

Nota

ORGANIC PHOSPHORUS IN DIAGNOSTIC SURFACE HORIZONS OF DIFFERENT BRAZILIAN SOIL ORDERS⁽¹⁾

Ruthanna Isabelle de Oliveira⁽²⁾ Antonio Carlos Gama-Rodrigues⁽³⁾, Emanuela Forestieri Gama-Rodrigues⁽³⁾, Francisco Costa Zaia⁽⁴⁾, Marcos Gervasio Pereira⁽⁵⁾ & Ademir Fontana⁽⁶⁾

SUMMARY

Phosphorus availability in tropical soils may be regulated by the decomposition and mineralization of the labile organic phosphorus fraction (Po); therefore, studies assessing the actual contribution of Po to soil composition are necessary. The objective of this study was to evaluate the total and labile Po content in diagnostic surface horizons of different soil types and to assess which soil properties control the accumulation of these P fractions. Samples of different diagnostic surface horizons were studied, namely histic H and O, chernozemic A, and humic A, collected from several Brazilian states. The total fractions of inorganic P (Pi) and organic P (Po) were determined using the sequential acid-base extraction method, and the labile P fraction was determined by extraction with sodium bicarbonate. The recovery rate of Pi + Po relative to nitric-perchloric extraction of total P (TP) ranged from 46 to 99 %. Total Po ranged from 35 to 1077 mg kg⁻¹ (mean of 298 mg kg⁻¹). The labile Po fraction values ranged from 7.2 to 99.5 mg kg⁻¹ (mean of 27.1 mg kg⁻¹). Po represented, on average, 36 to 46 % of the total P extracted and over 70 % of the labile P in all diagnostic horizons. TP was the main property driving Po accumulation in soils according to correlation and multiple regression analyses. Horizons with low P adsorption capacity were observed as leading to high Po lability.

Index terms: histic, chernozemic A, humic A, phosphorus availability, labile phosphorus.

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⁽²⁾ Master's degree, Soil Laboratory, UENF. Av. Alberto Lamego 2000, Parque Califórnia. CEP 28013-602 Campos dos Goytacazes (RJ), Brazil. E-mail: ruthanna_oliveira@hotmail.com

⁽³⁾ Professor, Soil Laboratory, UENF. E-mail: tonygama@uenf.br, emanuela@uenf.br

⁽⁴⁾ Post Doctoral student, Soil Laboratory, UENF. FAPERJ Scholarship. E-mail: zaia@uenf.br

⁽⁵⁾ Professor, Soil Department, Universidade Federal Rural do Rio de Janeiro. BR 465, km 7. CEP 23890-000 Seropédica (RJ), Brazil. E-mail: gervasio@ufrj.br

⁽⁶⁾ Researcher, Embrapa Solos. Rua Jardim Botânico, 1024, Bairro Jardim Botânico. CEP 22460-000 Rio de Janeiro (RJ), Brazil. E-mail: ademir.fontana@cnps.embrapa.br

RESUMO: FÓSFORO ORGÂNICO EM HORIZONTES DIAGNÓSTICOS SUPERFICIAIS DE DIFERENTES CLASSES DE SOLO

Em solos tropicais, a disponibilidade de fósforo (P) pode ser regulada pela decomposição e mineralização da fração lábil de P orgânico (Po), tornando necessários estudos para saber a sua real contribuição no solo. O objetivo deste trabalho foi avaliar o teor de Po total e lábil em horizontes superficiais de diferentes classes de solo e quais as propriedades do solo exercem controle na acumulação dessas frações de P. Foram estudadas amostras de diferentes horizontes diagnósticos superficiais, a saber: H e O hístico; A chernozêmico; e A húmicos, coletados em vários estados do Brasil. Para a determinação das frações totais de P inorgânico (Pi) e orgânico (Po), foi usado o método da extração-sequencial ácido-alcálica, e a fração lábil de P foi determinada pela extração com bicarbonato de sódio. A taxa de recuperação de Pi + Po em relação à extração nítrico-perclórica do P total (PT) variou de 46 a 99 %. O Po total variou entre 35 e 1077 mg kg⁻¹, com uma média de 298 mg kg⁻¹. Para a fração lábil do Po, os teores variaram entre 7,2 e 99,5 mg kg⁻¹, com uma média de 27,1 mg kg⁻¹. O Po variou, em média, de 36 a 46 % do P total extraído. Em relação ao P lábil, o Po representou mais de 70 % para todos os horizontes diagnósticos. O PT foi o principal atributo controlador da acumulação de Po nos solos pelas análises de correlação e regressão múltipla. Verificou-se que horizontes com baixa capacidade de adsorção de P proporcionaram alta labilidade de Po.

Termos de indexação: hísticos, A chernozênicos, A húmicos, disponibilidade de fósforo, fósforo lábil.

INTRODUCTION

The biological productivity of natural, agricultural, and forest systems is often considered to be limited by the availability of phosphorus (P) in tropical soils (Cardoso et al., 2003; Vincent et al., 2010; Reed et al., 2011). Phosphorus deficiency is caused by its precipitation in solution with ionic forms of Fe, Al, and Ca, and primarily by its adsorption to Fe and Al oxides and oxyhydroxides, which are usually present in larger amounts in weathered and clayey soils (Novais et al., 2007). Under these conditions, P uptake by plants is regulated by organic P (Po) turnover (Tiessen, 2005). The proportion of total Po in the total P composition of soil increases in soils in advanced stages of weathering (Nziguheba & Bünemann, 2005). The content of Po may range from 11 to 40 % of the total P present in the surface layer (Palm et al., 2007).

There are several methods for quantifying the total Po (consisting of different Po compounds) in soil (Turner et al., 2005). Bowman's sequential extraction (Bowman, 1989) has been widely used in studies investigating different soil types and Brazilian land use systems (Condon et al., 1990; Guerra et al., 1996; Matos et al., 2006; Cunha et al., 2007; Zaia et al., 2008, 2012). The results of these studies show a wide variation in Po contents, which are strongly influenced by the concentration of clay, organic C, and total P. In addition, the labile Po fraction (rapid mineralization compounds) has been extracted in sodium bicarbonate (Bowman & Cole, 1978) and is also closely associated with physical and chemical soil properties, especially available P (Guerra et al., 1996; Cunha et al., 2007; Zaia et al., 2008, 2012).

Turner & Engelbrecht found high Po contents in soils with high contents of organic C (28 to 104 g kg⁻¹)

in Panama. However, studies of Po in soils formed by different pedogenic processes and with variable (medium to high) organic matter content are still rare in Brazil. These soils have horizons of organic (histic O and H) and mineral (chernozemic A and humic A) constitutions. Studies examining Po content and its labile fraction in these soils are especially important in low-input production systems, with little or no use of P fertilization, because these systems are heavily used in family farming (Friedrich & David, 2009; Ebeling et al., 2013).

The objective of this study was to quantify the total and labile Po contents in diagnostic surface horizons of soils from different regions of Brazil and to assess which soil properties affect accumulation of the P fractions.

MATERIALS AND METHODS

This study was conducted with 38 samples of diagnostic surface horizons of different soil types from different regions of Brazil. A total of 10 samples of histic horizons (O, H), 12 of chernozemic A horizons, and 16 of humic A horizons were used.

The origin, type of diagnostic horizon, horizon thickness, particle size, and chemical properties of the samples are shown in tables 1, 2, and 3. Total soil phosphorus (TP) was estimated by nitric-perchloric digestion (Bataglia et al., 1983). Remaining phosphorus (Prem) was measured in equilibrium solution after homogenizing a 5-cm³ soil sample with 50 mL of a 10 mmol L⁻¹ CaCl₂ solution containing 60 mg L⁻¹ P for 1 h to estimate the buffering capacity potential of P in the soil (Alvarez V. et al., 2000).

Extractable P was estimated using Mehlich-1 extractant (available P), and the total Fe_2O_3 and Al_2O_3 contents were extracted by sulfuric acid digestion, following Embrapa (1997). The pH values, total organic carbon (TOC) contents, sum of bases (SB), hydrogen contents (H^+), cation exchange capacity (CEC), exchangeable aluminum (Al^{3+}), base saturation (V), and sand, silt, and clay contents were obtained from Fontana (2009) and measured using methods described by Embrapa (1997).

Bowman's extraction method was used to quantify the total P of organic compounds (Po) (Bowman, 1989). Inorganic P (Pi) was determined after the clarification of acid and alkaline extracts with activated charcoal (Guerra et al., 1996). The Pi, total P (TP) and Po in acidic and alkaline extracts were determined, and the

total Po was calculated as the sum of the Po in the acid and alkaline extracts as follows:

$$\text{Po}_{\text{acid}} = \text{TP}_{\text{acid (digested)}} - \text{Pi}_{\text{acid (extracted)}}$$

$$\text{Po}_{\text{alkaline}} = \text{TP}_{\text{alkaline (digested)}} - \text{Pi}_{\text{alkaline (extracted)}}$$

$$\text{Po}_{\text{total}} = \text{Po}_{\text{acid}} + \text{Po}_{\text{alkaline}}$$

The labile Po (rapid mineralization) was determined by extraction with $0.5 \text{ mol L}^{-1} \text{ NaHCO}_3$ (Bowman & Cole, 1978). Activated carbon was also used to clarify the extracts and to estimate Pi. Labile Po was calculated as the difference between TP and Pi. The Pi concentrations of all extracts and digestions were determined following Murphy & Riley (1962).

The data obtained from the contents of the Pi, Po, and Pi+Po fractions of the surface horizons of different

Table 1. General, morphological, and chemical characteristics of Histic O and H horizon samples

Profile	Hor.	Depth	Site	TOC ⁽¹⁾	pH(H_2O)	SB	H^+	CEC	Al^{3+}	V	P ⁽²⁾	TP ⁽³⁾	Prem ⁽⁴⁾	Al_2O_3	Fe_2O_3
		cm		g kg^{-1}				$\text{cmol}_c \text{ kg}^{-1}$		%	mg kg^{-1}		mg L^{-1}		g kg^{-1}
RJ2	O1	0-42	Itatiaia/RJ	170.4	4.8	1.92	33.0	34.92	0.0	5	3.8	2482.5	3.3	97	55
RS2	O	0-25	Cambará do Sul/RS	81.6	4.0	2.07	17.4	23.97	4.5	9	14.4	550.0	2.9	92	51
MS2	Hdo1	0-40	Porto Morumbi/MS	182.4	4.4	3.51	22.8	27.93	1.6	13	35.0	2117.5	11.7	194	23
PR2	Hdp1	0-20	Tijucas do Sul/PR	224.8	4.4	9.40	34.1	44.20	0.7	21	47.7	1932.5	7.0	126	25
RS1	Hdp	0-10	Cambará do Sul/RS	109.8	5.4	7.70	38.1	47.18	1.4	16	10.4	870.0	4.1	86	24
RS4	Hpj	0-16	Viamão/RS	470.0	3.0	8.00	83.6	97.10	5.5	8	26.4	357.5	58.5	6	1
RS5	Hdpj	0-35	Viamão/RS	541.1	3.7	21.90	52.4	74.90	0.6	29	20.8	882.5	51.5	7	7
RS5	Hdj	35-46	Viamão/RS	414.9	3.5	10.20	45.0	57.40	2.2	18	38.4	1018.5	49.1	35	6
SC1	H2	17-67	Gravata/SC	445.7	4.6	23.30	15.8	39.68	0.6	59	13.2	832.5	42.2	58	14
SP1	Hp1	0-12	Taubaté/SP	231.0	5.2	3.15	57.8	61.40	0.5	5	6.6	1662.5	3.5	106	7

⁽¹⁾ TOC: total organic carbon; pH in water; SB: sum of bases; hydrogen (H^+); CEC: cation exchange capacity; Al^{3+} : aluminum; V: base saturation. Source: Fontana (2009). ⁽²⁾ P: available phosphorus by Mehlich-1. ⁽³⁾ TP: total phosphorus (nitric-perchloric digestion). ⁽⁴⁾ Prem: remaining phosphorus.

Table 2. General, morphological, chemical, and particle size characteristics of Chernozemic A surface horizon samples

Profile	Hor.	Depth	Site	TOC ⁽¹⁾	pH(H_2O)	SB	H^+	CEC	V	Sandy	Silt	Clay	P ⁽²⁾	TP ⁽³⁾	Prem ⁽⁴⁾	Al_2O_3	Fe_2O_3
		cm		g kg^{-1}				$\text{cmol}_c \text{ kg}^{-1}$	%		g kg^{-1}		mg kg^{-1}		mg L^{-1}		g kg^{-1}
MS1	A2	25-50	Ladario/MS	34.5	7.3	21.20	0.0	21.20	100	261	223	516	133.0	705.0	43.9	55	24
PF1	Ap	0-30	Italva/RJ	14.4	7.4	10.18	0.8	11.01	93	673	127	200	8.2	447.5	43.4	54	28
PF2	Ap	0-17	Italva/RJ	13.6	7.2	13.31	0.8	14.14	94	516	256	228	3.2	210.0	32.4	75	26
PF3	Ap	0-15	Cordeiro/RJ	12.0	6.9	3.39	1.3	4.71	72	674	129	197	1.6	335.0	51.2	52	16
PF3	A2	15-27	Cordeiro/RJ	16.2	6.9	10.82	3.8	14.62	74	658	190	152	4.2	312.5	56.3	57	23
PF6	Ap	0-40	Pinheiral/RJ	16.3	6.7	15.54	3.3	18.84	82	462	334	204	10.2	615.0	43.5	58	97
PF6	A2	40-60	Pinheiral/RJ	10.8	6.6	5.01	2.1	7.16	70	485	260	255	3.0	422.5	43.3	58	56
PF7	Ap	0-25	Itaperuna/RJ	21.1	7.5	13.78	0.8	14.61	94	514	453	33	24.2	1245.0	38.5	127	75
RJ1	Ap	0-19	Euclidelândia/RJ	16.5	8.2	10.08	0.1	10.18	99	488	241	271	4.6	352.5	41.5	102	50
RS1	A	0-80	Bagé/RS	14.9	6.1	26.01	3.7	29.71	88	93	397	510	2.2	147.5	40.8	102	42
SC2	Ap	0-80	Ipira/SC	28.9	7.2	20.60	2.1	22.70	91	104	597	299	8.6	1102.5	30.2	142	210
SC2	A2	80-160	Ipira/SC	22.8	6.0	10.95	6.0	16.95	65	10	496	494	1.0	880.0	10.9	175	250

⁽¹⁾ TOC: total organic carbon; pH in water; SB: sum of bases; hydrogen (H^+); CEC: cation exchange capacity; V: base saturation. Source: Fontana (2009). ⁽²⁾ P: available phosphorus by Mehlich-1. ⁽³⁾ TP: total phosphorus (nitric-perchloric digestion). ⁽⁴⁾ Prem: remaining phosphorus.

Table 3. General, morphological, chemical, and particle size characteristics of Humic A surface horizon samples

Profile	Hor.	Depth	Site	TOC ⁽¹⁾	pH(H ₂ O)	SB	H ⁺	CEC	Al ³⁺	V	Sandy	Silt	Clay	P ⁽²⁾	TP ⁽³⁾	Prem ⁽⁴⁾	Al ₂ O ₃	Fe ₂ O ₃
		cm		g kg ⁻¹				cmol _c kg ⁻¹		%		g kg ⁻¹		mg kg ⁻¹		mg L ⁻¹		g kg ⁻¹
BA1	A1	0-35	Camaçari/BA	63.5	3.7	3.80	73.1	80.00	3.1	5	631	301	68	5.6	247.5	28.6	15	9
BA1	A2	35-40	Camaçari/BA	27.9	5.3	1.60	10.1	13.00	1.3	12	737	78	185	3.6	135.0	17.7	31	9
ES1	Ap	0-10	Linhares/ES	31.7	6.1	3.30	6.6	10.20	0.3	32	759	60	181	3.4	332.5	40.3	33	9
P12	Ap1	-	Cidade não localizada/SP	22.3	5.3	2.13	6.6	9.23	0.5	23	416	107	477	1.6	210.0	16.3	167	48
P12	Ap2	-	Cidade não localizada/SP	15.8	5.2	1.00	6.7	8.80	1.1	11	368	141	491	0.4	252.5	7.5	194	51
PF5	A1	0-20	Nova Friburgo/RJ	32.3	4.4	0.80	13.5	18.50	4.2	4	350	160	490	13.6	1778.3	6.0	169	107
PF5	A2	20-40	Nova Friburgo/RJ	25.9	4.5	1.60	13.5	18.60	3.5	9	380	180	440	10.6	2247.5	4.7	173	101
RJ	A	0-24	Rio das Ostras/RJ	52.5	5.8	12.29	8.3	20.59	0.0	60	396	317	287	5.6	325.0	35.6	96	19
RJ2	A1	0-25	Itatiaia/RJ	66.2	5.0	1.52	17.3	21.16	2.3	7	480	229	291	31.8	1385.0	26.8	130	36
RJ2	A2	25-45	Itatiaia/RJ	48.5	5.6	1.26	12.6	15.29	1.4	8	590	152	258	28.0	1520.0	9.3	116	44
RS	A2	15-30	Gramado/RS	63.1	4.7	5.20	28.3	38.50	5.0	14	55	425	520	7.0	895.0	26.4	84	49
RS	A3	30-50	Gramado/RS	40.7	4.8	3.80	14.8	24.10	5.5	16	73	330	597	3.0	450.0	1.6	144	66
RS2	A	25-55	Cambará do Sul/RS	48.2	4.1	1.07	23.4	28.97	4.5	4	376	188	436	0.8	452.5	3.8	103	69
RS3	A2	15/18-30/34	Canela/RS	51.3	4.8	0.50	35.0	42.60	7.1	1	580	150	270	3.0	962.5	7.2	188	84
SP1	AP	8-49	Taubaté/SP	51.0	3.6	0.57	24.9	28.77	3.3	2	507	255	238	2.0	680.0	11.5	88	9
SC1	A	0-170	Lages/SC	25.1	4.6	2.27	11.8	18.17	4.1	12	179	373	448	13.2	350.0	22.5	108	38

⁽¹⁾ TOC: total organic carbon; pH in water; SB: sum of bases; hydrogen (H⁺); CEC: cation exchange capacity; Al³⁺: aluminum; V: base saturation Source: Fontana (2009). ⁽²⁾ P: available phosphorus by Mehlich-1. ⁽³⁾ TP: total phosphorus (nitric-perchloric digestion). ⁽⁴⁾ Prem: remaining phosphorus.

soil types had a normal distribution according to the Lilliefors test. The mean and standard deviation were obtained for descriptive statistics. Simple Pearson correlation analysis and multiple regression between the total organic and labile P and the chemical and physical soil properties were carried out for each diagnosis horizon and for the set of horizons (histic H + chernozemic A + humic A) using the software Statsoft (2007).

RESULTS AND DISCUSSION

The results regarding the TP (Pi + Po) extracted by Bowman's method showed that a marked proportion of the TP of samples determined by digestion was extracted from the soil horizons (mean of 79 %). The mean recovery rate [(Pi + Po)/TP] was 71 % (variation of 46 to 99 %) in histic horizons, 82 % (variation of 67 to 92 %) in chernozemic A horizons, and 81 % (variation of 52 to 97 %) in humic A horizons (Table 4). The recovery rates found by Condron et al. (1990) ranged from 30 to 107 % of the TP; the recovery rates found by Guerra et al. (1996) ranged from 48 to 109 %; the rates found by Cunha et al. (2007) ranged from 50 to 82 %; and the rates found by Zaia et al. (2012) ranged from 44 to 168 % in the surface layers of different soil types.

There was wide variation in total Po contents within each soil horizon group (Table 4). The total Po variation ranged from 82 to 1077 mg kg⁻¹ (mean of

440 mg kg⁻¹) in histic horizons, from 44 to 279 mg kg⁻¹ (mean of 161 mg kg⁻¹) in chernozemic A horizons, and from 35 to 982 mg kg⁻¹ (mean of 261 mg kg⁻¹) in humic A horizons. The smallest amplitude of total Po contents occurred in the chernozemic A horizons and the largest in the humic A horizons. These results were higher than the values found in the literature (Condron et al., 1990; Guerra et al., 1996; Duda, 2000). Organic soils or mineral horizons with high organic matter content would have high Po content (Stevenson & Cole, 1999; Bowman & Moir, 1993). Duda (2000) found a Po content of 688 mg kg⁻¹ in organic soil in the histic H horizon. Guerra et al. (1996) and Duda (2000) observed Po contents of 70 and 88 mg kg⁻¹, respectively, for a Latossolo Vermelho-Amarelo (Oxisol) in humic A horizons.

There was also a wide variation of labile Po content within each soil horizon group (Table 4). Labile Po values ranged from 19.7 to 78.0 mg kg⁻¹ (mean of 48 mg kg⁻¹) in histic horizons, from 7.2 to 17.5 mg kg⁻¹ (mean of 10.6 mg kg⁻¹) in chernozemic A horizons, and from 7.2 to 99.5 mg kg⁻¹ (mean of 27.1 mg kg⁻¹) in humic A horizons. In addition, the lowest and the highest amplitude of labile Po contents occurred in the chernozemic A and humic A horizons, respectively. The wide variation in labile Po is within the range found in the literature for tropical soils formed by different pedogenetic processes (Cunha et al., 2007; Zaia et al., 2008, 2012). Duda (2000) reported a labile Po content of 50.1 mg kg⁻¹ in a histic H horizon of an organic soil, and Guerra et al. (1996) reported a

Table 4. P fractions in surface horizons of different soil types

Profile	Hor.	Pi + Po ⁽¹⁾		Pi		Po	
		Total ⁽²⁾	Labile ⁽³⁾	Total	Labile	Total	Labile
mg kg ⁻¹							
Histic							
RJ2	O1	2160 (87) ⁽⁴⁾	22.7	1083 (50.2) ⁽⁵⁾	3 (13.2) ⁽⁶⁾	1077 (49.8) ⁽⁵⁾	19.7 (86.8) ⁽⁶⁾
RS2	O	347 (63)	63.2	226 (65.2)	11 (17.2)	121 (34.8)	52.2 (82.6)
MS2	Hdo1	1447 (68)	90.1	750 (51.8)	12 (13.3)	697 (48.2)	78.0 (86.7)
PR2	Hdp1	1595 (83)	73.2	1057 (66.3)	25 (34.1)	538 (33.7)	48.2 (65.9)
RS1	Hdp	860 (99)	46.2	443 (51.5)	7 (15.2)	417 (48.5)	39.2 (84.8)
RS4	Hpj	246 (69)	87.5	164 (66.5)	36 (41.1)	82 (33.5)	51.5 (58.9)
RS5	Hdpj	407 (46)	76.3	201 (49.3)	26 (34.1)	206 (50.7)	50.3 (65.9)
RS5	Hdj	742 (73)	93.3	415 (56.0)	48 (51.4)	327 (44.0)	45.3 (48.6)
SC1	H2	542 (65)	69.3	260 (48.0)	10 (14.4)	282 (52.0)	59.3 (85.6)
SP1	Hp1	977 (59)	40.8	329 (33.7)	7 (17.2)	648 (66.3)	33.8 (82.8)
Average		932	66.3	493	18.5	440 (46)	48.0 (75)
SD ⁽⁷⁾		601	22.4	335	14.2	296	14.9
Chernozemic A							
MS1	A2	647 (92)	23.3	438 (67.6)	12 (51.5)	210 (32.4)	11.3 (48.5)
PF1	Ap	406 (91)	13.8	241 (59.3)	4 (29.0)	165 (40.7)	9.8 (71.0)
PF2	Ap	157 (75)	9.4	102 (65.0)	2 (21.4)	55 (35.0)	7.4 (78.6)
PF3	Ap	247 (74)	9.3	157 (63.7)	2 (21.4)	90 (36.3)	7.3 (78.6)
PF3	A2	234 (75)	9.2	153 (65.1)	2 (21.7)	82 (34.9)	7.2 (78.3)
PF6	Ap	537 (87)	23.5	353 (65.7)	6 (25.5)	184 (34.3)	17.5 (74.5)
PF6	A2	378 (89)	13.8	245 (64.9)	2 (14.5)	133 (35.1)	11.8 (85.5)
PF7	Ap	1063 (85)	18.4	740 (69.6)	6 (32.7)	323 (30.4)	12.4 (67.3)
RJ1	Ap	323 (92)	18.5	212 (65.5)	6 (32.4)	111 (34.5)	12.5 (67.6)
RS1	A	103 (70)	13.9	60 (57.9)	4 (28.9)	44 (42.1)	9.9 (71.1)
SC2	Ap	736 (67)	18.2	458 (62.1)	6 (32.9)	279 (37.9)	12.2 (67.1)
SC2	A2	801 (91)	9.2	538 (67.1)	1 (10.8)	263 (32.9)	8.2 (89.2)
Average		434	15.1	308	4.3	161 (36)	10.6 (73)
SD		286	5.2	202	3.0	89	2.9
Humic A							
BA1	A1	219 (88)	27.5	140 (63.9)	8 (29.0)	79 (36.1)	19.5 (71.0)
BA1	A2	115 (85)	18.2	77 (66.7)	4 (21.9)	38 (33.3)	14.2 (78.1)
ES1	Ap	300 (90)	27.5	160 (53.3)	6 (21.9)	140 (46.7)	21.5 (78.1)
P12	Ap1	155 (74)	23.2	121 (77.6)	4 (17.2)	35 (22.4)	19.2 (82.8)
P12	Ap2	141 (56)	13.8	103 (72.8)	4 (29.1)	38 (27.2)	9.8 (70.9)
PF5	A1	1733 (97)	35.8	1420 (81.9)	10 (27.9)	313 (18.1)	25.8 (72.1)
PF5	A2	1880 (84)	32.4	898 (47.7)	10 (30.8)	982 (52.3)	22.4 (69.2)
RJ	A	273 (84)	22.5	143 (52.2)	8 (35.5)	131 (47.8)	14.5 (64.5)
RJ2	A1	1107 (80)	78.5	975 (88.1)	10 (12.7)	132 (11.9)	68.5 (87.3)
RJ2	A2	1393 (92)	27.6	448 (32.1)	7 (25.3)	945 (67.9)	20.6 (74.7)
RS	A2	781 (87)	109.5	331 (42.4)	10 (9.1)	450 (57.6)	99.5 (90.9)
RS	A3	350 (78)	13.8	228 (64.9)	2 (14.5)	123 (35.1)	11.8 (85.5)
RS2	A	340 (75)	9.2	223 (65.5)	2 (21.7)	117 (34.5)	7.2 (78.3)
RS3	A2	898 (93)	32.2	555 (61.8)	6 (18.6)	343 (38.2)	26.2 (81.4)
SP1	Ap	355 (52)	13.7	118 (33.1)	6 (43.7)	238 (66.9)	7.7 (56.3)
SC1	A	280 (80)	55.3	208 (74.0)	10 (18.1)	73 (26.0)	45.3 (81.9)
Average		645	33.8	384	6.7	261 (39)	27.1 (76)
SD		575	26.0	382	2.8	292	24.1
Overall average		688 (79)	42.6	390	11.2	298	31.4
SD		530	30	325	11.5	262	22.8

⁽¹⁾ Pi + Po: inorganic phosphorus + organic phosphorus. ⁽²⁾ Total soil P extracted, as determined by Bowman method. ⁽³⁾ Total labile soil P extracted, as determined by 0.5 mol L⁻¹ NaHCO₃. ⁽⁴⁾ Percentage of total soil P, as determined by nitric-perchloric digestion. ⁽⁵⁾ Percentage of total soil P (Pi + Po) extracted. ⁽⁶⁾ Percentage of total labile soil P (Pi + Po) extracted. ⁽⁷⁾ SD: Standard deviation.

content of 11.0 mg kg^{-1} in a surface humic A horizon of a Latossolo (Oxisol).

The Pi contents predominated in the TP composition of the soil (Pi + Po) for all horizons (values above 50 %), except for the histic horizons (H2 and Hp1) and humic A horizons A2 (PF5, RJ2, and RS) and Ap (SP1) (Table 4). The Po contents contributed at an average of 36, 39, and 46 % of the TP for the chernozemic A, humic A, and histic horizons, respectively. There was a greater range of variation (approximately 12 to 68 %) in the distribution of the organic fraction of soil samples in the humic A horizons. In the histic horizons, the variation was from 33 to 66 %, and in the chernozemic A horizons, the variation observed was more uniform, approximately 30 to 42 %. Guerra et al. (1996) reported a Po contribution of 24 % to TP in a humic A horizon of a Latossolo Vermelho-Amarelo (Oxisol), and Duda (2000) observed a Po contribution of 49 % to TP in a histic H horizon in an Organossolo (Histosol). In tropical soils, in general, there is a large prevalence of the inorganic fraction; therefore, Po represents approximately 26 % of the TP (Condrón et al., 1990; Guerra et al., 1996; Cunha et al., 2007; Zaia et al., 2008; Turner & Engelbrecht, 2011; Zaia et al., 2012; Gama-Rodrigues et al., 2014).

The Po content predominated in the total labile P composition in all soil horizons, with mean values of 73, 75, and 76 %, for the chernozemic A, histic, and humic A horizons, respectively (Table 4). However, the contribution of the labile organic fraction was highly variable within each horizon. The labile organic fraction ranged from 49 to 89 % in the histic and chernozemic A horizons, and 56 to 91 % in the humic A horizons. The range of variation of the labile Po proportion was much lower compared to the total Po in all horizons. Bowman & Cole (1978), Zaia et al. (2008; 2012) also observed the predominance of the labile organic fraction, indicating that P availability, in the short-term, would not be fully assessed by measurements of available P (Novais & Smith, 1999). The labile Po contributed 10 %, on average, to the total Po content in the soils.

The soils used in this study show wide variation in particle size and chemical properties (Tables 1, 2, and 3) and differences in the contents of the extracted P fractions (Table 4). Thus, the use of correlation and regression analyses to assess how P fractions vary in relation to other soil properties and the relationships between the different P fractions was possible.

The values of the correlations between total and labile Po and between the chemical properties and particle size of the surface horizons of the different soil types are shown in table 5. The total and labile Po contents were positively and significantly correlated with TP by digestion for the set of diagnostic horizons (histic H + chernozemic A + humic A). However, there were no significant correlations between labile Po and TP in each diagnostic horizon,

although the correlations between total Po and TP were significant for all soil horizons. Total Po was negatively and significantly correlated with Prem only for the set of horizons. However, labile Po was not significantly correlated with Prem either for the set of horizons or for each diagnostic horizon. The total and labile Po fractions were positively correlated with the respective total and labile Pi fractions for the set of diagnostic horizons. However, considering each diagnostic horizon, there was no significant correlation between total Po and total Pi only in the humic A horizon, whereas a significant correlation between the labile P fractions occurred only in the A humic horizons.

The degree of association of organic P fractions with soil properties differed markedly among the diagnostic horizons and for the set of diagnostic horizons (histic H + chernozemic A + humic A). Total Po was positively and significantly correlated to TOC, Al_2O_3 , Fe_2O_3 , and silt contents only in the chernozemic A horizons. Labile Po was positively and negatively correlated with TOC contents and pH values, respectively, for the set of horizons; and it was positively correlated with silt in the humic A horizons. There were no significant correlations between the organic P fractions and the properties of the histic horizons.

However, a more detailed analysis using multiple regressions of the organic P fractions (Table 6) indicates that all the properties of the histic horizons significantly affected labile Po, except for TP, which was not considered in the backward multiple regression analysis. In contrast, the TP, sum of bases (SB), pH, Prem, Al_2O_3 , and Fe_2O_3 had a significant direct effect on total Po. For the chernozemic A horizons, labile Po was estimated in the multiple regression with Fe_2O_3 , SB, TOC, available P, pH, Prem, and clay, and all of these explanatory variables had a direct significant effect on labile Po. In contrast, multiple regression for estimating total Po was composed of TP, silt, TOC, clay, Fe_2O_3 , and SB, and all these variables showed a direct significant effect. Multiple regression also indicated that in humic A horizons, the variables Prem, clay, SB, and TOC had a direct significant effect on labile Po; whereas PT, pH, Prem, silt, and clay had a direct significant effect on total Po (except for available P). The multiple regression used to estimate labile Po for the set of diagnostic horizons had a low coefficient of determination ($R^2 = 0.434$; $p < 0.01$), and none of the explanatory variables considered directly affected this Po fraction. However, multiple regression composed of all the properties, which was used to estimate total Po, showed a high coefficient of determination ($R^2 = 0.832$; $p < 0.0001$), although only TP directly affected this P fraction.

The results of the correlations and multiple regressions indicate the lack of a close association between Po and organic matter in the soil horizons

Table 5. Coefficient of correlation between total organic P (TPo) and labile organic P (LPo) with chemical properties and particle size distribution in the surface horizons of different soil types

	Histic ⁽¹⁾		Chernozemic A		Humic A		Set of horizon	
	TPo	LPo	TPo	LPo	TPo	LPo	TPo	LPo
TPi ⁽²⁾	0.814**	-0.237	0.972***	0.379	0.442	0.283	0.618***	0.252
LPi ⁽³⁾	-0.508	0.186	0.410	0.510	0.394	0.630**	0.086	0.497***
Total P	0.947***	-0.221	0.983***	0.373	0.814***	0.252	0.889***	0.347*
P	-0.197	0.520	0.276	0.154	0.439	0.435	0.133	0.195
Prem	-0.606	0.277	-0.485	0.037	-0.315	0.364	-0.454**	-0.044
TOC ⁽⁴⁾	-0.469	0.188	0.652*	0.191	0.078	0.426	0.162	0.524***
pH(H ₂ O)	0.603	-0.335	0.100	0.194	0.009	0.009	-0.189	-0.518***
SB ⁽⁵⁾	-0.464	0.266	0.139	0.265	-0.153	0.108	-0.209	-0.061
Al ₂ O ₃	0.620	0.254	0.573*	-0.006	0.249	-0.052	0.312	-0.015
Fe ₂ O ₃	0.450	-0.286	0.654*	0.171	0.445	0.038	0.112	-0.246
Silt ⁽⁶⁾	-	-	0.626*	0.295	-0.041	0.505*	-	-
Clay ⁽⁶⁾	-	-	-0.069	-0.111	0.054	0.197	-	-

⁽¹⁾ Number of observations: 10, 12, 16, and 38, for Histic, Chernozemic A, Humic A. and set of horizons, respectively. ⁽²⁾ TPi: total inorganic P. ⁽³⁾ LPi: labile inorganic P. ⁽⁴⁾ TOC: total organic carbon. ⁽⁵⁾ SB: sum of bases. ⁽⁶⁾ Correlations of total Po and labile Po with silt and clay were made only for Chernozemic A and Humic A. * p<0.05; ** p<0.01; *** p<0.001.

studied, and indicate that TP was the major property that positively regulated Po accumulation in the soil for the soil horizons studied. Zaia et al. (2012) reported similar results for soils under cacao agroforests. However, Cunha et al. (2007) found positive correlations between Po (total and labile) and TOC for soils under grassland and forest systems. Turner & Engelbrecht (2011) found close positive correlations between total Po (determined by nuclear magnetic resonance) and TP and TOC in soils under natural forests in Panama. Similar results were reported by Gatiboni et al. (2013) when reviewing different methods of soil P fractionation.

The direct positive effect of Prem on labile Po, shown by the multiple regression analyses for the three soil horizon types studied, would indicate that soils with low P adsorption capacity enable high Po lability. As labile Po comprised most of the total labile P (over 70 %), P availability would be regulated by the mineralization of Po. The relationships of Po with particle size and total Fe and Al oxides were fairly inconsistent, showing that these soil properties would be minimally relevant in the Po stabilization process of the soil types studied. Turner & Engelbrecht (2011) reported the absence of a significant correlation between total Po and Fe and Al oxides of low crystallinity (extracted by ammonium oxalate) and clay, but rather that Po was correlated with Mn oxides in soils with high organic matter content in Panama. Similar results were reported by Gama-Rodrigues et al. (2014) for tropical soils from different parts of the world. However, Guerra et al. (1996) and Duda (2000) observed significant correlations between total Po and total Fe and Al oxides (extracted by sulfuric acid digestion), in soils with low to medium TOC content. Condon et al. (1990) also found positive and

significant correlations between total Po and Al and Fe oxides (extracted by citrate dithionite) in soils of northeastern Brazil and Ghana. The relationship between Po and clay may be either positive (Guerra et al., 1996; Cunha et al., 2007) or negative (Zaia et al., 2012), with the magnitude and direction of this relationship varying according to different soil types. These results show the need for additional studies regarding the Po stabilization mechanism in soils with high organic matter content because it is commonly assumed that Po, especially in the form of phosphate monoesters (not determined in this study), is stabilized in soils by association with Fe-oxalate and Al-oxalate oxide forms (Harrison, 1987; Ognalaga et al., 1994; Celi & Barberis, 2007).

The weak relationship between Po and pH in the soils studied was also reported by Guerra et al. (1996) for Latossolos (Oxisols) and Argissolos (Ultisol or Alfisol). Harrison (1987) and Gama-Rodrigues et al. (2014) reported that only a small proportion of the variation in Po contents was due to the pH in surface horizons in several parts of the world. However, the significant negative correlation between labile Po and pH (Table 5) would indicate that soils with high pH tend to have lower proportions of P in organic form due to the higher mineralization rate (Cunha et al., 2007).

The results found in this study show the importance of pedogenic processes in determining P status in the soils studied, in which the P supply for plants would be regulated by the turnover of Po, which largely prevailed in the labile fraction. Generally, Po mineralization in tropical soils ranges from 15 to 76 % (Rita et al., 2013). The Po fraction is the main source of P available to plants in low-input agricultural and forest systems in the tropical region (Negassa &

Table 6. Multiple regressions of the labile organic P (LPo) and total organic P (TPo) fractions with chemical properties and particle sizes in the surface horizons of different soil types

Chemical property	Regression coefficient	β (Direct effect)	Regression coefficient	β (Direct effect)
Histic				
	LPo		TPo	
pH(H ₂ O)	-30.1898 (p=0.0023)	-1.479*	250.94 (p=0.0001)	0.619*
SB	2.6164 (p=0.0015)	1.308*	-15.6255 (p=0.0001)	-0.394*
Prem	0.4621 (p=0.0205)	0.707*	9.2396 (p=0.0002)	0.712*
P	-0.6299 (p=0.0045)	-0.601*	-	-
TP	-	-	0.3804 (p<0.0001)	0.896*
TOC	-0.1661 (p=0.0024)	-1.773*	-	-
Al ₂ O ₃	0.4013 (p=0.0009)	1.488*	-0.7164 (p=0.0032)	-0.134*
Fe ₂ O ₃	-0.6586 (p=0.0033)	-0.797*	4.0049 (p=0.0003)	0.244*
Constant	185.919		-1224.02	
R ²	0.998 (p=0.0063)		0.999 (p<0.0001)	
Chernozemic A				
	LPo		TPo	
pH(H ₂ O)	5.3201 (p=0.0001)	1.085*	-	-
SB	0.5911 (p=0.0001)	1.306*	2.5068 (p=0.0515)	0.180*
Prem	0.3036 (p=0.0002)	1.163*	-	-
P	0.2672 (p<0.0001)	3.310*	-	-
TP	-	-	0.3472 (p<0.0001)	1.332*
TOC	-1.7904 (p<0.0001)	-4.264*	-3.4857 (p=0.0231)	-0.270*
Fe ₂ O ₃	0.1503 (p<0.0001)	3.855*	0.2736 (p=0.0404)	0.228*
Clay	-0.0064 (p=0.0083)	-0.326*	0.0985 (p=0.0367)	0.163*
Silt	-	-	-0.2983 (p=0.0076)	-0.483*
Constant	-27.4449		40.4563	
R ²	0.990 (p=0.0008)		0.993 (p<0.0001)	
Humic A				
	LPo		TPo	
pH(H ₂ O)	-	-	231.501 (p=0.0229)	0.545*
SB	-4.7423 (p=0.0092)	-0.557*	-	-
Prem	2.1689 (p=0.0004)	1.063*	-11.5382 (p=0.0525)	-0.467*
P	-	-	-9.6953 (p=0.1022)	-0.304
TP	0.0101 (p=0.0636)	0.264	0.4738 (p=0.0007)	1.021*
TOC	0.8568 (p=0.0036)	0.558*	-	-
Clay	0.1409 (p=0.0005)	0.861*	-0.9767 (p=0.0322)	-0.492*
Silt	-	-	1.3127 (p=0.0376)	0.474*
Constant	-89.6878		-885.978	
R ²	0.800 (p=0.0028)		0.804 (p=0.0083)	
Set of horizons ⁽¹⁾				
	LPo		TPo	
pH(H ₂ O)	-7.0344 (p=0.0387)	-0.411	31.303 (p=0.1490)	0.152
SB	-	-	0.4066 (p=0.4660)	0.011
Prem	0.3605 (p=0.1262)	0.292	-3.5659 (p=0.0524)	-0.241
P	-	-	-1.0927 (p=0.1528)	-0.093
TP	0.0095 (p=0.0723)	0.269	0.4014 (p<0.0001)	0.949*
TOC	0.0298 (p=0.2150)	0.186	0.0075 (p=0.4901)	0.004
Al ₂ O ₃	0.1038 (p=0.1427)	0.244	-1.1318 (p=0.0444)	-0.222
Fe ₂ O ₃	-0.0823 (p=0.1365)	-0.189	-0.3788 (p=0.2488)	-0.072
Constant	38.953		5.6126	
R ²	0.434 (p=0.0047)		0.832 (p<0.0001)	

TP: total soil P by nitric-perchloric digestion; P: P extracted by Mehlich-1; Prem: remaining phosphorus; TOC: Total organic carbon; SB: Sum of bases. * significant at p<0.05. ⁽¹⁾ Set of horizons: Histic + Chernozemic A + Humic A.

Leinweber, 2009; Reed et al., 2011). However, the magnitude of the effect of Po on available P depends on soil type, climate, types of P sources, and land use history (Gama-Rodrigues et al., 2014).

CONCLUSIONS

1. Organic P content was high in the surface horizons with medium and high organic matter content in the different types of soil. However, TP was the main property controlling Po accumulation in the soil, where total Po constituted, on average, 40 % of the total recovered P.

2. The contents of the organic P fractions (total and labile) varied widely within and among the diagnostic horizons.

3. The labile organic fraction largely dominated the labile inorganic fraction in all diagnostic horizons studied.

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LITERATURE CITED

- ALVAREZ V., V.H.; NOVAIS, R.F.; DIAS, L.E. & OLIVEIRA, J.A. Determinação e uso do fósforo remanescente. *Bol. Inf. Soc. Bras. Ci. Solo*, 25:27-32, 2000.
- BATAGLIA, O.C.; FURLANI, A.M.C.; TEIXEIRA, J.P.F.; FURLANI, P.R. & GALLO, J.R. Métodos de análise química de plantas. Campinas, Instituto Agrônomo de Campinas, 1983. 48p. (Boletim técnico, 78)
- BOWMAN, R.A. & COLE, C.V. Transformation of organic phosphorus substrates in soil as evaluated by NaHCO_3 extraction. *Soil Sci.*, 125:95-101, 1978.
- BOWMAN, R.A. A sequential extraction procedure with concentrated sulfuric acid and diluted base for soil organic phosphorus. *Soil Sci. Soc. Am. J.*, 53:326-366, 1989.
- BOWMAN, R.A. & MOIR, J.O. Basic EDTA as an extractant for soil organic phosphorus. *Soil Sci. Soc. Am. J.*, 57:1516-1518, 1993.
- CARDOSO, I.M.; van der MEER, P.; OENEMA, O.; JANSSEN, B.H. & KUYPER, T.W. Analysis of phosphorus by ^{31}P -NMR in Oxisols under agroforestry and conventional coffee systems in Brazil. *Geoderma*, 112:51-70, 2003.
- CELI, L. & BARBERIS, E. Abiotic reactions of inositol phosphates in soil. In: TURNER, B.L.; RICHARDSON, A.E. & MULLANEY, E.J., eds. *Inositol phosphates: Linking agriculture and the environment*. Wallingford, CAB International, 2007. p.207-220.
- CONDRON, L.M.; MOIR, J.O.; TIESSEN, H. & STEWART, J.W.B. Critical evaluation of methods for determining total organic phosphorus in tropical soils. *Soil Sci. Soc. Am. J.*, 54:1261-1266, 1990.
- CUNHA, G.M.; GAMA-RODRIGUES, A.C.; COSTA, G.S. & VELLOSO, A.C.X. Fósforo orgânico em solos sob florestas montanas, pastagens e eucalipto no norte fluminense. *R. Bras. Ci. Solo*, 31:667-671, 2007.
- DUDA, G.P. Conteúdo de fósforo microbiano, orgânico e biodisponível em diferentes classes de solos. Itaguaí, Universidade Federal Rural do Rio de Janeiro, 2000. 158p. (Tese de Doutorado)
- EBELING, A.G.; ANJOS, L.H.C.; PÉREZ, D.V.; PEREIRA, M.G. & NOVOTNY, E.H. Atributos físicos e matéria orgânica de Organossolos Háplicos em distintos ambientes no Brasil. *R. Bras. Ci. Solo*, 37:763-774, 2013.
- EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisa de Solos. Manual de métodos de análise de solo. 2.ed. Rio de Janeiro, 1997. 212p.
- FONTANA, A. Fracionamento da matéria orgânica e caracterização dos ácidos húmicos e sua utilização no Sistema Brasileiro de Classificação do Solo. Rio de Janeiro, Universidade Federal Rural do Rio de Janeiro, 2009. 82p. (Tese de Doutorado)
- FRIEDRICH, A.C. & DAVID, C. A agricultura familiar no contexto da rizicultura no município de Agudo-RS. *Geog.: Ensino Pesq.*, 13:334-345, 2009.
- GAMA-RODRIGUES, A.C.; SALES, M.V.S.; SILVA, P.S.D.; COMERFORD, N.B.; CROPPER, W.P. & GAMA-RODRIGUES, E.F. An exploratory analysis of phosphorus transformations in tropical soils using structural equation modeling. *Biogeochemistry*, 118:453-469, 2014.
- GATIBONI, L.C.; BRUNETTO, G.; RHEINHEIMER, D.S. & KAMINSKI, J. Fracionamento químico das formas de fósforo do solo: Usos e limitações. In: ARAÚJO, A.P. & ALVES, B.J.R., eds. *Tópicos em ciência do solo*. Viçosa, MG, Sociedade Brasileira de Ciência do Solo, 2013. v.8. p.141-187.
- GUERRA, J.G.M.; ALMEIDA, D.L.; SANTOS, G.A. & FERNANDES, M.S. Conteúdo de fósforo orgânico em amostras de solos. *Pesq. Agropec. Bras.*, 31:291-299, 1996.
- HARRISON, A.F. Soil organic phosphorus: A review of world literature. Wallingford, CAB International, 1987. 150p.
- MATOS, E.S.; MENDONÇA, E.S.; VILLANI, E.M.A.; LEITE, L.F.C. & GALVÃO, J.C.C. Formas de fósforo no solo em sistemas de milho exclusivo e consorciado com feijão sob adubação orgânica e mineral. *R. Bras. Ci. Solo*, 30:625-632, 2006.

- MURPHY, J. & RILEY, J.P. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chem. Acta*, 27:31-36, 1962.
- NEGASSA, W. & LEINWEBER, P. How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: A review. *J. Plant Nutr. Soil*, 172:305-325, 2009.
- NOVAIS, R.F. & SMYTH, T.J. Fósforo em solo e planta em condições tropicais. Viçosa, MG, Universidade Federal de Viçosa, 1999. 399p.
- NOVAIS, R.F.; SMYTH, T.J. & NUNES, F.N. Fósforo. In: NOVAIS, R.F.; ALVAREZ V., V.H.; BARROS, N.F.; FONTES, R.L.F.; CANTARUTTI, R.B. & NEVES, J.C.L., eds. *Fertilidade do solo*. Viçosa, MG, Sociedade Brasileira de Ciência do Solo, 2007. p.472-550.
- NZIGUHEBA, G. & BÜNEMANN, E. Organic phosphorus dynamics in tropical agroecosystems. In: TURNER, B.L.; FROSSARD, E. & BALDWIN, D.S., eds. *Organic phosphorus in the environment*. Wallingford, CAB International, 2005. p.243-268.
- OGNALAGA, M.; FROSSARD, E. & THOMAS, F. Glucose-1-phosphate and myo-inositol hexaphosphate adsorption mechanisms in goethite. *Soil Sci. Soc. Am. J.*, 58:332-337, 1994.
- PALM, C.; SANCHEZ, P.; AHAMED, S. & AWITI, A. Soils: A contemporary perspective. *Ann. Rev. Environ. Res.*, 32:99-129, 2007.
- REED, S.C.; TOWNSEND, A.R.; TAYLOR, P.G. & CLEVELAND, C.C. Phosphorus cycling in tropical forests growing on highly weathered soils. In: BÜNEMANN, E.K.; OBERSON, A. & FROSSARD, E., eds. *Phosphorus in action: Biological processes in soil phosphorus cycling*. Berlin, Springer, 2011. p.339-369.
- RITA, J.C.O.; GAMA-RODRIGUES, A.C.; GAMA-RODRIGUES, E.F.; ZAIA, F.C. & NUNES, D.A.D. Mineralization of organic phosphorus in soil size fractions under different vegetation covers in the north of Rio de Janeiro. *R. Bras. Ci. Solo*, 37:1207-1215, 2013.
- STATSOFT, Inc.. STATISTICA (data analysis software system), version 8.0, 2007.
- STEVENSON, F.J. & COLE, M.A. *Cycles of soils: carbon, nitrogen, phosphorus, sulfur, micronutrients*. 2.ed. New York, John Wiley, 1999. 427p.
- TIESSEN, H. Phosphorus dynamics in tropical soils. In: MULLINS G., ed. *Phosphorus, agriculture and the environment*. Madison, ASA, CSSA, SSSA, 2005. p.253-262. (Agronomy Monograph 46)
- TURNER, B.L.; CADE-MENUN, B.J.; CONDRON, L.M. & NEWMAN, S. Extraction of soil organic phosphorus. *Talanta*, 66:294-306, 2005.
- TURNER, B.L. & ENGELBRECHT, B.M.J. Soil organic phosphorus in lowland tropical rain forests. *Biogeochemistry*, 103:297-315, 2011.
- VINCENT, A.G.; TURNER, B.L. & TANNER, V.J. Soil organic phosphorus dynamics following perturbation of litter cycling in a tropical moist forest. *Eur. J. Soil Sci.*, 61:48-57, 2010.
- ZAIA, F.C.; GAMA-RODRIGUES, A.C. & GAMA-RODRIGUES, E.F. Formas de fósforo no solo sob leguminosas florestais, floresta secundária e pastagem no Norte Fluminense. *R. Bras. Ci. Solo*, 32:1191-1197, 2008.
- ZAIA, F.C.; GAMA-RODRIGUES, A.C.; GAMA-RODRIGUES, E.F.; MOÇO, M.K.S.; FONTES, A.G.; MACHADO, R.C.R. & BALIGAR, V.C. Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. *Agrofor. Syst.*, 86:197-212, 2012.