



## Organic phosphorus in a clayey Oxisol after deforestation in the eastern Amazon

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### Abstract

In tropical oxidic soils, organic phosphorus (Po) plays an important role in plant nutrition. In addition, Po cycling in clay soils is very complex due to the greater participation and influences of active clay fractions on nutrient availability. The objective of this study was to evaluate the effects of converting a native forest to a secondary forest or *Brachiaria brizantha* pasture on the Po contents of clayey Oxisols in the eastern region of Amazonia, Itupiranga, in the State of Pará. Soil samples were collected from areas of native forest (NF), secondary forest of 8-10 years (SF), and pastures of 1-2 years (P1-2), 5-7 years (P5-7) and 10-12 years (P10-12) in 3 replicates for each land-use type and depth sequential P fractionation was conducted to obtain the following 3 fractions: sodium bicarbonate-, acid- and alkali-soluble. The samples obtained from the different land use types indicated different P accumulation abilities, suggesting that slash-and-burn clearing of a forest increased the soil P contents. On average, the total organic phosphorus (Pot) content corresponded to 21% of the total soil phosphorus (Pt), with a predominance of the moderately labile fraction (Po-H<sup>+</sup>), followed by the labile form (Pol) and the moderately resistant fraction (Po-OH<sup>-</sup>), with average Pot contents of 65%, 21% and 15%, respectively. Over a short-term period, the P availability represented by Pol was higher in the soils from the native forest and secondary forests. In addition, the available P over a medium-term period, as represented by Po-H<sup>+</sup>, indicated a higher P content in the pasture soil.

**Key words:** Phosphorus fractions, particle-size fractionation, Amazon forest, land use.

### Introduction

The use of fractionation to elucidate the dynamics of phosphorus (P) in the soil provides a biological and geochemical view of the nutrient fractions and allows an analytical view of chemically sorbed forms of P<sup>1,2</sup>. The compartmentalization of Po is associated with its biological availability, which depends on its association with organic and mineral components<sup>3</sup>. The compartmentalization of Po is associated with the nutrient availability of the culture according to its association with organic and mineral components<sup>3</sup>. Furthermore, the lability of P can be influenced by other management practices and land use factors; however, these factors have not been fully clarified<sup>4-7</sup>. Temporary fallow conditions and the type of secondary vegetation established after the definitive abandonment of crops may play important roles in correcting soil P levels<sup>8</sup>. In addition, the high adaptability of *Brachiaria* grass to acidic soils in grassland areas with low P levels has been studied<sup>9-11</sup>.

The slash-and-burn practice in tropical regions for clearing forestland is traditionally applied due to its low cost and rapid nutrient mineralization, including P mineralization<sup>12,13</sup>. However, over medium-term periods, the P stock generally decreases, mainly due to nutrient losses through volatilization and soil erosion<sup>14-16</sup>. The use of fire converts the soil organic matter and the O horizon, which alters the biological nutrient immobilization and mineralization rates<sup>15,17,18</sup>.

Biological mineralization and P availability are closely related with the Po content<sup>7,19-21</sup>. The organic form of P represents 20-96% of the Pt<sup>22-25</sup>. In soils that are P-deficient as a result of low total P contents or sorption phenomena, the importance of this compartment is more pronounced<sup>26</sup>.

Studies regarding the effects of adding organic matter on the redistribution of P have demonstrated a positive correlation between Po and soil carbon<sup>27,28</sup>. Li *et al.*<sup>29</sup> correlated highly and moderately resistant P fractions with organic carbon (OC), but not in the labile fraction.

Turner and Blackwell<sup>30</sup> did not observe this analogy between OC and Po in acidic soils (pH < 4). This result was corroborated by Zaia *et al.*<sup>31</sup>, who proposed that additional studies on the cycling of this nutrient should be conducted. The relationship between the organic phosphorus (Po) and organic matter content is affected by the specific forms of Po in the soil<sup>29</sup> because mineralization of this form of P can be essential for supplying inorganic phosphorus (Pi) for plant development<sup>20,32,33</sup>.

The fractions of Po can also be influenced by soil texture because the pedogenic processes affect the association of Po with different soil particle size fractions<sup>34-36</sup>.

Although total phosphorus (Pt) and clay contents are often correlated<sup>37-39</sup>, the P fractionation results and total organic phosphorus (Pot) are not always correlated<sup>31,40</sup>. The accumulation

of OC in different soil fractions has been reported in the literature<sup>41-43</sup>. The contributions of organic matter (OM) to the availability of Po in agricultural soils should be highlighted, including the formation of reserve compartments for nutrients, which are also known as microaggregates<sup>44-46</sup>.

In the Amazon, P is the main limiting nutrient for plant nutrition due to high temperatures and high rainfall<sup>4, 10, 47, 48</sup>. The impacts of soil management on soil Po transformations are best understood when assessing the distribution of different forms of P in soil particle-size fractions<sup>34, 49</sup>. The objective of this study was to evaluate the effects of replacing native forests with secondary forest or pasture on the Po fractions in the surface samples of yellow Oxisol clayey soils in the eastern region of the Amazon.

## Materials and Methods

**Description of the study area and sampling:** The study areas are located in the Settlement Project "Benfica" (5° 16' 00" S and 49° 50' 00" W), 80 km from the town of Itupiranga, southeast of Pará State, Brazil. According to the Köppen classification system, this region is classified as Aw, which corresponds to a humid tropical climate with a dry season. Soil samples were collected during the dry season. In addition, the average annual temperature was 26°C, and high amounts of rainfall and precipitation of up to 2,000 mm occurred each year.

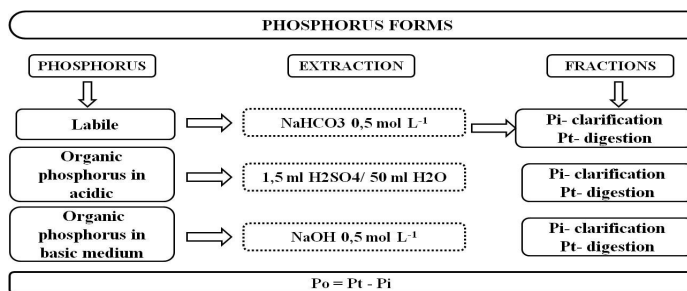
The areas were divided according to soil use and management as follows: native forest (NF); secondary forest (SF): 8-10 years after cutting and burning the original forest; and grass pastures (*Brachiaria brizantha*) of 1-2 years (P1-2), 5-7 years (P5-7) and 10-12 years (P10-12). The pasture areas were used for extensive livestock after burning firing the original vegetation.

The soils in the study area were predominantly Dystrophic Oxisols with a clayey texture. For sampling, a transect measuring approximately 100 m in length was delimited perpendicular to the declivity of the land. Twenty single samples were collected at each collection point to form each of the composite samples at depths of 0-0.02, 0.02-0.05 and 0.05-0.1 m in each area. Overall, ten equidistant samples were collected along the transect.

**Analysis:** Chemical and granulometric analyses were performed following the methodological procedures of EMBRAPA<sup>50</sup>, as shown in Table 1. More detailed soil characteristics from this study area were presented and discussed by Silva *et al.*<sup>42</sup>.

During the first stage of soil analysis, the particle size distribution of the soil organic matter was determined by considering fractions of 53-2000 µm (total sand), 0-53 µm (clay + silt) and 0-2 µm (clay total) according to the method of Gavinelli *et al.*<sup>51</sup> and as described in Silva *et al.*<sup>42</sup>. In the second step, the fractions were analyzed to determine their Pt contents and to quantify the different forms of Po in the different fractions.

The Pt contents were determined according to Olsen and Sommers<sup>52</sup>. The fractionation of P (Fig. 1) was performed based on the methods proposed by Bowman and Cole<sup>53</sup> and Bowman<sup>54</sup>, with the adaptations suggested by Guerra<sup>55</sup> regarding the use of activated purified charcoal. The Pi and Pt alkaline extracts of NaHCO<sub>3</sub> and NaOH refer to the fractions of labile phosphorus and the moderately resistant portions, respectively. An acid extract in H<sub>2</sub>SO<sub>4</sub> was obtained in the moderately labile fraction. The Pt contents were determined from these extracts by digesting nitril perchlorate (HNO<sub>3</sub>:HClO<sub>4</sub>) 1:1.5 (v/v) according to the methodology proposed by Olsen and Sommer<sup>52</sup>. Measurements of the extracts were taken using spectrophotometry according to the methods of Murphy and Riley<sup>56</sup>. The Po was obtained by taking the difference of the Pt and Pi.



**Figure 1.** Schematic diagram of the sequential fractionation of soil organic phosphorus<sup>53, 54</sup>.

**Table 1.** Chemical properties and particle sizes of the Oxisol soils at different depths and under different land uses.

Soil use	pH	P	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	CTC	V	SOM	Clay	Silt	Sand
	H <sub>2</sub> O	mg kg <sup>-1</sup>	cmol <sub>c</sub> .kg <sup>-1</sup> of soil				%	g kg <sup>-1</sup> soil			
Layer 0-0.02 (m)											
NF <sup>(1)</sup>	4.4	9.4	0.6	0.2	0.1	9.3	12.2	22.2	367	46	587
SF <sup>(2)</sup>	5.2	12.7	2.4	1.1	0.7	9.5	23.4	26.38	322	53	625
P1-2 <sup>(3)</sup>	6.3	15.6	4.2	1.8	0.4	9.9	65.4	22.86	344	68	588
P5-7 <sup>(4)</sup>	6.4	9.2	3.7	2	1.2	9.8	69.7	26.4	353	74	573
P10-12 <sup>(5)</sup>	5.1	5.2	2.1	1.5	0.3	9.8	40.8	24.27	444	70	486
Layer 0.05-0.1 (m)											
NF	4.2	3.9	0.1	0.4	0.1	6.9	9.5	12.47	503	50	447
SF	4.8	2.9	0.7	0.6	0.3	6.2	29.9	13.5	416	56	528
P1-2	4.7	3.4	0.7	0.6	0.1	7	23	12.71	499	53	448
P5-7	5.2	2.2	1.3	0.7	0.4	5.9	39.4	15.88	504	50	446
P5-10	4.8	2.3	1.2	0.8	0.1	7.4	31	12.57	506	66	428

(1) Native forest, (2) secondary forest 8-10 years, (3) pasture 1-2 years, (4) pasture 5-7 years, (5) and pasture 10-12 years; P: available phosphorus; CTC: CTC at pH 7.0; V: base saturation; m: aluminium saturation.

**Other calculations:** Different forms of P, expressed in  $\text{kg m}^{-2}$ , were calculated using the following equation:  $P = P_s \times d \times L$ . Here,  $P_s$  is the phosphorus content expressed in  $\text{mg kg}^{-1}$  soil,  $d$  is the density of the soil, and  $L$  is the thickness (in m) of the layers <sup>57</sup>.

**Statistical analysis:** The results obtained for the studied variables were analyzed using a factorial  $5 \times 3$  arrangement with five land-use types and three depths. An analysis of variance (ANOVA) was performed, and the averages were compared using Duncan's test with a 5% probability level (SAEG 8.1 <sup>58</sup> statistical program).

## Results and Discussion

**Total phosphorus (Pt):** The Pt significantly affected the type of soil use when considering the Pt concentrations and the studied particle-size fractions, except for the fine fraction (0-2  $\mu\text{m}$ ) at depths of 0:02- 0:05 m and 0.05-0.1 m and the silt fraction at depths of 0-0.02 m (Table 2).

**Table 2.** Concentrations of Pt ( $\text{mg kg}^{-1}$  fraction) in the size fractions of the Oxisol soils under different land-use types and depths.

Soil Use	NF	SF	P1-2	P5-7	P10-12
mg $\text{kg}^{-1}$					
0-2 $\mu\text{m}$					
0-0.02	493.9 b	574.3 ab	718.3 a	593.0 ab	596.1 ab
0.02-0.05	423.6 ns	469	503.6	573.2	438.8
0.05-0.1	382.9 ns	444.9	433.3	468.4	424.8
2-53 $\mu\text{m}$					
0-0.02	481.6 ns	451.8	543.3	436.9	586
0.02-0.05	390.2 b	373.5 b	472.0 ab	677.5 a	452.6 ab
0.05-0.1	421.8 ab	376.3 ab	281.1 b	585.8 a	316.3 b
53-2.000 $\mu\text{m}$					
0-0.02	18.6 c	32.8 bc	51.8 a	53.8 a	39.8 ab
0.02-0.05	15.1 b	25.6 ab	39.4 a	31.5 ab	33.6 ab
0.05-0.1	16.1 c	18.2 bc	35.6 ab	15.4 c	39.6 a
Total soil					
0-0.02	205a	209.3a	278.1a	265.3a	281 a
0.02-0.05	202a	199a	246.6a	317a	246a
0.05-0.1	203.4a	208.1a	237.3a	301.2a	247a

Native forest (NF), secondary forest of 8-10 years (SF), pasture of 1-2 years (P1-2), pasture of 5-7 years (P5-7) and pasture of 10-12 years (P10-12). Averages followed by the same lower-case letter in the same column and the same capital letter in the same line did not differ according to Duncan's test with an error margin of 5%; ns: not significant.

Generally, soils under pasture have high P contents in different fractions. The highest observed P content was  $718.3 \text{ mg kg}^{-1}$  at P1-2 in the clay fraction of the 0-0.02-m layer, which significantly differed from the area under NF, which had a Pt concentration of  $493.9 \text{ mg kg}^{-1}$ . This increase in the soil Pt concentration under secondary forest and pasture can be attributed to organic matter (OM) mineralization after burning <sup>18,21,38</sup>.

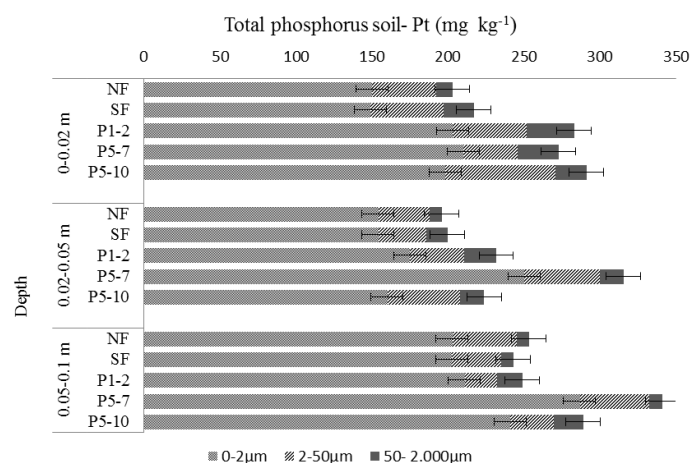
The age of the pasture did not affect the soil Pt concentration, indicating the effective recycling of organic matter and nutrients in this system. The use of fire in these areas has different effects on nutrient dynamics, and the factors that affect this practice include time, temperature and humidity <sup>14, 16, 33, 38</sup>. Bahr *et al.* <sup>11</sup> observed that the initial increment in the soil Pt was minimized within 30 years of implementing this system.

In the topsoil (0-0.02 m), the Pt content generally increased in the secondary forest and pasture, indicating the bioaccumulation of P and the occurrence of anthropogenic activity in these areas <sup>40</sup>. In a Cerrado Oxisol, Resende *et al.* <sup>38</sup> observed a reduction of 51% with increasing depth (4 m) compared with the Pt in the 0-0.1 m layer.

The largest variations were recorded in the thicker soil fractions (53-2000  $\mu\text{m}$ ), which increased by 189% in the soil in the P5-7 treatment relative to the forest soil at a depth of 0-0.02 m. In the 0-0.02-m layer, this increase was 71% in the SF, 144% in the P5-7 and 175% in the P1-2. The concentration of Pt generally decreased with increasing depth.

The highest Pt concentration observed in the sand fraction resulted from the enrichment of the soil after burning the epigeous biomass<sup>15</sup>. In addition, the C4 plants (mainly tropical grasses) have high P demands and biomass production. These traits favor the incorporation of P into plant tissues and increase the entry of organic waste and the bioavailable reservoir element <sup>9,10,32</sup>. In the Brazilian Cerrado region, *Brachiaria brizantha* is important for P cycling in soils that have been subjected to phosphate fertilization for 10 years <sup>4</sup>.

The main contributions of Pt in the soil clay fraction occurred in the surface layer (which averaged 71%), the layer immediately below the surface layer (76%), and at a depth of 0.05-0.1 m (80%) (Fig. 2). In contrast, the thicker fraction had the smallest contribution (5%).



**Figure 2.** Percent distributions of the Pt contents in different size fractions of an Oxisol with soil depth under native forest (NF), secondary forest of 8-10 years (SF), pasture of 1-2 years (P1-2), pasture of 5-7 years (P5-7) and pasture of 10-12 years (P10-12) in Itupiranga, State of Pará.

The active fractions of the soil are partially responsible for P adsorption based on multiple positive correlations between silicated clays and Fe and Al oxides with P fractions <sup>35,38,39</sup>. Oxisols with high levels of clay can absorb more than  $2 \text{ mg cm}^{-3}$  of P, which is equivalent to  $4000 \text{ kg ha}^{-1}$  <sup>26</sup>. Macdonald *et al.* <sup>8</sup> reported that labile P is sensitive to changes in soil clay contents and pH; however, no changes were observed for the Pt.

The Pt contents in the global soil with different uses were similar, averaging  $256 \text{ mg kg}^{-1}$  soil in the surface layer, in agreement with the indices that were proposed by Oliveira *et al.* <sup>15</sup> for highly weathered Oxisols in the tropics. Higher Pt concentrations of  $851.92 \text{ mg kg}^{-1}$  were observed in Oxisols of organic coffee plantations. Turner and Engelbrecht <sup>27</sup> studied 19 soils in a rainforest in the

Republic of Panama using NaOH-EDTA extraction and obtained Pt concentrations of 74 to 1650 mg kg<sup>-1</sup>.

The different OM concentrations resulting from different soil uses are less active for P sorption when they have lower Fe and Al oxide contents, which have acidic pH electropositive charges that attract the orthophosphate anion<sup>37</sup>.

**Labile organic phosphorus (Pol):** The type of soil use affected the Pol contents in all of the particle-size fractions, mainly for the surface layer (Table 3). In this layer, the average contents were 6.2 mg kg<sup>-1</sup> in the finest fraction, 3.6 mg kg<sup>-1</sup> in the intermediate fraction, and 1.2 mg kg<sup>-1</sup> in the largest fraction.

The oldest pastures have lower Pol concentrations because the nutrients that are made immediately available after firing may be partially absorbed or otherwise lost from the ecosystem<sup>12</sup>. The reduction of carbon stocks by between 14% and 19% during the conversion of forests to grasslands or annual crops by using fire has reduced the availability of P after 5 years of abandonment<sup>11</sup>. Smaller Pol concentrations of 1.8 to 0.2 mg kg<sup>-1</sup> were observed in the coarser fraction, regardless of depth. In addition, Pol was dominant in the finer fraction, and the percentage contribution of Pol increased with soil depth, averaging 44% in the surface layer and approximately 50% in the subsurface layers. The variations of the Pol contents in the different soil fractions followed the OM content variations<sup>42</sup>, which indicated a strong correlation between the Pol and organic matter contents in the soil.

Generally, the highest Pol content in the clay fraction was attributed to the low crystallinity and high specific surface area of the amorphous Fe and Al clays, which are abundant in Oxisols and increase the ability of this fraction to adsorb phosphate anions<sup>37, 39</sup>. Herlihy and McGrath<sup>35</sup> observed the following correlations between the maximum P sorption (Langmuir equation) and the soil properties: oxides of Al > silicate clays > OC > Fe oxides.

Higher Pol contents of 8.2, 6.6 and 6.5 mg kg<sup>-1</sup> were observed in P10-12, P1-2 and NF, respectively, in the surface layer. These results suggest that the presence of this P fraction is related to the organic

soil components, regardless of the particle size, and is mainly concentrated in the surface layer<sup>7, 28, 34</sup>.

The high Pol concentrations in the 0-0.02-m layer coincide with a significant increase in the OC (as observed by Silva *et al.*<sup>42</sup>) and microbial carbon contents<sup>17</sup> in these areas, highlighting the strong relationship between Pol and soil microbial biomass. In addition, the relationships between the increasing Pol and OC contents were noted by Muukkonen *et al.*<sup>36</sup> and Olibone and Rosolem<sup>24</sup>, who provided evidence of the blocking action of organic anions on P adsorption sites on the surfaces of oxides, influencing nutrient availability<sup>1, 22, 48</sup>. The finding that Pol was predominant over labile Pi (with percentages of up to 96% in SF) suggested that the available P would be closely associated with the Pol fractions in oxidic soils with low available Pol<sup>7, 19-21</sup>.

The major contributions of Pol in the Ptl were observed in the silt fraction in the secondary forest soil at depths of 0-0.02 m (96% Pol/Ptl), which may be associated with greater CO concentrations in this fraction<sup>41-43</sup>. In the silt fraction, a predominance of slightly humidified organic matter and microorganisms attached to the mineral phases of the soil exists, which reduces the recalcitrant fraction and potentially explains the high Pol fraction.

**Organic phosphorus in acidic (Po-H<sup>+</sup>):** The Po-H<sup>+</sup> content differed significantly between the systems in the fine (0.05-0.1 m depth), intermediate (0-0.02 m depth) and thick (depths 0-0.02 m and 0.02 to 0.05) fractions (Table 4).

On average, the surface concentration of Po-H<sup>+</sup> was 41 mg kg<sup>-1</sup>, which decreased with increasing depth and by 21% for the 0.02 to 0.05 m layer (31 mg kg<sup>-1</sup> soil). The variation in the Po-H<sup>+</sup> contents between the two subsurface layers was nearly zero and did not accompany an increase in the clay content. In contrast, Li *et al.*<sup>29</sup> proposed that the buildup of this fraction of P in clay particles resulted from the enrichment products of microbial metabolism.

The highest values were observed at depths of 0-0.02, likely due to greater deposition of carbon compounds, which are more resistant to decomposition and favor microbial growth<sup>17</sup> because the main form of moderately available Pol was connected by Al

**Table 3.** Labile organic P (Pol) content and percent distribution in the Oxisol size fractions with depth under different land-use types.

Depth (m)	NF		SF		P1-2		P5-7		P10-12	
	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)
0-2µm										
0-0.02	6.5ab	66	4.8b	56	6.6ab	53	5.1ab	61	8.2a	72
0.02-0.05	5.7a	73	4.5a	67	4.6a	57	3.6a	64	4.6a	70
0.05-0.1	4.2a	76	4.2a	70	4.1a	67	3.3a	73	3.2a	73
2-53µm										
0-0.02	3.8ab	83	5.6a	84	2.5b	66	2.7b	71	3.2ab	84
0.02-0.05	1.3a	72	2.2a	96	3.1a	76	1.4a	88	1.5a	75
0.05-0.1	3a	75	1.1a	73	1.9a	76	1.7a	89	1.6a	94
53-2.000µm										
0-0.02	1.8a	86	1.4ab	70	0.8ab	40	1.5ab	68	4.3a	22
0.02-0.05	1a	59	1a	71	0.2a	29	1.2a	75	1.8ab	12
0.05-0.1	1a	77	0.4a	57	0.5a	71	0.8a	80	1.16a	11

Native forest (NF), secondary forest of 8-10 years (SF), pasture of 1-2 years (P1-2), pasture of 5-7 years (P5-7) and pasture of 10-12 years (P10-12). Averages followed by the same lower-case letter in the same column and the same capital letter in the same line did not differ according to Duncan's test with an error margin of 5%

**Table 4.** Organic phosphorus content and percent distribution in the acid (Po-H<sup>+</sup>) size fractions of an Oxisol with depth under different land-use types.

Depth (m)	NF		SF		P1-2		P5-7		P10-12	
	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)
0-2µm										
0-0.02	27.4a	25	24.2a	23	22a	25	13.4a	11	22.0a	17
0.02-0.05	15.8a	16	16.68a	17	21.9a	19	18.8a	16	13.5a	14
0.05-0.1	19.2a	20	23.1a	22	23.0a	23	14.6a	14	8.4b	9
2-53µm										
0-0.02	7.1b	20	7.6b	25	16.3ab	37	23.6a	54	10.2b	27
0.02-0.05	11.6a	44	9.7a	31	16.33a	55	8.9a	40	12.1a	38
0.05-0.1	10.2a	41	7.9a	33	9.3a	54	4.7a	29	7.0a	25
53-2.000µm										
0-0.02	2.8b	18	1.1b	6	2.3b	14	4.5a	24	0.3b	38
0.02-0.05	1.9ab	23	0.48b	4	2.8a	18	1.9ab	22	0.3a	50
0.05-0.1	1.2a	16	0.3a	3	1.1a	11	0.57a	10	0a	0

Native forest (NF), secondary forest of 8-10 years (SF), pasture of 1-2 years (P1-2), pasture of 5-7 years (P5-7) e pasture of 10-12 years (P10-12). Averages followed by the same lower-case letter in the column and capital letter in the line did not differ by the Duncan test with an error margin of 5%.

and Fe, humic substances and fulvic acids<sup>54</sup>. However, Duda *et al.*<sup>32</sup> did not find a positive correlation between the Po-H<sup>+</sup> and microbial soil phosphorus.

As shown by the PoI, the largest Po-H<sup>+</sup>/Pt-H<sup>+</sup> contributions were observed in the silt fraction (55%) in the pasture soil of 1-2 years at a depth of 0.02 to 0.05 m. The smallest contributions of Po-H<sup>+</sup> in Pt-H<sup>+</sup> occurred in the sand fraction (3%) of the secondary forest soil at a depth of 0.05-0.1 m. A reduction in the percentage of ownership in the clay fraction permitted higher contributions in the 2-53-µm fraction, with an average contribution of approximately 29% in the deepest layer and 37% in the middle layer.

The predominance of Po-H<sup>+</sup>/Pt-H<sup>+</sup> in the silt fraction (Table 4), mainly in the soil under pastures, potentially originated from the biological metabolites of flora and microbial fauna that were associated with the soil solid phase and from slightly humidified OM that formed microaggregates when high concentrations of OM were present<sup>44</sup>.

Burak *et al.*<sup>45</sup> physically fractionated a Red Oxisol soil and observed that portions of the clay and silt fractions of the microaggregates formed where nutrients accumulated efficiently. In addition, Oxisols have microaggregates that are similar to those of silt particles, which form from the cementing action of iron oxides and poorly crystalline Al with clumping clay. These microaggregates result in the overestimation of the silt contents relative to the phosphate contents<sup>46</sup>.

The interpretation of the slash-and-burn system responsible for greater Pi contents in the liquid phase is supported by several studies<sup>11,18,21,38</sup>. Schafer and Mack<sup>14</sup> suggested the accumulation of P when fires are managed over a short time interval. Furthermore, the availability of P favors the conversion of Pi to Po, which is incorporated into microbial biomass or plant tissues, with reservoir Pm values ranging from 24 to 39% Pt in some studies<sup>13,23</sup>. This temporary immobilization protects the nutrients from fixation in the soil<sup>7</sup>.

Furthermore, the greater Po-H<sup>+</sup>/Pt-H<sup>+</sup> ratio in the pasture soil relative to the forest soil may be important for soil fertility in grasses

given that the moderately labile form works as a P reserve compartment for plants in the short- and medium-terms Duda *et al.*<sup>32</sup> observed a positive correlation of 0.67 between available P and Po-H<sup>+</sup>. According to Bowman<sup>54</sup> and Guerra *et al.*<sup>28</sup>, additional labile fractions may participate in the development and accumulation of plant nutrients.

**Organic phosphorus in basic medium (Po-OH<sup>-</sup>):** At all three analyzed depths, Po-OH<sup>-</sup> represented the smallest Po fraction for all land-use types (Table 5). The lowest and highest Po-OH<sup>-</sup> contents were observed in the top layers of the soil, with 4.1 mg kg<sup>-1</sup> in the SF soil and 16.8 mg kg<sup>-1</sup> in the P10-12 soil, respectively. Generally, a greater Po-OH<sup>-</sup> concentration occurred at P10-12 for all of the analyzed depths. This observation was very important because the Brachiaria grass could solubilize forms of P that are not labile<sup>10</sup>.

In addition, a slight increase was observed in the Po-OH<sup>-</sup> content as a function of increasing depth: » 4.2 mg kg<sup>-1</sup> in the upper soil layer; » 4.5 mg kg<sup>-1</sup> soil in the middle tier (+9%); and » 4.6 mg kg<sup>-1</sup> in the deeper soil layer (+10%). Despite the small clay fraction, these values averaged 3.1 and 5.2-fold greater than the values in the silt and sand fractions in the upper layer and 3.3 and 5.7-fold greater in the innermost layers of the two fractions, respectively. The distribution of Po in the studied particle-size fractions followed the same pattern that was previously observed for other Po forms. The highest Po-OH<sup>-</sup> concentrations occurred in the clay fraction, which decreased as the size of the particle-size fraction increased. In addition, the Po-OH<sup>-</sup> concentration increased with greater depth as the clay content increased from 60% in the surface layer of the soil to 66% in the subsurface layers

According to Neufeldt *et al.*<sup>34</sup>, the smallest variations in the clay soil potentially resulted from the high contributions of the Po-OH<sup>-</sup> in the clay fraction due to large amounts of organic matter-bound phosphorus (P-MO) relative to inorganic phosphorus bound to quartz. Agbenin and Tiessen<sup>49</sup> reported similar results regarding the accumulation of Po-OH<sup>-</sup> in the finer fractions of the soil due to the stabilization of P on the surfaces of these solid soil

**Table 5.** Organic phosphorus content and percent distribution in the basic (Po-OH<sup>-</sup>) size fractions of an Oxisol with depth under different land-use types.

Depth (m)	NF		SF		P1-2		P5-7		P10-12	
	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)	mg kg <sup>-1</sup>	(%)
0-2µm										
0-0.02	3.7a	37	3.86a	48	3.6a	56	1.9a	20	6.5a	45
0.02-0.05	3.8a	35	3.07a	46	2.4a	36	5.7a	44	7.1a	50
0.05-0.1	2.8a	29	3.36a	44	3.9a	45	4.6a	38	7.73a	50
2-53µm										
0-0.02	2.22a	61	1.3a	38	1.4a	67	0.36a	10	2.5a	54
0.02-0.05	2.5a	60	0.7a	35	1.71a	74	0.78a	27	2.6a	55
0.05-0.1	2.5ab	61	0.7b	41	1.14b	55	0.57b	36	3.3a	81
53-2.000µm										
0-0.02	0.62a	22	0.5a	24	0.74a	23	1.4a	44	1.07a	33
0.02-0.05	0.67ab	33	1.4ab	67	0.33b	13	1.56a	70	0.51ab	18
0.05-0.1	0.55a	27	0.97a	45	0.9a	43	1.17a	57	1.1a	38

Native forest (NF), secondary forest of 8-10 years (SF), pasture of 1-2 years (P1-2), pasture of 5-7 years (P5-7) and pasture of 10-12 years (P10-12). Averages followed by the same lower-case letter in the same column and the same capital letter in the same line did not differ according to Duncan's test with an error margin of 5%.

components. The importance of Po-OH<sup>-</sup> for plant nutrition is that the finer clay and silt fractions may be considered as not only sources for recalcitrant P forms but also as sources of labile Po<sup>34,49</sup>.

From these results, we highlight the following points: i) the Po-OH<sup>-</sup>/Pt-OH<sup>-</sup> increased with greater depth in all of the particle-size fractions, and ii) the highest Po-OH<sup>-</sup>/Pt-OH<sup>-</sup> ratios were observed in the silt fraction. Therefore, the first assertion indicates that the alkali-soluble Po fraction can be stabilized with humic acids, potentially through their association with clays because the clay content increased with increasing depth. The second assertion suggests that Po is associated with clay minerals by through Fe and Al, which form stable microaggregates that make it difficult to rupture the sodium resin dispersing agent used in this study.

The percentage distribution of Po-OH<sup>-</sup> along the profile varied greatly in the thicker soil fractions (silt and sand). In the silt fraction, the lowest percentage was 31% in the upper layer and up to 35% in the deeper layer. For the sand fraction, the percentage varied

from 32% in the topsoil to 36% at greater depths. However, the sand fractions had smaller percentages of Po-OH<sup>-</sup> in the upper soil layers in the NF (32%) and SF (20%) areas. These results suggest that the Po-OH<sup>-</sup> is associated with humified soil organic matter because the types of soil that use the carbon from this fraction had lower Po-OH<sup>-</sup> contents than the pasture soils<sup>42</sup>. Santos *et al.*<sup>4</sup> suggested that the less-labile fractions were buffered relative to the labile fractions regarding the supply of P to the corn. When using cover crops under suitable conditions, the balance between the P and decomposed biomass used in the cultures potentially permitted desorption of recalcitrant forms of this element<sup>2</sup>.

**Characterization of Po in yellow Oxisol:** The distribution of Po relative to Pt was only 21% of the Pt on average (Table 6). Zaia *et al.*<sup>19</sup> reported that Po represents 22.6 to 39.6% of the total Pt extracted from soils, which is the lowest percentage that was observed in the area under secondary forests. Other studies

**Table 6.** Relationships between Pol and Ptl (Pol/Ptl) and between Pot and Pt (Pot/Pt) in an Oxisol for different types of land use and at different depths (average of three replicates).

Fractions (µm)	0-2	2-50	50-2.000	0-2	2-50	50-2.000	0-2	2-50	50-2.000
Depth (m)	0-0.02			0.02-0.05			0.05-0.1		
Soil Use	Pol/ Ptl (%)								
NF	66	83	86	73	72	59	76	75	77
SF	56	84	70	67	96	71	70	73	57
P1-2	53	66	40	57	76	29	67	76	71
P5-7	61	71	68	64	88	75	73	89	80
P10-12	72	84	38	70	75	50	73	94	60
Soil Use	Pot/ Pt (%)								
NF	25	31	42	16	44	47	17	36	36
SF	22	30	16	15	39	20	19	30	19
P1-2	20	42	12	17	57	14	17	60	14
P5-7	10	77	27	11	21	32	10	17	36
P10-12	19	22	29	15	34	15	10	45	12

Native forest (NF), secondary forest of 8-10 years (SF), pasture of 1-2 years (P1-2), pasture of 5-7 years (P5-7) and pasture of 10-12 years (P10-12).

reported that the fractions with the greatest potential mineralization percentages reached 47%, 56.9% and 59%<sup>5,6,15</sup>.

Generally, total inorganic phosphorus (Pit) predominantly occurs around the Pot that genetically evolves in tropical soils<sup>19,28,32</sup>. However, the form of soil used appears to be preponderant for accumulating of Po. For example, Lobato *et al.*<sup>25</sup> studied Oxisols under no-tillage and reported a percentage of 96% relative to Pt. The clay fraction had an average Pot content that was relatively constant with increasing depth, with 34 mg kg<sup>-1</sup> in the soil surface layer and » 26 mg kg<sup>-1</sup> in the subsurface soil layers. These values are slightly greater than those found in the silt (2 times greater at the 3 studied depths) and approximately 9 times greater than those found in the sand fraction.

The Pot content decreased with increasing depth, and the largest variations occurred in the grassland soils (51% reduction and 41% for the layer of 0.05-0.1 m in P10-12). These results showed that the highest percentage of Po occurred in the upper soil layer, especially in the disturbed ecosystems (the forest and secondary forests), and in the finer soil fraction (which occurred for microbial carbon)<sup>17</sup>.

The greater Pot contents observed in the pasture soils relative to the native and secondary forests can be understood by considering the C dynamics discussed in Silva Junior *et al.*<sup>42</sup>. These authors reported that the Pot content increased with pasture age.

The high contributions of the aboveground biomass and the roots of the *Brachiaria* grass<sup>32</sup> probably contributed to this result. Vincent *et al.*<sup>20</sup> reported that the Po accounts for 16% of the P that is required for plant growth in Oxisols under forests; however, a reduction of 23% occurred after removing the litter for 3 years in the experiment.

The Pot, which was obtained as the sum of Pol + Po-H<sup>+</sup> + Po-OH<sup>-</sup>, was variable, mainly in the topsoil layer, and decreased with increasing depth. Independent of the analyzed particle-size fraction, a relationship between the dominance of Po-H<sup>+</sup>/Pot over other forms of Po was observed, which reached a maximum percentage of 88% (P1-2 years) and an average of 68% at a depth of 0.02 to 0.05 m.

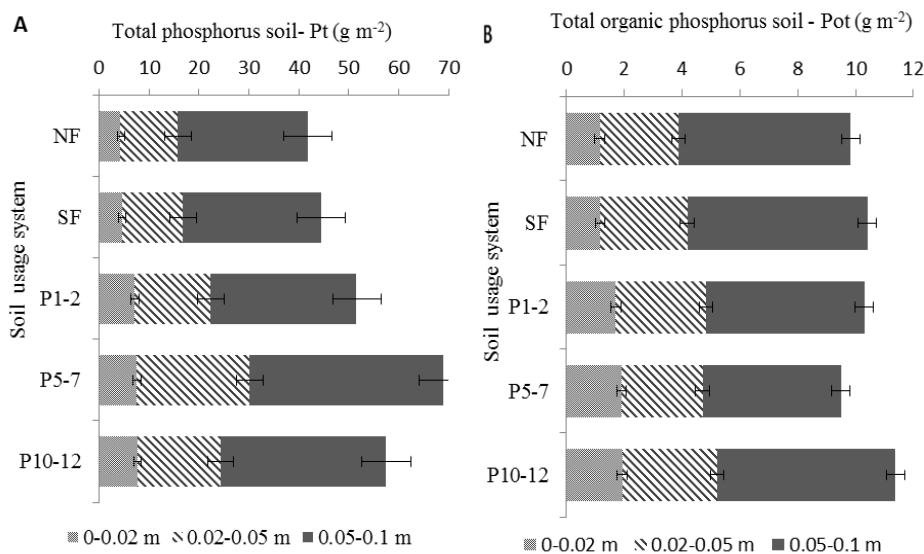
The dominance of the moderately labile soluble Po content is

important for evaluating soil fertility. The positive correlation between the Po-H<sup>+</sup> and Pot in the soil indicates that this fraction can serve as a P reservoir for vegetables<sup>3,22,32</sup>. This result contrasts the results reported by Li *et al.*<sup>29</sup>, in which the Pol concentration decreased with the fractions as follows: Po-OH<sup>-</sup>, Po-H<sup>+</sup>, and Pol. The labile fraction had a greater moderately resistant fraction for all evaluated land-use types, except for grazing lands of 10-12 years. Similarly, the Pol was mainly associated with soil microorganisms and was lowest in older pastures due to reductions in microbial biomass carbon, as observed by Melo *et al.*<sup>17</sup> in the same area. Due to the impacts of anthropogenic activities on biochemical attributes after the installation of the system, these results were consistent with those obtained by Guerra *et al.*<sup>28</sup>.

The lowest contributions of Pol to the Ptl content occurred in the thickest fraction (58%), followed by the finest fraction (66.6%) and silt fraction (79.7%). The sand fraction had the smallest contribution, which was observed in the pasture soil of 1-2 years at depths of 0.02 to 0.05 m (29% Pol/Ptl). In addition, the greatest contribution was observed in the silt fraction in the secondary forest soil at a depth of 0-0.02 m (96% Pol/Ptl). The variation in the Pol/Pot ratio (as described for Po-OH<sup>-</sup>/Pot) increased as the diameter of the particle-size fraction increased.

A certain level of P in solution is necessary for maintaining the balance between Pi in the solid phase and the readily available P<sup>47</sup>. The predominance of Pol surrounding labile inorganic (Pil) that was demonstrated here and in other studies<sup>3,5,19,28,32</sup> indicates the intrinsic relationship between organic waste and the availability of this nutrient, which weakly links this fraction to the soil matrix. Duda *et al.*<sup>32</sup> corroborated this result when considering 12 of the 14 soil classes from Brazil with 50-91% Pol compared with Pil. Turner and Blackwell<sup>30</sup> reported the interference of soil pH because they observed a 20% increase in Po in acid soils (pH <4) and a reduction of CO with no correlation between them.

In the soils under native forest, 41.9 g m<sup>-2</sup> of Pt was stored along the studied profile (Fig. 3A). The replacement of the natural ecosystem (NF) by secondary forest and pasture increased the Pt in the soil, and the amount of Pt in the secondary forest soil was 44.5 g m<sup>-2</sup>, which increased to 51.6 g m<sup>-2</sup> in P1-2 and reached 69.0 g m<sup>-2</sup> in P5-7. In the topsoil, the replacement of forest by pasture



**Figure 3.** Total soil phosphorus (Pt) and total organic phosphorus (Pot) at a depth of 0-0.1 m in a clayey Oxisol soil with different types of land use in Itupiranga, State of Pará.

significantly increased the Pt stock. The amount of Pt in the pastures was  $\gg 7.5 \text{ g m}^{-2}$ , which differed in the NF and SF areas ( $4.5 \text{ g} \gg \text{m}^{-2}$ ).

On average, 15% of the Pot stock occurred in the topsoil, with the highest percentage (56%) occurring in the deeper layer (Fig. 3B). This finding confirmed the results of Zaia *et al.*<sup>31</sup>, who observed that 15% of the Pot was stored in the 0-5 cm layer and only 23% was stored in the 5-15-cm layer in cacao agroforestry soils in Bahia, Brazil.

As observed for the accumulation of Pt, the pastures experienced significant increases in the Pot stock relative to the native and secondary forests. The amounts of Pot along the studied profile varied from  $9.5 \text{ g m}^{-2}$  in the pasture soil of 5-7 years to  $11.4 \text{ g m}^{-2}$  in the grazing soil of 10-12 years. In areas of native forest and secondary forest, these values were  $9.9 \text{ g m}^{-2}$  and  $10.4 \text{ g m}^{-2}$ , respectively.

The largest stocks of Po-H<sup>+</sup> that were observed in the upper layers of the pasture soils potentially resulted from burning vegetation, which introduces Pi to the soil through ashes. The management of fires over a short period can result in the accumulation of P<sup>14</sup>. This effect is most pronounced in the upper soil layer and decreases with increasing depth due to the low mobility in the P in the profile<sup>6</sup> and the higher amounts of organic residues in the soil<sup>29</sup>.

Overall, the results of this study indicate the introduction of P to the soil after the conversion of forests to pastures and secondary forests. This added P mainly remains immobilized as inorganic P with some Po.

### Conclusions

1. The conversion of the natural forests into pastures resulted in small increases in the Pt and Pot contents, which represented an average of 21% of the Pt in the topsoil (0-0.02 m).
2. The fractions of Po in the soil demonstrated the potentials of the variable particle-size fractions for accumulating Po relative to the land-use, sampling depth and clay fraction.
3. The predominance of Pol (ranging from 29-96%) suggested the importance of the contribution of the organic compartment to the available P.
4. The results showed that the short-term availability of phosphorus (as represented by Pol) may be lower in pasture soils than in native forest and secondary forest soils. In addition, the phosphorus stock that may be available over medium terms (as represented by Po-H<sup>+</sup>) was greater in the pastures than in the native and secondary forest areas.

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