0(+22%)
P ₈₀ Si ₂₄₀	18.7 (-70%)	45.8 (+4%)	26.72 (+41%)
P ₈₀ Si ₄₁₀	25.7 (-59%)	46.1 (-27%)	17.9 (-61%)
P ₂₄₀ Si ₀	26.3 (-60%)	23.4 (-38%)	30.4 (-32%)
P ₂₄₀ Si ₂₄₀	25.7 (-67%)	27.1 (-35%)	28.2 (+33%)
P ₂₄₀ Si ₄₁₀	23.5 (-72%)	32.6 (-4%)	31.1 (-37%)
P ₄₁₀ Si ₀	30.5 (-56%)	33.1 (+50%)	37.1 (+33%)
P ₄₁₀ Si ₂₄₀	21.8 (-52%)	34.9 (+24%)	47.9 (+48%)
P ₄₁₀ Si ₄₁₀	27.4 (-57%)	33.9 (+13%)	39.9 (+35%)
C. V. (%)	9.00	10.34	18.24
Soil form native vegetation	29.54	59.85	1.95

Note. 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.

Before bean cultivated, was observed increase in Po-NaOH 0.5 fraction and decreasing in Po-bicarbonate with the increase of P-fertilizer rates in soil (Table 4 and Figure 2). The reduction is due to the higher mineralization of Po promoted by phosphate addition and uptake of P by plants (Tokura et al., 2011). The Po-NaHCO₃ fraction is related with organic compounds with faster decomposition, which sustains and is regulated by soil microbial biomass, once can be quickly mineralized (Gabitoni et al., 2008a, 2008b). As reported by Seybold et al. (1999), the transformation of Pi to Po in sand soils in relation to clay soil is easier to occur, due to lower amount of adsorption site in this soil, resulting in higher resilience of sand soil than clay soil in relation to Pi for Po transformation, as observed into the results in this research higher Pi fractions in detriment of Po fractions (Tables 3 and 4).

As reported by Kämpf and Curi (2000), the organic compounds showed an effect in inhibition in the process of Fe and Al oxides crystallization, which favors the micro-crystallization of higher specific surface. As reported by Tokura et al. (2002), decreasing P desorption into mineral phase with increasing weathering is compensated by partition increasing of organic phase in P supply for plants. Thus, the organic P fraction can have relevant partition as nutrients sources by plants throughout releasing P by organic matter decomposition and mineralization (Novais & Smyth, 1999; Cunha, Gama-Rodrigues, Costa, & Velloso, 2007). Although, the precipitation reaction and adsorption of P, that regulate the retention and the P release in soil, generally act with great intensity and fastness, the permanent mineralization of organic compounds of these nutrients contribute to maintain in short and long time the levels of labile P forms in soil, available for plants (Novais et al., 2007).

The significant correlation of Po-NaOH 0.5 with the variables DMAP, DMG and P-DMAP (Table 5), indicate that this Po fraction buffer the labile P fraction, which resulted in decreasing of Po-NaOH 0.5 after bean cultivation (Figure 2). As reported by Salcedo (2006), cropping increases soil microbial activity, resulting in higher mineralization of soil organic matter. However, higher amount of Po-NaOH 0.5 was observed in soil cropped with bean in relation to native vegetation (Table 5). These results reinforce the idea of Po accumulation, which can be an important P source for plants, although it is not quantified by usual method available for P.

3.3 Forms of P in Soil

Silicon fertilizer as orthosilicic acid (H₄SiO₄) source together with P-fertilizer didn't contribute to decrease P adsorption, which supports that silicon has lower affinity with P adsorption sites. The form of labile P and moderately labile were predominant (Figure 3), what is in accordance with the fact of magnitude of adsorption of P be dependable of quantity of constituents with capacity of adsorbed molecules (Bahia Filho, Braga, Resende, & Ribeiro, 1983). The P forms in soil altered after bean cultivation, resulting in decreasing P after the cultivation in higher amount in labile forms, followed by moderately labile and stable P forms (Table 6). This decreasing in P form indicated that these P forms contribute to bean nutrition, even the stable fraction. The confirmation of this contribution is based on positive and significant correlation of Pi-NaOH 0.1, Pi-NaOH,

Po-NaOH 0.5 and P-HCl with DMAP, DMG and P-DMAP (Table5). In condition of sand soil, it is possible to infer that moderately and stable P fraction is dynamic and contribute to plant nutrition.

There was increment in stable P fraction after bean cultivation which indicates that this P form doesn't contribute to bean nutrition. The stable P forms showed negative correlation with the DMAP, DMG and P-DMAP (Table 5). The behavior of P-fertilizer showed that the P availability turn to moderately and stable P fractions, due to surface reaction of clay mineral and Fe and Al oxides, resulting in inner complex sphere (Novais & Smyth, 1999).

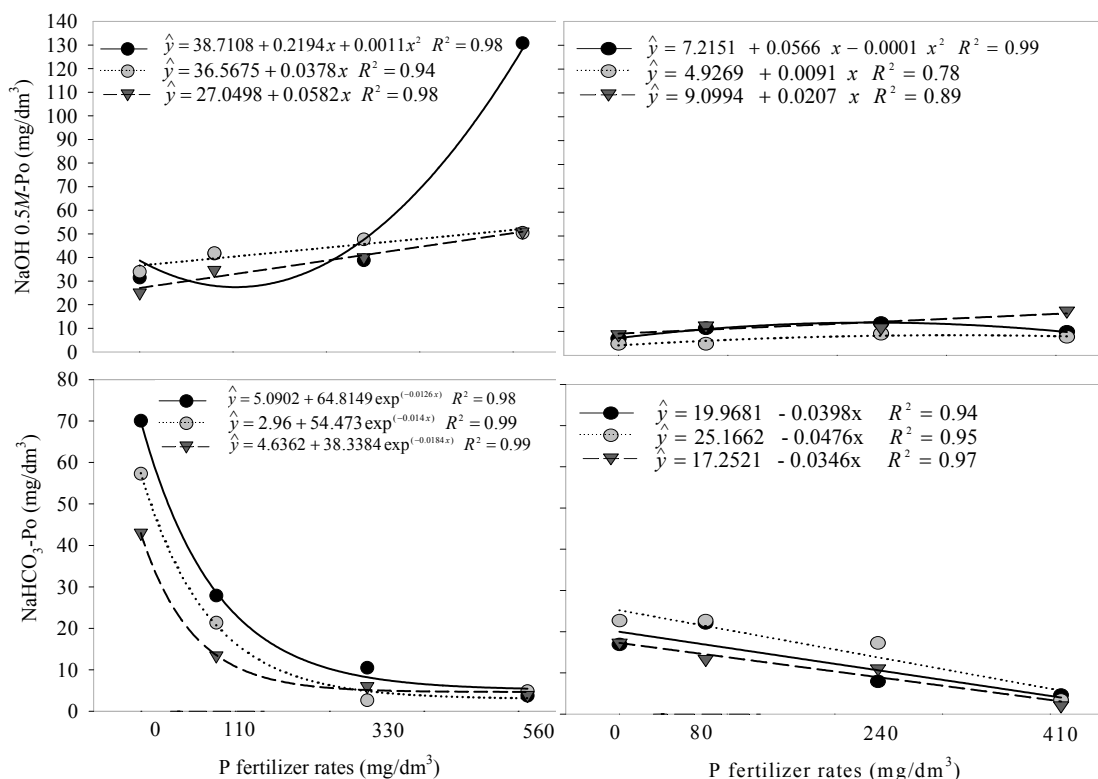


Figure 2. Soil organic P fractions affected by P and Si fertilizer under common bean cultivation

Table 5. 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	0.75**	0.76**	0.87**
NaHCO ₃ -Pi	0.75**	0.76**	0.86**
NaHCO ₃ -Po	-0.84**	-0.84**	-0.91**
NaOH 0.1 M-Pi	0.94**	0.94**	0.88**
NaOH 0.1 M-Po	0.00ns	0.00ns	0.25ns
NaOH 0.5 M-Pi	0.91**	0.94**	0.88**
NaOH 0.5 M-Po	0.48**	0.53**	0.45**
HCl-Pi	0.61**	0.67**	0.69**
Residual-Pi	-0.39*	-0.43**	-0.50**
Labile-P ¹	0.74**	0.73**	0.85**
Moderately labile-P ²	0.91**	0.90**	0.93**
Stable-P ³	-0.37*	-0.34*	-0.34*

Note. ** significant at 1% of probability. * significant at 5% of probability. NS no-significant. ¹ Labile P forms (resin-Pi, NaHCO₃-Po, and NaHCO₃-Pi), ² moderately labile (NaOH 0.1 M-Po, NaOH 0.1 M-Pi, NaOH 0.5 M-Po, and NaOH 0.5 M-Pi), and ³ stable P fractions (HCl-Pi, and residual-Pi).

Table 6. Soil phosphorus forms after common bean cultivated

Treatments ¹	P forms		
	Labile P ²	Moderately labile P ³	Stable P ⁴
	----- mg dm ⁻³ -----		
P ₀ Si ₀	31.9 (-67%)	138.4 (+29%)	20.3 (+0.5%)
P ₀ Si ₂₄₀	29.2 (-68%)	87.0 (-22%)	22.6 (+41%)
P ₀ Si ₄₁₀	29.1 (-71%)	101.6 (-13%)	24.2 (+28%)
P ₈₀ Si ₀	46.7 (-52%)	137.1 (+19%)	23.1 (+17%)
P ₈₀ Si ₂₄₀	46.9 (-52%)	104.0 (+19%)	16.9 (-19%)
P ₈₀ Si ₄₁₀	53.7 (-37%)	100.3 (-24%)	13.4 (-38%)
P ₂₄₀ Si ₀	99.5 (-37%)	114.7 (-15%)	22.2 (+13%)
P ₂₄₀ Si ₂₄₀	98.0 (-40%)	115.7 (+7%)	14.1 (-19%)
P ₂₄₀ Si ₄₁₀	96.7 (-45%)	130.0 (-3%)	17.8 (-27%)
P ₄₁₀ Si ₀	158.4 (-23%)	170.7 (+22%)	22.5 (+28%)
P ₄₁₀ Si ₂₄₀	135.8 (-25%)	163.9 (+26%)	20.1 (+31%)
P ₄₁₀ Si ₄₁₀	146.3 (-34%)	151.5 (+10%)	15.9 (-30%)
CV (%)	5.31	3.82	3.46
Soil from native vegetation	30.48	91.54	22.22

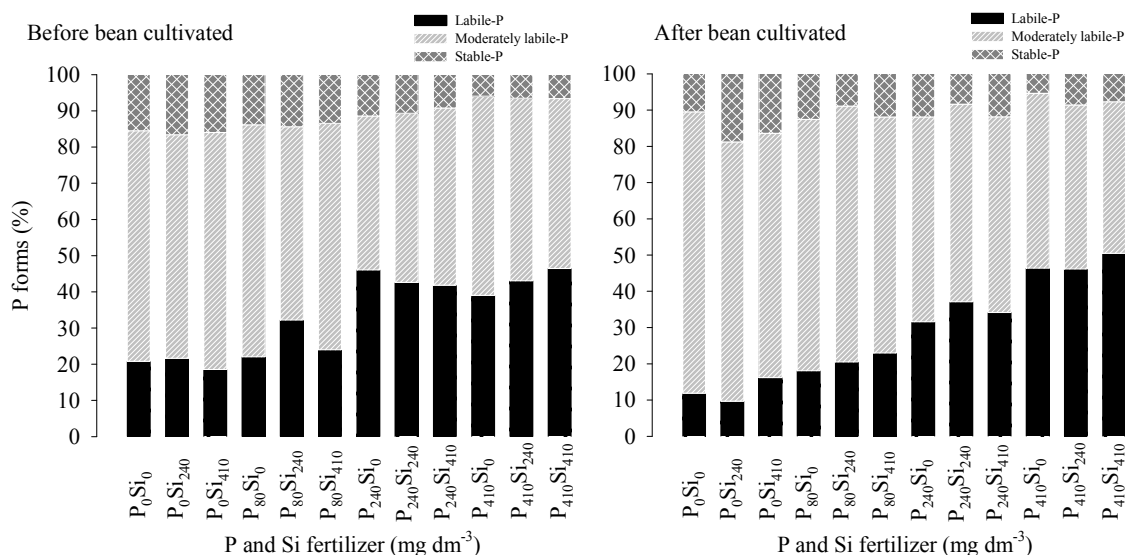


Figure 3. Effects of Si and P-fertilizer rates on soil P fractions before and after common bean cultivated. ¹Labile P forms (resin-Pi, NaHCO₃-Po, and NaHCO₃-Pi), ²moderately labile (NaOH 0.1 M-Po, NaOH 0.1 M-Pi, NaOH 0.5 M-Po, and NaOH 0.5 M-Pi), and ³stable P fractions (HCl-Pi, and residual-Pi)

4. Conclusion

Phosphorus fractions in soil are little affected by Si-fertilizer rates. P uptakes by bean plants are correlated with the labile and moderately labile fractions.

P-fertilizer rates increment majority the stable P fraction in soil and in lower proportion the labile and moderately labile P fractions in soil. Po-NaHCO₃ is the only that contribute to bean plant nutrition.

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