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Inorganic and organic soil phosphorus and sulfur pools in an Amazonian multistrata agroforestry system

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Abstract

In the central Amazon basin, the effects of secondary vegetation and primary forest on inorganic and organic P and S pools were compared with those of different fruit and timber tree species in a multistrata agroforestry system. The soils (Xanthic Ferralsols) were low in readily available P and S. Fertilizer applications increased the less accessible nutrient pools more than the plant available pools. For example, dilute-acid extractable P increased substantially (from 2 to 76 mg P kg^{-1}), whereas Mehlich P (plant available) increased less (from 3 to 19 mg P kg^{-1}). In contrast, the recalcitrant soil P pools, such as the residual P, did not increase on the short term, but only after more than six years following application. The proportion of less available ester-sulfate S was significantly higher in fertilized sites than in unfertilized sites, in contrast to soluble inorganic sulfate S or carbon-bonded S. The marked increase of successively available soil P and S pools through fertilization was advantageous with respect to the long-term effect of nutrient applications. Soil nutrient availability was not only related to the amount of nutrients applied but was also influenced by tree species. Nutrient return by litterfall and litter quality played an important role in soil P and S dynamics. Incorporation of applied nutrients into successively available organic nutrient pools will decrease potential P fixation and S losses by leaching and increase long-term nutrient availability. Therefore, tree species with rapid above-ground nutrient cycling and high quality litter (such as annato [*Bixa orellana*] and peach palm [*Bactris gasipaes*]) should constitute the majority of crops in multistrata agroforestry systems on infertile soils to ensure adequate medium to long term availability of P and S.

Introduction

It is generally believed that nutrient cycling is more efficient in multistrata agroforestry systems than in monoculture plantations (Nair et al., 1999). This may be due in part to the complicated spatial and temporal arrangements of these cropping systems. Measurement of single-tree effects is one of the approaches used to assess nutrient dynamics in these systems. Using observations of single-trees, it is possible to collect information about how each species affects soil nutrient dynamics in natural forest and savanna ecosystems (Zinke, 1962; Rhoades, 1997). Subsequently, nutrient fluxes may be managed for different objectives by manipulating species selection and/or abundance.

Soils in the central Amazon are characterized by severe P limitations for plant growth (Cochrane and Sanchez, 1982) and land use has to consider soil P replenishment. Soil P dynamics can be determined by a variety of analytical methods. The sequential extraction developed by Hedley et al. (1982) offers the possibility of examining various inorganic and organic P pools differing in their origin and plant availability (Cross and Schlesinger, 1995). This analytical tool yields valuable information about P pathways in tropical cropping systems (Tiessen et al., 1992; Beck and Sanchez, 1996; Kass et al., 1999; Maroko et al., 1999). The transformation and availability of P supplied in commercial fertilizer can be assessed as well as the additions of P in organic sources (Nziguheba et al., 1998; Kass et al., 1999). Cross and Schlesinger (1995) showed that hydroxide inorganic P and total organic P fractions constituted a large portion of P in weathered tropical soils in contrast to less developed soils, where acid inorganic P dominates.

Even less information exists regarding S availability and dynamics in tropical soils, which may differ considerably from those in temperate climates (Neptune et al., 1975). If fertilization is able to meet the crop demands for the main nutrients N, P and K, S may become limiting, especially when fertilizers containing large amounts of S are substituted by fertilizers with a low S content (Janzen and Ellert, 1998). Organic S is generally the most abundant form of S in agricultural soils with rapid fluxes between plant available inorganic and organic S fractions (Janzen and Ellert, 1998). Therefore, different organic pools have to be assessed to evaluate soil S dynamics and the effects of trees on S availability.

The objectives of this study were: (i) to characterize the soil inorganic and organic P and S pools of a Xanthic Ferralsol in the central Amazon; (ii) to assess the influence of fertilization on these soil pools; and (iii) to determine single tree effects on soil P and S status in a multistrata agroforestry system.

Materials and methods

Study site and experimental setup

This study was conducted at the Empresa Brasileira de Pesquisa Agropecuaria (Embrapa) – Amazônia Ocidental experimental station on the terra firme near Manaus, Brazil. The average temperature is 26 °C and average precipitation is 2,503 mm yr^{-1} (1971 to 1993) with a maximum between December and May. The natural vegetation is a tropical rainforest. The soils are classified as Xanthic Ferralsols (FAO, 1990) or Typic Hapludox (Soil Survey Staff, 1997) and are clayey, strongly aggregated, with medium organic C and N contents (18.9 and 1.6 mg g^{-1}, respectively), low pH (4.0–4.5) and low cation exchange capacity (21 $mmol_c$ kg^{-1}) (Schroth et al., 1999).

The experimental fields were cleared from primary forest in 1980 and were planted with rubber trees (*Hevea brasiliensis*) in 1981. The rubber plantation was abandoned in 1986 and the secondary forest which developed on the fields was cut and burned in 1992 to plant the current experiment. The influence of different fruit and timber tree species on soil P and S pools was determined in a five-years-old multistrata agroforestry system in comparison to spontaneous vegetation and primary forest on comparable sites. These species were: *Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum. (cupuassu), whose fruit is used for juice and ice cream; *Bactris gasipaes* Kunth. (peach palm), managed for heart of palm production; *Bertholletia excelsa* Humb. & Bonpl., producing Brazil nut; *Bixa orellana* L., an important local dye (annatto); a legume cover crop (*Pueraria phaseoloides* (Roxb.) Benth) and spontaneous gramineous vegetation between the trees. Cupuassu and Brazil nut were grown alternately in the same row with a 7 m spacing. In the adjacent rows, at a distance of 4 m, either annatto (4 m spacing within the row) or peachpalm (2 m spacing within the row) were grown. The plots were 48 × 32 m and trees in the border rows were not included in the analyses. Additionally, comparable sites were chosen with: secondary regrowth of *Vismia* spp. (a pioneer tree species), which developed in plots (also 48 × 32 m) left bare at the installation of the agroforestry experiment and thus had the same age as the agroforestry system; and primary forest under *Eschweilera* spp. and *Oenocarpus bacaba*, which are typical tree species in the terra firme rainforest. The primary forest sites were situated along-side the agroforestry experiment, which had a total area of 15 ha, permitting its inclusion in the experiment. The plots were arranged in a completely randomized design with three replicates. In April and December 1997, the trees in the agroforestry system were fertilized beneath their canopies according to local recommendations (Table 1). The *Pueraria* and the gramineous vegetation received lime (2.1 Mg ha^{-1}) and Atifos (19 kg P ha^{-1}) in 1996. The agroforestry experiment, including the secondary forest sites, received some P fertilizer in the early 1980s during the preceeding rubber plantation. The primary forest sites did not receive any fertilizer. Annatto was pruned once per year after the harvest in April. Peach palm was harvested for heart of palm (involves cutting one or more of the multiple stems to harvest the terminal bud) twice per year in May and December.

Soil P and S analyses

In September 1997, composite soil samples (four subsamples) from 0 to 0.05 m depth were formed by mixing cores taken at two points at 0.5 m distance from two trees in each replicate. Composite soil samples (four randomized subsamples) were also taken under the legume and gramineous covers. In October 1997, January, March and May 1998, additional samples were taken in the same manner at 0 to 0.05, 0.05 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m depth. The soil was air-dried and sieved to pass 2 mm. 0.5 g soil was sequentially extracted according to a modified Hedley procedure (Table 2; Tiessen and Moir, 1993). The resin extractable inorganic P was determined separately due to the low amounts of readily available P in forest soils using the method outlined by Tiessen and Moir (1993). Additionally, plant available P was extracted with the Mehlich 3 method (Mehlich, 1984). Inorganic P was determined using the molybdate ascorbic acid method (Murphy and Riley, 1962). Total P in the extracts was analyzed with an ICP-OES. In the September samples, total soil S was measured with an automatic CNHS analyzer after dry combustion. Inorganic and organic S fractions were determined by digestion and distillation (Kowalenko, 1993). For total hydriodic acid extractable S (HI-S), 0.2 g soil were digested in hydriodic acid reducing reagent. N_2 gas was blown through the digestion tube, the volatilized hydrogen sulfide captured in 1N NaOH and measured photometrically after adding bismuth reagent. Solution and adsorbed SO_4^{2-} were determined by extraction with KH_2PO_4 and digestion of the extract as described above. The resulting values were used to calculate organic S, ester-sulfate-S and C-bonded S according to the following equations:

$$\text{organic S} = \text{total S} - \text{inorganic S} \quad (1)$$

$$\text{ester S} = \text{HI S} - \text{inorganic S} \quad (2)$$

$$\text{C bonded S} = \text{organic S} - \text{ester S} \quad (3)$$

Table 1. Annual fertilizer applications to trees in a multistrata agroforestry system in the central Amazon.

Species	Density	N[a]		P		S	
	(trees ha^{-1})	(g $tree^{-1}$)	(kg ha^{-1})	(g $tree^{-1}$)	(kg ha^{-1})	(g $tree^{-1}$)	(kg ha^{-1})
Cupuassu	93.3	95.4	8.9	77	7.2	108.9	10.2
Peach palm	312.5	42.4	13.3	11	3.4	48.4	15.1
Annatto	156.3	84.8	13.3	39.6	6.2	96.8	15.1
Brazil nut	93.3	42.4	4.0	22	2.1	48.4	4.5
Total	655.4		39.5		18.9		44.9

[a] N and S as ammonium sulfate (21.2% N; 24.2% S) and P as triple superphosphate (22% P). Annual totals were split between two equal applications (April and December). Total P applied from planting until 1997 amounted to 154, 91, 194, 149 g P $tree^{-1}$ for cupuassu, peach palm, annatto, Brazil nut, respectively.

Table 2. Sequential P extraction method and properties of soil P pools.

Extraction procedure[a]	Pool	Pool properties[b]
0.5 M $NaHCO_3$, 16 h	Bicarbonate-P_i Bicarbonate-P_o	Immediately plant available P; bound to mineral surfaces Readily plant available P; bound to mineral surfaces
0.1 M NaOH, 16 h	Hydroxide-P_i Hydroxide-P_o	Successively available P; bound to oxides Long-term availability; more strongly bound to oxides and in humic compounds
1 M HCl, 16 h	Dil. acid-P	Successively available P; Ca-bound
Concentrated HCl, 10 min, 80 °C	Acid-P	Long-term available P; Ca-bound and occluded P
5 M HNO_3 and concentrated $HClO_4$, 200 °C until dry	Residual-P	Highly resistant and occluded P

[a] Modified from Tiessen and Moir (1993).
[b] Modified from Cross and Schlesinger (1995) and Tiessen and Moir (1993).

Statistical analyses

The results were compared by analysis of variance using a completely randomized design (Little and Hills, 1978). For the Hedley-P, logarithmic values were used due to inhomogeneity of variances. In case of significant effects, means were compared by LSD at $P < 0.05$ (Little and Hills, 1978).

Results

Soil P pools

The highest P contents were found in intermediately available soil pools (hydroxide and acid-P) and the lowest in the easily available and residual P fractions (resin-, bicarbonate- and residual-P; Table 3). The regularly fertilized soils under the tree species in the multistrata system had significantly higher P contents (total values and for individual pools) than the unfertilized forest soils. However, soils under the secondary forest and the grass or *Pueraria* covers had the same amount of residual P than under the tree crops. Soils under the primary forest tree species *Oenocarpus* and *Eschweilera* had lower total P contents than under secondary forest (*Vismia* spp), spontaneous gramineous vegetation and *Pueraria*. This effect was more pronounced in the recalcitrant than the easily available P pools. The bicarbonate-P_i and dilute-acid P fractions increased significantly after fertilization (Figure 1). Soils under cupuassu, however, had significantly lower total P contents than soils under the other fertilized tree species ($P < 0.05$). Immediately before applying fertilizer, the depth distribution of Mehlich-P showed only slightly higher values under annatto and peach palm throughout the soil profile (Figure 2). After fertilization, the P contents increased to a depth of 0.1 m, but remained fairly constant below. Tree species had no significant effect on the dynamics of Mehlich-P among the fertilized sites ($P > 0.05$). In contrast, sequential extraction produced significant differences of the P depth distribution between tree species (Figure 3). When measured in respect to fertilization, three of the fractions were significantly higher in the topsoil beneath the tree crops than under the *Vismia* fallow. Whereas the differences for dilute-acid P decreased sharply with increasing depth, they increased in hydroxide-P_i and acid-P, and under annatto in dilute-acid P fractions as well. Soils below 0.05 m depth under annatto had significantly higher hydroxide- and dilute-acid P contents than under cupuassu.

Soil S pools

Most of the soil S was in organic form, the largest portion being C-bonded S (Table 4). Inorganic soil S was higher under peach palm, annatto and Brazil nut, but the amount of total, organic or C-bonded S did not differ significantly ($P < 0.05$) among tree species. Soils under cupuassu did not show a significant S increase in any fraction compared to

Table 3. Inorganic and organic soil P pools at 0–0.05 m depth under different trees in a multistrata agroforestry system and natural vegetation in a central Amazonian upland soil.

P pools	Resin-P[1]	Bicarb-P_i	Bicarb-P_o	Hydr-P_i	Hydr-P_o	dil. Acid-P	Acid-P	Res-P	Sum inorganic[2]	Sum organic[3]	Total P
	($\mu g\ g^{-1}$)										
Cupuassu	3.6 bc	8.5 bc	14.3 b	36.8 ab	52.7 ab	12.1 b	68.0 ab	13.7 a	144.1 b	66.9 bc	211.0 b
Peach palm	12.9 a	34.0 ab	42.8 a	82.6 a	65.4 a	113.3 a	78.6 a	10.7 a	319.2 a	108.2 ab	427.4 a
Annatto	12.6 ab	42.7 a	55.5 a	111.8 a	56.7 a	119.2 a	84.0 a	13.3 a	370.9 a	112.2 a	483.1 a
Brazil nut	15.3 a	67.9 a	53.3 a	128.4 a	62.6 a	59.5 ab	61.6 ab	18.7 a	336.1 a	115.9 a	452.0 a
Pueraria	2.6 c	6.2 bc	5.3 b	37.3 ab	34.7 ab	3.4 bc	19.7 b	14.5 a	87.1 bc	40.0 cd	127.1 bc
Gramineae	1.8 c	1.3 c	22.1 a	35.1 ab	38.2 ab	9.6 bc	26.2 b	10.9 a	83.1 c	60.4 bc	143.5 bc
Vismia	1.5 c	3.4 c	4.1 b	22.1 ab	37.0 ab	2.8 bc	23.0 b	13.2 a	64.5 c	41.1 cd	105.6 c
Oenocarpus	0.9 c	0.3 d	10.3 b	9.4 b	29.4 b	1.6 c	4.2 c	6.1 b	21.6 d	39.7 cd	61.3 d
Eschweilera	0.9 c	3.7 c	4.9 b	8.3 b	28.2 b	1.7 c	5.4 c	4.2 b	23.3 d	33.1 d	56.4 d
Mean fert. trees[4]	11.1 a	38.3 a	41.5 a	85.0 a	59.4 a	76.0 a	73.0 a	14.1 a	292.6 a	100.8 a	393.4 a
Mean fert. cover[5]	2.2 b	3.7 b	13.7 ab	36.2 a	36.4 b	6.5 b	22.9 b	12.7 a	85.1 b	50.2 ab	135.3 b
Mean unfert. forest[6]	0.9 c	2.0 b	7.6 b	8.9 b	28.8 b	1.6 c	4.8 c	5.1 b	22.5 c	36.4 b	58.8 c

[1] Resin-P was analyzed separately.
[2] Sum inorganic = bicarbonate-P_i + hydroxide-P_i + dil. acid-P + acid-P + residual-P.
[3] Sum organic = bicarbonate-P_o + hydroxide-P_o.
[4] Fertilized sites: cupuassu, peach palm, annatto, Brazil nut.
[5] Fertilized covers: *Pueraria*, gramineous vegetation.
[6] Unfertilized forest: *Oenocarpus*, *Eschweilera*.
Values in one column (species and fertilizer effect were calculated separately) followed by the same letter are not significantly different at $P < 0.05$ ($n = 3$).

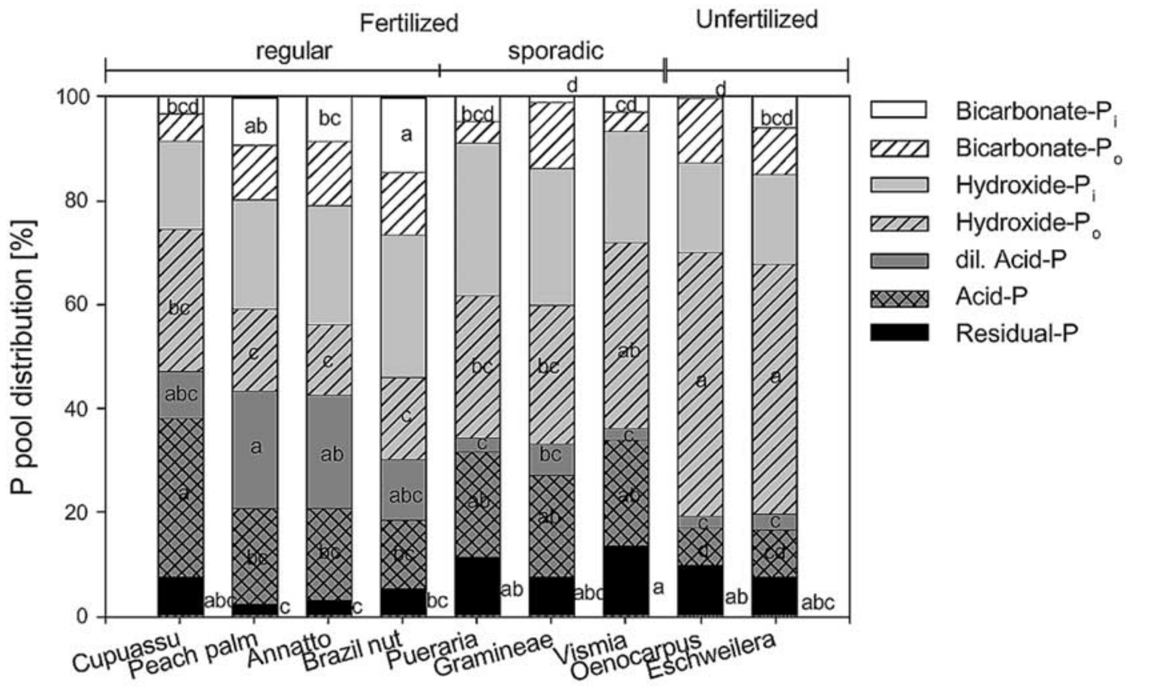

Figure 1. Relative distribution of P pools in soils under cupuassu, annatto, Brazil nut, peach palm, *Pueraria* and gramineous vegetation in an agroforestry system and under fallow (*Vismia* spp.), as well as under primary forest sites (*Oenocarpus* and *Eschweilera*) in the central Amazon.

n = 3; bars of the same fraction with the same letter (only shown for fractions with significant main effects) are not significantly different at $P < 0.05$.

the unfertilized soils. The most pronounced increase was found in HI-extractable and ester-sulfate-S fractions, especially under peach palm. The differences between the unfertilized sites were not significant.

Discussion

Properties of P and S pools under natural vegetation

The low values for acid extractable P and readily available P, and the larger values of P_o were consistent with the observations of Cross and Schlesinger (1995) that highly weathered soils have more P in successively available organic P fractions. The low amounts of residual-P, however, were surprising. Total P reserves were very limited in comparison to other tropical soils, including Ferralsols (Cross and Schlesinger, 1995; Friesen et al., 1997; Maroko et al., 1999; Lilienfein et al., 2000), emphasizing the need for sound P management practices in central Amazonian Ferralsols.

The studied soils contained a larger proportion of C-bonded S compared to studies of forest soils along an elevation gradient in Puerto Rico (23 to 77%; Stanko-Golden and Fitzgerald, 1991) and in Southern Brazilian agroecosystems (30 to 64%; recalculated from Neptune et al., 1975). As in the case of P, the amount of easily available inorganic sulfate-S was very low.

Fertilizer effects on soil P and S pools

The easily available resin- and bicarbonate-P_i pools reacted strongly and rapidly to P applications, as was shown for a Ferralsol in eastern Colombia (Friesen et al., 1997). However, in contrast to the cited work, the soils at our site also showed a large increase of the dilute-acid P

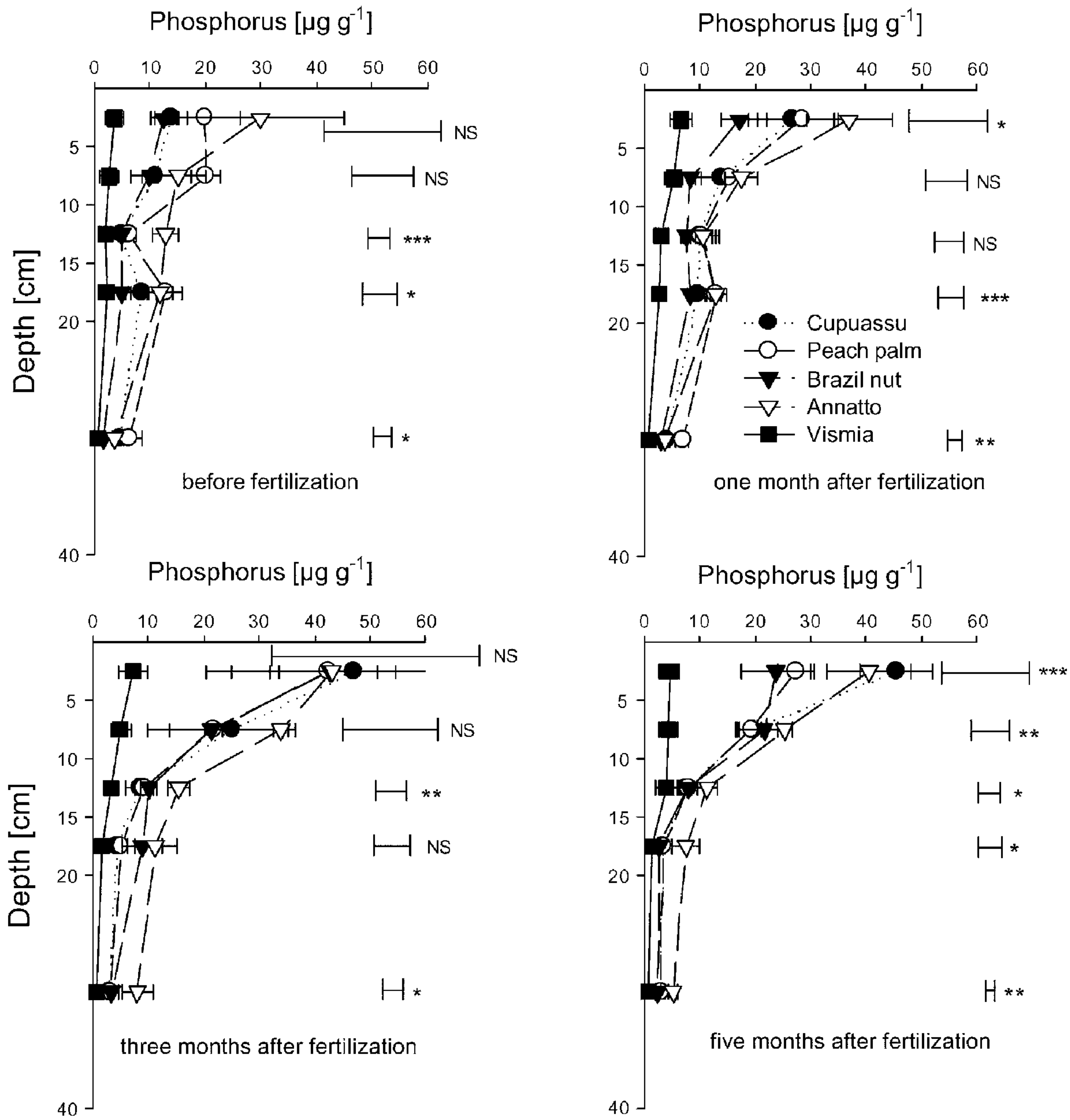

Figure 2. Distribution of Mehlich P in soils under cupuassu, annatto, Brazil nut, peach palm in an agroforestry system (fertilized) and secondary vegetation (*Vismia* spp; not fertilized) immediately before and 1, 3 and 5 months after fertilization in the central Amazon.

Means and standard errors; $n = 3$; bars indicate the least significant difference LSD at $P < 0.05$; *, **, *** and NS = significant from analysis of variance at $P < 0.05$, 0.01, 0.001 or not significant, respectively.

content (mainly Ca-bound P) whose proportional increase surpassed that of the bicarbonate-P_i contents. The dilute-acid P fraction is not mobile (Figure 3, i.e., it stays in the topsoil), but it does show a rapid response to fertilization (data not shown). Different results were also obtained for sugarcane on an Ultisol in Brazil, which still had 60% of the applied P in the bicarbonate- and

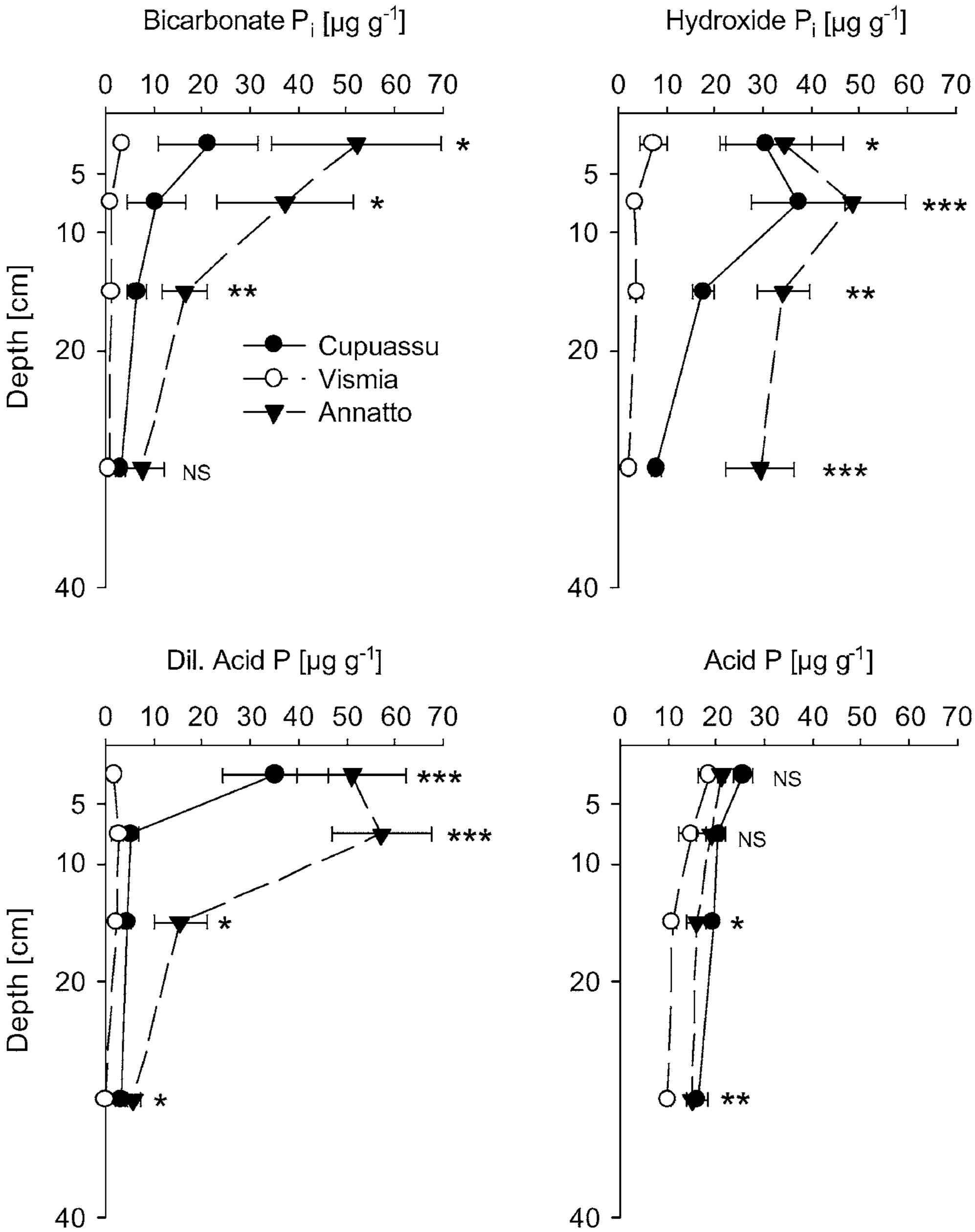

Figure 3. Depth distribution of Hedley P fractions under fertilized cupuassu and annatto in an agroforestry system and under unfertilized secondary vegetation (*Vismia* spp) in the central Amazon.

Means and standard errors; $n = 3$; from analysis of variance of logarithmic values; *, **, *** and NS = significant at $P < 0.05$, 0.01, 0.001 or not significant, respectively.

hydroxide-P fractions even at plant harvest 18 months after fertilization (Ball-Coelho et al., 1993).

The low residual P contents, showing no significant increase after regular P applications to the trees in comparison to the legume and grass cover, suggests that the fertilizer was not occluded in iron oxides to the same extent as occurred in

Table 4. Amounts and proportions of inorganic and organic soil S pools at 0–0.05 m depth, under different trees in a multistrata agroforestry system (fertilized) and natural vegetation (unfertilized), in a central Amazonian upland soil.

S pools	Inorganic sulfate-S	Organic S	HI-S	Ester-sulfate-S	C-bonded S	Total S
	μg g^{-1} (%)					
Cupuassu	30.5 (6.2)	482 (93.8)	59.2 (11.9)	28.7 (5.7)	454 (88.2)	513 (100)
Peach palm	54.1 (8.5)	744 (91.5)	319.2 (41.0)	265.2 (32.5)	479 (59.0)	798 (100)
Annatto	58.6 (8.9)	594 (91.1)	155.0 (23.7)	96.5 (17.8)	497 (76.3)	652 (100)
Brazil nut	87.3 (12.9)	572 (87.1)	232.4 (35.6)	145.1 (22.7)	427 (64.4)	659 (100)
Pueraria	37.5 (6.6)	530 (93.4)	78.6 (14.1)	41.2 (7.5)	489 (85.9)	568 (100)
Gramineae	15.5 (3.0)	485 (97.0)	105.5 (21.4)	90.1 (18.3)	395 (78.6)	501 (100)
Vismia	17.9 (3.0)	584 (97.0)	84.0 (13.9)	66.1 (10.9)	518 (86.1)	602 (100)
Oenocarpus	39.7 (7.0)	531 (93.0)	100.8 (17.3)	61.2 (10.2)	471 (82.7)	571 (100)
Eschweilera	35.3 (6.9)	464 (93.1)	55.0 (11.2)	19.7 (4.2)	444 (88.9)	499 (100)
Site effect	* (NS)	NS (NS)	*** (***)	** (**)	NS (***)	NS (nd)
$LSD_{0.05}$	39.7 (nd)	nd (nd)	102.8 (10.0)	113.0 (12.8)	nd (10.0)	nd (nd)

nd = not determined
NS = not significant; ***, ** and * = significant at $P < 0.001$, 0.01, 0.05.

savanna Ferralsols in Colombia (Friesen et al., 1997) or Brazil (Lilienfein et al., 2000). The Central Amazon Ferralsols contain a higher amount of kaolinite and less iron oxides than the Cerrado Ferralsols (Demattê and Demattê, 1993), a finding that explains the lower occlusion. The unfertilized primary forest sites in our study also had very low soil P contents in both acid and residual fractions, with 4.2 to 5.4 and 4.2 to 6.1 μg g^{-1} compared to Ferralsols with 33 and 54 μg g^{-1} under native savanna (Friesen et al., 1997) or 120 and 108 μg g^{-1} under Cerrado vegetation (Lilienfein et al., 2000), respectively. P contents only increased in the residual fraction a long time after P additions in fertilizer and/or organic matter, as in the case of the fallow fertilized about 15 years earlier and where biomass was slashed and burned five years earlier. Residual P did not increase, in comparison to the fallow, after recent fertilizer additions, in the case of the tree crops or the cover crop. Apparently, fertilizer P remained in plant available forms for a long period after its application.

Although the soils in the central Amazon do not show as much P occlusion as Ferralsols from other parts of tropical South America, they are extremely P limited (Cochrane and Sanchez, 1982), while N is in relatively good supply (Schroth et al., 1999 from similar multistrata agroforestry systems at our site). Therefore, a large portion of the fertilizer P was probably incorporated into the microbial biomass resulting in the large increase of organic P fractions. Indeed P applications increased microbial biomass, but N applications did not (da Silva Jr. and Lehmann, unpubl. data). Nurwakera (1991) also reported a similar increase of organic P after fertilization at a nearby site. Similarly, Tiessen et al. (1992) found a large incorporation of added fertilizer P into organic P (hydroxide-P_o) on a Ferralsol in northeastern Brazil. Soil management which enhances the ability of the soil microbial biomass to recycle P would prevent P from being occluded in oxide aggregates. The proportion of fertilizer P recycled through plant biomass and entering the soil organic P fractions was equally important as is discussed below.

In contrast to P, there is generally no danger of S occlusion, but leaching losses can be problematic. This may be the reason for the small increase of inorganic sulfate-S in the fertilized soils in comparison to the unfertilized soils. Immobilization of S in organic fractions occured only for the ester-sulfate-S fraction; not the C-bonded S. The ester-sulfate-S pool is more reactive than the C-bonded S and forms more rapidly after S additions as was shown with ^{35}S labelling (Ghani et al., 1993), especially in soil horizons with high microbial activity (Schindler et al., 1986). This also means that S can be rapidly remobilized from this pool and become available for plant uptake. On the other hand, higher amounts of S were taken up by test plants (*Sorghum vulgare*) from ^{35}S-labelled carbon-bonded S than ester-sulfate-S (Freney et al., 1975). A high incorporation of added inorganic S in organic S would increase the long-term availability by preventing S leaching. However, the pathways of S between soil pools are not completely understood and more information is needed about the chemical compounds in the different S fractions (Janzen and Ellert, 1998).

Single-tree effects on soil P and S pools in multistrata agroforestry

The amount of fertilizer added did not correlate with the different amounts of soil P and S measured under each tree species in the agroforestry system. Soils under cupuassu had lower readily available (resin and bicarbonate; 67 to 88% lower) and successively available (hydroxide- and dilute acid; 55 to 90% lower) P contents than the soils under the other trees in the agroforestry system, despite the fact that cupuassu received respectively 7, 4, and 2 times more fertilizer P than peach palm, Brazil nut and annatto during the experimental year. The differences in total P applied to the different tree species since forest clearing were lower but still 80% higher for cupuassu than for peach palm. The relationship between tree species was less pronounced for S but showed the same trend. The low P contents in soils under cupuassu (Table 3) cannot be explained by fertilization or P uptake alone. The biomass production of cupuassu was only about 30% greater than that of peach palm (Lehmann et al., 2000) and lower than the biomass production of annatto and Brazil nut (Wolf, 1997). In addition, the foliar P contents of annatto and peach palm were more than twice as high as those of cupuassu (Lehmann, unpubl. data), and total P export in cupuassu fruit harvest, during the five years since planting, only amounted to 1.8 g P tree^{-1} (0.14 mg P g^{-1} fresh fruit [Cravo and Souza, 1996]; 12.5 kg fresh fruit tree^{-1}) in comparison to 8.6 g P tree^{-1} in annatto (3.9 mg P g^{-1} seed [Wolf, 1997]; 2.2 kg dry matter tree^{-1} [Macêdo, unpubl. data]). A higher P uptake by cupuassu than peach palm and annatto did not seem plausible since the recalcitrant acid-P pool under cupuassu increased in the same way as it did under the other fertilized trees. Since the organic P pools were lower under cupuassu than the other species, recycling of labile P sources is the most likely explanation of observed differences. The total return of P, in above-ground litter and pruning residues, amounted to 1, 3, 4, and 30 g P tree^{-1} yr^{-1} for cupuassu, Brazil nut, peach palm and annatto, respectively (Uguen et al., unpubl. data). Above-ground biomass of annatto and peach palm was pruned after or during harvesting, a practice that accounts for the high value, which is comparable to the amount supplied in fertilizers (Table 1). The low P return in cupuassu litter, which also had high C-to-N ratios (Lehmann et al., 2001), may explain the relatively low amounts of available soil P under cupuassu. McGrath et al. (2000) even found P immobilization in decomposing litter of cupuassu in contrast to peach palm in Acre, Brazil. Similarly, on a Luvisol in Western Kenya, resin-, bicarbonate- and hydroxide-P were significantly elevated after addition of *Tithonia diversifolia* leaves (high-P), but not by maize stover (low-P) (Nziguheba et al., 1998). Apart from the amount of P added in biomass or litter, competition of organic acids (from the decomposing litter) with sorption sites can increase the availability of added fertilizer P (Iyamuremye and Dick, 1996).

The small amount and proportion of ester-sulfate-S under cupuassu in comparison to the other fertilized tree species may also be explained by different S return rates in litter. Additionally, Ghani et al. (1993) showed that more sulfate was incorporated into the organic S pool and less soil-extractable S was present when glucose was added, indicating that leaching of soluble S would be diminished when easily degradable C sources are present in soil. In the presence of sufficient inorganic sulfate-S, this would also increase ester-sulfate-S contents. Soils under cupuassu, however, had wide C-to-N ratios and cupuassu leaves were of low quality (Lehmann et al., 2001) indicating slow decomposition. The differences of HI-S between sites, however, were small suggesting that leaching losses under the fertilized trees in the agroforestry system were high.

P distribution in the soil profile as affected by tree species

Beck and Sanchez (1996) reported that 327 kg P ha^{-1} had moved into the subplow layer (0.15–0.4 m) after 13 years. A surface application of 40 Mg ha^{-1} yr^{-1} *Erythrina poeppigiana* to an Inceptisol throughout 13 years did not increase HCl-P_i at 0.1–0.2 m depth, but the application of cattle manure (Kass et al., 1999), with large amounts of P, did increase HCl-P_i at this depth. In our study, the distribution of the more readily available P fractions (e.g., bicarbonate-P_i) resembled that of the Mehlich-P. The acid-P fractions, however, showed more P in the subsoil under the fertilized cupuassu and annatto than under the unfertilized *Vismia*. This was also observed for hydroxide-P_i under annatto, suggesting that either mainly recalcitrant P forms were transported into the subsoil or that they accumulated after plant uptake of the available P. P transport into the subsoil may have occurred through soil fauna activity, root turnover and to a minor extent leaching in this highly permeable Ferralsol.

Conclusions

The differential P and S extraction methods demonstrated that there were contrasting P and S dynamics among experimental treatments on this Central Amazonian Ferralsol. The studied soils showed low amounts of residual P and applied fertilizer P entered the recalcitrant P fractions only a long time after application. Therefore, applied P remained plant available due to low amounts of oxides in the Ferralsols. Low fertilizer applications may be sufficient for long-term uptake, a possibility that is especially important for tree crops. The amount of available soil P and S was not only dependent on fertilization, but also on tree species selection. Particularly the ability of a tree species to return P through litterfall was important for soil P availability. In order to decrease the risk of P fixation and leaching of S, the incorporation of applied P and S into organic and intermediate available soil pools was of similar importance. In an agroforestry system with a mixture of perennial crops, care should be taken to include tree species with a high return of nutrients through litter decomposition and nutrient mineralization. Annatto and peach palm performed this function, particularly because they were periodically pruned. Additionally, a high microbial activity will enhance the conservation of added nutrients through incorporation into an organic nutrient pool, and can be managed by litter manipulation.

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