Soil phosphorus properties and management for perennial crops in the central Amazon

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Abstract

Tree crop production is gaining considerable importance in the central Amazon. However, the soils in the central Amazon are extremely poor in available P. The present contribution assesses the soil P status of central Amazonian upland soils, the effects of fertilization on soil P availability and tree crop growth, as well as the influence of large P recycling by tree crops on soil P availability. Soil fertility management has to target the prevalent P deficiency by adequate P fertilization. P fixation to clay minerals was not a major obstacle for P management in the highly weathered soils of the central Amazon due to their high kaolinite contents. P fertilization to tree crops is effective in aleviating P deficiency and increasing crop growth. Large P return to soil by litterfall, throughfall and stemflow was found to improve soil P availability. Tree crops were found to be P conservative with respect to exports. Once fertilization replenished P for biomass production, P fertilization can be reduced to match P exports by harvests.

Keywords
Central Amazon; Nutrient Cycling; Perennial Crops; Phosphorus; P Fixation; Soil Types

1 Predominant soils in the Brazilian Amazon

The predominant soils (Tab. 1) which are used for agriculture in the Amazon, are Latossolos (Oxisols) and Podzolicos (Ultisols), covering an area of approximately 75% of the region (Nicholaides et al., 1983). The Oxisols, Psamments, Aquepts, Aquults, Entisols (Várzeas) and Inceptisols occur in flat to slightly undulating terrain (Tab. 1), which facilitates mechanization for agricultural use. They are not subject to great erosion risks. On the other hand, Ultisols, Alfisols and some Entisols occur in undulated to strongly undulated terrain, requiring care in the use of mechanization to avoid erosion.

The main chemical limitations (Tab. 2) of the soils in the central Amazon are the deficiency of P, K, S, Ca, Mg, Zn, as well as P fixation, high Al toxicity, and low cation exchange capacity (CEC) (Dematê & Dematê, 1997). The contents of

Soil Classification System			
U. S. Soil Taxonomy	Brazilian System	Amazon (%)	Relief
Oxisols	Latossolo Amarelo + Latossolo Vermelho-Amarelo	34	Flat to slightly undulating
Ultisols	Podzólico Vermelho-Aamarelo	39	Undulated to strongly undulated
Alfisols	Podzólico Vermelho-Amarelo eutrófico	6	undulated to strongly undulated
	Terra Roxa Estruturada	1	
Entisols (Psamments)	Areia Quartzosa + Podzol Hidromórfico	5	Flat
Alfisols /Inceptisols (Aquepts; Aquults)	Plintossolo	4	Flat
Entisols	Litólico + Cambissolo	6	Strong undulated to mountain
Entisols; Inceptisols	Gley + Aluvial	4	Flat
Others		1	

Source: Adapted from Dematê & Dematê (1997)

Tab. 1: The major soil orders in the Amazon region of Brazil (4.8 million km^2)

Ca and Mg rarely surpasses 2.0 $cmolc.kg^{-1}$. In the great majority of the soils the aluminum saturation surpasses 50%, which is considered toxic for most cultures. The base saturation is normally below the critical value for the main crops and, together with high aluminum content, they represent the largest obstacle for crop root development (DEMATÊ & DEMATÊ, 1997). The mayor physical problems for perennial and semi-perennial cultures in Amazonian soils are low soil water retention and therefore drought stress (Tab. 2). The major constraint for crop production, however, is the P availability (Tab. 2).

Limiting Factors	% of the Amazon Region
Chemical	
Phosphorus deficiency	96
Potassium deficiency	77
Aluminum toxicity	73
Sulfur deficiency	72
Calcium deficiency	70
Magnesium deficiency	70
Phosphorus fixation	65
Zinc deficiency	62
Copper deficiency	30
Low CEC	55
Without important limitation	7
Physical	
Low humidity retention	56
Poor drainage and risk of inundation	24
Drought (> 3meses) for:	
- Perennial and semi-perennial crops	53
- Annual crops	0
Shallow soils	8
Sloping areas (> 30%)	6
Laterites in the subsoil	4
Sandy soil up to 2m	5
Risk of erosion	8

Source: Dematê & Dematê, 1997

Tab 2: Major limiting factors to agricultural use in Brazilian Amazon soils.

2 Phosphorus constraints to continuous soil use in the Brazilian Amazon

The main problem for agricultural development which we are facing in the Brazilian Amazon are the chemical limitations and especially the low levels of available P in most soils. Therefore, we will only focus on the problem of soil phosphorus.

As mentioned previously, the low P contents in the soils of the Amazon region are one of the main problems for the development of sustainable agriculture. The P contents rarely exceed 4 mg kg^{-1}, being below the critical level for most crops (Tab. 3). Also the total P contents are lower than in Oxisols from other parts of south America (Tab. 3).

The diagnosis is made through soil analysis and the main method used in Brazil is Mehlich 1. This method is suitable for acid soils like Oxisols and Ultisols, but research has shown that this method extracts a very large amount of P from soils such as Várzea (Entisols), and Terra Roxa estruturada eutróficas. As those soils have high contents of calcium, it is possible that part of the P is present as calcium phosphate which is not available to plants.

SMYTH & CRAVO (1990a), defined 6 and 8 mg kg^{-1} Mehlich 1 soil P as critical levels in an Oxisol of the region of Manaus for corn, and cowpea, respectively. These results were successfully tested on similar soils in Pará (DEMATÊ & DEMATÊ, 1997).

A single P application of 176 kg ha^{-1} to the first crop (rotation of corn and cowpea) increased soil P levels to over 45 mg kg^{-1} (Fig. 1), which were as high as after an initial application of 88 mg kg^{-1} up to 4 years. This indicated an advantage of a single but large application over several but small applications.

Soil	Region	Clay [%]	Extractant	Available P [mg kg^{-1}]	Organic P [mg kg^{-1}]	Total P [mg kg^{-1}]	Source
Various Oxisols (cultivated)	Central Amazônia	60-80	Mehlich 1	>5.0 (10)^1	nd	nd	[1]
Various Oxisols (cultivated)	Central Amazônia	60-80	Mehlich 1	3.0-4.9 (13)^1	nd	nd	[1]
Various Oxisols (cultivated)	Central Amazônia	60-80	Mehlich 1	<3.0 (77)^1	nd	nd	[1]
Oxisol (primary forest)	Central Amazônia	60-80	Mehlich 1	2.3	nd	46.0	[8]
Oxisol (burned forest)	Central Amazônia	60-80	Mehlich 1	9.8	nd	99.8	[8]
Oxisol (Pasture of 1 yr)	Central Amazônia	60-80	Mehlich 1	3.3	nd	64.8	[8]
Oxisol (Pasture of 2 yr)	Central Amazônia	60-80	Mehlich 1	2.0	nd	60.0	[8]
Oxisol (Pasture of 6 yr)	Central Amazônia	60-80	Mehlich 1	2.8	nd	60.0	[8]
Oxisol (Pasture of 7 yr)	Central Amazônia	60-80	Mehlich 1	2.3	nd	61.0	[8]
Oxisol (Pasture of 8 yr)	Central Amazônia	60-80	Mehlich 1	2.0	nd	62.0	[8]
Oxisol (Control)	Central Amazônia	60-80	Mehlich 1	3.5	nd	60.0	[9]
Oxisol (Indigofera tinctoria)	Central Amazônia	60-80	Mehlich 1	9.4	nd	nd	[9]
Oxisol (Desmodium ovalifolium)	Central Amazônia	60-80	Mehlich 1	7.5	nd	nd	[9]
Oxisol (Mucuna conchinchinensis)	Central Amazônia	60-80	Mehlich 1	5.0	nd	nd	[9]
Oxisol (Flemingia congesta)	Central Amazônia	60-80	Mehlich 1	4.4	nd	nd	[9]
Xanthic Hapludox (fallow)	Central Amazônia	59	Mehlich 3	3.6	41.1	106	[2]
Xanthic Hapludox (primary forest)	Central Amazônia	59	NaHCO3	2.0	36.4	59	[2]
Udox	Central Amazônia	68	Mehlich 1	1.6	15.3	nd	[4]
Udult	Central Amazônia	54	Mehlich 1	2.4	16.8	nd	[4]
Xanthic Hapludox	Central Amazônia	>60	Mehlich 1	3.0	27.4	104	[5]
Hapludult (PVA)	Amazonia Oriental	49	Mehlich 1	3.7	nd	141	[3]
Oxisol (LA, LVA, LE, LRd) - 39 profiles	Amazônia Oriental	19 - 89	Mehlich 1	1 – 8	nd	nd	[10]
Alfisol (TRe) – 4 profiles	Amazônia Oriental	64 - 73	Mehlich 1	1 - 8	nd	nd	[10]
Alfisol (TRd)– 5 profiles	Amazônia Oriental	66 - 77	Mehlich 1	1 - 22	nd	nd	[10]
Ultisol (PVA) – 19 profiles	Amazônia Oriental	17 - 79	Mehlich 1	1 - 11	nd	nd	[10]
Various soils – 33 profiles	Amazônia Oriental	8 - 81	Mehlich 1	1 – 30	nd	nd	[10]
Anionic Acrustox	Cerrado	68	NaHCO3	6.7	112.1	388	[6]
Tropeptic Haplustox	Colombia	nd	Bray-2	1.5	63.0	181	[7]

Tab. 3: Soil phosphorus status of clayey upland soils in the central Amazon in comparison to other clayey soils in South America.

1 values in parenthesis denote proportion of total examined soils which fall into this class
[1] Cravo and Macêdo (1999) (N=146; agricultural fields)
[2] Lehmann et al. (2000) (N=3; fallow and primary forest)
[3] Singh et al. (1983)
[4] Tucci (1991)
[5] Nurwakera (1991) (N=4; cleared fields; total P as the sum of all fractions)
[6] Lilienfein et al. (2000) (N=3; natural vegetation)
[7] Friesen et al. (1997)
[8] Teixeira (1987)
[9] Canto (1986)
[10] Companhia Florestal Monte Dourado (1989)

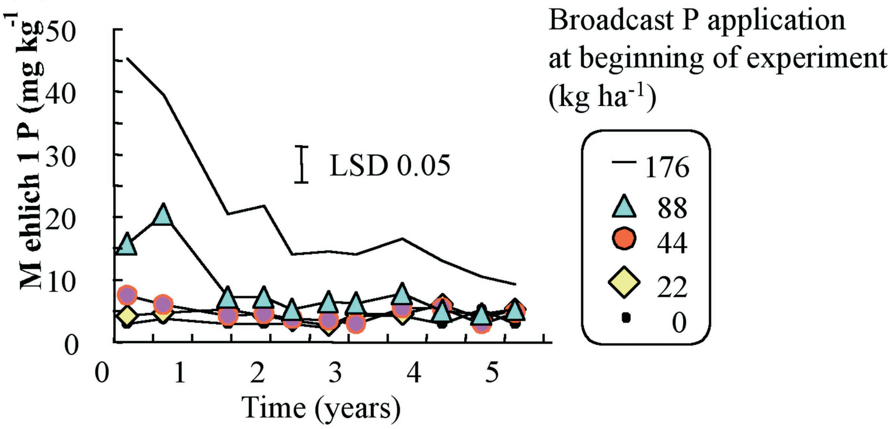

Fig. 1: Mehlich 1 available soil P for broadcast P rates as a function of time after application to the initial crop (Smyth and Cravo, 1990b).

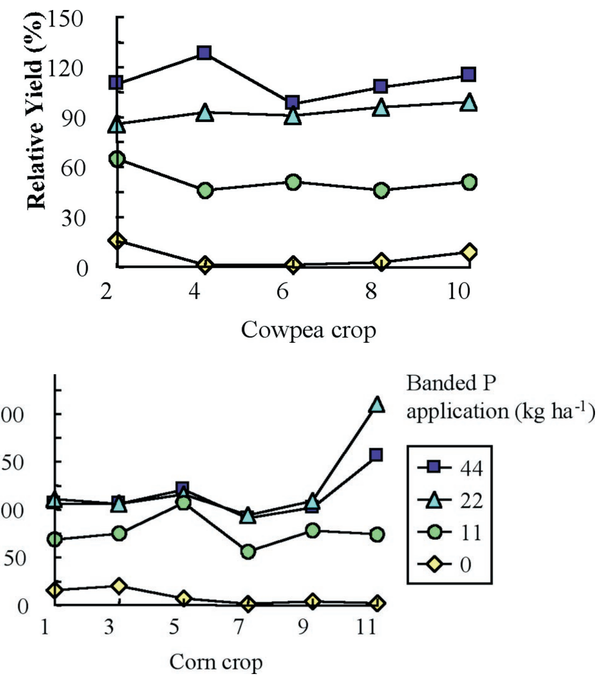

Fig. 2: Relative yields of five cowpea (left) and six corn (right) crops, grown in rotation, as a function of banded P rates. Banded P rates of 11, 22 and 44 kg ha^{-1} were applied to the first 11, 8, and 4 crops, respectively, to a total of 176 kg P ha^{-1}. The reference yield is from broadcast P application of 176 kg P ha^{-1} to the first corn crop only (SMYTH and CRAVO, 1990b).

For the first 10 crops, crop yields of corn 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 totalling to 176 kg P ha^{-1} (Fig. 2). Yields were even lower when only 11 kg P ha^{-1} were applied to each crop. Therefore, single but higher amounts of fertilizer P are superior to continuous but lower P applications. The disadvantage of single or fewer but higher applications is that the initial investments for purchasing the fertilizer are very high, and may be out of the financial capacity of small-farmers in the Amazon region.

This higher efficiency of a single application may be due to the low fixation of P by Fe/Al oxides in comparison to other highly weathered soils. The Amazonian oxisols have lower relations between adsorbed and soil solution P as seen from the adsorption isotherms from central Amazonian in comparison to Cerrado oxisols (Fig. 3). The low amounts of available P (Table 2) are apparently not caused by high P fixation but by the low amounts of total P in these soils.

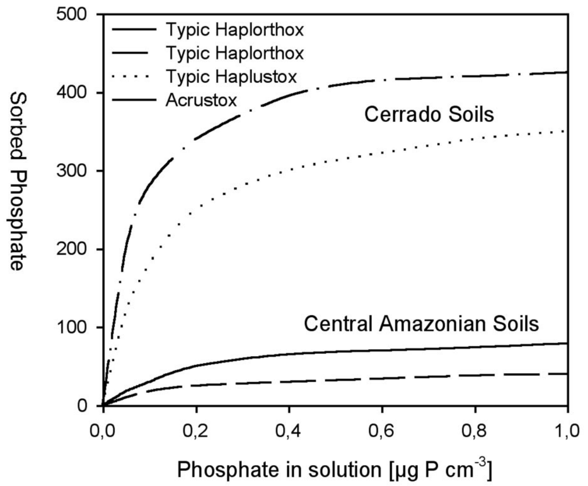

Fig. 3: Phosphorus adsorption isotherms (non-exchangeable phosphorus) of clayey soils from Amazonian upland (UEPAE 74 % clay; Profile 4B 34 % clay) and Cerrado (DRL 50 % clay; RYL 45 % clay) determined by isotopic exchange using 32P (LEMARE, 1982).

The low P fixation in Amazonian Oxisols can also be shown by the low proportion of residual P in comparison to other Oxisols and Ulisol from South America (Fig. 3). In the Oxisols under natural vegetation without fertilization the residual P does not exceed 20% of total P in the central Amazon (Fig. 4), but reaches up to 60% in an Oxisol from North-Eastern Brazil (TIESSEN et al., 1992).

What do these results mean for phosphorus management of perennial crops in the central Amazon?

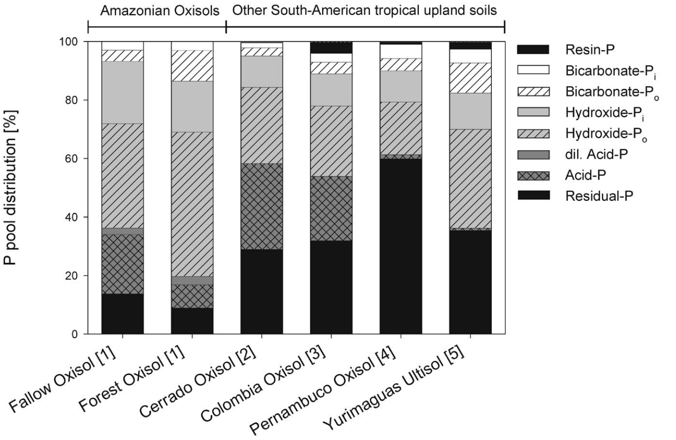

Fig. 4: Distribution of P pools in clayey soils of the Amazonian upland (Xanthic Hapludox) in comparison to other highly weathered soils from tropical South America under natural vegetation. [1] LEHMANN et al. (2000); [2] LILIENFEIN et al. (2000); [3] FRIESEN et al. (1997); [4] TIESSEN et al. (1992); [5] BECK and SANCHEZ (1996).

3 Phosphorus fertilization to perennial crops in the central Amazon

Fertilization experiments with 6-year-old cupuaçu showed that foliar P responses to P fertilization were low and already low amounts of added P result in responsive P levels (Tab. 4). Large amounts of added P did not further increase foliar P. The same was found in experiments with cupuaçu seedlings (Tab. 5). Cupuaçu is a plant which has low foliar P concentrations and may therefore react less to P fertilization than other crops with higher P contents (Tab. 6). However, these results show that P fertilization of perennial crops in Amazonian upland soils such as the investigated oxisols can be conservative and tree crops readily react to the applied P. If a recapitalization of soil P contents as shown for annual crops above is a feasible alternative, this is an interesting issue for future research, but information about this is lacking at the moment.

Fertilization level	Phosphorus				Fruit production (1997/1998)
	Mehlich 1 soil P	Young leaf	Intermediate leaf	Old leaf	
(g tree^{-1})	(mg kg-1)	(mg g^{-1})	(mg g^{-1})	(mg g^{-1})	(fruits per tree)
115.5 P, 95.4 N	14.89 a	1.16 ab	1.13 a	0.96 a	7.99 b
77 P, 95.4 N	10.52 a	1.13 ab	0.97 bc	0.88 a	16.53 a
23.1 P, 28.6 N	7.96 a	1.20 a	0.97 ab	0.88 a	9.29 b
23.1 P, no N	7.96 a	1.09 b	0.97 c	0.86 a	8.02 b

Tab. 4: Soil and foliar P contents and fruit production of cupuaçu (*Theobroma grandiflorum*) (6 years old) as a function of fertilization (n=18).

FIGUEIREDO (1999)
Means in one column followed by the same letter are not significantly different at $p<0.05$ (Tukey).

Rate of P applied (kg ha^{-1})	Soil extracted P (mg kg^{-1})	Leaf P content (mg g^{-1})	Aerial dry matter production (g plant^{-1})
0	8.47 F	0.20 E	30.59 E
30	11.46 E	0.22 D	36.47 C
60	14.47 D	0.22 D	37.32 B
120	18.37 C	0.26 C	38.21 A
180	25.45 B	0.28 B	35.33 D
240	29.14 A	0.30 A	35.88 CD

Tab. 5: Mehlich 1 available soil P, leaf P content, and dry matter production of cupuaçu (*Theobroma grandiflorum*) seedlings (9 months old) as a function of different P rates applied.

BRITO (2000)

4 Phosphorus budgets in perennial crop plantations

Once sufficient fertilizer P has been applied to the perennial crop for optimal production, the P budget of harvested products will determine how much fertilizer has to be applied. The biomass P contents and yield data are listed in Tab. 6 for a range of perennial crops grown in the central Amazon in comparison to annual crops and timber tree plantations. The fruit crops with high foliar P concentrations generally had also high P concentrations in their harvestable products. The P exports of oil palm and peach palm were higher than the other fruit trees, largely due to their high yields.

The litterfall was highest under annatto *(Bixa orellana)* in comparison to other perennial crops in the central Amazon (Tab. 7). P return with throughfall and stemflow was at least one order of magnitude lower than with litter, and was highest under peach palm, which had the highest amounts of water in stemflow (SCHROTH et al., 2000). The highest P return to soil was noted under those trees which also had high foliar P concentrations (Tab. 6).

Species	Age [yr]	Above ground P [g tree^{-1}]	Leaf P [mg g^{-1}]	Harvest P [mg g^{-1}]	Yield [kg tree^{-1} yr^{-1}]	Calculated P-export [g tree^{-1} yr^{-1}]
Paullinia cupana	6	nd	3.40[5]	11.0[1]	0.36[1]	4.0
Theobroma grandiflorum	6	11.4	1.01[5]	0.14[3]	19.7[4]	2.8
Theobroma grandiflorum	8	nd	nd	1.3[9]	3.62[9]	4.7
Bixa orellana	4	11[2]	2.88[5]	3.9[2]	0.66[4]	2.6
Bactris gasipaes (heart of palm)	6	9[2]	1.58[5]	3.4[6]	0.28[6]	0.95
Bactris gasipaes (fruit)	4	16-31[2]	1.59[5]	0.7[9]	nd	nd
Bactris gasipaes (fruit)	8	nd	nd	0.7	26.2[9]	18.7
Bertholletia excelsa	4	18.5[2]	1.27[5]	nd	nd	nd
Carica papaya	1	6.3[7]	1.85[7]	0.2[7]	33[7]	6.75
Elaeis guineensis	8	410.6[8]	1.6 a 1.7[8]	2.0[8]	75.4[10]	150.8
Ceiba pentandra[1] (Sumauma)	5	2.75	2.11	0.008	116.2	0.90
Virola surinamensis [11] (Ucuuba)	5	3.29	0.94	0.043	11.3	0.46

nd not determined

[1] Cravo et al. (1999)

[2] Wolf (1997)

[3] Cravo and de Souza (1996)

[4] fresh fruit; JLV Macedo (unpublished data)

[5] N=12; J Lehmann (unpublished data)

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

[7] Cunha, R. J. P., 1979

[8] Viégas (1993)

[9] McGrath et al. (2000)

[10] Rodrigues, M. R. L., 1993

[11] Neves, E. J. M., 1999

Tab. 6: Foliar and harvest P contents and stocks.

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[1]	0.12[2]	1.12
Theobroma grandiflorum	0.92[3]	nd	0.92
Bixa orellana	30[1]	0.32[2]	30.32
Bactris gasipaes (fruit)	4[1]	0.88[2]	4.88
Bactris gasipaes (fruit)	21[3]	nd	20.97
Bertholletia excelsa	3	nd	nd

[1] Uguen et al. (unpublished data)

[2] in 4 m^2 around the tree Schroth et al. (2000)

[3] McGrath et al. (2000)

Tab. 7: Annual P return to soil with litter and rain under different tree crops in the central Amazon.

Consequently, the proportion of annual P reflux by litterfall and stemflow/throughfall to P in above ground biomass was highest under annatto with more than 250% (Fig. 3). The lowest proportion was found under cupuaçu. The proportion of P export by harvest to above ground biomass, however, was not higher for annatto than cupuaçu. This indicated that annatto has a more rapid P cycling and may therefore need less fertilizer than cupuaçu. A fertilizer recommendation must also consider the P reflux apart from the P export by harvest.

The P export relationship was similar in other perennial crops, but increased above 100% in the semi-perennial papaya (Fig. 5). Therefore, perennial crops are P conservative but large differences exist between tree species. In contrast, the P reflux of <10% under unfertilized Eucalyptus forests in Australia was lower than under the perennial crops shown here (Attiwill and Adams, 1993).

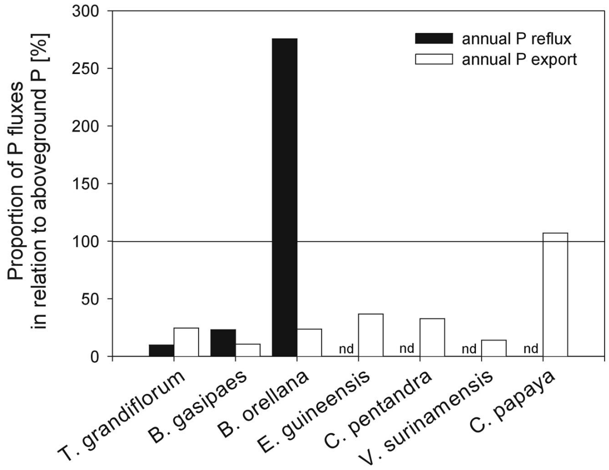

Fig. 5: Proportion of recycled phosphorus (litterfall and throughfall, where available) and exported phosphorus in relation to above ground phosphorus stocks in different fruit tree cultures in the central Amazon and other selected agricultural crops and tree stands; all references from Tab. 6 and 7.

5 Conclusions

The P properties of Amazonian upland soils make them suitable for sustainable P management, since P fixation is low and effectivity especially of one-time P applications is high. Perennial crops are especially suitable for a sustainable P management, because a large proportion of the applied P is returned and a low proportion of the above ground P is exported with harvestable products.

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