

# Tillage systems and cover plants change organic fractions of phosphorus in oxisol of eastern Amazonia

Rafael Silva Guedes<sup>1,\*</sup> , Luís Reynaldo Ferracciú Alleoni<sup>2</sup> , Benedito Luiz Correia<sup>3</sup> , Luis Wagner Rodrigues Alves<sup>4</sup> , Sílvia Junio Ramos<sup>1</sup> , Antonio Rodrigues Fernandes<sup>5</sup> 

1. Instituto Tecnológico Vale Desenvolvimento Sustentável – Tecnologia Ambiental – Belém (PA), Brazil.
2. Universidade de São Paulo – Escola Superior de Agricultura “Luiz de Queiroz” – Departamento de Ciência do Solo – Piracicaba (SP), Brazil.
3. Universidade Federal Rural de Pernambuco – Colégio Agrícola Dom Agostinho Ikas – São Lourenço da Mata (PE), Brazil.
4. Empresa Brasileira de Pesquisa Agropecuária – Centro de Pesquisa Agroflorestal do Amapá – Macapá (AP), Brazil.
5. Universidade Federal Rural da Amazônia – Instituto de Ciências Agrárias – Belém (PA), Brazil.

**ABSTRACT:** Due to the large extent of degraded areas in the Amazon, the use of conservation systems is very important to contain the advance of the agricultural frontier, and may favor the availability of nutrients such as phosphorus (P). This study evaluated effect of tillage systems on and cover plants distribution of organic P fractions (Po) in oxisol under soybean and grasses in crop successions. The experimental design was completely randomized with four replicates and five treatments: (i) conventional tillage (CT) with annual soil tillage; (ii) no-till (NT) in succession with *Urochloa ruziziensis* (NT1); (iii) NT in succession with *U. brizantha* (NT2); (iv) NT in succession with *Panicum maximum* (NT3); and (v) a control consisting of a fragment of native vegetation (NV). The Po fractions were quantified at depths of 0-5, 5-10, and 10-20 cm, before and after soybean cultivation and the P fractions were analyzed. The samples at a depth 0-5 and 5-10 cm had increased levels of biomass P in the NT1 and NT2. In addition, at depths of 0-5 and 5-10 cm, the treatments in no-tillage systems accumulated the most of the Po labile fractions. These results showed that conservation systems tend to accumulate most of the P fractions in soil through decomposition of organic residues. Thus, no-tillage system was shown to be important for Po supply, where the use of *U. brizantha* ‘Piatã’ (NT2) favored higher levels of organic P in labile and moderately labile fractions in soil, which was considered the best alternative for Po supply among the species tested.

**Key words:** *Glycine max*, organic phosphorus fractionation, humic fractions, no-till.

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Osvaldo Guedes Filho

\*Corresponding author:  
rafael.guedes@pq.itv.org

## INTRODUCTION

Oxisols cover 32% of the Brazilian territory and occur throughout the country under a variety of different edaphic and climatic conditions (Santos et al. 2011). They are the most widespread soil type in the Brazilian Amazon and extremely important for that region, where they are the most common soil type in agricultural lands. These soils are poor in nutrients mainly in available phosphorus (P) (Quesada et al. 2011).

Phosphorus added either as mineral or organic fertilizer tends to migrate out of the soil solution and into the solid phase, making these soils a P sink; however, they can be transformed from less to more labile forms and become a source of P in weathered tropical soils depending on the soil management system (Zamuner et al. 2008).

The tillage systems and the quantities of P applied and exported from soils determine which P forms accumulate within soils (Tiecher et al. 2012). Phosphorus accumulates in the surface layer (0 to 10 cm) when soils are cultivated over long



time periods using soil-conservation management strategies and tends to accumulate as organic fractions (Redel et al. 2007). However, soils that are subject to conventional agriculture tend to accumulate inorganic poorly labile forms of P (Zamuner et al. 2008), due to ploughing and harrowing that facilitate oxidation and gradual reduction of organic matter (OM) contents. Rodrigues et al. (2016) confirmed that 70-85% of P added was bound in inorganic forms associated to Fe/Al oxyhydroxides. However, Rheinheimer et al. (2019) reported a significant increase in organic P fractions under no-tillage. This process depends on some factors such as pH, microbial activity (Jin et al. 2006; Wang et al. 2017) and the management of soil organic matter, and should be considered in adapted rotation systems to obtain better crop yields (Leithold et al. 2015).

The cover crops may change the P dynamics in soils due to the recycling of P mobilized as plant residue promoting microbial activity. Thus, Tiecher et al. (2012) analyzed the effect of some species (as oat, radish, wheat and fallow) under conventional tillage (CT) and no-tillage (NT), observing the accumulation of organic residues increasing the Po content in the soil.

Forage species are highly recommended as cover plants due to their ability to accumulate P and incorporate them into the soil; however, it is desirable that these species have a high capacity for root and biomass production (Damon et al. 2014). Among forages widely used in agricultural production systems, *Urochloa ruziziensis* has been recommended as the main forage, because it has a deep rooting system and is highly productive, reaching a dry mass of 15 t·ha<sup>-1</sup>·year<sup>-1</sup>. The soil cover of *Panicum maximum* 'Massai' was analyzed by Valentim and Moreira (1994), who found 81-100% of cover and high adaptation in soils with low P and low moisture contents, while *Urochloa brizantha* c 'Piatã' has shown great potential in integrated production systems in addition to high growth (60 cm) as function as P fertilizing (Dan et al. 2011; Dias et al. 2015).

In some regions of Brazil (mainly south and southeast), conservation tillage and cover crops using forage species is well established using mainly *Urochloa* species (Ferreira et al. 2010). The soil cover promoted by forage species contributes to reducing erosion and leaching processes and improve the soil quality and productivity of crops (Sá et al. 2014). However, these systems have been recently introduced in the Brazilian Amazon, and their benefits are not well reported.

Fractionation or sequential extraction makes it possible to study P dynamics in soils by separating fractions with different extractants (Zhang and Kovar 2009). Understanding organic P fractions in no-tillage systems in the Amazon region based on plant cover crops in the early years of cultivation can be a tool that enables better use of P fertilization.

As highly weathered oxisols require high fertilizer application rates, the accumulation of P in the labile and moderately labile fractions, which are more accessible to the plants, may prevent excessive P in soils and reduces economic losses and environmental damage. Therefore, a detailed understanding of organic phosphorus (Po) fractions can help develop management strategies to maintain or increase crop productivity and to reduce the need for fertilization (Vincent et al. 2010). The authors of this work hypothesized that conservations systems and the cultivation of the cover crops may be a way to increase Po fractions in the soil. Therefore, this study aims to assess the effect of tillage systems on distribution of Po fractions in oxisol under soybean and grasses in crop successions.

## MATERIAL AND METHODS

### Location and characterization of the experimental area

The study was performed in Paragominas, located in the northeastern portion of Pará state, Brazil (02°51'54"S; 48°23'40"W; elevation 88 m). Soils in the region have been classified as oxisols (Soil Survey Staff 2014). The topography varies from flat to softly rolling slopes. The climate is classified as Aw, according to the Köppen classification, that is, a rainy tropical with a well-defined dry season, with an average annual temperature of 26.5 °C and an annual rainfall of 1800 mm (Rodrigues et al. 2003).

In 2008, before the experiment was established, the entire area was prepared using conventional methods (light plowing and leveling). The no-tillage treatments (NT) were not lightly plowed or leveled between 2009 and 2011. The soybean seeding consisted of 12 plants·m<sup>-1</sup> with 45 cm row spacing. All treatments were fertilized receiving 350 kg·ha<sup>-1</sup> of NPK (4-20-20 formula) annually applied superficially in the row planting. The experimental design was completely randomized with four tillage systems, one native area and four replicates: (i) a conventional tillage with one light plowing and two leveling annually in November (CT) of soybean (*Glycine max*) 'Sambaíba' cultivated three years in succession with rice (*Oryza sativa*)

and maize (*Zea mays*) 'BRS 1030'; (ii) NT of soybean, cultivated three years in succession with *Urochloa ruziziensis* (NT1); (iii) NT of soybean, cultivated three years in succession with *Urochloa brizantha* 'Piatã' (NT2); (iv) NT of soybean, cultivated three years in succession with *Panicum maximum* 'Massai' (NT3) (Table 1); and (v) a fragment of native vegetation (NV). Soybean was always cultivated between February and May and the cover crops was grazed on August. The NV area was a 20-year-old succession characterized by a complex association of woody-shrubby species.

**Table 1.** Evolution of treatments for evaluation.

Treatment	2008	2009	2010	2011
CT	Soybean	Soybean/Rice	Soybean/Maize	Soybean
NT1	Soybean	Soybean/Ruziziensis	Soybean/Ruziziensis	Soybean
NT2	Soybean	Soybean/'Piatã'	Soybean/'Piatã'	Soybean
NT3	Soybean	Soybean/'Massai'	Soybean/'Massai'	Soybean

CT-Conventional tillage, NT1, No-till in succession with *Urochloa ruziziensis*/soybean, NT2, No-till in succession with *Urochloa brizantha* 'Piatã'/soybean, NT3-No-till in succession with *Panicum maximum* 'Massai'/soybean.

## Sampling and physical and chemical characterization

The plots measured 0.03 hectare (30 × 10 m). To determine how Po fractionation varied at different depths, soils were collected at depths of 0-5, 5-10, and 10-20 cm in two times: first in December (2010) prior to planting and fertilizing for the soybean crop, and second collected in May (2011) and subsequently at harvest. Soil samples were collected using a stainless auger along the plant rows. Five samples were combined into a composite sample, summing four composite samples per plot and 16 composite samples per treatment.

The soil pH was measured in water using a soil:solution ratio of 1:2.5. Calcium and Mg were extracted with 1 mol·L<sup>-1</sup> KCl and determined using an atomic absorption spectrometry. Extractable K was extracted using the Mehlich-1 solution method and determined using a flame photometry. Available P was extracted using resin (van Raij et al. 1986) and Mehlich-1 solution 0.05 mol·L<sup>-1</sup> HCl and 0.0125 mol·L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub> both quantified by colorimetry. Exchangeable Al (Al<sup>3+</sup>) was extracted with a 1 mol·L<sup>-1</sup> KCl solution and determined using titration with 0.025 mol·L<sup>-1</sup> NaOH. The potential acidity (H+Al) was determined via extraction with 0.5 mol·L<sup>-1</sup> calcium acetate at pH 7.0 and quantified by titration with 0.025 mol·L<sup>-1</sup> NaOH. Total cationic exchange capacity (CEC pH 7) was calculated as Ca<sup>2+</sup> + Mg<sup>2+</sup> + K + H + Al; bases saturation (V) = (Ca<sup>2+</sup> + Mg<sup>2+</sup> + K) × 100 / CEC; Al saturation (m) = Al<sup>3+</sup> × 100 / (Ca<sup>2+</sup> + Mg<sup>2+</sup> + K + Al<sup>3+</sup>) and the organic matter content was estimated using the soil organic carbon concentration as measured by wet combustion (OM = OC × 1,724) (Donagema et al. 2011). Soil granulometric analysis was performed via the pipette method (Gee and Or 2002). Soil chemical and texture attributes are provided in Table 2.

## Phosphorus analysis

Total P was determined from the acid digestion (HNO<sub>3</sub> and HCl concentrated in the ratio 3:1 in microwave according to the EPA 3051a method (Leytem 2009). Total organic P (total Po) was determined using the method of ignition, in which Po was converted by oxidation into inorganic P at a temperature of 550 °C and extracted by 1 mol·L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub> which was determined by colorimetry (Kuo 1996).

Organic P was sequentially fractionated into the following pools by the respective extractants: labile Po, by 0.5 mol·L<sup>-1</sup> NaHCO<sub>3</sub> shaking for 16 h; Po contained in biomass by 0.5 mol·L<sup>-1</sup> NaHCO<sub>3</sub> with previous fumigation with CHCl<sub>3</sub> shaking for 16 h; moderately labile Po by 1 mol·L<sup>-1</sup> HCl shaking for 3 h; Po bound to fulvic acid and Po bound to humic acid by 0.5 mol·L<sup>-1</sup> NaOH after shake (6 h) and acidification with HCl; for nonlabile Po the solid residue was heated at 550 °C and extracted in 1 mol·L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub> shaking for 1 h (Zhang and Kovar 2009).

For all extractions, an aliquot was taken for digestion with potassium persulfate for the determination of inorganic P (Pi). Thus, Po was determined as the difference between total P and Pi for each fraction. The analytical procedure described by

**Table 2.** Soil attributes before the primary agricultural crop (2008).

Depth	pH <sup>a</sup>	OM	P <sup>b</sup>	P <sup>c</sup>	Al <sup>3+</sup>	H+Al	K	Ca <sup>2+</sup>	Mg <sup>2+</sup>	CEC	V	m	Sand	Clay
		g·kg <sup>-1</sup>	mg·kg <sup>-1</sup>	mmol <sub>c</sub> ·kg <sup>-1</sup>										g·kg <sup>-1</sup>
NT1 <sup>d</sup>														
0-5 cm	5.3	39.6	17.1	16.2	1.5	52.6	3.4	28.4	6.1	90.5	41.9	3.9	45	615
5-10 cm	5.0	29.0	13.5	13.3	2.7	50.5	1.1	18.2	11.0	80.8	37.5	8.1	43	638
10-20 cm	4.8	26.9	6.6	7.5	3.6	51.5	1.0	17.0	5.6	75.1	31.5	13.1	47	705
NT2 <sup>e</sup>														
0-5 cm	5.4	43.4	17.4	15.2	1.1	49.5	4.5	33.2	13.6	100.8	50.9	2.2	43	570
5-10 cm	5.6	35.8	15.2	17.3	1.9	54.3	1.8	24.2	8.1	88.4	38.6	5.2	43	590
10-20 cm	5.1	32.1	13.5	8.1	1.4	52.7	1.5	23.8	5.1	83.1	36.6	4.4	41	670
NT3 <sup>f</sup>														
0-5 cm	5.4	44.6	12.2	9.8	1.1	49.1	2.7	29.8	7.0	88.6	44.6	2.8	45	619
5-10 cm	5.3	36.7	9.9	16.4	1.9	57.1	1.4	27.5	6.1	92.1	38.0	5.2	46	610
10-20 cm	5.1	31.7	7.3	7.6	2.2	54.9	3.8	23.4	4.8	86.9	36.9	6.4	42	700
CT <sup>g</sup>														
0-5 cm	5.6	44.1	11.4	14.1	1.4	56.3	4.0	36.3	10.0	106.6	47.2	2.7	47	600
5-10 cm	5.4	36.7	10.8	11.9	1.1	49.9	1.7	32.2	8.9	92.7	46.1	2.6	43	670
10-20 cm	5.2	36.4	8.1	7.2	2.0	45.3	1.5	26.1	8.2	81.1	44.1	5.4	38	690
NV <sup>h</sup>														
0-5 cm	5.8	75.0	8.0	1.2	1.3	62.5	1.3	54.6	16.9	135.3	53.8	1.7	53	660
5-10 cm	5.2	52.6	10.6	0.6	2.8	58.5	0.8	23.0	8.0	90.3	35.2	8.1	49	667
10-20 cm	5.0	37.7	9.5	0.4	3.8	53.9	0.6	17.2	4.9	76.6	29.6	14.4	49	690

<sup>a</sup>pH, Determined in water; <sup>b</sup>P, Extracted via Mehlich-1; <sup>c</sup>P, Extracted via Resin; <sup>d</sup>NT1 – No-till in succession with *Urochloa ruziziensis*/soybean; <sup>e</sup>NT2 – No-till in succession with *Urochloa brizantha* 'Piatã'/soybean; <sup>f</sup>NT3 – No-till in succession with *Panicum maximum* 'Massai'/soybean; <sup>g</sup>CT – Conventional tillage; <sup>h</sup>NV – fragment of native vegetation.

Zhang and Kovar (2009) was modified with the goal of extracting Pi from the fulvic acid and nonlabile organic P fractions (nonlabile Po), thereby avoiding an overestimate of Po values in these fractions. A new sequential extraction was performed to determine Pi in the acidified NaOH extract and to determine fulvic acid Po as the difference between P total and Pi. One sample of final residue of this extraction was subjected to incineration and other sample was not incinerated, this procedure was used to obtain the total nonlabile Po content as the difference between the incinerated and the nonincinerated samples.

## Statistical analysis

All determinations were made in triplicate and the data were statistically treated in the R environment version 3.5.6 for Windows. The statistical procedure was performed differentiating samples of 0-5, 5-10, and 10-20 cm, comparing management systems and the two sampling periods. Analysis of variance was performed (ANOVA) as well as normality (Shapiro–Wilk) and variance homogeneity (Levene) tests. If homogeneity was observed, a least significant difference (LSD) was applied; and if there were no homogeneity, a Dunnett T3 as post hoc. Cluster and principal components analysis of phosphorus forms in the soils were performed considering all depths. All data were analyzed at a 95% confidence level ( $p < 0.05$ ).

## RESULTS AND DISCUSSION

The no-till systems (NT) showed higher levels of biomass P than in the samples collected in conventional tillage (CT) after cultivation (Table 3). Specifically, the contents of the biomass P fraction increased ( $p < 0.05$ ), at a depth of 0-5 cm, in

**Table 3.** Organic phosphorus fractions before (2010) and after soybean cultivation (2011) at varying depths under different soil management systems (conventional and no-tillage).

Treatment	Biomass P <sup>n</sup>		Labile Po <sup>b</sup>		Mod. labile Po <sup>c</sup>		Fulvic Po <sup>d</sup>		Humic Po <sup>e</sup>		Nonlabile Po <sup>f</sup>	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
mg·kg <sup>-1</sup>												
0-5 cm												
NV <sup>a*</sup>	22	19	37	40	20	13	50	53	38	20	146	231
NT1 <sup>b</sup>	17 aB	25 aA	15 bB	34 bA	16 bA	9 bB	51 aB	71 aA	38 aB	50 aA	132 bB	189 aA
NT2 <sup>c</sup>	17 aA	20 aA	28 aB	41 aA	29 aA	13 aB	45 aA	49 bA	30 bA	35 aA	140 bB	184 aA
NT3 <sup>d</sup>	16 aB	27 aA	15 bB	23 cA	25 aA	11 abB	49 aA	55 abA	16 cB	43 aA	175 bA	165 aA
CT <sup>e</sup>	17 aA	10 bA	28 aA	24 cB	25 aA	13 aB	47 aA	46 bA	13 dB	39 aA	192aB	206 aA
CV <sup>f</sup> (%)	15	29	8	4	14	15	23	20	6	24	16	16
5-10 cm												
NV	13	9	26	20	29	5	45	43	24	16	178	200
NT1	13 aB	22 aA	20 aB	28 bA	12 cA	14 bA	59 aA	51 aA	36 aA	33 aA	147 aB	232 aA
NT2	9 aB	18 abA	24 bB	33 aA	20 bA	10 cB	47 aB	65 aA	29 bA	18 bB	153 aB	229 abA
NT3	12 aA	16 bA	15 cB	31 aA	29 aA	17 aB	54 aA	48 aA	14 cA	17 bcA	132 aB	207 bA
CT	13 aA	8 cA	15 cB	22 cA	4 dB	7 dA	36 aA	45 aA	6 dB	15 bcA	175 aB	221 abA
CV (%)	30	24	6	5	6	18	31	14	12	19	21	10
10-20 cm												
NV	3	6	17	22	4	6	30	34	7	13	199	221
NT1	7 abA	7 bA	19 bA	8 cB	15 bA	6 cB	39 aA	43 bA	21 aA	8 bB	172 aB	254 abA
NT2	10 aB	20 aA	24 aB	36 aA	4 cB	15 aA	40 aA	38 bcA	10 cA	10 aA	174 aB	229 abA
NT3	3 cA	7 bA	20 bA	9 cB	17 bA	10 bB	40 aA	33 bcA	14 bA	14 aA	157 aB	216 bA
CT	5 bcA	5 bA	25 aA	24 bA	21 aA	6 cB	39 aB	62 aA	6 dB	12 aA	115 bB	265 aA
CV (%)	36	68	5	7	16	14	23	36	17	30	10	11

<sup>a</sup>Values not considered in ANOVA, only used as a reference; <sup>b</sup>NV – Fragment of native vegetation; <sup>c</sup>NT1 – No-till in succession with *Urochloa ruziziensis*/soybean; <sup>d</sup>NT2 – No-till in succession with *Urochloa brizantha* 'Piatã'/soybean; <sup>e</sup>NT3 – No-till in succession with *Panicum maximum* 'Massai'/soybean; <sup>f</sup>CT – Conventional tillage; <sup>g</sup>CV – Coefficient of variation. <sup>h</sup>P in microbial biomass; <sup>i</sup>Labile Po; <sup>j</sup>Moderately labile Po; <sup>k</sup>Po linked to fulvic acids; <sup>l</sup>Po linked to humic acids; <sup>m</sup>Nonlabile Po. Within each P fraction, means followed by the same uppercase letter in a row (years) and lowercase letter in a column (tillage systems) are not significantly different ( $p \leq 0.05$ ) according to LSD test.

the NT1 (no-till in succession with *U. ruziziensis*) and NT3 (no-till in succession with *Panicum maximum* 'Massai') systems, compared to the first sampling period (Table 3).

The microbial biomass is very dynamic to the P immobilization from the soil solution when its availability in the system is high and when it is gradually released as microorganisms die (Bünemann 2015). It is possible that these NT management systems increased biological activity in the surface layer and consequently increased biomass P content. The increase in biomass P may be associated with the breakdown of organic matter or by the specific mineralization of organic phosphate through the actions of phosphatase-type exoenzymes (McGill and Cole 1981). According to Pacheco et al. (2013), *U. ruziziensis* straw has shorter permanence when compared to *U. Brizantha*. An increase in the decomposition rates and the release of nutrients in the soil can stimulate of soil microbial biomass probably due to stimulation of biological activity promoted by cultivation of soybeans and the humidity and temperature conditions found in no-till systems (Costa et al. 2015).

The NT system was more efficient than the CT treatment at promoting the accumulation of P biomass. Even in deeper soil layers, the NT system provides a higher supply of P to soils over longer periods than the other systems. Alterations in the distribution of the organic P formed in soils depend on the quantity of P exported during harvests, on soil preparation techniques, and on the ability of plants to access reserves of less labile forms of P (Damon et al. 2014).

Levels of labile Po in the soil samples from all layers of the NT2 treatment increased significantly after soybean crop. However, the levels of labile Po declined in the soil surface layer of the CT system (Table 3), which suggests that labile Po was consumed due to its high accessibility to the plants. The labile Po fraction reached a maximum of 12% of total Po in the surface layer of the NV and NT2 systems (Fig. S1).

The labile Po fraction is generally very changed in soils mainly when tillage systems to soil conservation such as no-till were applied generating an accumulation of P forms. As observed with the biomass P values, the decomposition of crop residue and the accumulation of organic residues stimulate microbial activity, thus favoring the accumulation of organic P in the upper layers of the soil (Sharpley and Smith 1985). On the other hand, conventional tillage systems expose the soil adsorption sites and increase the contact between ions P and soil colloids, thus increasing the fixation, especially in outer sphere complexes and subsequently for inner sphere complexes (Fink et al. 2014).

The concentration of labile Po decreased with increasing depth, particularly in the native area, as also observed by Dieter et al. (2010), who observed similar reduction by evaluating the Pi and Po extracted by  $0.5 \text{ mol}\cdot\text{L}^{-1} \text{ NaHCO}_3$  (equivalent to labile P). Amazonian soils in forested areas have low P levels and the main source for biomass decomposition is litter on the soil surface, so that the labile fraction of the Po considerably reduces with depth (Quesada et al. 2011).

All treatments showed declines in moderately labile Po levels superficially (0 to 5 cm layer) (Table 3, Fig. S1). The moderately labile Po fraction is highly soluble and reactive with the crystalline and low-crystalline forms of Fe and Al, generating an accumulation trend similar to the nonlabile fraction (Gérard 2016). Roots can also induce high phosphatase activity in the rhizosphere, which increases the amount of P available to plants via less available forms like moderately labile (Celi and Barberis 2005).

The Po fraction bonded to fulvic acids showed larger changes as a function of cultivation time in the 0 to 5 cm layer. Among tillage systems, only the NT1 system stored more of this fraction than the CT system in the 0 to 5 cm layer (Table 3). Moreover, fulvic organic P levels tended to increase in the 10 to 20 cm layer of the CT system after cultivation.

The highest values of Po bound to fulvic acid between N1 and CT reflect an improvement in protecting the soil using previous ground cover plants *Urochloa ruziziensis* has a prostrate growth that quickly covers the soil surface, as well as a stem that lasts a long time in the soil due to a high C/N ratio. This phenomenon may explain why the fulvic acid remained in the surface layer (Silva and Mendonça 2007). The *Urochloa ruziziensis* species has been used to avoid the effects of erosion and soil washing in newly established pastures and is also highly recommended for no-tillage methods, cover crops formation, and soil protection (Pariz et al. 2010). However, at deeper layer CT accumulate more of this fraction because fulvic acid is a humic substance with high total acidity, is soluble at all pH levels and can migrate to greater depths (Gonet et al. 2008). Therefore, the solubility of the fulvic Po fraction suggests that, when soils are unprotected, rainfall promotes its accumulation at greater depths. In the case of soil conservation tillage systems such as NT, however, the fraction tends to accumulate in the surface layer.

At a depth of 0 to 5 cm in both conventional and the no-till systems, levels of Po bonded to humic acids increased (Table 3). The Po bonded to humic acids is a stable fraction important to maintenance of organic matter in the soil, but in quantitative terms, the nonlabile Po fraction was more important than the other organic fractions at all depths studied (Table 3).

The patterns of humic Po observed in the systems highlight the stability of this fraction that tends to accumulate in the soil when there is entry of organic matter, so that in soils of the wet tropical region, humic acids become an important reserve of quickly available Po (He et al. 2011; Quesada et al. 2011). Other important source observed in large portion in this study, the nonlabile Po can assist with maintaining labile P fractions, and all P fractions may be available in the short, medium and long term, suggesting that much of the P applied as fertilizer or OM can be recovered (Guo et al. 2000). In highly weathered soils such as oxisols, which have high levels of iron and aluminum oxides, the OM levels can be a key to recovery P retained in the soil (Guedes et al. 2016).

The lower total P levels in the deeper layer of the soil in the NV (Table 4) are due to low P inputs to layer and the low mobility of P compared to the others systems studied. In forest soils, the nutrient source is mainly supplied by cycling organic materials on the soil surface, unlike other treatments that received phosphate fertilizer during the growing seasons of each year. The variations in levels of total P are smaller than the variations in labile, and this behavior is not reflected in the availability of labile fractions (Pavinato et al. 2010).

**Table 4.** Contents of total P, total organic P (total Po) before soybean planting and after planting at different depths of samples from an oxisol under different management systems.

Treatment	Total P		Total Po	
	Before	After	Before	After
	mg·kg <sup>-1</sup>			
	0-5 cm			
NV <sup>a</sup>	638	703	304	365
NT1 <sup>b</sup>	644 bA	701 aA	261 bB	367 aA
NT2 <sup>c</sup>	583 bB	793 aA	280 bB	332 bA
NT3 <sup>d</sup>	474 cB	701 aA	287 bB	341 abA
CT <sup>e</sup>	751 aA	778 aA	312 aA	319 bA
CV <sup>f</sup> (%)	8	8	13	12
	5-10 cm			
NV	670	668	309	287
NT1	613 aA	675 abA	281 aB	372 aA
NT2	569 aB	657 bA	276 abB	366 aA
NT3	572 aB	728 aA	251 bB	329 abA
CT	598 aA	637 bA	244 bB	312 bB
CV (%)	10	6	19	15
	10-20 cm			
NV	324	320	256	297
NT1	562 aA	571 aA	269 aA	321 bA
NT2	532 aA	511 aA	249 aA	343 abA
NT3	493 aA	589 aA	247 aA	285 cA
CT	501 aA	542 aA	208 bB	368 abA
CV (%)	19	11	31	35

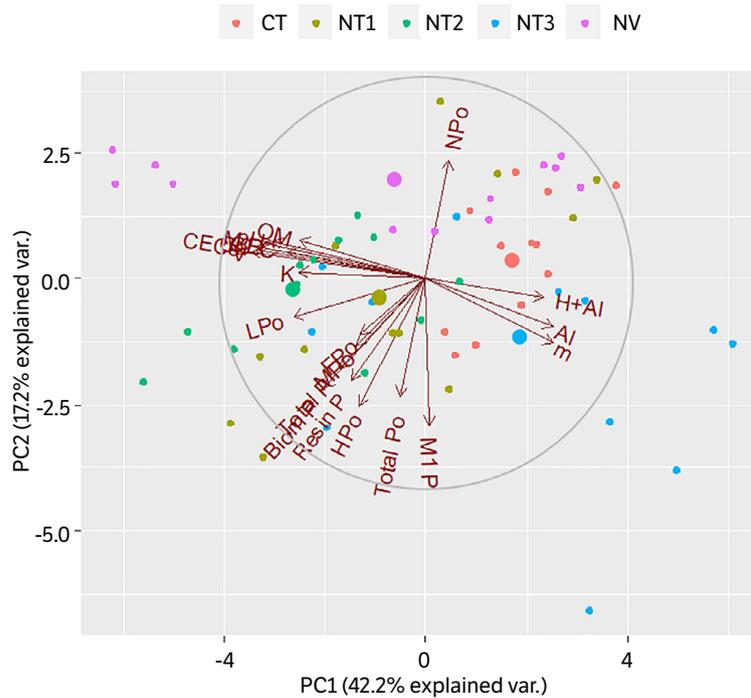
<sup>a</sup>Values not considered in ANOVA, only used as a reference; <sup>a</sup>NV – Fragment of native vegetation; <sup>b</sup>NT1 – No-till in succession with *Urochloa ruziziensis*/soybean; <sup>c</sup>NT2 – No-till in succession with *Urochloa brizantha* 'Piatã'/soybean; <sup>d</sup>NT3 – No-till in succession with *Panicum maximum* 'Massai'/soybean; <sup>e</sup>CT – Conventional tillage; <sup>f</sup>CV – Coefficient of variation. Within each P fraction, means followed by the same uppercase letter in a row (years) and lowercase letter in a column (tillage systems) are not significantly different ( $p \leq 0.05$ ) according to the LSD test.

With principal components analysis, it was possible to extract two components (PC1 and PC2), which explained 60% of the data variance (Table S1). The NT3 treatment was strongly correlated – above 0.70, according to Manly (1994) – with the values of m%, Al<sup>3+</sup> and H+Al in PC1 (Table S1 and Fig. 1). These attributes were observed in greater proportion in NT3 and CT treatments.

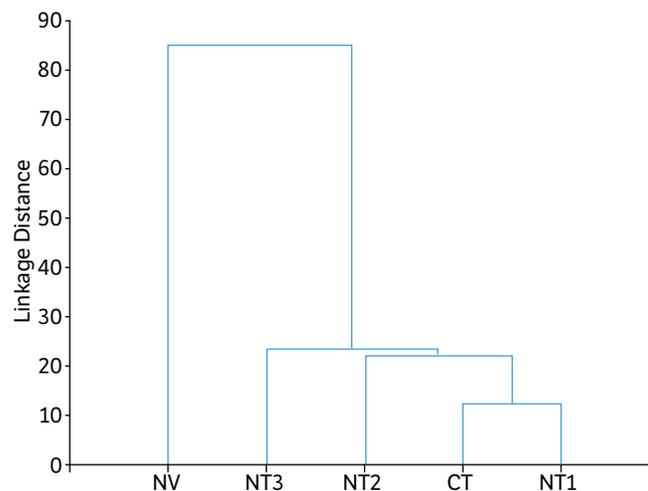
The NT2 treatment have a higher contribution of the variables related to soil fertility, such as exchangeable bases, CEC, as well as pH and labile Po fraction. However, for NT1 and NT2 a higher contribution of available P levels was observed (extracted by resin and Mehlich-1), Total P, biomass P, labile Po, and moderately labile Po (Table S1, Fig. 1). Thus, NT2 supplied greater quantity of the main Po fractions to soil in relation to other treatments, showing also one of the higher fertility levels. Figure 1 shows that most of the Po fractions were dependent on the available P levels as well as levels of m, Al<sup>3+</sup> and potential acidity.

Cluster analysis (Fig. 2) shows that CT and NT1 treatments showed a higher level of similarity in relation to variables considered in the PCA, while NV showed greater dissimilarity due to lower P levels found in this soil.

The fractions obtained from the phosphorus fractionation scheme and fertility analysis were used to perform cluster and principal component analysis (PCA) in order to summarize information referring to set of variables and responses obtained in the experiment. Phosphorus and Al<sup>3+</sup> levels in the soil are often related to acidity levels, which in Amazonian soils becomes a critical factor for the P fertilization management. The high soil acidity reduces P availability, promoting the increase of less labile P fractions due to protonation in the colloidal surface, stimulating retention of inorganic and organic P forms (Barrow et al. 2015).



**Figure 1.** Principal component analysis biplot for treatments considering all depths: NT1 – No-till in succession with *Urochloa ruziziensis*/soybean; NT2 – No-till in succession with *Urochloa brizantha* ‘Piatã’/soybean; NT3 – No-till in succession with *Panicum maximum* ‘Massai’/soybean; CT – Conventional tillage; NV – Fragment of native vegetation. Highlighted points represent the average of treatments.



**Figure 2.** Cluster analysis for treatments considering all depths: NT1 – No-till in succession with *Urochloa ruziziensis*/soybean; NT2 – No-till in succession with *Urochloa brizantha* ‘Piatã’/soybean; NT3 – No-till in succession with *Panicum maximum* ‘Massai’/soybean; CT – Conventional tillage; NV – Fragment of native vegetation.

## CONCLUSION

The distribution of organic P fractions varied between tillage systems, mainly in the surface soil layer, but did not alter the total P. Furthermore, the humic Po, fulvic Po, and nonlabile Po fractions were more expressive than the other organic fractions.

Among the evaluated systems, the tillage system using the *Urochloa brizantha* ‘Piatã’ (NT2) excels in providing increased the most of organic P fractions being considered the best alternative to cover crops formation and supply Po among the species tested. The use of this forage in no-tillage cultivation in Amazon region can be important for soil management.

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## AUTHOR'S CONTRIBUTION

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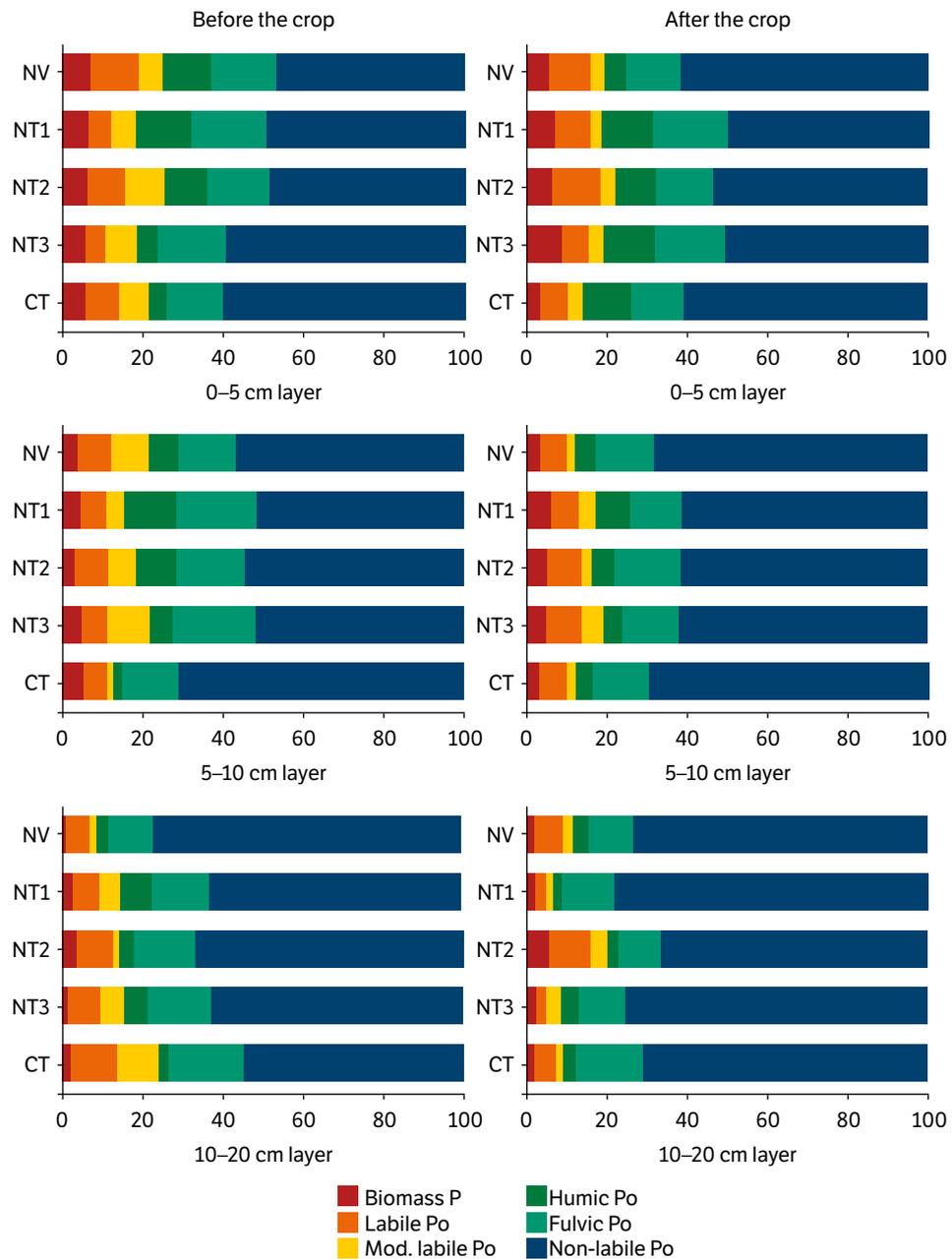
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**SUPPLEMENTARY FILE****Table S1.** Description of variance explained with factor loadings (unrotated) related to soils.

Component	Eigenvalue	Total variance (%)	Cumulative Eigenvalue	Cumulative (%)
1	8.84	44.22	8.84	44.22
2	3.25	15.23	12.09	59.45
	Factor Loadings			
Variables	Factor 1*	Factor 2*		
pH	<b>-0.85</b>	0.21		
OM	<b>-0.70</b>	0.23		
Resin P	-0.40	-0.55		
M1 P	0.03	<b>-0.81</b>		
H+Al	0.65	-0.08		
Al	<b>0.70</b>	-0.23		
Mg	<b>-0.91</b>	-0.24		
K	<b>-0.70</b>	0.01		
Ca	<b>-0.94</b>	0.16		
CEC	<b>-0.76</b>	0.16		
CECe	<b>-0.94</b>	-0.16		
V	<b>-0.96</b>	0.13		
m	<b>0.70</b>	-0.33		
Total Po	-0.13	-0.64		
Total P	-0.47	-0.51		
Biom P	-0.54	-0.59		
LPo	<b>-0.72</b>	-0.22		
MPo	-0.38	-0.31		
HPo	-0.36	<b>-0.71</b>		
FPo	-0.36	0.31		
NPo	0.13	0.66		

\*values > 0.70 (marked) are significant (Manly 1994).



**Figure S1.** Distribution of organic P fractions before and after the soybean crop, at varying depths of an oxisol for the following tillage systems: NT1 – No-till in succession with *Urochloa ruziziensis*/soybean; NT2 – No-till in succession with *Urochloa brizantha* 'Piatã'/soybean; NT3 – No-till in succession with *Panicum maximum* 'Massai'/soybean; CT – Conventional tillage; NV – Fragment of native vegetation.