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# Phosphorus Forms in Ultisol Submitted to Burning and Trituration of Vegetation in Eastern Amazon

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**ABSTRACT:** The use of fire to prepare agricultural areas is a technique still used by small farmers in eastern Amazon. This type of management changes the dynamics of soil nutrients, especially phosphorus, which constitutes the most limiting nutrient for crop production in tropical soils. This study was carried out to evaluate changes in phosphorus forms in an *Argissolo Amarelo Distrófico* (Ultisol) submitted to burning and trituration of secondary forest in eastern Amazon. The evaluated systems were: slash-and-burn of vegetation; slash-and-mulch of vegetation; and secondary vegetation. The labile, moderately labile, moderately recalcitrant, available and total phosphorus fractions were assessed at the soil depths of 0.00-0.05, 0.05-0.10 and 0.10-0.20 m. The results showed a predominance of soluble P in acid (moderately labile P) over other forms in all management systems. The management systems influence the content and distribution of the forms of P, where the slash-and-mulch system presented the prevalence of the labile fraction, and the slash-and-burn system contained less labile forms. The slash-and-mulch system favored the accumulation of labile P and total organic P.

**Keywords:** shifting cultivation, tropical soils, phosphorus fractions, organic phosphorus.

## INTRODUCTION

Agriculture is the main cause of fires in the Brazilian Amazon region, especially in the family farm, since burning for field preparation before planting is used as a secular technique by family farmers in the Amazon and in many other tropical regions (Sá et al., 2007). Among the main consequences of successive burning in tropical forests are reduced C storage, biodiversity loss (Sampaio et al., 2003), declining yield, and loss of resilience in vegetation (Rodrigues et al., 2007).

In highly weathered soils, such as in the Amazon, phosphorus (P) is regarded as the most limiting nutritional factor to crop production, mainly because of its low availability (Zaia et al., 2008a), precipitation with ionic forms of Fe, Al and Ca, and adsorption by Fe and Al oxy-hydroxides (Novais et al., 2007; Zaia et al., 2008b). The biogeochemical cycle of P is modified during vegetation and litter burning, by converting the organic P into orthophosphate (Certini, 2005), which is easily reactive with soils. Several studies have shown a relationship between vegetation burning and availability and quantities of P forms in soils (Giardina et al., 2000; Galang et al., 2010; Oliveira et al., 2011; Resende et al., 2011).

In northeastern Pará state, the modified implement TRITUCAP has been used for soil preparation, involving the cutting, grinding and deposition of secondary vegetation on the soil surface (Kato et al., 1999; Denich et al., 2004, 2005; Reichert et al., 2014, 2015a). This technique was developed under the “Tipitamba” project, a partnership between Embrapa Eastern Amazon and German researchers (Comte et al., 2012). This system has several advantages such as improved physical and chemical soil properties and a reduction in the fallow time (Joslin et al., 2011; Comte et al., 2012).

Management systems and land use that provide the preservation of soil organic matter (SOM) favor P availability (Busato et al., 2005), increase the organic content of organic P (Po), and reduce the effects of inorganic P (Pi) adsorption on the soil mineral phase (Cunha et al., 2007). Many studies have shown the positive effect of adding plant residues to soil, which increases the most labile forms of P and favors their availability to plants (Matos et al., 2006; Ribeiro et al., 2007; Partelli et al., 2009; Xavier et al., 2009). Thus, the characterization of P forms in soils regarding the function of a crop system or soil management is central to understanding the P cycle, especially on highly weathered soils.

The hypothesis of the current study is that alternative tillage with managed vegetation rather than fire increases the content and availability of P in soils. The aim of this study was to evaluate the changes in P forms on an *Argissolo Amarelo Distrófico* under management systems of burning and mulching in a secondary forest in eastern Amazon.

## MATERIALS AND METHODS

The study was conducted in Igarapé-Açu, in northeast Pará (01° 07’ 15” S, 47° 36’ 12” W). According to the Köppen classification, the climate is Am. The soil was classified as *Argissolo Amarelo Distrófico* (Santos et al., 2013) and Ultisol (Soil Survey Staff, 2014), with a sandy loam texture (624 g $kg^{-1}$ sand; 251 g $kg^{-1}$ silt; 125 g $kg^{-1}$ clay).

The experimental design was completely randomized, with three treatments and five replications, with the following management systems: traditional area of management “slash-and-burn” (SB); alternative management “slash-and-mulch” (SM); and adjacent secondary vegetation as a reference area (SV). The treatments were deployed in November 2001 at approximately 2 ha plot, with <1 % slope. Soil samples were collected in January 2010 at the depths of 0.00-0.05, 0.05-0.1 and 0.1-0.2 m. Each compost sample was taken for five simple samples. The system with secondary vegetation, at the time of collection, had been fallow for 40 years. The land use in the study areas is presented in figure 1.

Soil management in the SB area encompassed two cycles: the use of fire in 2001 and again in 2006. After the total burning of vegetation, corn *(Zea mays* L.) and cassava *(Manihot esculenta* Crantz*)* were cultivated, followed by 36 months of natural fallow until the next crop. Soil management in the SM system was performed with the implement TRITUCAP. Coupled to a tractor, the equipment uses two circular saws and blades (helical blades) to cut and grind the secondary vegetation (Denich et al., 2004). Besides soil management, SM differed from SB by a shorter fallow time and the use of fertilizer plants *(Inga edulis* Mart. and *Acacia mangium* Willd*)*. In Igarapé-Açu, the estimated total biomass in a four-year secondary forest is 44.44 Mg $ha^{-1}$ (Reichert et al., 2015b).

The soil chemical characterization (0.0-0.2 m) in each area was performed according to Embrapa (1997) (Table 1). The total P content (Pt) was determined from nitric-perchloric digestion (Olsen and Sommers, 1982) and the P content available through Mehlich-1 extractor (Embrapa, 1997). The organic labile P contents were obtained by $NaHCO_3$ 0.5 mol $L^{-1}$ extraction (Bowman and Cole, 1978a), while the moderately labile and moderately resistant fractions, soluble in sulfuric acid and sodium hydroxide, respectively, were obtained employing the sequential extraction method (Bowman, 1989) (Figure 2). Soil Pi contents of each fraction were determined following clarification of the extracts with activated charcoal, previously purified (Guerra et al., 1996). Phosphorus forms content in acidic and alkaline extracts were quantified by Murphy and Riley (1962) method. Organic P (Po) of each fraction was obtained by the difference between Pt and Pi.

The results of P fractions were subjected to analysis of variance and where significant effect ($p<0.05$) compared the test medium by Duncan 5 % of probability. The following model was used:

$$\gamma_{ij} = \mu + \tau_i + e_{ij}$$

where $\mu$ = experimental overall average; $\tau$ = effect due to treatment i (i = 3); and $e$ = experimental random error (j = 5).

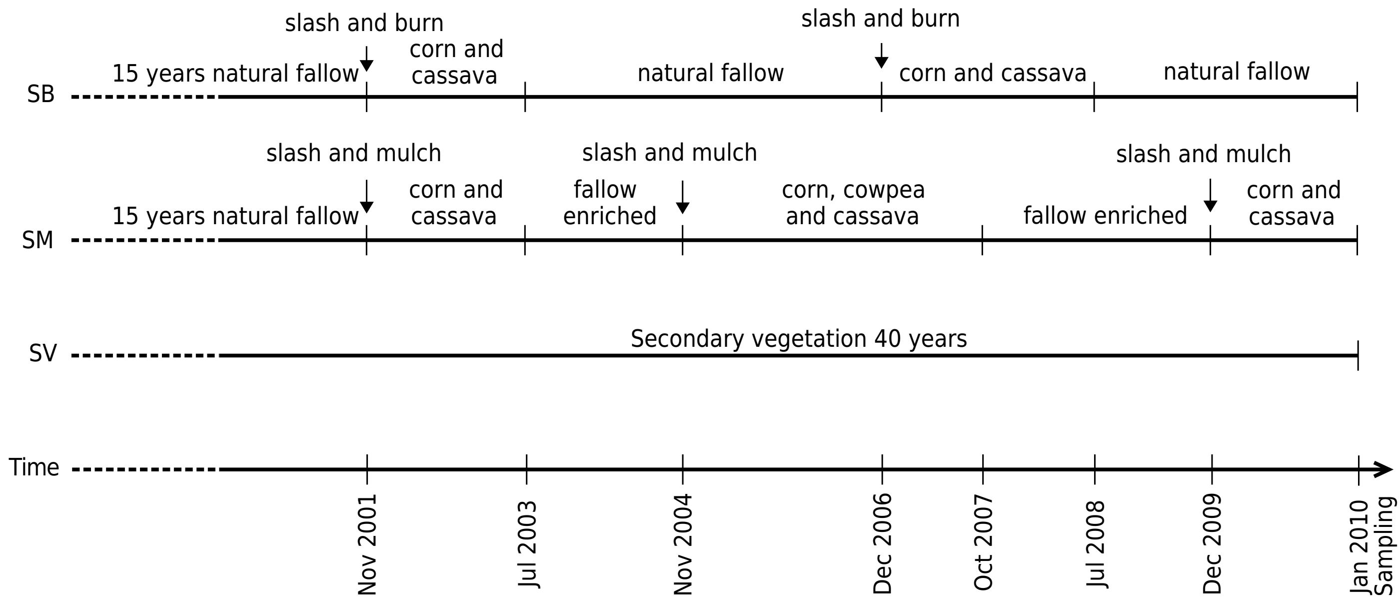


**Figure 1.** Plot history. Slash-and-burn (SB), slash-and-mulch (SM) and secondary vegetation (SV) systems at different depths in an *Argissolo Amarelo Distrófico* (Ultisol).

**Table 1.** Soil chemical properties of an *Argissolo Amarelo Distrófico* (Ultisol) under slash-and-burn (SB), slash-and-mulch (SM) and secundary vegetation (SV) systems at different depths

| Management system | pH($H_2O$) | N | MO | C | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | H+Al | CTC | V | m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | g $kg^{-1}$ | | | mmol$_c$ $dm^{-3}$ | | | | | % | |
| | | | | | 0.00-0.05 m | | | | | | |
| SB | 5.1 | 1.4 | 16.9 | 9.8 | 0.9 | 29.3 | 8.3 | 18.6 | 57.0 | 67.4 | 3.2 |
| SM | 5.0 | 1.6 | 19.0 | 11.0 | 1.0 | 25.8 | 7.3 | 30.6 | 64.5 | 52.7 | 7.5 |
| SV | 4.8 | 2.5 | 22.5 | 13.0 | 0.8 | 15.8 | 6.5 | 45.4 | 68.4 | 33.5 | 25.3 |
| | | | | | 0.05-0.10 m | | | | | | |
| SB | 5.2 | 1.3 | 15.0 | 8.7 | 0.6 | 22.5 | 6.8 | 24.8 | 54.6 | 54.8 | 7.8 |
| SM | 4.8 | 1.5 | 16.3 | 9.4 | 0.7 | 18.0 | 7.5 | 34.3 | 60.4 | 43.5 | 17.3 |
| SV | 4.7 | 1.4 | 12.9 | 7.5 | 0.5 | 6.8 | 4.3 | 33.0 | 44.6 | 26.0 | 44.6 |
| | | | | | 0.10-0.20 m | | | | | | |
| SB | 4.7 | 1.1 | 12.1 | 7.0 | 0.4 | 6.3 | 4.0 | 32.2 | 42.9 | 25.0 | 50.1 |
| SM | 4.9 | 1.3 | 13.6 | 7.9 | 0.5 | 10.5 | 4.8 | 32.6 | 48.4 | 32.6 | 35.2 |
| SV | 5.1 | 1.2 | 12.4 | 7.2 | 0.4 | 14.3 | 5.3 | 26.9 | 46.8 | 42.8 | 19.4 |

pH in water (1:2.5 soil:solution); N and C: determinated in dry combustion; MO: estimated by conversion factor 1.72; K: extracted by Mehlich-l; Ca and Mg: extracted by 1 mol $L^{-1}$ KCl; H+Al: extracted by 0.5 mol $L^{-1}$ calcium acetate at pH 7.0.

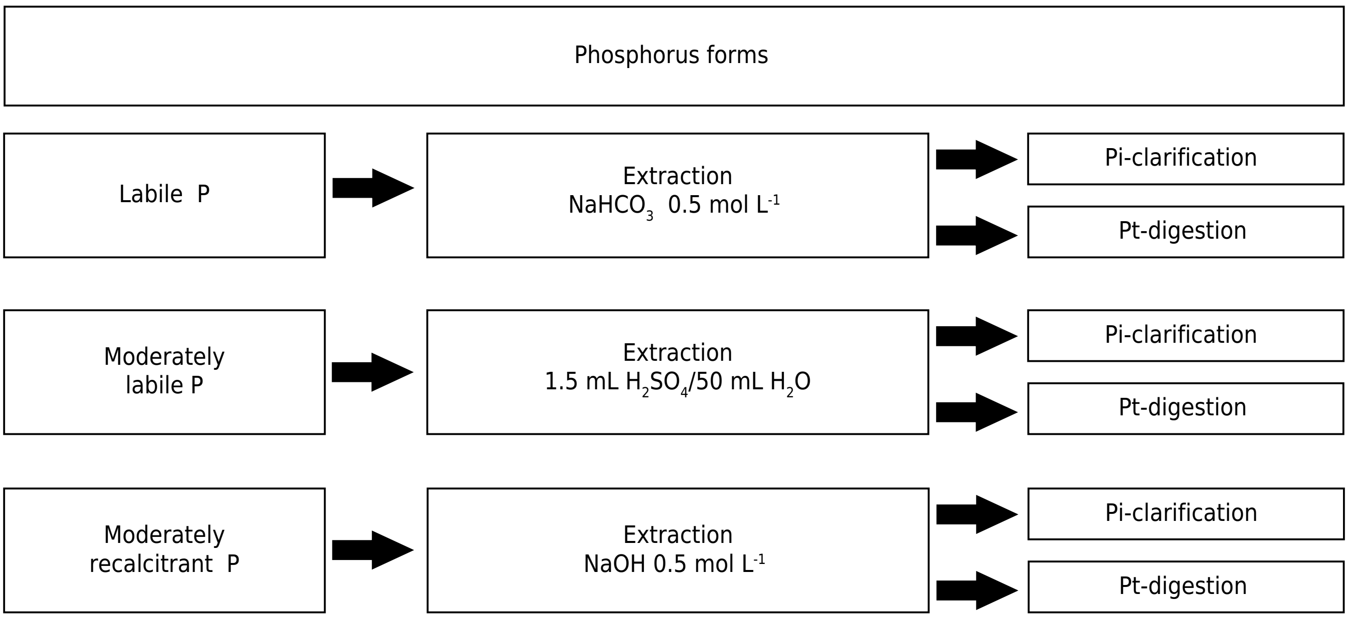


**Figure 2.** Schematic diagram of the sequential fractionation of soil organic phosphorus (Bowman and Cole, 1978a; Bowman, 1989).

## RESULTS AND DISCUSSION

### Available phosphorus (P-Mehlich)

Soil available P content was higher in the slash-and-mulch system at all depths (Table 2), probably due to higher the Po content, easily accessible to plants after mineralization. In tropical conditions, Po is of great importance to P conservation in soils (Cunha et al., 2007). In a study that assessed the fragmentation, decomposition and nutrient release of biomass from shredded secondary forest in the Amazon, Reichert et al. (2015b) observed a reduction in residual P in the crushed plant material and their release in soil solution, probably because the P concentration in plant tissue primarily occurred in cell vacuoles as inorganic P and monoesters (Giacomini et al., 2003), which are highly soluble forms.

Soil in the secondary vegetation system also presented a higher available P content compared to SB, at the depths of 0.00-0.05 and 0.10-0.20 m. Although combustion promotes the release of P from vegetation biomass and increases the available P content through the addition of ash (Kato et al., 1999; Giardina et al., 2000; Rheinheimer et al., 2003b; Silva et al., 2006), the results point out the unsustainability of the SB system, since the P levels were below those of the SV system. Phosphorus availability in areas with and without burning of vegetation in northeastern Pará was evaluated by Trindade et al. (2011), and they found a reduction in P availability of over the years in burned areas. Probably, this decrease is a burning effect, promoting fast mineralization of organic P, which subsequently, if not absorbed by plants or microorganisms, could be adsorbed into the soil and thus becoming less labile.

Although the SM system presented higher P available levels, they are still considered low (<10 mg $dm^{-3}$), pointing out the needed to use phosphate fertilizer to achieve economic viability (Kato et al., 1999; Denich et al., 2004).

### Labile inorganic and organic P (Pil and Pol)

Soil in the SM system showed the highest Pil and Pol levels at all studied depths (Table 2). This result emphasizes the positive effect of plant residue deposition on the ground, since SOM increases and microbial activity contributes to the increase of labile forms of P, in addition to decreased adsorption and consequent increased availability of P to plants (Andrade et al., 2003; Souza et al., 2006). The addition of organic residues to soil promotes the incorporation of P into the biological cycle, thus maintaining the fractions of labile P (Xavier et al., 2009). Moreover, Oliveira et al. (2011) showed that pasture burning reduces microbial P production, due to a decrease in accumulated biomass on the ground surface.

The deposition of biomass in the SM system favored Pol accumulation in the soil. Organic anions released by biomass transformation block P adsorption sites (Iyamuremye et al., 1996), reducing the phosphate binding energy to the functional groups of inorganic soil colloids (Rheinheimer et al., 2003a). This fraction is easily mineralized, supporting plants

**Table 2.** Contents of fractions of P in an *Argissolo Amarelo Distrófico* (Ultisol) under slash-and-burn (SB), slash-and-mulch (SM) and secondary vegetation (SV) systems at different depths

| Manegement system | Pil | Pol | $Pi\text{-}H^{+}$ | $Po\text{-}H^{+}$ | $Pi\text{-}OH^{-}$ | $Po\text{-}OH^{-}$ | Pit | Pot | Pit + Pot | P-Mehlich | Pt[1] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | mg $dm^{-3}$ | | | | | | | | | | |
| | 0.00-0.05 m | | | | | | | | | | |
| SB | 4.0 b | 5.2 c | 22.5 b | 14.0 a | 6.1 a | 5.4 b | 32.6 b | 24.5 b | 57.1 (103)[2] | 2.80 c | 55.3 a |
| SM | 5.9 a | 9.8 a | 30.3 a | 13.6 a | 5.7 a | 7.1 a | 42.0 a | 30.4 a | 72.4 (114) | 5.08 a | 63.5 a |
| SV | 3.9 b | 7.8 b | 17.3 c | 12.1 a | 6.3 a | 4.6 b | 27.5 c | 24.5 b | 52.0 (72) | 4.00 b | 72.5 a |
| | 0.05-0.10 m | | | | | | | | | | |
| SB | 4.0 b | 4.4 b | 18.4 b | 13.5 a | 6.2 a | 5.4 a | 28.6 b | 23.3 b | 51.9 (100) | 2.00 b | 52.1 b |
| SM | 5.7 a | 6.7 a | 24.3 a | 15.5 a | 5.7 a | 5.9 a | 35.8 a | 28.1 a | 63.9 (102) | 5.00 a | 62.7 a |
| SV | 3.3 b | 3.8 b | 13.0 c | 10.6 b | 5.8 a | 5.0 a | 22.0 c | 19.4 c | 41.4 (96) | 2.00 b | 43.1 b |
| | 0.10-0.20 m | | | | | | | | | | |
| SB | 3.0 b | 3.2 b | 16.4 b | 11.4 a | 5.8 a | 5.2 b | 25.1 b | 19.8 b | 44.9 (87) | 1.30 c | 51.7 a |
| SM | 4.8 a | 4.8 a | 21.1 a | 13.0 a | 6.1 a | 7.2 a | 32.0 a | 25.0 a | 57.0 (93) | 3.30 a | 61.1 a |
| SV | 3.0 b | 4.0 ab | 14.5 c | 9.1 a | 5.4 a | 5.4 b | 22.9 b | 18.4 b | 41.3 (97) | 2.00 b | 42.5 a |

Pil: Inorganic phosphorus labile; Pol: Organic phosphorus labile; $Pi\text{-}H^{+}$: Moderately labile inorganic phosphorus; P-Mehlich: Available phosphorus extracted by Mehlich-1; $Po\text{-}H^{+}$: Moderately labile organic phosphorus; $Pi\text{-}OH^{-}$: Moderately recalcitrant inorganic phosphorus; $Po\text{-}OH^{-}$: Moderately recalcitrant organic phosphorus; Pit: Total inorganic phosphorus; Pot: Total organic phosphorus; Pt: Total phosphorus. [1] Total phosphorus determined by Olsen and Sommers (1982). [2] Percent recovery relative to Pt. Means followed by the same letter in the column, by depth, do not differ by Duncan test ($p<0.05$).

and microorganisms (Rheinheimer et al., 2008). This reservoir can be very important to soil fertility, especially in low fertility soils (Guerra et al., 1996), like eastern Amazonian soils.

Labile organic P (PoI) predominated over PiI, in all systems and evaluated depths, which was also observed by other authors (Bowman and Cole, 1978b; Guerra et al., 1996; Solomon et al., 2002; Matos et al., 2006; Cunha et al., 2007; Zaia et al., 2008a,b; Partelli et al., 2009). This fact highlights the importance of the organic fraction, especially in deficient soils, like weathered ones where available P is probably related to Po fractions (Guerra et al., 1996; Cunha et al., 2007).

### Inorganic and organic moderately labile phosphorus (Pi-$H^+$ and Po-$H^+$)

Higher levels of Pi-$H^+$ in all depths (Table 2) occurred in soil in the SM system. As observed for PiI, the mineralization of Po probably released Pi. Through binding with Fe and Al oxy-hydroxides, its concentration increased in the SM system. Studying different soil management systems in the Brazilian *Cerrado*, Neufeldt et al. (2000) found that total P extracted with HCl (less labile) increased from 99 mg $kg^{-1}$, in soil under original *Cerrado* vegetation, to 158 and 151 mg $kg^{-1}$, in areas with grain cultivation and pasture, respectively. This increase was associated with the effect of P addition through the application of soluble phosphate fertilizers, of which inorganic P was probably released to the solution and easily chemisorbed by Al and Fe. However, in this study, this increase may have been due to the mineralization of Po derived from the incorporation of plant residues spread over the soil following plant shredding.

Our study shows that the Pi-$H^+$ contents were higher in the SB system compared to the SV system for all depths tested. This result indicates that vegetation burning in the SB system, responsible for the release of P contained in the aerial biomass of the vegetation and the litter (Giardina et al., 2000), resulted in an increase in inorganic phosphorus availability and, probably, also increased the chemisorption of nutrients to Al and Fe oxides (Galang et al., 2010). In our study, sampling was performed four years after the last burning in the area under the SB system, demonstrating the ephemeral effect of ash addition.

Significant differences were observed in Po-$H^+$ content only in the 0.05-0.10 m depth, where the means were higher for the SM and SB systems. The highest Po-$H^+$ content for the SB system may be explained by the accumulation of ash, derived from the burning, containing calcium phosphate in its composition (Ball-Coelho et al., 1993), which can also be a source of Pi and support both microbial activity and the formation of the Po-Ca complex (Correia, 2010). On the other hand, the Po-$H^+$ content in the SM system is superior to the content found in the SV system due to the higher availability of organic matter (Table 1), considering that Po may be easily associated with SOM (Tiessen and Moir, 1993).

### Inorganic and organic moderately resistant phosphorus (Pi-$OH^-$ e Po-$OH^-$)

No difference was observed between the two systems at all depths studied, i.e., the accumulation and the depletion of the Pi-$OH^-$ were equivalent; thus, management using the SM and SB systems did not interfere in this P fraction. No significant effect in the P content extracted with NaOH was also observed by Lilienfein et al. (2000) for seven different soil uses/managements of Oxisol in the Brazilian *Cerrado*.

The soil under the SM system presented a higher content of Po-$OH^-$ at the depths 0.00-0.05 and 0.10-0.20 m. The secondary forest shredded vegetation contributed to the higher fraction Po-$OH^-$ content, since the moderately resistant fraction, extracted in alkaline medium, is associated with humic acids (Schlesinger et al., 1998). Preservation of SOM leads to the supply of more resistant forms that, despite its difficult availability, plays an important role as a reservoir compartment of P, and is capable of being released on a long-term basis (Bowman and Cole, 1978b).

### Inorganic and organic total phosphorus (Pit and Pot)

Highest contents of Pit and Pot in all the sampled depths (Table 2) were observed for the SM system. Busato et al. (2005), studying sugarcane management systems, found higher concentrations of Po in soils where sugarcane trash was incorporated for 55 years, indicating that sugarcane crop residues maintenance may contribute to the increase of this fraction. The accumulation of organic matter and consequently of organic P, in minimum tillage systems, result from the crop residue left over the soil surface (Núñes et al., 2003). These same authors also showed that most of these residues, rich in P, could provide Pi through the mineralization of Po, enabling microbial re-assimilation, plant absorption and reaction with mineral components.

The Po forms percentage in Pot showed the prevalence of the fraction extracted in acid medium in all the systems, independently of depth (Figure 3). This result is in accordance with those obtained by Matos et al. (2006), who observed a prevalence of soluble in acid Po in a *Argissolo Vermelho-Amarelo Distrófico* (Dystrophic Red-Yellow Ultisol) cultivated with exclusive corn and intercropped with beans. The P fractions extracted with NaOH and $H_2SO_4$ seem to play a major role in the process of available P maintenance (Araújo et al., 2004), and there is evidence of the participation of these fractions, often considered less labile, in the supply of P to corn due to their noted decrease (Santos et al., 2008).

Soil under the SM system presented higher percentage of Po in more labile forms (Pot and Po-$H^+$), suggesting that soil management with the preservation and addition of organic matter may contribute more easily to the available P in the soil, since the more recalcitrant forms are slowly released. Studying the bioavailability of accumulated P forms in soil cultivated under No-tillage system with different quantities of P added, Gatiboni et al. (2007) concluded that, on a long-term basis, all the P forms in soil influence the bioavailability of P, although the liberation of P through the recalcitrant forms occured at an unsatisfactory rate and in insufficient quantities for plant absorption.

There was a prevalence of Pit over Pot in soil Pt (Figure 4), as noted by other authors (Guerra et al., 1996; Núñes et al., 2003; Rocha et al., 2005; Cunha et al., 2007; Zaia et al.,

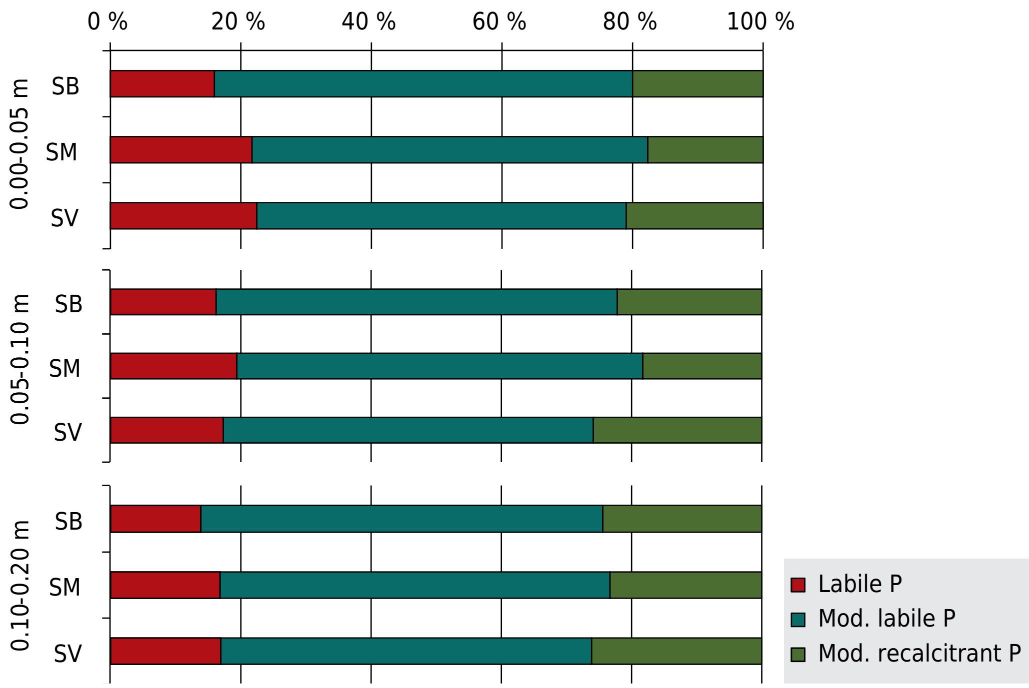


**Figure 3.** Percentage of labile, moderately labile and moderately recalcitrant phosphorus in the total phosphorus recovered, in slash-and-burn (SB), slash-and-mulch (SM) and secondary vegetation (SV) systems at different depths in an *Argissolo Amarelo Distrófico* (Ultisol).

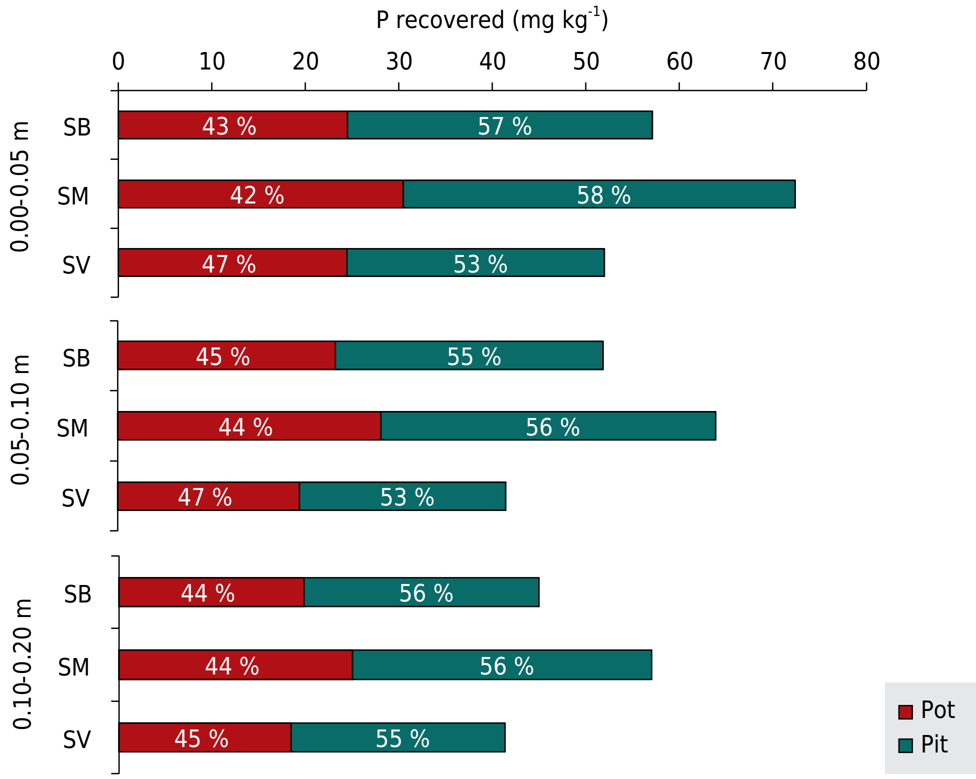


**Figure 4.** Percentage distribution of total organic P (Pot) and total inorganic (Pit) in relation to total P recovered, in slash-and-burn (SB), slash-and-mulch (SM) and secondary vegetation (SV) systems at different depths in an *Argissolo Amarelo Distrófico* (Ultisol).

2008). The Pot percentage observed in the present study, which ranged from 42 to 47 %, was superior to that found by Núñes et al. (2003) in an *Argissolo Vermelho-Amarelo* (Ultisol) under a minimum tillage system, where the Po participation in Pt was approximately 29 % .This Pot percentage was also within the range found by Guerra et al. (1996) for several soils in Brazil, where the organic fraction ranged from 13 to 47 % of total the Pt recovered, in *Neossolo Quartzarênico* (Entisol) and *Argissolo Vermelho-Amarelo* (Ultisol) samples, respectively. However, Xavier et al. (2009), evaluating the organic fertilization and the use of green manures in different fractions of P in soil in areas under organic agriculture in Ceará, found that the organic P compartment was responsible for over 50 % of the soil Pt in all the evaluated areas, indicating that the Po forms play a vital role in P cycling and plant nutrition in sandy soils. Despite the higher contribution of Pit, the Pot percentages found in the present study are significant, as suggested by Partelli et al. (2009), who obtained a mean of 43 % Pot in soils cultivated with Conilon coffee under different organic production systems.

The recovery percentage of the method, i.e., the relation (Pi+Po/Pt), ranged from 72 to 114 % of Pt, with a mean of 99 % (Table 2). Using the same method, Zaia et al. (2008b) found recovery rates ranging from 40 to 169 %, Partelli et al. (2009) from 51 to 111 %, and Guerra et al. (1996) between 48 and 109 %, with a mean of 63 %.

### Total phosphorus (Pt)

Soil management significantly affected the Pt content in soil at the 0.05-0.10 m depth (Table 2). The SM system resulted in a higher Pt content at this depth. The other systems show that the adoption of management practices that maintain SOM favor the accumulation of P in the soil, especially due to the contribution of Po. Studying P losses by erosion and the distribution of chemical forms of P influenced by the soil preparation system, Núñes et al. (2003) observed that stands under minimum tillage present higher Pt contents. The authors suggest that this is a result of the reduction of soil losses by erosion, as well as of the favored accumulation of P by crop residues left on the soil surface.

In soil cropped to sugarcane, Busato et al. (2005) found that the adoption of a management system without burning that includes the preservation of the crop residues for a long period, besides preventing the emission of atmospheric pollutants, enabled a higher P content in the soil not only on the surface (0.00-0.20 m) but also in the subsurface (0.20-0.40 m), supporting the findings of our study. In soil under no-tillage (NT) compared to adjacent areas where crops have never been grown, Tokura et al. (2002) also found that the Pt values were higher over time in the NT system due to the cycling of nutrients, favoring the activity of microorganisms and, consequently, the mineralization of Po. Furthermore, Tiecher et al. (2012), studying the distribution of P forms in soils under NT and conventional planting, also found a higher content of Pt on the soil superficial surface under NT as a result of both reduced loss to erosion and the decomposition of vegetal residues.

## CONCLUSIONS

Slash-and-mulch system increases soil phosphorus availability due to a higher nutrient cycling; however, soil available P is still not enough to fulfill the needs of the following crops, therefore necessitating the addition of phosphate fertilizers.

Soil under slash-and-mulch system showed prevalence of the labile fraction, whereas soil under the slash-and-burn system showed a predominance of the less labile fraction ($P-H^+$ and $P-OH^-$).

A wide prevalence of the Pol fraction over the Pil and great contribution of the Pot fraction to the soil Pt occurred in all management systems, demonstrating the importance of the organic fraction to the availability and maintenance of P in the soil.

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## REFERENCES

Andrade FV, Mendonça ES, Alvarez V VH, Novais RF. Addition of organic and humic acids to Latosols and phosphate adsorption effects. Rev Bras Cienc Solo. 2003;27:1003-11. doi:10.1590/S0100-06832003000600004

Araújo EA, Lani JL, Amaral EF, Guerra A. Uso da terra e propriedades físicas e químicas de Argissolo Amarelo Distrófico na Amazônia Ocidental. Rev Bras Cienc Solo. 2004;28:307-15. doi:10.1590/S0100-06832004000200009

Ball-Coelho B, Salcedo IH, Tiessen H, Stewart JWB. Short- and long-term phosphorus dynamics in a fertilized Ultisol under sugarcane. Soil Sci Soc Am J. 1993;58:1027-34. doi:10.2136/sssaj1993.03615995005700040025x

Bowman RA, Cole CV. Transformations of organic phosphorus substrates in soils as evaluated by $NaHCO_3$ extraction. Soil Sci. 1978a;125:49-54. doi:10.1097/00010694-197801000-00008

Bowman RA, Cole CV. An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Sci. 1978b;125:95-101. doi:10.1097/00010694-197802000-00006

Bowman RA. A sequential extraction procedure with concentrated sulfuric acid and dilute base for soil organic phosphorus. Soil Sci Soc Am J. 1989;53:362-6. doi:10.2136/sssaj1989.03615995005300020008x

Busato JG, Canellas LP, Velloso ACX. Fósforo num Cambissolo cultivado com cana-de-açúcar por longo tempo. I: Fracionamento seqüencial. Rev Bras Cienc Solo. 2005;29:935-44. doi:10.1590/S0100-06832005000600011

Certini G. Effects of fire properties of forest soils: a review. Oecologia. 2005;143:1-10. doi:10.1007/s00442-004-1788-8

Comte I, Davidson R, Lucotte M, Carvalho CJR, Oliveira FA, Silva BP, Rousseau GX. Physicochemical properties of soils in the Brazilian Amazon following fire-free land preparation and slash-and-burn practices. Agric Ecosyst Environ. 2012;156:108-15. doi:10.1016/j.agee.2012.05.004

Correia BL. Formas de fósforo em Latossolo sob cana-de-açúcar colhida sem queima [tese]. Piracicaba: Escola Superior Luiz de Queiroz; 2010.

Cunha GM, Gama-Rodrigues AC, Costa GS, Ary CXV. Fósforo orgânico em solos sob florestas montanas, pastagens e eucalipto no norte fluminense. Rev Bras Cienc Solo. 2007;31:667-72. doi:10.1590/S0100-06832007000400007

Denich M, Vielhauer K, Kato MSA, Block A, Kato OR, Sá TDA, Lücke W, Vlek PLG. Mechanized land preparation in forest-based fallow systems: The experience from Eastern Amazonia. Agrofor Syst. 2004;61:91-106. doi:10.1023/B:AGFO.0000028992.01414.2a

Denich M, Vlek PLG, Sá TDA, Vielhauer K, Lücke W. A concept for the development of fire-free fallow management in the Eastern Amazon, Brazil. Agric Ecosyst Environ. 2005;110:43-58. doi:10.1016/j.agee.2005.05.005

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. Centro Nacional de Pesquisas do Solo. Manual de métodos de análise de solo. 2ª. ed. Rio de Janeiro: 1997.

Galang MA, Markewitz D, Morris LA. Soil phosphorus transformations under forest burning and laboratory heat treatments. Geoderma. 2010;155:401-8. doi:10.1016/j.geoderma.2009.12.026

Gatiboni LC, Kaminski J, Rheinheimer DS, Flores JPC. Biodisponibilidade de formas de fósforo acumuladas em solo sob sistema plantio direto. Rev Bras Cienc Solo. 2007;31:691-9. doi:10.1590/S0100-06832007000400010

Giacomini SJ, Aita C, Vendruscolo ERO, Cubilla M, Nicoloso RS, Fries MR. Matéria seca, relação C/N e acúmulo de nitrogênio, fósforo e potássio em misturas de plantas de cobertura de solo. Rev Bras Cienc Solo 2003;27:325-34. doi:10.1590/S0100-06832003000200012

Giardina CP, Sanford Jr RL, Dockersmith IC. Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. Soil Sci Soc Am J. 2000;64:399-405. doi:10.2136/sssaj2000.641399x

Guerra JGM, Almeida DL, Santos GA, Fernandes MS. Conteúdo de fósforo orgânico em amostras de solos. Pesq Agropec Bras. 1996;31:291-9.

Iyamuremye F, Dick RP, Baham, J. Organic amendments and phosphorus dynamics: I. Phosphorus chemistry and sorption. Adv Agron. 1996;161:426-35. doi:10.1097/00010694-199607000-00002

Joslin AH, Markewitz D, Morris LA, Oliveira FA, Figueiredo RO, Kato OR. Five native tree species and manioc under slash and mulch agroforestry in the eastern Amazon of Brazil Plant growth and soil responses. Agrofor Syst. 2011;81:1-14. doi:10.1007/s10457-010-9356-1

Kato MSA, Denich M, Vlek PLG. Fire-free alternatives to slash-and-burn for shifting cultivation in the eastern Amazon region: the role of fertilizers. Field Crops Res. 1999;62:225-37. doi:10.1016/S0378-4290(99)00021-0

Lilienfein J, Wilcke W, Ayarza MA, Vilela L, Lima SC, Zech W. Chemical fractionation of phosphorus, sulphur, and molybdenum in Brazilian savannah Oxisols under different land use. Geoderma. 2000;96:31-46. doi:10.1016/S0016-7061(00)00002-1

Matos ES, Mendonça ES, Villani EMA, Leite LFC, Galvão JCC. Formas de fósforo no solo em sistemas de milho exclusivo e consorciado com feijão sob adubação orgânica e mineral. Rev Bras Cienc Solo. 2006;30:625-32. doi:10.1590/S0100-06832006000400003

Murphy J, Riley JP. A modified single solution method for the determination of phosphate in natural waters. Anal Chem Acta. 1962;27:31-6. doi:10.1016/S0003-2670(00)88444-5

Neufeldt H, Silva JE, Ayarza MA, Zech W. Land-use effects on phosphorus fractions in Cerrado oxisols. Biol Fertil Soils. 2000;31:30-7. doi:10.1007/s003740050620

Novais RF, Smyth TJ, Nunes FN. Fósforo. In: Novais RF, Alvarez V VH, Barros NF, Fontes RLF, Cantarutti RB, Neves JCL, editores. Fertilidade do solo. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2007. p.471-550.

Núñes JEV, Sobrinho NMBA, Mazur N. Consequências de diferentes sistemas de preparo do solo sobre distribuição química e perdas de fósforo de um Argissolo. Bragantia. 2003;62:101-9. doi:10.1590/S0006-87052003000100013

Oliveira LB, Tiecher T, Quadros FLF, Santos DR. Fósforo microbiano em solos sob pastagem natural submetida à queima e pastejo. Rev Bras Cienc Solo. 2011;35:1509-15. doi:10.1590/S0100-06832011000500005

Olsen SR, Sommer LE. Phosphorus. In: Miller RH, Kenney DR, editors. Methods of soil analysis. Madison: American Society of Agronomy; 1982. p.403-30.

Partelli FL, Busato JG, Vieira HD, Viana AP, Canellas LP. Qualidade da matéria orgânica e distribuição do fósforo no solo de lavouras orgânicas de café Conilon. Cienc Rural. 2009;39:2065-72. doi:10.1590/S0103-84782009000700017

Reichert JM, Bervald CMP, Rodrigues MF, Kato OR, Reinert DJ. Mechanized land preparation in eastern Amazon in fire-free forest-based fallow systems as alternatives to slash-and-burn practices: hydraulic and mechanical soil properties. Agric Ecosyst Environ. 2014;192:47-60. doi:10.1016/j.agee.2014.03.046

Reichert JM, Rodrigues MF, Bervald CMP, Kato OR. Fire-free fallow management by mechanized chopping of biomass for sustainable agriculture in eastern Amazon: effects on soil compactness, porosity, and water retention and availability. Land Degrad Develop. 2015a. doi:10.1002/ldr.2395

Reichert JM, Rodrigues MF, Bervald MPB, Brunetto G, Kato OR, Schumacher MV. Fragmentation, fiber separation, decomposition, and nutrient release of secondary-forest biomass, mechanically chopped-and-mulched, and cassava production in the Amazon. Agric Ecosyst Environ. 2015b;204:8-16. doi:10.1016/j.agee.2015.02.005

Resende JCFR, Markewitz D, Klink CA, Bustamante MMC, Davidson EA. Phosphorus cycling in a small watershed in the Brazilian Cerrado: impacts of frequent burning. Biogeochemistry. 2011;105:105-18. doi:10.1007/s10533-010-9531-5

Rheinheimer DS, Anghinoni I, Conte E. Sorção de fósforo em função do teor inicial e de sistemas de manejo de solos. Rev Bras Cienc Solo. 2003a;27:41-9. doi:10.1590/S0100-06832003000100005

Rheinheimer DS, Santos JCP, Fernandes VBB, Mafra AL, Almeida JA. Modificações nos atributos químicos de solo sob campo nativo submetido à queima. Cienc Rural. 2003b;33:49-55. doi:10.1590/S0103-84782003000100008

Rheinheimer DS, Cassol PC, Kaminski J, Anghinoni I. Fósforo orgânico do solo. In: Santos GA, Silva LS, Canellas LP, Camargo FAO, editores. Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais. 2ª. ed. Porto Alegre: Metrópole; 2008. p.101-11.

Ribeiro KA, Oliveira TS, Mendonça ES, Xavier FAS, Maia SMF, Souza HHF. Qualidade do solo na cultura do cajueiro anão precoce cultivado sob diferentes sistemas de manejo. Rev Bras Cienc Solo. 2007;31:341-51. doi:10.1590/S0100-06832007000200016

Rocha AT, Duda GP, Nascimento CWA, Ribeiro MR. Fracionamento do fósforo e avaliação de extratores do P-disponível em solos da ilha de Fernando de Noronha. Rev Bras Eng Agríc Amb. 2005;9:178-84. doi:10.1590/S1415-43662005000200005

Rodrigues MACM, Miranda IS, Kato MSA. Flora e estrutura da vegetação secundária após o uso de diferentes trituradores florestais. Pesq Agropec Bras. 2007;42:459-65. doi:10.1590/S0100-204X2007000400002

Sá TDA, Kato OR, Carvalho CJR, Figueiredo RO. Queimar ou não queimar? De como produzir na Amazônia sem queimar. Rev USP. 2007;72:90-7. doi:10.11606/issn.2316-9036.v0i72p90-97

Sampaio FAR, Fontes LEF, Costa LM, Jucksch I. Balanço de nutrientes e da fitomassa em um Argissolo Amarelo sob floresta tropical amazônica após a queima e cultivo com arroz. Rev Bras Cienc Solo. 2003;27:1161-70. doi:10.1590/S0100-06832003000600020

Santos HG, Jacomine P KT, Anjos LHC, Oliveira VAVL, Francisco J, Coelho MR, Almeida JA, Cunha TJF, Oliveira JB, coordenadores. Sistema brasileiro de classificação de solos. 3ª. ed. Brasília, DF: Embrapa; 2013.

Santos JZL, Furtini Neto AE, Resende AV, Curi N, Carneiro LF, Costa SEVGA. Frações de fósforo em solo adubado com fosfatos em diferentes modos de aplicação e cultivado com milho. Rev Bras Cienc Solo. 2008;32:705-14. doi:10.1590/S0100-06832008000200025

Schlesinger WH, Bruilnzeel LA, Bush MB, Klein EM, Mace KA, Raikes JA, Whittaker RJ. The biogeochemistry of phosphorus after the first century of soil development on Rakata Island, Krakatau, Indonesia. Biogeochemistry. 1998;40:37-55. doi:10.1023/A:1005838929706

Silva GR, Silva Jr ML, Melo VS. Efeitos de diferentes usos da terra sobre as características químicas de um Latossolo Amarelo do Estado do Pará. Acta Amaz. 2006;36:151-8. doi: 10.1590/S0044-59672006000200004

Solomon D, Lehmann J, Mamo T, Fritzsche F, Zech W. Phosphorus forms and dynamics as influenced by land use changes in the sub-humid Ethiopian highlands. Geoderma. 2002;105:21-48. doi:10.1016/S0016-7061(01)00090-8

Souza FR, Faquin V, Torres PRF, Baliza DP. Calagem e adubação orgânica: influência na adsorção de fósforo em solos. Rev Bras Cienc Solo. 2006; 30:975-83. doi:10.1590/S0100-06832006000600007

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: USDA-Natural Resources Conservation Service; 2014.

Tiecher T, Rheinheimer DS, Kaminski J, Calegari A. Forms of inorganic phosphorus in soil under different long term soil tillage systems and winter crops. Rev Bras Cienc Solo. 2012;36:271-81. doi:10.1590/S0100-06832012000100028

Tiessen H, Moir JO. Characterization of available P by sequential extraction. In: Carter MR, editor. Soil sampling and methods of analysis. Boca Raton: Lewis; 1993. p.75-86.

Tokura AM, Furtini AEN, Curi N, Faquin V, Kurihara CH, Alovisi AA. Formas de fósforo em solo sob plantio direto em razão da profundidade e tempo de cultivo. Pesq Agropec Bras. 2002;37:1467-76. doi:10.1590/S0100-204X2002001000015

Trindade EFS, Kato OR, Carvalho EJM, Serafim ECS. Disponibilidade de Fósforo em solos manejados com e sem queima no Nordeste Paraense. Amazônia: Cienc Desenv. 2011;6:7-19.

Xavier FAS, Oliveira TS, Andrade FV, Mendonça ES. Phosphorus fractionation in a sandy soil under organic agriculture in Northeastern Brazil. Geoderma. 2009;151:417-23. doi:10.1016/j.geoderma.2009.05.007

Zaia CF, Gama-Rodrigues AC, Gama-Rodrigues EF. Formas de fósforo no solo sob leguminosas florestais, floresta secundária e pastagem no norte fluminense. Rev Bras Cienc Solo. 2008a;32:1191-7. doi:10.1590/S0100-06832008000300027

Zaia CF, Gama-Rodrigues AC, Gama-Rodrigues EF, Machado RCR. Fósforo orgânico em solos sob agrossistemas de cacau. Rev Bras Cienc Solo. 2008b;32:1987-95. doi:10.1590/S0100-06832008000500020