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Phosphorus management for perennial crops in central Amazonian upland soils

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Abstract

The present contribution discusses the soil P status of central Amazonian upland soils, the effects of tree crops on soil P availability and the factors controlling soil P cycling in land use systems with tree crops. Soil fertility management has to target the prevalent P deficiency by adequate P fertilization, especially in southern and northern municipalities of central Amazônia where the largest areas with severe P deficiency are found. P fixation to clay minerals is not a major obstacle for P management in the highly weathered upland soils of the central Amazon due to their low Al- and Fe-oxide contents. Low total soil P amounts are mainly responsible for low P availability. Tree crops are found to be especially suitable for land use under low-P-input conditions. Their large P return to soil by litterfall and pruning improves soil P availability. Additionally, litter quality affects P release and soil P availability. Both aspects, quantity and quality effects, are strongly dependent on tree species. Phosphorus sorption does not seem to be reduced by different litter types confirming earlier results that P fixation is not a major problem in central Amazonian upland soils. In conclusion, biological approaches are more important than physical approaches to improve soil P availability in central Amazonian Oxisols. With large P cycling through soil microbial biomass and between plant and soil, a higher availability of added P can be maintained and P applications only need to replenish P exports by harvest. Low P additions will improve productivity also for long-term uptake by trees. This is of high importance in regions with poor infrastructure and the lack of financial resources.

Introduction

Phosphorus is limiting plant growth worldwide in many soils (World Bank, 1994). Especially the acid soils of the humid tropical lowlands possess low P availability (Sanchez and Logan, 1992). At the same time, the global reserves of apatite, which is needed for producing P fertilizers, are limited and known reserves may exhaust in about 100 years with the current growth of P usage (Stevenson and Cole, 1999). Sound management strategies need to be developed to utilize applied and native soil P more effectively thus reducing P fertilizer demands.

Continuous production of annual crops in highly weathered Oxisols of the central Brazilian Cerrado savanna demand high P fertilization (Yost et al., 1981). But also soils of the central Amazon require P fertilization above all other nutrients (Smyth and Cassel, 1995). Less than 16 kg P ha^{-1} crop^{-1} seriously decreased yields of a variety of annual crops (Smyth and Cassel, 1995). In this region, perennial tree crops are traditionally important for local markets and are also gaining increasing importance for export markets.

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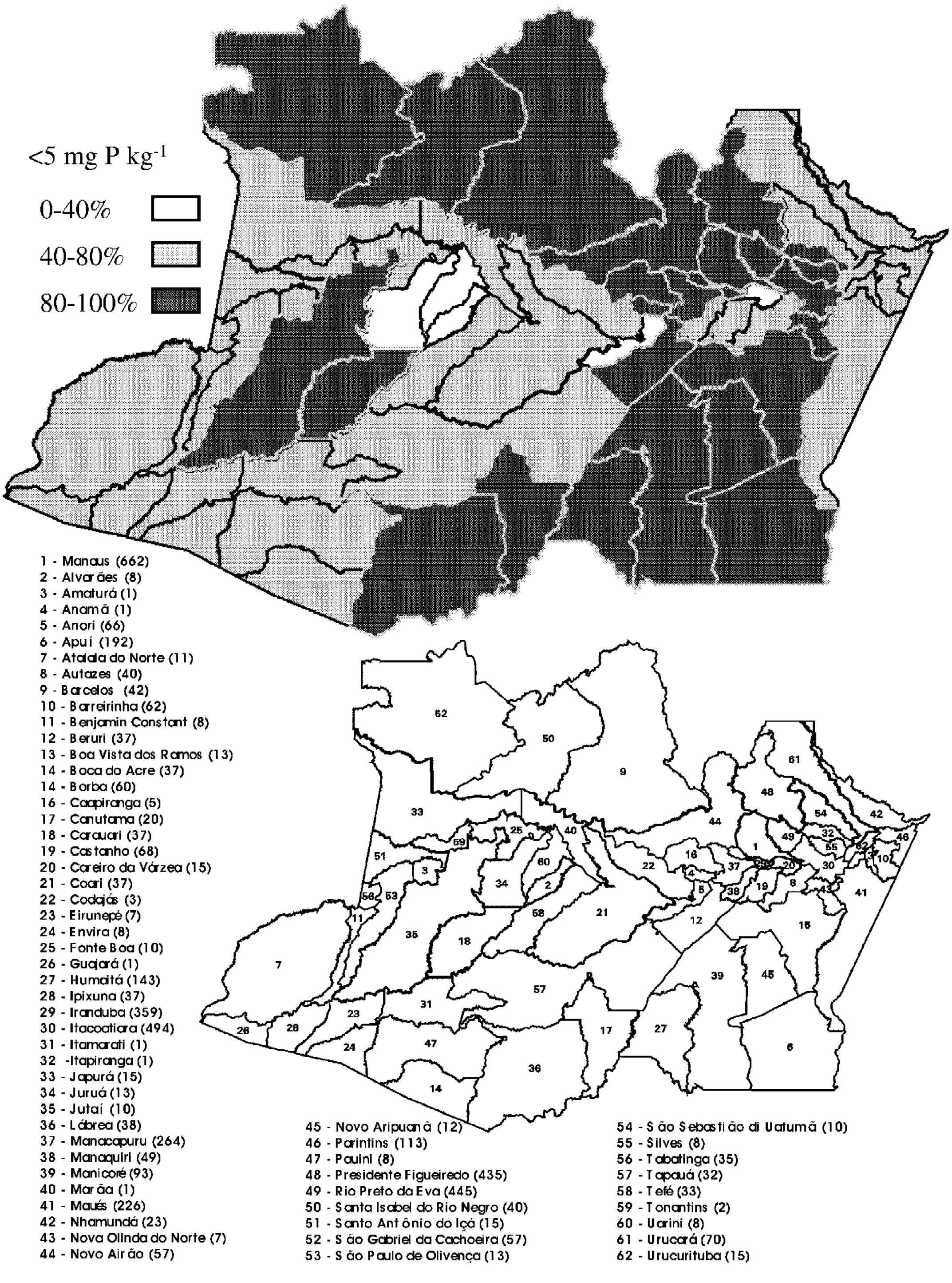

Figure 1. Proportion of highly P-deficient soils (< 5 mg kg^{-1} Mehlich-1-extractable P) in the municipalities of central Amazônia; values in brackets indicate numbers of analyzed samples (*N*=4633; obtained from the data-bank of the Embrapa-Amazônia Ocidental; data from Moreira et al., 2000).

Their P management may differ from that of annual crops, as they may have different patterns of P uptake, export with harvest and return to soil. Very little comprehensive information, however, is available about the P fluxes in tree crop production which affect the P management of the trees. The effects of P management are closely linked to the P status and behavior in soils. Therefore, we present a survey of soil P of central Amazonian soils (State of Amazonas, Brazil), the P economy and soil P amelioration of some important indigenous tree crops in the central Amazon.

Soil phosphorus constraints for crop production in the central Amazon

Most upland soils in the Amazon are highly weathered. Thirty-four percent of the soils are classified as Oxisols, 39% as Ultisols (Dematê and Dematê, 1997). The same authors reported that 96% of the soils in the whole Amazon basin are P-limited. This was the limitation which comprised the largest area of all evaluated parameters and made P the most important constraint for crop production on a landscape level. As seen from Figure 1, the highest percentage of soils with severest P deficiency (< 5 mg P kg^{-1}) is located in the north and southeast of central Amazônia (we restricted our survey to the State of Amazonas, Brazil). The soil data were derived from the data bank of the Empresa Brasileira de Pesquisa Agropecuária (Embrapa – Amazônia Ocidental), which comprised agricultural soils analyzed during the past 25 years irrespectively of their management and origin within the counties (Moreira et al., 2000). Only few soils with pronounced P constraints ($< 40\%$) are located in areas with a high proportion of alluvial soils near large rivers (Anori, Careiro da Várzea, Alvaraes, Uarini and Juruá counties; classified as floodplains by Sombroek, 2000). However, counties near larger rivers do not automatically have a large proportion of agricultural soils with sufficient P. The loamy plains in the western part of the central Amazon still have 40–80% P-deficient soils. The northern counties have large areas with the highest P constraints ($> 80\%$), which are regions with poor soils around the Rio Negro blackwater basin (eastern sedimentary uplands and crystalline shield uplands, Sombroek, 2000). Interestingly, the proximity to the main river pathways where P fertilizers are more accessible did not reduce the prevalent P deficiency, indicating that P fertilizer is not used to a large extent. Therefore, P management strategies are the most important tools for improving crop yields and agricultural land use in the central Amazon.

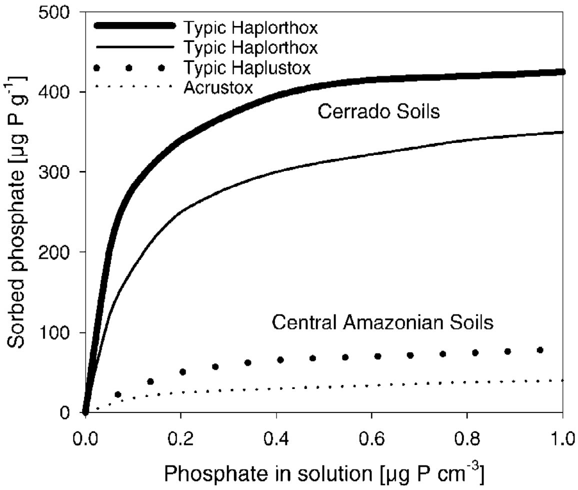

Figure 2. Phosphorus adsorption isotherms (non-exchangeable phosphorus) of clayey soils from central Amazonian upland (UEPAE 74% clay; Profile 4B 34% clay; near Manaus, Brazil) and Cerrado (DRL 50% clay; RYL 45% clay; savanna region in central Brazil) determined by isotopic exchange using ^{32}P (redrawn after LeMare, 1982 with permission of Blackwell Publishers).

When compared to other highly weathered upland soils from tropical South America, available P contents are low in central Amazonian soils (see Table 1). Seventy-seven percent of the central Amazonian upland soils from agricultural fields analyzed by Cravo and Macêdo (1999) had less than 3 mg kg^{-1} soil (N=146) as did 69% of the soils shown in Figure 1 (N=4633). Smyth and Cravo (1990) defined 6 and 8 mg kg^{-1} soil P (Mehlich-1 extraction) as critical levels on an Oxisol of the Manaus region for maize and cowpea, respectively. These results were confirmed for similar soils in Pará (Dematê and Dematê, 1997). Phosphorus deficiency is, therefore, prevalent in crop production throughout the central Amazon.

Phosphorus cycling in upland soils of the central Amazon

Phosphorus fixation was stated by Dematê and Dematê (1997) to be the reason for the low P availability in 65% of the soils of the whole Amazon basin. Sanchez et al. (1991) gave a percentage of only 16 as high P-fixing soils in the Amazon. Iron and Al oxides are mainly responsible for the specific bondage of phosphate to exchange sites. The situation in the central Amazon, however, is different from that in other parts

Table 1. Soil phosphorus status of clayey upland soils in the central Amazon in comparison to other clayey soils in South America

Soil	Region	Vegetation	Clay [%]	Extractant	Available P [mg kg^{-1}]	Total P [mg kg^{-1}]	Organic P [mg kg^{-1}]	Organic P [% of total]	Source
Hapludox	central Amazonia	cleared forest	> 60	Mehlich 1	3.0	104	27.4	26	[1]
Hapludox	central Amazonia	natural forest	68	Mehlich 1	1.6	nd	15.3	-	[2]
Udult	central Amazonia	natural forest	54	Mehlich 1	2.4	nd	16.8	-	[2]
Hapludox	central Amazonia	natural forest	59	Mehlich 3	3.6	106	41.1	39	[3]
Hapludox	central Amazonia	fallow (7 yrs.)	59	$NaHCO_3$	2.0	59	36.4	62	[3]
Hapludox	central Amazonia	natural forest	60–80	Mehlich 1	2.3	46	nd	-	[4]
Hapludox	central Amazonia	burned forest	60-80	Mehlich 1	9.8	100	nd	-	[4]
Hapludox	central Amazonia	pasture (1 yr.)	60–80	Mehlich 1	3.3	65	nd	-	[4]
Hapludult	eastern Amazonia	natural forest	49	Mehlich 1	3.7	141	nd	-	[5]
Acrustox	Cerrado	natural woodland	68	$NaHCO_3$	6.7	388	112.1	29	[6]
Haplustox	Colombia	natural savanna	nd	Bray-2	1.5	181	63.0	35	[7]

[1] Nurwakera (1991) (N=4; total P as the sum of all fractions).
[2] Tucci (1991).
[3] Lehmann et al. (2001b) (N=3).
[4] Teixeira (1987).
[5] Singh et al. (1983b).
[6] Lilienfein et al. (2000) (N=3).
[7] Friesen et al. (1997).

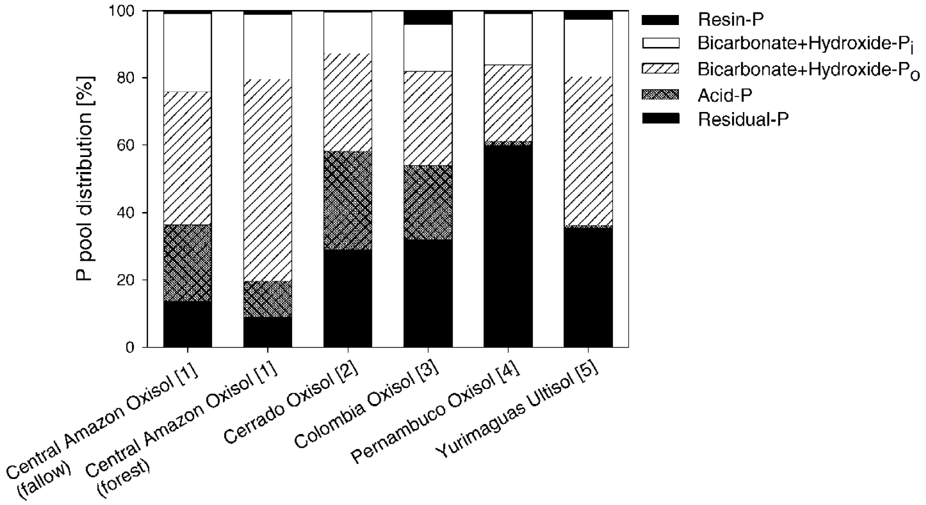

Figure 3. Distribution of P pools in clayey soils of the Amazonian upland (Xanthic Hapludox) in comparison to other weathered soils from tropical South America under natural vegetation. Sequential extractions were done following the Hedley fractionation (Tiessen and Moir, 1993) and inorganic and organic bicarbonate- and hydroxide-P were pooled, respectively. [1] Lehmann et al. (2001b); [2] Lilienfein et al. (2000); [3] Friesen et al. (1997); [4] Tiessen et al. (1992); [5] Beck and Sanchez (1996).

of the Amazon. It is not P fixation which causes the low P availability in central Amazonian Oxisols. In fact, P fixation is low as reported by LeMare (1982) in comparison to Cerrado Oxisols (Figure 2). Consequently, Oxisols of the central Amazon also possess a lower proportion of recalcitrant P (residual-P obtained from sequential P extractions) than Oxisols of the Cerrado (Figure 3). The different soil P pools are obtained by sequentially extracting P with increasing recalcitrance from labile and plant available P (resin-P) to highly adsorbed P (residual-P) which is unavailable to plants (Tiessen and Moir, 1993). The same could be observed in comparison to upland soils from the eastern and the western Amazonian basin as

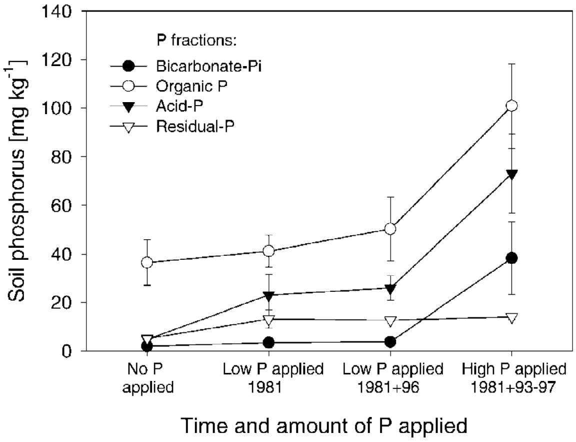

Figure 4. Soil P pools of Xanthic Ferralsols in the central Amazon with different P fertilization history measured in 1997; No P applied – primary forest (*N*=6), Low P applied 1981 – secondary forest, fertilized around 1981 for a rubber plantation which was abandoned 4 years later (*N*=3), Low P applied 1981+96 – cover crops supplied with a second application of 19 kg P ha^{-1} in 1996 (*N*=6), High P applied 1981+93–97 – different tree crops fertilized with additional 120 kg P ha^{-1} during a 5-year period (*N*=12); organic P is the sum of bicarbonate and hydroxide extractable organic P, all fractions were extracted using sequential fractionation (means and standard errors; details in Lehmann et al., 2001).

well as the Colombian savanna (Figure 3). The low fixation in Amazonian Oxisols can be explained by the low amount of Fe and Al oxides and the prevalence of kaolinite (Singh et al., 1983a).

Therefore, the reason for the low soil P availability in the central Amazon is less a high P fixation but rather low total P contents. Total P contents rarely exceeded 100 mg kg^{-1} and are considerably lower than in Oxisols from other parts of South America (Table 1). In contrast to the residual P, the proportion of organic P is higher than in other highly weathered soils, mainly Oxisols (Table 1 and Figure 3). Therefore, availability of native soil P is probably more related to the mineralization of organic P than to P fixation in central Amazonian upland soils. Additionally, high fertilizer P applications enter the organic P pools to a larger extent than the highly adsorbed P (residual-P, Figure 4), which indicates that even in fertilized soils the biological control of P availability may be more important than occludation and irreversible fixation of P (physical control). In soils where no P was applied (soils under undisturbed primary forest, Figure 4), only long-term exposure to fertilizer P for about 16 years increased the residual-P pool (Low P applied 1981). Interestingly, additional low P applications for 1 year (Low P applied 1981+96) and high applications during 5 years before sampling (High P applied 1981+93–97) did not increase this P pool (Figure 4). Phosphorus fixation into unavailable forms (residual-P) is, therefore, a long-term process and was not affected on the short term by the amount of P applied. Phosphorus in successively available form (Acid-P, Figure 4) reacted more pronouncedly and more rapidly to P applications than the residual-P. The plant-available P (bicarbonate-Pi), however, followed the pattern of organic P emphasizing that P availability is more affected by organic P dynamics than by occludation and fixation of P.

The low P immobilization by fixation to oxides could also be shown by a fertilizer experiment (Smyth and Cravo, 1990). A single P application of 176 kg ha^{-1} to the first crop (rotation of maize and cowpea) increased soil P levels to over 45 mg kg^{-1} (Mehlich-1 extractant) in a Hapludox, and was up to 4 years afterwards as high as in the first year after an initial application of 88 mg kg^{-1}. For the first 10 crops, yields of maize and cowpea were not higher with split applications for each cropping season with 44 and 22 kg P ha^{-1} in comparison to a single application at the beginning, all totaling to 176 kg P ha^{-1}. Yields were even lower when 11 kg P ha^{-1} were applied to each crop throughout the whole experimental period (also totaling to 176 kg P ha^{-1}). Therefore, single but higher amounts of fertilizer P were superior to continuous but lower P applications. The same concept may be successful for perennial crops. In an agroforestry system with papaya (*Carica papaya*) available soil P contents exceeded 100 mg kg^{-1} (Mehlich-3 extractant) even 2 years after fertilization of papaya had stopped indicating the long-term effect of P fertilizer additions (Schroth et al., 2001c). Additionally, the recapitalization of soil P at the start of a plantation improves early tree growth and facilitates the establishment of a cover crop (Schroth et al., 2001b). The disadvantage of fewer but higher applications is that the initial investments for purchasing the fertilizer are very high, and may be beyond the financial capacity of small farmers in the Amazon region. Soil erosion may also make large one-time investments into soil-P risky.

Perennial crops may additionally improve soil P availability through a more efficient P recycling and accessibility to the permanent root system of tree crops than annual crops. In the following sections, the mechanisms for elevated soil P availability under tree crops and the implications for P management are discussed.

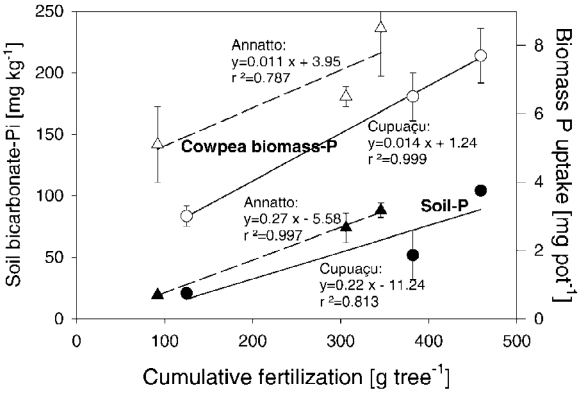

Figure 5. Soil bicarbonate extractable inorganic P (Campos et al., 2000) and biomass P uptake of cowpea (*Vigna unguiculata*) (C. Campos and J. Lehmann, unpublished data) grown in soil from cupuaçu (*Theobroma grandiflorum*) and annatto (*Bixa orellana*) as a function of total applied fertilizer-P (8 years) on a Xanthic Hapludox in the central Amazon. Cowpea was grown in 3 kg soil (pots with 0.18 m diameter) at field capacity in the greenhouse for 45 days. The soil without the litter layer (0–0.1 m) was collected from two different individual trees per replicate (randomized complete block design) (means and standard errors; *N*=3 and 4 for the soil and biomass data, respectively).

Tree-effects on soil P availability

Trees are able to maintain (reported for Mg) or even increase (reported for Ca) soil nutrient availability due to large nutrient cycling and soil protection from erosion (Sanchez et al., 1985). Whether large P cycling can also improve soil P availability is less clear. The potential for trees to improve soil P contents is low as the biomass usually contains low amounts of P (Buresh and Tian, 1998). In the central Amazon annatto (*Bixa orellana*) (and similarly peach palm, *Bactris gasipaes*), however, was found to maintain higher soil P availability than cupuaçu (*Theobroma grandiflorum*) (Figure 5). For the same amount of fertilizer applied per tree, the soil under annatto was richer in available P than the soil under cupuaçu, and cowpea plants grown in pots with annatto soil in a greenhouse experiment had higher foliar P concentrations than cowpea grown in pots with cupuaçu soil (Figure 5).

The largest P increase under the trees in comparison to native vegetation was noted in moderately plant-available P pools such as the hydroxide extractable organic P and the dilute acid-extractable P (Lehmann et al., 2001b). The increases in organic P pools were higher under and near the canopy of annatto than that of cupuaçu (Lehmann, 2001). This result suggested that tree-specific effects were responsible for the accumulation of plant-available P in soil.

Increases of soil P availability require a large P return (quantity effect) and a P return of biomass with a high P availability (quality effect). These effects will be discussed in the following sections.

Phosphorus recycling in agroecosystems with perennial crops

Quantity effect

P losses by leaching are negligible in the clayey soils of the central Amazon, as both inorganic and organic P concentrations in the soil solution are very low (Schroth et al., 2000). Once sufficient fertilizer P is applied to the perennial crop for tree growth, the P export by harvest will determine, on the long-term, how much P has to be replenished by fertilization. Biomass P contents and yield data are listed in Table 2 for a range of perennial crops grown for fruit, dye and timber production in the central Amazon in comparison to annual crops. All P pools of the trees are given on a per tree basis, as many of these species are planted in agroforestry systems where the planting density can vary substantially between systems. This 'single-tree' approach is common in savanna and forest ecology research (Zinke, 1962). The tree crops with high foliar P concentrations generally had also high P concentrations in their harvestable products. The P exports of oil palm (*Elaeis guinensis*) and peach palm (only for fruit production) were higher than those of other fruit trees, largely due to their high yields but not due to high P contents of the product. If peach palm is planted for heart of palm production, it is not left to grow to become a large tree but is cut every 3–5 months and very low amounts of P are exported with the harvest.

Unlike most annual crops, tree crops have a low proportion of their above-ground biomass harvested each year. Considerably less than 40% (P partitioning index) of their above-ground biomass P (standing biomass-P not including litter) was annually exported by a variety of perennial tree crops in the central Amazon (Figure 6). The proportion of P in harvested papaya fruit, however, amounted to more than 100% of its above-ground biomass. The percentage higher than 100 is a result of continuous fruiting of the papaya throughout the year which led to a higher cumulative annual P export with the fruit than total biomass P (including the fruit) at a given time. This semi-perennial,

Table 2. Canopy and harvest P contents and stocks of perennial and annual crops on central Amazonian upland soils

Species	Age	Above-ground P	Leaf P [mg g^{-1}]	Harvest P [mg g^{-1}]	Yield	Calculated P-export
Perennial crops	[yr]	[g $tree^{-1}$]			[kg $tree^{-1}$ yr^{-1}]	[g $tree^{-1}$ yr^{-1}]
Paullinia cupana	6	nd	3.40[e]	11.0[a]	0.36[a]	4.0
Theobroma grandiflorum	6	11.4	1.01[e]	0.14[c]	19.7[d]	2.8
Theobroma grandiflorum	8	nd	nd	1.3[i]	3.62[i]	4.7
Bixa orellana	4	11[b]	2.88[e]	3.9[b]	0.66[d]	2.6
Bactris gasipaes (heart of palm)	6	9[b]	1.58[e]	3.4[f]	0.28[f]	0.95
Bactris gasipaes (fruit)	4	16–31[b]	1.59[e]	0.7[i]	nd	nd
Bactris gasipaes (fruit)	8	nd	nd	0.7	26.2[i]	18.7
Bertholletia excelsa	4	18.5[b]	1.27[e]	nd	nd	nd
Carica papaya	1	6.3[g]	1.85[g]	0.2[g]	33[g]	6.75
Elaeis guinensis	8	410.6[h]	1.7[h]	2.0[h]	75.4[j]	150.8
Timber trees		[g $tree^{-1}$]			[kg $tree^{-1}$]	[g $tree^{-1}$]
Carapa guianensis[k]	8	73	0.99	0.82	11.3	9.2
Hymenaea courbaril[k]	8	44	1.54	0.48	47.2	22.6
Cedrela odorata[k]	8	44	3.24	0.67	16.8	11.3
Swietenia macrophylla[k]	8	13	1.56	0.59	14.2	8.4
Annual crops		[kg ha^{-1} yr^{-1}]			[kg ha^{-1} yr^{-1}]	[kg ha^{-1} yr^{-1}]
Vigna unguiculata[l]	-	4.9	-	-	679	2.51
Zea mays[l]	-	17.4	-	-	1070	5.03
Glycine max[l]	-	10.4	-	-	1183	6.04

nd=not determined.

[a] Cravo et al. (1999)

[b] Wolf (1997).

[c] Cravo and De Souza (1996).

[d] Fresh fruit; J.L.V. Macedo (unpublished data).

[e] N=12; Lehmann et al. (2001c).

[f] Cravo et al. (1996); calculated assuming two harvests per year.

[g] Cunha (1979).

[h] Viégas (1993).

[i] McGrath et al. (2000).

[j] Rodrigues (2000).

[k] Dünisch and Schwarz (2001); the export is a harvest of timber wood (excluding bark) which would have occurred if the trees were cut after 8 years.

[l] Cravo and Smyth (1997) and T.J. Smyth (personal communication); average from 7, 6 and 3 harvests for cowpea, maize and soybean, respectively.

highly selected tree crop obviously invested more P resources into their fruits than the other tree crops. Similarly, the P export from annual crops was found to exceed 50% of their above-ground biomass when only the grains were harvested, apart from maize with a P partitioning index of 30% (Figure 6). If the leaves of annual crops are used for human consumption (in some regions, cowpea leaves are eaten as spinach) or animal feed, almost all P taken up by the crop is not returned to the soil.

The annual P return by litterfall and to a lower extent by stemflow and throughfall was significant under the investigated tree crops (Table 3). Phosphorus return with throughfall and stemflow was one order of magnitude lower than with litter and reached up to the same amount than with litter. Among the fruit trees, P return with stemflow was high under peach palm due to high amounts of stemflow water (Schroth et al., 2001a). The largest P return to soil was noted under those trees which also had high foliar P concentra-

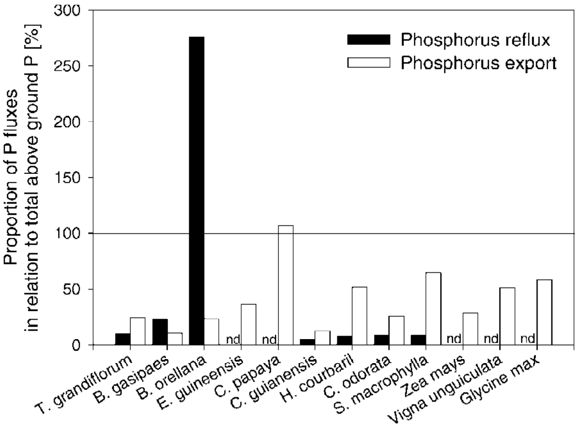

Figure 6. Proportion of recycled phosphorus and exported phosphorus in relation to above-ground phosphorus stocks in different fruit tree cultures in the central Amazon and other selected agricultural crops and tree stands; references from Tables 2 and 3.

Table 3. Annual P return to soil with litter and rain under different tree crops in the central Amazon

Species	Litter-P[1] [g tree^{-1} yr^{-1}]	Throughfall + stemflow-P [g tree^{-1} yr^{-1}]	Total internal P reflux [g tree^{-1} yr^{-1}]
Theobroma grandiflorum	1[a]	0.12[b]	1.12
Theobroma grandiflorum	0.92[c]	nd[f]	0.92
Bixa orellana	30[a]	0.32[b]	30.32
Bactris gasipaes (fruit)	4[a]	0.88[b]	4.88
Bactris gasipaes (fruit)	21[c]	nd[f]	20.97
Bertholletia excelsa	3[a]	nd[f]	3
Bertholletia excelsa	10.8[d]	nd[f]	10.8
Carapa guianensis[e]	1.21	2.17	3.38
Hymenaea courbaril[e]	2.07	1.27	3.34
Cedrela odorata[e]	2.74	1.18	3.92
Swietenia macrophylla[e]	0.65	0.46	1.11

[a] K. Uguen et al. (unpublished data).
[b] In 2 m^2 around the tree; Schroth et al. (2001a).
[c] McGrath et al. (2000).
[d] Ten-year-old trees in degraded pastures; Kato (1995).
[e] In 10 m^2 around the tree stem; deposition (rainfall) deducted from throughfall/stemflow; Dünisch and Schwarz (2001).
[f] Not determined: In these cases, total reflux was calculated assuming that no throughfall/stemflow occured.

tions (Table 2). Phosphorus return to soil by litter was largest under annatto (*Bixa orellana*) in comparison to the other investigated perennial crops, which was an effect of regular pruning (Table 3).

Consequently, the percentage of annual P reflux (litterfall and stemflow/throughfall) to P in above-ground biomass was the largest under annatto with 275% (Figure 6). The lowest percentage was found under cupuaçu with 10%. The proportion of P export by harvest to above-ground biomass, however, was not higher for annatto than cupuaçu (24 and 25%, respectively). This indicated that annatto had a more rapid P cycling and may therefore keep P in available form thereby improving soil P availability in comparison to cupuaçu. This was confirmed by the soil analyses presented above (Figure 5). Apart from the P export by harvest fertilizer, recommendations must, therefore, consider the P reflux in litter of tree crops. In the case of annatto this was to a large part a consequence of shoot pruning.

An important question in this respect is why some of the trees have a higher P uptake and return than others, and if and how these can be managed. Higher biomass P concentrations and uptake can be the result of an effective mycorrhization, root exudation or P solubilization by micro-organisms in the rhizosphere as discussed in other contributions in this issue. However, very little information is available for tree crops in the Amazon and a discussion is beyond the scope of the present contribution.

Quality effect

A large P return alone will not improve soil P availability. P is contained in organic material and P release is controlled by mineralization of organic P compounds. The P release largely depends on the quality of the organic material which is returned to soil. Cupuaçu leaves initially immobilized P and did not release any P for the whole observation period of 1 year after exposure in a litterbag experiment in southern Amazônia (McGrath et al., 2000). The large P immobilization by cupuaçu litter was considered to be the reason for the low soil P availability observed under cupuaçu in comparison to that under other tree crops (e.g. peach palm) in the same experiment (McGrath et al., 2000).

The P release is controlled by the demand and availability of P for microbial growth. In a controlled incubation experiment, P in microbial biomass was significantly higher in soil amended with annatto than with cupuaçu leaves after just one week (Figure 7). The same was observed for microbial C (J. Silva Jr. and J. Lehmann, pers. comm.). The amount of microbial P, however, is not a sufficient indicator of P availability or release from litter. Microbial P was not found to correlate with growth or P uptake of beans grown on Ultisol and Oxisol from various land-use systems in Southern Brazil (Fernandes et al., 1998). However, the slow formation of the microbial P pool in soil amended with cupuaçu compared to annatto leaves supported the findings reported above that cupuaçu litter im-

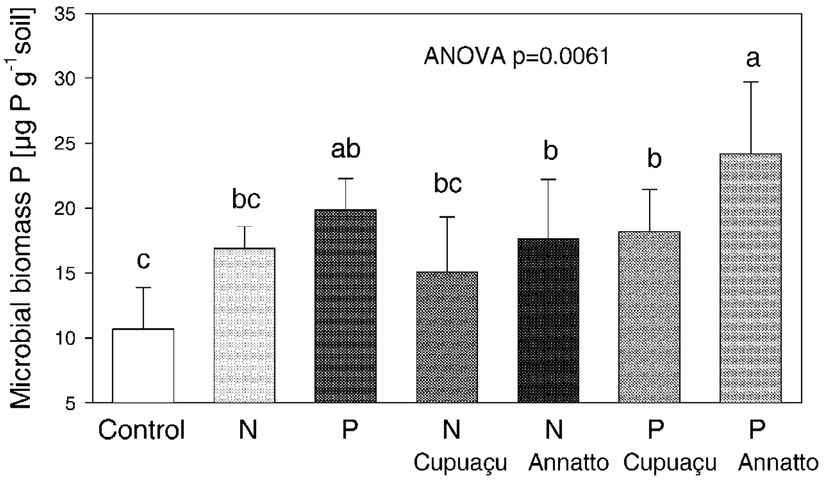

Figure 7. Soil microbial P as affected by additions of mineral P (40 mg P kg^{-1} soil as triple superphosphate) or N (0.4 g N kg^{-1} soil as ammonium sulfate) applied alone or together with leaves (20 g DM kg^{-1} soil) of cupuaçu (*Theobroma grandiflorum*) or annatto (*Bixa orellana*) to a Xanthic Hapludox from the central Amazon compared to no additions (control); incubations were done at 25 °C and field capacity for 1 week and microbial P was analyzed using fumigation extraction after Schinner et al. (1996) (means and standard errors; *N*=5; J. da Silva Jr and J. Lehmann, unpublished data).

mobilized P. The extent of microbial decay is largely controlled by the litter quality. Cupuaçu was found to have higher foliar C–N (28) and polyphenol–N (0.6) ratios than other tree crops such as peach palm (12 and 0.3, respectively) (Lehmann et al., 2001a) and annatto (C–N ratio of 13), and has higher C–P ratios (446) than peach palm (283) and annatto (156; calculated from Table 2) which explains the slower P release.

In contrast, P adsorption did not differ between a Hapludox under annatto and cupuaçu in the central Amazon (C. Campos and J. Lehmann, unpubl. data). The soil was shaken with a solution containing 20, 50, 100, 200, 400 mg P kg^{-1} soil for 16 h (Fox and Kamprath, 1970) and P was measured colorimetrically in the solution. P adsorption was not significantly different for soils receiving annatto or cupuaçu litter. Studies from P fixing soils reported higher P availability after additions of organic acids due to competition with P for exchange sites (Hue, 1991; Lopez-Hernandez et al., 1986). Identical effects can be achieved by organic matter added to soil as shown for leaf mulch applied to a Kandiudalf in Western Kenya (Nziguheba et al., 1998) or to a Haplustox in the Cerrado of Brazil (LeMare et al., 1987). Differences of P adsorption between sites were not found to explain different P availability for the studied central Amazonian Oxisols.

Therefore, these studies indicate that P availability in the Oxisols of the central Amazon is more linked to the mineralization of organic P than to the adsorption–desorption processes of inorganic P in comparison to other highly weathered upland soils in the tropics.

Conclusions

Phosphorus deficiency is wide-spread in the central Amazon and is more prevalent in soils of the northern and southern regions consisting of highly weathered upland soils and sandy plain soils. Farmers in many of these regions have little access to commercial P fertilizer due to high prices of the products and the transport. The P properties of central Amazonian upland soils make them suitable, however, for sustainable P management under low-P-input condition, since P fixation is comparatively low and a long-term process, and the effectiveness especially of one-time P applications is high. Irregular P supply to remote areas are in principle not an obstacle for sound P management. Perennial crops are especially suitable for a sustainable P management, because a large proportion of the applied P is returned to soil with litter and a low proportion of the above-ground P is exported with harvestable products. Tree species vary considerably, however, in this respect. Similarly, the quality of the organic P return to soil varied between tree species and significantly affected its effect on available soil P. High-P containing litter was found to improve soil P availability through rapid mineralization. These quantity and quality effects were shown to make an agronomic difference with respect to soil P availability. Phosphorus sorption, on the other hand, was not significantly affected by tree species and physical control of P availability played a less important role than expected from a highly weathered Oxisol. The results imply that P availability is less controlled by P fixation than by organic P which makes up a larger proportion of total P than in other South American Oxisols. Therefore, P management for perennial crops in central Amazonian Oxisols has to target soil biological processes (biological approach). Environmental properties which favor a high microbial biomass and activity should be optimized, such as soil water, temperature, labile soil organic matter and soil reaction. Management options should be developed including the selection of high P-cycling tree crops or inclusion of cover crops. If large amounts of P were maintained in the soil microbial cycle and the plant–soil cycle, the availability of applied P was high. Then, soil P applications have only to replenish P exports by harvests. Already low amounts of P applications may improve tree crop performance on the long-term. More information is needed on P budgets of tree crops and the impact of management and species effects on soil biological processes.

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