



Land use and altitude: how do they influence the phosphorus fractions?

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ABSTRACT. Soil use and management systems modify phosphorus (P) dynamics by changing the different P compartments. However, the interaction between land-use change and altitude is not clear. This study aimed to evaluate the effect of land use on P forms in different soil aggregate classes of Ultisols located at two altitudes. Soil samples were collected in four land-use systems (agroforestry system, secondary forest, pasture, and eucalyptus) located at two altitudes in the Atlantic Forest biome, Brazil. Phosphorus fractions were assessed using sequential fractionation. In general, recalcitrant forms represented about 70% in the agroforestry system, 66% in the eucalyptus, 65% in the pasture, and 57% in the secondary forest relative to the total P content of all land uses at both altitudes. The soil aggregate classes of smaller diameter presented higher P contents in all fractions. The smallest soil aggregate classes showed up to 65% more P than the classes with smaller diameters in the different land-use systems and altitudes.

Keywords: aggregate class; agroforestry systems; eucalyptus; pasture; sequential fractionation.

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Introduction

Low phosphorus (P) availability is one of the most limiting constraints for agricultural and forestry systems in tropical soils (Darch et al., 2016; Rodrigues, Pavinato, Withers, Teles, & Herrera, 2016; Mao et al., 2017). These soils are usually highly weathered, rich in iron and aluminum oxides, and highly P buffered (Novais & Smith, 1999).

The maintenance of soil organic matter (SOM) by using management systems that favor the addition of plant residues into the soil has been pointed out as a practice that improves the use of P by plants (Rocha et al., 2019). Thus, SOM needs to be considered to understand better the P cycle (Chapius Lardy, Brossard, Lopes, & Laurent, 2002; Rocha Junior, Ribeiro, Mesquita, Andrade, & Mendonça, 2018).

Organic substances from SOM mineralization compete with P adsorption sites, especially iron (Fe) and aluminum (Al) oxides, or promote the complexation of elements such as Fe and Al, preventing their bonding with P (Pavinato & Rosolem 2008). This mechanism is especially important in tropical soils of the Atlantic Forest biome, where P deficiency is mainly attributed to the strong adsorption to oxides (Xavier, Almeida, Cardoso, & Mendonça, 2011). In general, the total P content increases when management favors an increase in carbon (C) and the use of fertilizers, and decreases due to intensive cultivation systems with low P replenishment (Damodar Reddy, Subba Rao, & Rupa, 2000).

Conservationist systems such as agroforestry systems (AFS) and native vegetation may have higher P contents in different soil compartments due to the different contributions of SOM relative to monocultures (Rocha Junior et al., 2018;). Rita, Gama-Rodrigues, Gama-Rodrigues, Zaia, and Nunes (2013) found higher labile P contents in AFS (4.8 mg kg⁻¹) than in the native vegetation (3.3 mg kg⁻¹), proving the AFS potential in accumulating more available P forms. Cardoso et al. (2003) found higher total phosphorus (Pt) contents in AFS (319 mg kg⁻¹) than in a monoculture system (260 mg kg⁻¹). Zaia, Gama-Rodrigues, and Gama-Rodrigues (2008) observed higher P contents in forest systems with high SOM input (119 mg kg⁻¹) than in the pasture (85 mg kg⁻¹).

Therefore, the knowledge of the P fractions allows inferring which compartment contributes better to the P management and, consequently, its availability to plants. The sequential P extraction method proposed by Hedley, Stewart, and Chauhan (1982) was used in this study. This method has been widely applied and recognized worldwide (Hou, Xiang, Heenan, & Dazhi, 2018) and has become the standard for understanding

soil P dynamics. Thus, we investigated the effects of altitude, soil use systems, and soil aggregate classes on different P fractions in the Atlantic Forest biome.

Material and methods

Study areas

The study was carried out using Ultisol samples from two regions located at different altitudes belonging to the municipality of Alegre, in southern Espírito Santo State, Brazil (Figure 1).

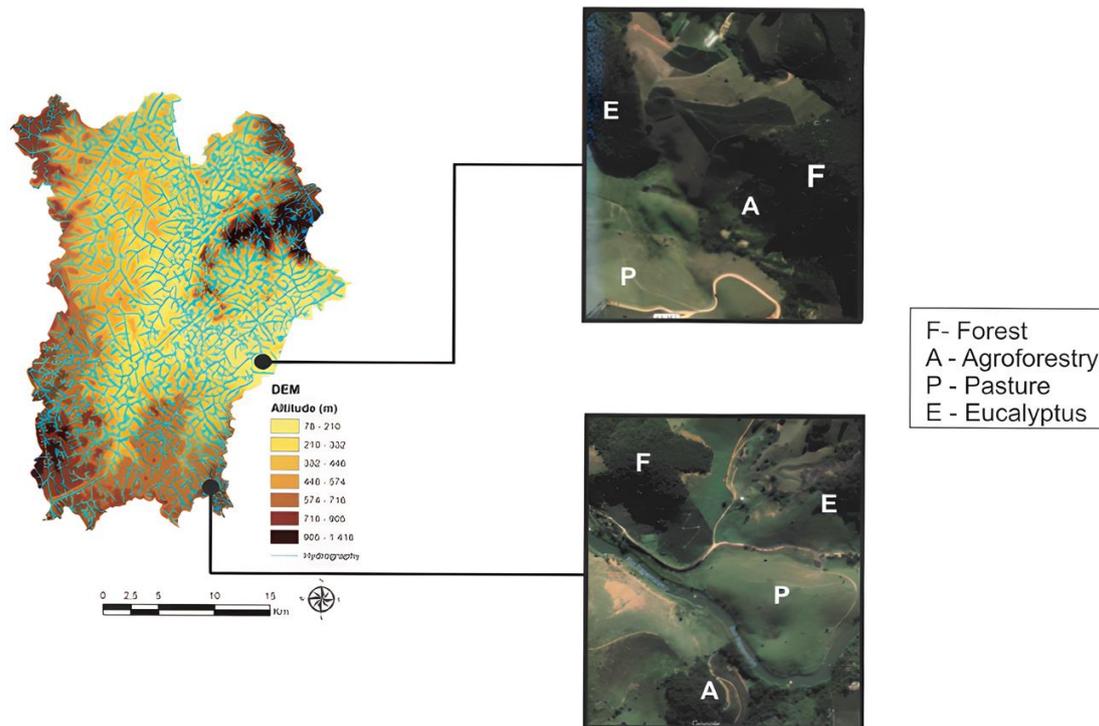


Figure 1. Location of the study regions, where A is the altitude of 100 m (*Rive*) and B, 700 m (*Lagoa Seca*) in Alegre, Espírito Santo State, Brazil.

This region belongs to the Caparaó microregion, with a predominance of Oxisols and Ultisols covered by the Atlantic Forest biome. The region presents an altitude varying from 119 to 1,227 m and relief varying from flat to steep, with a predominance of strong undulating relief (Mesquita et al., 2011). The samples were collected in the Ultisol area at two altitudes: 100 m (altitude 1), located in the district of Rive (20°44'01.4" S and 41°25'52.6" W), and 700 m (altitude 2), in the district of Lagoa Seca (20°51'32.2" S and 41°27'34.4" W). According to the Köppen classification, the regional climate is warm humid tropical (Cwa), with a cold and dry winter and average annual precipitation of 1,341 mm (Figure 2).

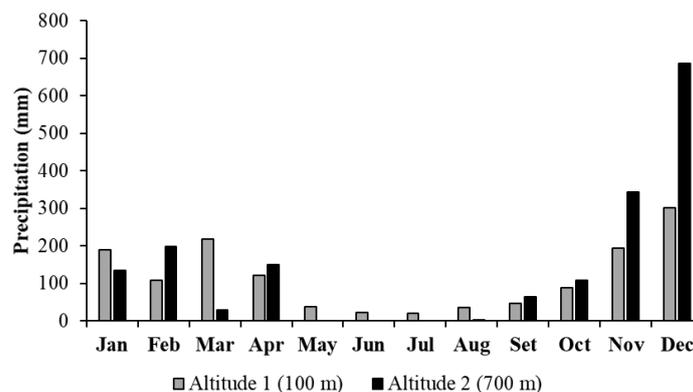


Figure 2. Mean precipitation (mm) for the municipality of Alegre, Espírito Santo State, Brazil, for 2016.

Source: Automatic station of the municipality of Alegre – INMET (2016).

The land-use systems evaluated at both altitudes consisted of a secondary forest (SF), agroforestry system (AFS), pasture (PAS), and eucalyptus (EUC). In general, the vegetation that comprises SF is classified as a seasonal semideciduous forest. This ecosystem is characterized by two defined climate seasons (rainy and dry seasons), which have a leaf seasonality of the dominant tree elements (Probio, 2004). It is characterized by the occurrence of dominant individuals such as *Piptadenia* sp. (angico), *Cariniana* sp. (jequitibá), *Ocotea* sp. and *Nectandra* sp. (sweetwood), and *Lecythis* sp. (Ururahyet, Collares, Santos, & Barreto, 1983), which have suffered anthropic interference for about 20 years due to wood extractions for sale and local use by producers and residents of the region.

The AFS area at altitude 1 consisted of coffee (*Coffea canephora*) intercropped with cedar (*Cedrela fissilis*) for nine years at a spacing of 2.5 × 1.0 m. This forest species was pruned in the first years and, subsequently, the coffee was planted. No mineral fertilization, soil acidity correction, or pest and disease control were carried out. Moreover, the AFS area at altitude 2 was composed of coffee (*Coffea arabica* L.) intercropped with inga (*Inga sessilis*) for 11 years in an area of 1.5 ha previously grown with pasture. The forest species was pruned after the first two years. The coffee was planted at this period at a spacing of 2.5 × 1.2 m (rows and plants, respectively). Weed management over the years was conducted by hoeing. Liming and fertilization were performed in the area, the latter using the NPK formulation 20-05-20 at the beginning of the rainy season taking into account the soil analysis. Pruning in inga trees was managed to allow sunlight to reach the coffee plants. Pest and disease control were not carried out.

The PAS areas at both altitudes have been managed with *Brachiaria decumbens* for approximately nine years at a clearing in the native forest. The systems never underwent pasture renewal, thus presenting a low soil cover during the dry season and renewal occurring during the rainy season. Weed management has been performed by using manual hoeing and herbicide. Limestone and fertilizer have been not used in this system at the two altitudes.

The EUC area at altitude 1 is characterized by the cultivation of *Eucalyptus grandis* at a spacing of 3 × 3 m for approximately five years. The EUC area at altitude 2 has been cultivated with *Corymbia citriodora* (Hook) (K.D. & L.A.S Johnson) for nine years at a spacing of 3 × 2 m in an area previously occupied by native forest. Planting fertilization in both EUC areas consisted of 100 g per plant of the NPK formulation 06-30-06 plus 0.25% B, 1.0% Zn, and 1.0% Cu. The fertilizer was applied in two side pits at 0.15 m from the seedlings.

Soil collection and characterization

Soil samples were collected in triplicates in the studied systems (SF, AFS, PAS, and EUC) at both altitudes (altitude 1 - 100 m and altitude 2 - 700 m). The samples were collected at a depth of 0-0.20 m in February 2016 from the same face of sun exposure for all studied systems.

Some of the soil samples were air-dried and sieved on a 2.0-mm mesh sieve aiming at chemical and physical analyses, according to EMBRAPA (2011). The other part of the samples were air-dried and physically separated by dry fractionation using a ROTAP sieve shaker for 15 min for aggregate diameter classes of 4-2 (class 1), 2-1 (class 2), 1-0.5 + 0.25-0.105 (class 3), and < 0.105 mm (class 4).

Moreover, three undisturbed soil samples were collected at the same depth to determine soil density and total porosity. The results of soil chemical and physical analyses are shown in Table 1.

Phosphorus fractionation

Phosphorus fractions were extracted sequentially according to the method proposed by Hedley et al. (1982). The method consists of sequential extractions of different P forms, with a distinction between organic and inorganic forms.

Each soil sample was subjected to a series of extractors for 16h: (a) anion-exchange resin, (b) 0.5 M NaHCO₃, (c) 0.1 M NaOH, (d) 1.0 M HCl, and (e) 0.5 M NaOH. The organic P (Po) was determined by the difference between inorganic P (Pi) and total P (Pt). Pt was determined after digestion in an autoclave using ammonium persulfate (Ebina et al., 1983). In all cases, P concentration was determined calorimetrically according to the method proposed by Murphy and Riley (1962) modified by Braga and Defelipo (1974).

Table 1. Chemical and physical attributes of the soil collected in the depth of 0-0.20 m in the two altitudes (100 and 700 m) in each system (agroforestry system- AFS, secondary forest- SF, pasture- PAS and eucalyptus- EUC), in the southern region of the state of Espírito Santo, Brazil.

Attributes	AFS	SF	PAS	EUC	AFS	SF	PAS	EUC
	----- 100 m -----				----- 700 m -----			
Sand (%) ^a	36.95	32.74	52.92	46.53	44.53	38.72	48.39	42.36
Silt (%) ^a	33.00	30.60	23.61	23.97	27.43	28.27	3.25	3.22
Clay (%) ^a	30.05	36.67	23.47	29.50	28.04	33.01	48.36	54.41
Bulk density (kg dm ⁻³)	1.07	1.02	1.27	1.22	1.21	1.10	1.03	1.19
pH (H ₂ O) ^b	6.48	4.69	5.28	5.23	6.58	4.70	4.85	5.02
P (mg dm ⁻³) ^c	2.20	1.56	0.50	0.75	2.05	0.94	0.63	0.66
K (mg dm ⁻³) ^c	156.72	48.80	35.97	61.64	264.79	59.00	26.43	22.81
Ca ⁺² (cmolc dm ⁻³) ^d	1.23	0.97	0.92	1.50	3.41	1.66	0.68	0.33
Mg ⁺² (cmolc dm ⁻³) ^d	0.70	0.63	0.43	0.95	1.26	0.55	0.09	0.18
Al ⁺³ (cmolc dm ⁻³)	0.00	0.36	0.13	0.02	0.00	1.14	0.92	1.00
H+Al (cmolc dm ⁻³)	2.77	6.90	4.70	4.37	3.99	8.91	7.55	7.43
SOC (dag kg ⁻¹) ^e	2.01	2.68	0.59	0.98	1.53	2.36	1.18	1.43
Total Nitrogen (dag kg ⁻¹)	0.18	0.20	0.11	0.16	0.11	0.20	0.14	0.11
T (cmolc dm ⁻³) ^f	2.33	2.08	1.57	2.62	5.34	2.36	0.84	0.57
V (%) ^g	45.75	19.76	23.23	36.29	57.23	20.92	10.00	7.09

^aPipette method (EMBRAPA, 2013); ^bpH in water (ratio 1: 2.5); ^cMehlich-1 extractant; ^dCaCl₂ 0.01 mol L⁻¹, soil to solution ratio 1:2.5; ^e Wet oxidation, soil organic carbon; ^f CTC effective; ^g base saturation.

Statistical analyses

This study was based on a comparative-measurement experimental design because the studied areas were not grouped (Adewopo et al., 2014). This design is based on the hypothesis that the soil properties of the studied systems (AFS, SF, PAS, and EUC) were similar before conversion and anthropic interference.

The statistical analyses were performed considering the contents of each P fraction. The data were tested for normality (Shapiro-Wilk test) and homoscedasticity (Bartlett test) before the analyses. A log transformation was performed when necessary to meet the parametric assumptions. The results were subjected to analysis of variance (F-test) at a 1 and 5% probability, considering the mean squared error, using the software SISVAR (Ferreira 2011).

Results

Phosphorus forms and lability were grouped into three fractions in the soil (Cross & Schlesinger, 1995). P Res and P Bic (Pi and Po) were grouped in the labile P fraction (LP). P NaOH 1 (Pi and Po) and P HCl were grouped in the moderately labile P pool (MLP). P NaOH 2 (Pi and Po) and P Residual were classified as restricted lability P (RLP).

The residual P (P-resid) fractions and P NaOH 0.5 mol L⁻¹ (Pt NaOH 2) were the most representative in the analyzed areas. P resid represented 45.65% in AFS and 37.42% in EUC compared to the total P, both at altitude 1 (Table 2). On the other hand, P-NaOH 2 represented 27.73% in EUC and 18.36% in SF. Together, these fractions represented, on average, 70% of the total P in AFS, followed by EUC (66%), PAS (65%), and SF (57%) (Table 2).

No significant differences were observed between altitudes regarding the LP compartment, unlike the PML fraction (Table 3, C1).

The C₂ (Table 4) showed greater relevance of AFS and SF, with higher P contents in the LP and MLP fractions than the other systems (EUC and PAS), both of which were higher in altitude 1. The highest P contents for the RLP fraction were observed at altitude 2. In general, C₃ (Table 4) showed that AFS was more relevant than EUC and PAS for all P fractions.

The C₄ (Table 4) showed that EUC had higher P content than PAS in all fractions, except for the MLP fraction at altitude 1, which may be associated with the higher amount of SOM provided by EUC, especially when compared to pasture.

Table 2. Soil phosphorus (P) fractions in the use systems (agroforestry system, secondary forest, pasture and eucalyptus), in four aggregate diameter class, being: 4-2 (class 1); 2-1 (class 2); 1-0.5 + 0.25-0.105 (class 3) and < 0.105 mm (class 4), at two altitudes (100 m and 700 m) at a depth of 0- 0.20 m.

System	Aggregate class ¹	Pi res.	Pt Bic	Pi Bic	Po Bic	PtNaOH	PiNaOH	PoNaOH	PtNaOH	PiNaOH	PoNaOH	P residual	ΣP ²
						1	1	1	2	2	2		
-----mg/ dm ⁻³ -----													
Agroforestry system Altitude 1	1	2.06	44.16	7.72	36.44	37.02	26.92	10.11	57.17	25.66	31.56	274.07	414.55
	2	0.48	44.09	9.58	34.46	38.74	23.85	14.90	63.53	32.83	30.71	258.80	405.6
	3	1.89	48.69	12.60	36.10	85.40	27.04	58.36	382.68	23.57	359.11	231.65	750.3
	4	1.93	363.06	8.02	354.99	355.78	40.37	315.42	198.01	21.78	176.24	234.92	1153.7
Agroforestry system Altitude 2	1	0.95	43.53	5.02	38.51	43.66	23.30	20.36	55.64	30.65	35.58	209.69	353.5
	2	1.27	42.69	6.64	36.05	46.06	17.90	28.17	53.97	16.96	37.07	128.56	272.6
	3	1.54	41.50	15.52	25.99	78.38	22.76	55.62	77.05	17.14	59.91	128.96	327.4
	4	2.20	348.56	10.37	338.20	247.96	36.97	210.99	154.73	21.64	133.08	146.27	899.7
Secondary forest Altitude 1	1	1.82	41.37	6.58	34.84	42.48	22.80	19.68	45.41	15.86	29.55	202.21	333.3
	2	0.39	42.26	8.52	33.74	41.57	19.13	22.45	50.61	18.64	31.98	122.74	257.6
	3	2.32	53.91	13.77	40.15	89.86	23.86	66.06	70.84	15.13	55.71	127.13	344.1
	4	2.40	286.54	10.71	275.84	364.75	37.69	327.01	198.28	10.46	187.82	105.87	957.8
Secondary forest Altitude 2	1	0.38	40.03	8.21	31.82	46.41	21.13	25.28	52.16	15.33	36.83	246.05	385.0
	2	1.26	41.57	6.95	34.62	39.04	17.31	21.72	53.72	20.11	33.62	219.37	355.0
	3	1.81	48.84	8.03	40.81	59.90	16.79	43.11	340.59	13.41	327.13	85.09	536.2
	4	2.11	396.79	7.31	389.48	210.12	31.84	178.33	136.00	11.30	124.70	166.17	911.2
Pasture Altitude 1	1	0.49	40.16	7.72	32.45	42.97	24.67	18.30	55.24	18.86	36.38	191.24	330.1
	2	0.53	43.12	7.61	35.51	43.16	22.09	21.12	55.84	22.95	32.94	139.58	282.2
	3	0.95	53.95	7.71	46.19	78.82	28.18	50.64	396.56	17.82	378.75	206.28	736.6
	4	0.65	313.40	7.02	306.39	270.99	40.92	230.08	170.50	15.30	155.16	149.85	905.4
Pasture Altitude 2	1	0.68	39.86	9.86	30.01	35.88	26.40	9.48	56.49	23.93	32.50	246.92	379.8
	2	0.62	40.61	8.77	31.79	35.89	24.15	11.75	56.92	24.39	32.53	141.35	275.4
	3	1.47	43.97	8.30	35.67	64.25	24.24	40.01	395.32	17.92	377.41	183.34	688.4
	4	1.23	362.86	9.11	353.69	242.09	39.76	202.28	132.17	18.60	113.58	132.85	871.2
Eucalyptus Altitude 1	1	0.80	42.30	6.10	36.25	45.92	24.33	21.59	53.16	15.63	37.54	155.15	297.3
	2	0.80	43.99	7.14	36.86	45.63	19.10	26.53	51.10	17.30	33.81	129.86	271.4
	3	1.62	53.07	10.29	42.78	84.85	24.44	60.41	131.81	17.14	114.68	210.30	481.7
	4	1.59	341.37	7.33	334.10	296.06	37.24	258.82	169.36	16.91	152.46	120.81	929.2
Eucalyptus Altitude 2	1	0.46	39.11	5.60	33.51	35.38	28.24	7.09	56.85	22.21	34.64	229.74	361.5
	2	0.45	42.40	6.54	35.86	44.10	24.16	19.95	55.07	24.15	30.92	137.05	279.1
	3	0.82	43.43	9.02	34.36	71.89	25.62	46.27	330.08	18.64	311.45	150.47	596.7
	4	0.53	311.21	5.28	305.88	202.76	42.12	160.64	138.15	10.29	127.87	105.81	758.5

Pi res.: inorganic P extracted by resin; Pt Bic: total P extracted by NaHCO₃; Pi Bic: inorganic P extracted by NaHCO₃; Po Bic: organic P extracted by NaHCO₃; Pt NaOH 1: total P extracted by NaOH 0,1 mol L⁻¹; PiNaOH 1: inorganic P extracted by NaOH 0,1 mol L⁻¹; Po NaOH 1: organic P extracted by NaOH 0,1 mol L⁻¹; Pt NaOH 2: total P extracted by NaOH 2 0,5 mol L⁻¹; PiNaOH 2: inorganic P extracted by NaOH 2 0,5 mol L⁻¹; Po NaOH 2: organic P extracted by NaOH 2 0,5 mol L⁻¹; 2: amount of fractions P.

Table 3. Orthogonal contrasts of the fractions of P (labile P- LP, moderately labile P- MLP, restricted labile P- RLP), for the different systems (agroforestry system, secondary forest, pasture and eucalyptus) at different altitudes, and aggregate classes.

Contrast	LP	MLP	RLP
C1	-4.27 ^{ns}	28.76 ^{**}	0.32 ^{ns}

C1: Altitude 1 vs Altitude 2 (+, -), LP: labile P, MLP: moderately labile P, RLP: restricted labile P. *, ** significant at 5% and 1% probability and 1% probability and "ns" not significant, respectively, by F Test.

Table 4. Orthogonal contrasts of the fractions of P (labile P- LP, moderately labile P- MLP, restricted labile P- RLP), for the different systems (agroforestry system, secondary forest, pasture and eucalyptus) at different altitudes, and aggregate classes.

Contrast	Altitude 1			Altitude 2		
	LP	MLP	RLP	LP	MLP	RLP
C2	-0.17 ^{ns}	18.40 ^{**}	-2.13 ^{ns}	10.67 [*]	4.92 [*]	-37.15 ^{**}
C3	9.22 ^{ns}	15.68 ^{**}	39.90 ^{**}	4.34 ^{ns}	12.50 ^{**}	-67.28 ^{**}
C4	-8.11 ^{ns}	-9.13 ^{**}	68.17 ^{**}	13.19 [*]	5.99 [*]	15.18 [*]

C2: SF+ AFS vs PAS + EUC (+ +, - -); C3: AFS vs EUC + PAS (2 +, - -); C4: EUC vs PAS (+, -), LP: labile P, MLP: moderately labile P, RLP: restricted labile P. *, ** significant at 5% and 1% probability and 1% probability and "ns" not significant, respectively, by F Test.

An increase in the P contents of all fractions (LP, MLP, and RLP) was observed according to a decrease in the diameter of soil aggregate classes, as shown by C₅, C₆, and C₇ (Table 5).

Table 5. Orthogonal contrasts of the fractions of P (labile P- LP, moderately labile P- MLP, restricted labile P- RLP), for the different systems (agroforestry system, secondary forest, pasture and eucalyptus) at different altitudes, and aggregate classes.

		Altitude 1			Altitude 2		
		C5	C6	C7	C5	C6	C7
AFS	LP	-162.4 ^{**}	1.65 ^{ns}	-314.41 ^{**}	-152.68 ^{**}	0.52 ^{ns}	-307.72 ^{**}
	MLP	-182.7 ^{ns}	-1.75 ^{ns}	-270.38 ^{ns}	-118.29 ^{ns}	-2.41 ^{ns}	-169.58 ^{ns}
	RLP	-230.0 ^{**}	-6.33 ^{ns}	184.70 ^{**}	-61.09 ^{ns}	1.62 ^{ns}	-77.66 ^{**}
SF	PL	-129.7 ^{**}	0.6 ^{ns}	-232.7 ^{**}	-183.2 ^{**}	-2.4 ^{ns}	-348.3 ^{**}
	MLP	-185.2 ^{ns}	0.93 ^{ns}	-274.9 ^{**}	-92.3 ^{ns}	7.36 ^{ns}	-150.2 ^{ns}
	RLP	-86.54 ^{ns}	-5.2 ^{ns}	-127.42 ^{ns}	-185.34 ^{**}	-1.57 ^{ns}	204.6 ^{**}
EUC	LP	-142.3 ^{**}	-3.0 ^{ns}	-259.2 ^{**}	-163.9 ^{**}	-0.64 ^{ns}	-318.7 ^{**}
	MLP	-131.8 ^{ns}	-0.21 ^{ns}	-192.16 ^{ns}	-117.27 ^{ns}	-0.02 ^{ns}	-177.8 ^{ns}
	RLP	-227.9 [*]	-0.59 ^{ns}	226.07 ^{**}	-207.05 ^{**}	-0.44 ^{ns}	263.12 ^{**}
PAS	LP	-154.9 ^{**}	-1.69 ^{ns}	-288.31 ^{**}	-136.8 ^{**}	-3.26 ^{ns}	-267.48 ^{**}
	MLP	-144.6 ^{ns}	0.27 ^{ns}	-211.21 ^{ns}	-97.58 ^{ns}	-8.75 ^{ns}	-130.90 ^{ns}
	RLP	-98.44 ^{**}	2.03 ^{ns}	-37.58 ^{**}	-178.16 ^{**}	1.79 ^{ns}	-191.96 ^{**}

C5: Class 1 + Class 2 vs Class 3 + Class 4 (2+, 2-); C6: Class 1 vs Class 2 (+, -); C7: Class 3 vs Class 4 (+, -). LP: labile P, MLP: moderately labile P, LRP: restricted labile P. * and ** significant at 5% and 1% probability and 1% probability, respectively, by F Test.

Discussion

The compartments P-resid and Pt NaOH 2 were the most abundant obtained in the sequential fractionation (Table 2), representing the most stable forms of P. This result is typical for the domain of tropical soils in the region. These soils are highly weathered, with a predominance of restricted P forms, especially those bonded to Fe and Al. Smeck (1985) stated that the residual P compartment represents the occluded P retained by structurally free minerals, more stable forms of organic P (Po), and insoluble forms of inorganic P (Pi). According to Novais and Smith (1999), this fraction is more evident in highly weathered soils than in poorly weathered soils.

The extractor NaOH 2 is more efficient to extract P in its low lability forms and with restricted availability for plant absorption. These P fractions are associated with phosphate bonded at high energy with Fe and Al oxides. Xavier et al. (2011) studied P fractions under different land uses (native vegetation, AFS, and coffee at the full sun) and verified that the fraction Pt NaOH 2 was the second most abundant.

The significant effect of the MLP fraction at altitude 1 (C₁, Table 3) may be related to the edaphoclimatic conditions of the region, leading to a higher nutrient cycling in the systems. According to Luizão (2007), nutrient cycling in tropical regions is favored by humidity and temperature conditions. In this case, the precipitation and SOM deposition represent the highest P inflow to the systems.

The SOM cycling at altitude 1 may have influenced the P contents of this fraction since the MLP fractions are directly associated with SOM. This result is corroborated by the high soil organic carbon contents in these systems (Table 1). The organic form was predominant in the MLP fraction. In this fraction, Pi is strongly adsorbed to Fe and Al oxides and Po to fulvic and humic acids (Rheinheimer, Cassol, Kaminski, & Anghinoni, 2008).

The MLP fraction is an important P pool for the different land-use systems, especially AFS and SF (Table 2). MLP can supply the most labile components and provide P for the most stable compartments (Busato, Canellas, & Velloso, 2005). Gatiboni, Kaminski, Rheinheimer, and Flores (2007) studied different P fractions in AFS and found high Pt contents in MLP (567 mg dm⁻³) compared to LP (103 mg dm⁻³) and RLP (306 mg dm⁻³).

The oxidic characteristic of tropical soils, the low availability of P contents, and the lack of phosphate fertilization may have contributed to the absence of significant differences between the altitudes for the LP pool (Table 3, C₁). In these soil types, most of the P is adsorbed to the surface of Fe and Al oxides, and liming and fertilization practices are necessary to provide the most labile P forms (Rheinheimer et al., 2008).

The highest P contents in the LP and MLP fractions of conservationist systems (C₂, Table 4) were observed in other studies (Gatiboni et al., 2007), with a decrease in P in low-labile fractions and an increase in labile fractions for the P dynamics in AFS.

According to Gatiboni et al. (2007), P accumulation in its most labile forms is expected in ASF due to an increase in the addition and types of residues to the soil. Tokura et al. (2002) found higher MLP in conservationist cultivation areas (26.6 and 13.3 mg kg⁻¹) than in non-cultivated areas (26.6 and 13.3 mg kg⁻¹). Maranguit, Guillaume, and Kuzyakov (2017) studied the P dynamics in monoculture systems and AFS and found that the decrease of MLP in the monoculture indicates that the more available P forms are associated with SOM. Soil P content, especially the most labile forms, is directly related to SOC and its lability is

associated with the mineralization of the organic fraction in which the phosphate ion is adsorbed, being its availability related to the SOM cycling in soils with low P addition (Costa et al., 2016).

Effects of climate, such as humidity and temperature variations, have favored SOM accumulation in areas of high altitude in the Atlantic Forest biome, resulting in high proportions of MLP (Araújo, Schaefer, & Sampaio, 2004). It could explain the higher relevance of altitude 1 than altitude 2 when evaluating the MLP fraction (C_2 , Table 4) and the higher P contents in the RLP fraction at altitude 1.

Higher P contents were observed in the MLP and RLP fractions in AFS than EUC and PAS (C_3 , Table 4). Xavier et al. (2011) studied the P fractions under different land-use systems in the Atlantic Forest biome and observed the highest total P content in the soil under native vegetation ($1,361 \text{ mg kg}^{-1}$), followed by AFS (988 mg kg^{-1}), and coffee monoculture (955 mg kg^{-1}). These authors also observed that the highest P_o contents in conservationist systems might have contributed to the high P_t contents, giving the organic compartment an important role in the availability of this nutrient in these systems.

The highest MLP values at altitude 1 in EUC (C_4 , Table 4) may be associated with litter accumulation in this system. Neufeldt, Silva, Ayarza, and Zech (2000) verified higher LP contents in the eucalyptus monoculture (50 mg kg^{-1}) than in pasture (38 mg kg^{-1}) and stated that the highest contents of this fraction are related to the high SOM cycling resulting from the high addition of litter in the EUC system. According to these authors, the most recalcitrant P forms predominate in pasture areas, indicating that this fraction did not contribute to the buffering of the more labile forms.

The increased P content in all fractions for the aggregate with small diameter (C_5 , C_6 , and C_7 , Table 5) can be justified by the higher specific surface area of the smaller soil particles, thus providing a larger available surface area to adsorb this nutrient. According to Brantley and Mellott (2000), the specific surface area of a soil sample is directly related to the mineralogy of the clay fraction, and both properties in a sample influence P adsorption.

Wright (2009) verified higher total P contents with a decrease in soil aggregate size for two land-use systems (pasture and sugarcane monoculture), attributing this result to the higher specific surface area provided by the smallest soil particles.

Adesodun, Adeyemi, and Oyegoke (2007) verified higher available P contents due to a decrease in aggregate class size in cultivated and non-cultivated soils. The same pattern was also observed for the SOC and TN contents, indicating a relationship between the dynamics of these elements. This trend of P accumulation in small aggregates differs from Mbagwu and Piccolo (1990) and Adesodun et al. (2007).

Rita et al. (2013) observed that the type of vegetation cover and hence SOM accumulation and nutrient addition to the soil directly affected the stability and formation of aggregates and that these factors together had significant effects on LP and the total P content. They also found the highest labile P contents in the aggregate class $< 0.25 \text{ mm}$ (11.8 mg kg^{-1}), followed by the class $> 2.0 \text{ mm}$ (3.5 mg kg^{-1}) and $2.0\text{-}0.25 \text{ mm}$ (2.2 mg kg^{-1}) in soils under forest cover.

Conclusion

The secondary forest and agroforestry system presented the highest P contents in the labile and moderately labile fractions compared to the conventional systems (eucalyptus and pasture) at both altitudes.

In general, the sequential fractionation of P showed that restricted labile forms predominated over the total P content for all land uses at both altitudes.

Soil aggregate classes with the smallest diameters showed higher P contents in all soil fractions of the Atlantic Forest biome.

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