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PHOSPHORUS DYNAMICS IN SHIFTING CULTIVATION SYSTEMS IN THE AMAZON

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Introduction

Phosphorus is a key limiting nutrient in the Amazon as well as in most other humid tropical forest ecosystems where shifting cultivation is the most widespread form of human intervention. In spite of the extensive research conducted on this element, the available information on P cycling in shifting cultivation systems is limited. This is in contrast with the more extensive knowledge about P cycling in natural ecosystems (Jordan, 1985; Vitousek and Sanford, 1986) as well as about the response of crops and pastures to P fertilization in the Amazon (Le Mare, 1982; Valverde and Bandy, 1982; Toledo and Serrão 1982; Smyth and Bastos, 1985; Lopes et al, 1987; Smyth and Cravo 1990ab). Low-input systems such as shifting cultivation, crop/managed fallow sequences, legume-based pastures and agroforestry occupy an intermediate position between the extremes represented by the natural system on one hand, and intensively managed agricultural systems on the other. The purpose of this paper is to review information on P cycling in shifting cultivation in the Amazon and identify knowledge gaps.

A phosphorus cycle model for shifting cultivation

Phosphorus cycling between plants and soils is more complicated than that of other plant nutrients. Organic (P_o) and inorganic (P_i) soil pools are both important in the P cycle, unlike that of nitrogen, which is primarily organic in nature and that of potassium which is primarily inorganic. A cycling model is presented for the two main portions of the shifting cultivation process: the cropping period and the fallow period (Nye and Greenland, 1960).

The cropping period. A conceptual P cycle for shifting cultivation during the cropping phase is shown in Figure 1. There is no primary organic P source. All P originates in the mineral fraction of the soil. Vegetative growth creates organic pools. Aboveground forest biomass P, including standing biomass, litter and the root mat are transformed into three compartments upon slash and burn: ash, unburned biomass (partially charred leaves, branches, trunks and stumps) and P lost to the atmosphere as particulate matter. The ash (P_i) then follows a basically inorganic pathway incorporating itself rapidly into the available soil P_i pool, which can be defined by a standard soil test extraction. The unburned biomass P as well as the forest root biomass P decompose slowly into the soil available P_i pool and the microbial P_o pool which in turn flow to the slow and passive P_o pools with turnover rates of tens or hundreds of years (Parton et al., 1988).

The microbial P_o pool upon mineralization produces $H_2PO_4^-$ ions which join the available P_i pool. The available P_i pool is largely regulated by the soil P sorption capacity which fixes and releases available P_i. The two primary inorganic P_i pools represent the P contained in weatherable minerals or in occluded forms that are slowly released to the available P_i pool. In Oxisols and Ultisols these two inorganic pools are thought to be very recalcitrant and of low solubility; therefore the fixed P_i and the microbial P_o pools are the ones that probably control available P_i. In contrast the more extensively studied Mollisols and Vertisols of the temperate region have large quantities of reactive P minerals, making the weatherable P_i pool a major control of available P_i.

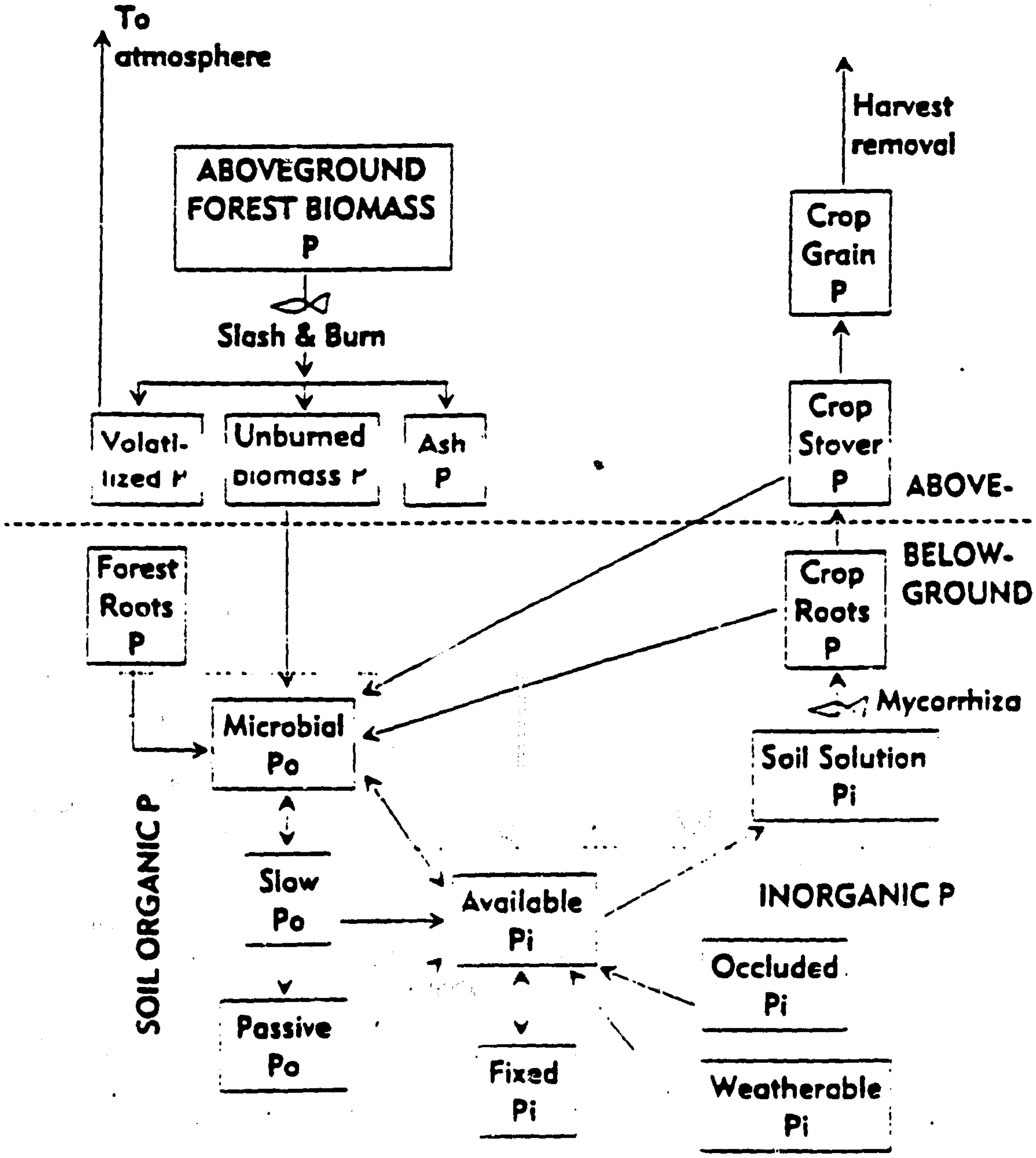

Figure 1. The P cycle during the cropping phase of shifting cultivation

The available P_i pool controls soil solution P_i composed of $H_2PO_4^-$ and $HPO_4^=$ ions which are the only forms of P that plants can utilize. Since P in the soil solution moves only by diffusion, increases in soil solution volume accessible to roots can be enhanced by mycorrhizal associations. Most crops grown immediately after slash and burn in the Amazon are highly mycorrhizal (Ruiz et al., 1989).

In cereals and grain legume crops P accumulates mainly in the grain, which is removed from the system at harvest. Rice, maize and sorghum concentrate about 70 percent of their P in the grain. If all the straw or stover is returned to the soil, only 30% of the P (Sanchez et al., 1989) is recycled.

Leaching losses are negligible, except in extremely sandy soils. Erosion losses are unlikely to be important in traditional shifting cultivation, but may be important when newcomers to the system practice shifting cultivation on steep slopes (Sanchez, 1976). Crop extraction, therefore, is the main P loss mechanism from the system.

The Fallow Period. After the cropping period, the field is abandoned and either a natural or managed fallow is allowed to grow. The P cycle during the fallow period is shown in Figure 2. The main P sources are probably the slowly decomposing, unburned above-ground biomass, large remaining forest roots, plus recycled crop residues. Ash input is not relevant. There are no large losses from the system in terms of crop harvest removal since only occasional fruit harvesting may take place. The below-ground reactions involving the various organic and inorganic P pools continue, with mycorrhizae facilitating P uptake by the fallow vegetation, perhaps more so than before, since key species of leguminous fallows have been found to have a higher percentage of mycorrhizal infection than annual crops (Ruiz et al., 1989). Phosphorus then accumulates in the fallow above-ground biomass and some of it is recycled back to the soil as above-ground litter. Below-ground root turnover also recycles P back to the soil.

Soil phosphorus pools

Data limitations. There is no data set available in the literature that provides quantitative information on the size of the pools and the magnitude of fluxes shown in the model described in Figures 1 and 2. The following section provides examples of some of the data available, drawn largely from the authors' research in Ultisols near Yurimaguas, Peru and Oxisols near Manaus, Brazil.

Available P_i. Topsoil available P determined by standard soil test procedures is the most common pool measured. Cochrane and Sanchez (1982) estimate that 90 percent of the soils in the Amazon have available topsoil P_i values lower than 7 mg kg^{-1} by the Bray II method (Table 1). This value is below the critical level, 8 to 15 mg kg^{-1}, associated with most crops (Marin 1977; Smyth and Cravo 1990b).

Available P_i in shifting cultivation systems has been estimated at different soil depths, ranging from as little as 3 cm (Ewel et al., 1981) to as deep as 100 cm (Russell, 1983). For P cycling, soil P pools should be measured as deep as the majority of fine roots penetrate, which is on the order of 50 cm in Oxisols and Ultisols of the Amazon (Szott 1987, Scholes and Salazar 1989). Ignoring subsoil available P grossly underestimates the size of this pool. For example Russell (1983) measured 35 kg P ha^{-1} in the top 20 cm of an Ultisol from Jari, Brazil but 103 kg P ha^{-1} in the top 100 cm. Likewise, we measured 6 kg ha^{-1} of available P_i in the top 15 cm of an Ultisol near Yurimaguas but a total of 13 kg ha^{-1} in the top 45 cm where most of the root development is concentrated.

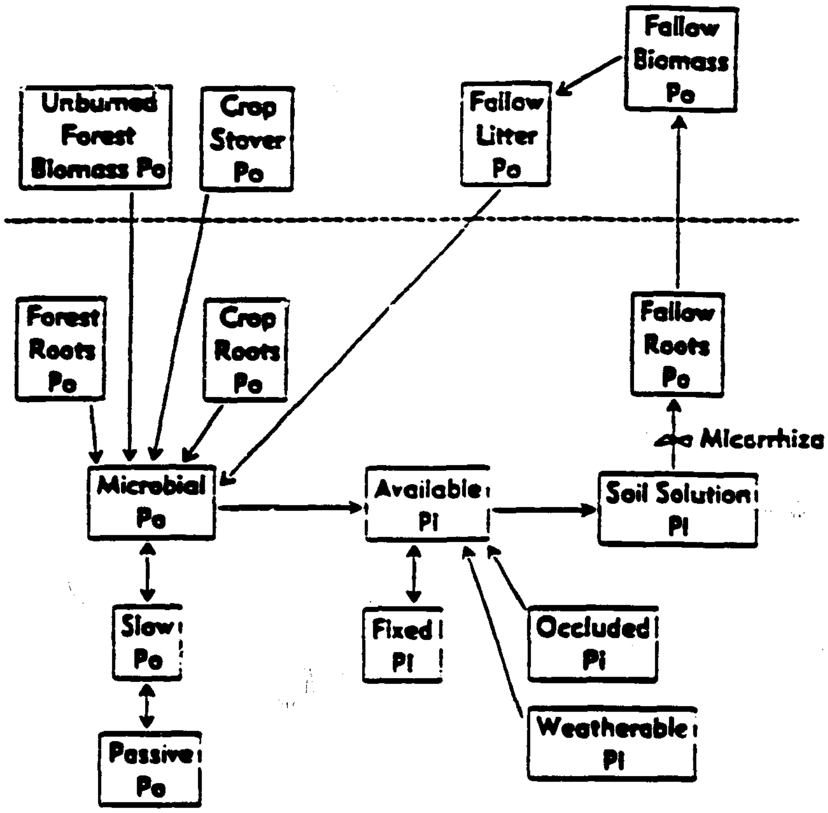

Figure 2. The P cycle during the fallow phase of shifting cultivation

Table 1. Phosphorus status of Amazonian soils (Cochrane and Sanchez 1982; Cochrane et al.1985)

Topsoil data (0-20 cm)	Million hectares	% of Amazon
Available P (Bray II):		
<-3 mg kg^{-1}	277	57
3-7 mg kg^{-1}	159	33
> 7 mg kg^{-1}	48	10
P Fixation (FCC):		
High	77	16
Low	406	84

A further important aspect of available P_i measurements is the quantitative difference in values among extraction procedures. Although such differences are not of orders of magnitude, they are relevant. Table 2 compares the values obtained on the same Oxisol by Mehlich 1 extraction, (also called double-acid or North Carolina extraction), the modified Olsen, and Bray I methods. Mehlich 1 is the routine procedure used in most soil test laboratories in Brazil; modified Olsen is used in Peru and many other countries while the Bray I method is used in Colombia. In Oxisols and Ultisol, the Mehlich 1 method gives consistently lower values than the modified Olsen, while Bray I gives the highest values. All methods are sensitive to the increase in available P_i with P fertilization (Table 2). It is also interesting to observe that the differences between methods decreased with continuous cultivation, (Table 2). If a choice of methods is possible at a given research site, we feel the modified Olsen method is preferable for budgeting P pools in Oxisols and Ultisols. Bray I tends to give very high values, while Mehlich 1 values are known not to be realistic when phosphate rock is applied (Sfredo et al., 1979; van Raij, 1978). Furthermore, the modified Olsen extraction can be used for simultaneous determinations of potassium and micronutrients and is also involved in the proposed sequential method of P fractionation of Hedley and co-workers (1982) which they call "bicarbonate-extractable P". Unfortunately few conversion factors from one method to the other are available (and are unlikely to exist across different soils, ed.). Some examples are shown in Smyth and Cravo (1990b) for Oxisols of Manaus.

Table 2. Available P_i values determined by different extraction methods in a clayey Oxisol near Manaus as a fraction of superphosphate applied shortly after burning (1 month) and its residual effect after 4 years (8 crops). Soil depth 0-15 cm, bulk density 1.04 Mg m^{-3}. Source: Smyth and Cravo (unpublished).

		Available Soil P measured by					
P Fertilizer applied	Crop No.	Mehlich 1	Modified Olsen	Bray I	Mehlich 1	Modified Olsen	Bray I
kg ha^{-1}		mg kg^{-1}			kg ha^{-1}		
0	1	3.0	7.4	13.2	5	12	21
	8	4.2	5.1	5.5	7	8	9
176	1	45.2	55.4	111.2	71	87	174
	8	16.5	12.5	18.7	26	20	29

Soil test values are concentration estimates and must be corrected for bulk density in order to express them in kg ha^{-1}, the unit used in the model. Bulk density with depth is seldom measured; furthermore topsoil bulk density changes during the course of shifting cultivation (Alegre et al., 1986). Estimates from the literature might be used as a first approximation, but actual bulk density determinations must be done at specific sties. Bulk density is highly correlated with soil texture, and this property has very high spatial variability in the humid tropics. Conversions from concentration values determined in the laboratory to mass values, therefore should be done with on-site bulk density determinations.

Soil solution P_i. Only orthophosphate is known to be taken up by plant roots. Soil solution measurements are unreliable because of large microspatial and temporal variability and the analytical precision required to detect very low concentrations.

Fixed P_i. Unlike high base status soils of the temperate region where most P cycling studies have been conducted, P fixation by iron and aluminum hydroxide surfaces is a major process controlling P cycling in most Oxisols and Ultisols. Although some degree of P fixation occurs in all such soils, the magnitude of this process is highly correlated with topsoil clay content in Oxisols, Ultisols and oxidic families of Alfisols and Inceptisols because iron and aluminum hydroxides are located in the clay fraction (Lopes and Cox, 1979). Phosphorus fixation is commonly estimated by P sorption isotherms as the amount of inorganic P added to reach a specific level of soil solution P_i (Fox and Kamprath, 1970). An example of the range found in soils representative of extensive areas in the Amazon is shown in Figure 3, where the P sorption isotherm of a clayey Oxisol near Manaus (82% clay) is compared with that of a sandy loam Ultisol near Yurimaguas (10% clay). In order to reach 0.1 mg kg^{-1} soil solution P, a level considered sufficient to most plants, about 420 kg P ha^{-1} need to be added to the high P-fixing Manaus Oxisol while only about 34 kg ha^{-1} will suffice for the Yurimaguas Ultisol.

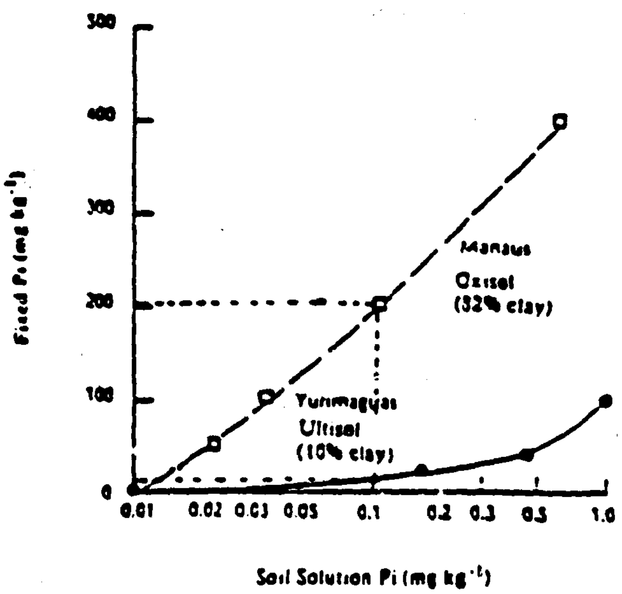

Figure 3. Contrasting P fixation capacities of two Amazonian soils determined by the Fox and Kamprath (1970) method. Source: Lopes et al. 1987

The relative abundance of soils with high and low P fixation in the Amazon is shown in Table 1, taken form the land resource study by Cochrane et al., (1985). This table is based on the fertility capability classification system criteria for high P fixation: topsoil clay content higher than 35% and a sesquioxide/clay ratio greater than 15% (Buol et al., 1975; Sanchez et al., 1982). Fortunately most of the Amazon soils do not suffer from high P fixation; therefore fixed P_i levels may be more commonly represented by the Yurimaguas curve in Figure 3 than by the Manaus curve. Nevertheless, 77 million hectares of the Amazon definitely has high P fixation capacity represented by the Manaus curve.

Phosphorus mineralized from the microbial P_o pool or released from other pools goes into the available P_i pool and some is quickly fixed by the sesquioxide surfaces. Fixed P is slowly released back to the available P_i pool and thus becomes available to plants. The fixed P_i pool therefore is not only a sink, but a major regulator of P dynamics in Oxisols and Ultisols. The relative size of this pool among different soils can be estimated by the Fox and Kamprath (1970) method at a given level of soil solution P_i.

Weatherable P_i and occluded P_i. The amount of P-bearing primary minerals, apatite, variscite, strengite, among others, is usually very low in Amazon soils, since most were developed from pre-weathered sediments. Occluded P_i consists of inorganic P compounds wrapped in sesquioxide coats that make them inaccessible to dissolution unless low oxidation-reduction potentials promote reduction of iron to the ferrous form. Localized anaerobic microsites may make temporary reduction possible in well drained soils. Although the rate of dissolution of P from these pools is very low, weatherable and occluded P_i may make important contributions to P cycling in the long run. No direct measurements of these two compartments are available from Amazon soils. These pools, however, may constitute the ultimate reservoir of P in these soils. Gross estimates of their size could be arrived at by subtracting total P_o, fixed P_i and available P_i from total P determinations.

Organic P soil pools. Organic pools are believed to account for 60 to 80 percent of the total soil P in Ultisols and Oxisols (Sanchez, 1976). This is in contrast with 20 to 50 percent found in glaciated soils from the northern temperate region. Direct measurements of P_o in Amazon soils are lacking.

Soil P_o is believed to consist of several functional pools, microbial P_o, slow P_o and passive P_o; but the estimation of the size of such pools is fraught with methodological difficulties. These three pools release P into the available P_i pool through mineralization but the major contribution is believed to come from the microbial P_o pool.

The microbial P_o pool may be the main source of available P_i but it is also capable of immobilizing P_i to meet microbial requirements. The slow P_o pool may exist in the organic matter stabilizing macroaggregates while the passive P_o may be found inside microaggregates (Elliott, 1986). Since iron and aluminum hydroxide coats largely control soil aggregation in Oxisols and Ultisols, there is likely to be a strong interaction between these P-fixing agents and the two less labile organic P pools.

Methodological advances need to be made before organic P pools can be estimated with a reasonable degree of reliability. Microbial P estimations by fumigation-extraction techniques in Oxisols and Ultisols are presently unreliable because of the P-fixing characteristics. Estimation of the size of the other two pools, could perhaps be done with the method of Hedley and co-workers (1982).

Total soil phosphorus. Total P contents in soils generally decrease with increasing stage of weathering (Westin and de Brito, 1969). Topsoil total P values average 6000 kg ha^{-1} in the United States Midwest and 1000 kg ha^{-1} in Ultisols of Southeastern United States (Olsen and Englestad, 1972). Mean total P contents in a samples of Amazon topsoil of 1268 Kg ha^{-1} were in the range of those found in the southeastern United States (Table 3). Subsoils contain even larger P stocks in spite of low concentrations due to their greater depth (Table 3).

Table 3. Total P content in Amazon soil samples, collected by Marbut and Manifold (1926) assuming a mean bulk density of 1.15 g cm^{-3}

Layer	No. of profile	Depth (cm) mean ± sd	kg P/ha mean ± sd	kg P/ha range
Topsoils	12	27 ± 8	1268 ± 1183	456 - 2283
Subsoils	14	100 ± 31	4708 ± 4307	304 - 11413

Extrapolations from Table 3 suggest a range of total P in Amazonian soils of the order of 700 to 11000 kg P ha^{-1} for the top 50 cm. The lower values may represent the most weathered soils and the higher value alluvial soils. A sandy loam Ultisol from Yurimaguas has the following total P values: 173 kg P ha^{-1} for the 0-15 cm layer, and a total of 786 kg ha^{-1} for the top 60 cm (Szott 1987).

It is hypothesized that the bulk of total P in the soil is in the passive P_o pool as well as in the occluded and weatherable P_i pools. This assertion needs quantification in order to understand the nature of these ultimate reserves of P in soils of the Amazon.

Biomass phosphorus pools

Above-ground forest biomass P levels have been extensively measured and range from 2 to 290 kg ha^{-1} in humid tropical forested ecosystems (Vitousek and Sanford, 1986). Above-ground biomass P levels in Oxisols and Ultisols fall within a narrower range: 21 to 101 kg ha^{-1} for primary forests or secondary forest fallows older than 10 years (Table 4).

Root P determinations are rare in the literature. Values for primary forests range from 5 to 69 kg P ha^{-1} (Table 4). The high value is for Spodosols where root P content is twice that held in above-ground biomass in these extremely infertile, sandy soils. In Oxisols, most of the biomass P is above-ground (Table 4). The same relationship was found in an 11-year old forest fallow on an Ultisol of Yurimaguas which contained 46 kg P ha^{-1} above-ground and 7 kg P ha^{-1} below-ground. Total soil P stocks, therefore, far exceed the biomass P stocks. This calls to question the common belief that most of the P in humid tropical ecosystems is held in the vegetation.

Such assertions are usually based on comparing topsoil available P_i, not total soil P at rooting depth, with total biomass P_o.

Table 4. Forest biomass P levels in several humid tropical forest ecosystems.

Location and (references)	Soil	Forest Age	Above-ground Biomass	Above-ground P	Below-ground Biomass	Below-ground P
			Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
Manaus, Brazil (1)	Oxisol	Primary	406	59	32	5
San Carlos, Venezuela (2,3)	Oxisol	Primary	264	31	33	20
	Spodosol	Primary	185	32	132	69
Carare, Colombia (4)	Oxisol	Primary	184	27	nd	nd
		16 yr	203	55	nd	nd
		5 yr	68	22	nd	nd
		2 yr	19	16	nd	nd
Yurimaguas, Peru (5)	Ultisol	11 yr	70	46	6	7
		2.4 yr	16	20	nd	nd
		1.4 yr	12	12	nd	nd
		0.7 yr	5	4	nd	nd
Yangambi, Zaire (6)	Ultisol	18 yr	142	101	33	nd
		8 yr	133	46	21	nd
		5 yr	96	31	22	nd
		2 yr	12	20	8	nd
Tai Forest Côte d'Ivoire (7)	Ultisol	15 yr	78	21	nd	nd
		6.5 yr	38	14	nd	nd
		4 yr	22	10	nd	nd
		2 yr	14	7	nd	nd
		1 yr	9	5	nd	nd

1. Klinge et al., 1975; 2. Jordan 1989; 3. Henem 1979 from Vitousek and Sanford 1986; 4. De las Salas 1978; 5. Szott 1987; Smyth, Palm and Alegre - unpublished; 6. Bartholemew et al., 1953; 7. Van Reuten and Jansen 1987.

Fluxes upon clearing and burning

The fate of biomass P upon slashing and burning is illustrated with data from an 11-year old secondary forest from Yurimaguas (Table 5). Upon slashing and burning the above-ground biomass P content of 46 kg ha^{-1}, 10 Kg (22%) of the P was recovered in the ash. An estimated 22 Kg (48%) remained as unburned above-ground biomass. The available Pi content of the topsoil increased 15 kg ha^{-1}, more than that provided by the ash suggesting that roots and fractions of organic debris may have burned and contributed to this increase. Of course inaccuracies in the methodologies can also contribute to this discrepancy.

Table 5. Phosphorus transfers upon burning an 11 year old fallow in Yurimaguas (Smyth, Palm and Alegre, unpublished).

	P content in pool	
	$kg\ ha^{-1}$	%
Before burning:		
Total above-ground biomass	46	100
Combustible biomass[a]	24	52
After burning:		
Non-combustible biomass[b]	22	48
Ash from burning	10	22
Increase in topsoil (0-15 cm)	15*	33
Unaccounted for	9-14	20-30

* Modified Olsen extraction

[a] Calculated from P contained in leaves, small branches, and forest floor litter.

[b] Amount of P contained in trunks and large branches, the majority of which did not burn.

Assuming this last increase represents the true contribution of the ash, and other quick release processes then about 20 percent of the biomass P prior to burning is unaccounted for. This fraction is probably swept away from the site as particulate matter in the fire column since there are no obvious mechanisms for volatilization of P. Although this may not constitute a net loss to the ecosystem because the particulate matter will be eventually deposited elsewhere, it is a loss to the site. Ewel et al., (1981) reported a loss of 51% of the above-ground biomass P (11 kg P ha^{-1}) right after burning in Costa Rica.

Ash P_i. Ash production and its rapid incorporation into the topsoil by rains is the first transfer of P from the vegetation to the soil upon slash and burn. Ash production levels vary with moisture content of the vegetation and with the thoroughness of the burn. Phosphorus inputs in the ash vary with location but change little with the type or age of fallow at one location. This is shown in Table 6 where ash P contents are considerably lower on Oxisols near Manaus than Ultisols of Yurimaguas. Ash production was similar after burning a primary forest near Manaus and a 12-year old forest fallow near Yurimaguas. Little differences were observed at Yurimaguas among fallows of different age, except in one case where the burn was very poor because of rain during the burn. *Pueraria phaseoloides* (kudzu) managed fallows produced similar ash contents to that of secondary forest fallows at Yurimaguas (Table 6).

Unburned above-ground biomass. Given the incomplete nature of many burns in udic environments with a weak dry season, much of the biomass remains unburned. This material is believed to mineralize slowly but in 2 to 3 years most shifting cultivation fields are essentially devoid of forest remains except for a few hardwood stumps. In cases where selected logging prior to burning or removal of unburned logs and branches for firewood after the burn takes place, there is a net removal of P from the system.

Table 6. Phosphorus inputs in the ash (Smyth and Bastos 1984; Sanchez 1987; Smyth, Palm and Alegre, unpublished).

Vegetation burned	kg P ha^{-1}
Manaus (Typic Acrorthox):	
Primary forest	6
12-yr old forest	8
4-yr old kudzu	3
Yurimaguas (Typic Paleudult):	
25-yr old forest	17
17-yr old forest	6*
11-yr old forest	10
1-yr old kudzu	17
5-yr old kudzu/guinean grass	12

* very poor burn due to wet conditions

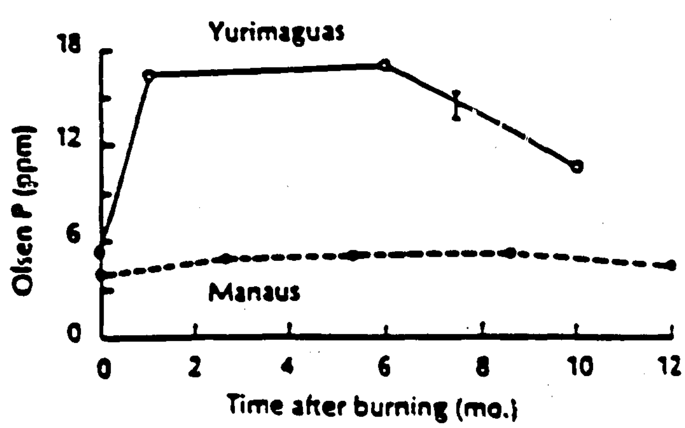

Figure 4. Topsoil available Pi dynamics during the first year after clearing and cropping without fertilization in Yurimaguas and Manaus. (Lopes et al. 1987)

Changes in Available Pi. Available P is the only pool for which there is sufficient data available about dynamics. Topsoil available P generally increases right after burning in response to the ash input and decreases during the cropping period (Seubert et al., 1977; Sanchez et al., 1983; 1985; Falesi 1976; Silva, 1981; Russell, 1983; Adedeji, 1984; Ramakrishnan, 1989; Andriesse and Koopmans, 1984; Stromgaard 1984). A definite increase in available P was evident in Yurimaguas, exceeding critical levels of 15 ppm for 6 months before a decrease started. In contrast small changes were observed in Manaus, with available P levels never rising above critical levels (Figure 4). Two factors account for this difference: 1) higher ash P_i inputs in Yurimaguas (Table 6), and 2) lower P fixing capacity of the Yurimaguas Ultisol as compared with the Manaus Oxisol.

Cropping removes considerable quantities of P from the system, since most of the P accumulated by grain crops is the grain. Sanchez and Benites (1987) report that 20 kg P ha^{-1} was removed in rice and cowpea grain in 7-crops during 3 years without fertilization. Topsoil available P levels therefore decline with time reaching values way below the critical level for such crops. Phosphorus fertilization is then needed for continuous cultivation, in order to replace what was removed or fixed. The decline pattern in available P_i and its reversal with fertilization is shown in Table 7 with data from another experiment from Yurimaguas.

Table 7. Available P dynamics after burning in a rice-cowpea low-input system in Yurimaguas (Smyth, Palm and Alegre, unpublished)

Sampling time	Available P (Olsen) mg kg^{-1}
Before burning	3.7 ± 1.0
After burning	10.6 ± 3.0
After 1st crop (rice)	4.7 ± 0.8
After 2nd crop (rice)	3.8 ± 0.9
After 3rd crop (cowpea)	4.7 ± 3.0
Fertilized with 22 kg P ha^{-1}	
After 4th crop (rice)	18.1 ± 2.7

The depletion process. A preliminary calculation using data from the experiment shown in Tables 5, 6, 7 and upland rice - cowpea crop uptake data is presented in Table 8 as an indication of the P depletion process during the cropping phase of shifting cultivation under a low-input system. During the first year, 3 crops accumulated 15.5 kg P ha^{-1} but returned 40% of that amount back to the soil as straw and roots. During the second year, the next 3 crops yielded less, accumulating 12.2 kg P ha^{-1} and recycling about the same proportion back to the soil.

Topsoil available P_i levels, determined by the Olsen extraction fell below 10 mg kg^{-1} (20 kg P ha^{-1} in this soil with a bulk density of 1.3 g cm^{-3}) after the first crop. Phosphorus fertilizer was added after the third crop but no significant yield responses were obtained.

Rough estimates are made in Table 9 on the rates of biomass P mineralization, soil P release from the less labile organic and inorganic forms, and rates of P fixation of newly available P. We assume that 10% of the remaining above and below-ground biomass P was mineralized per year, that only 0.01% of the total topsoil P was released every year, that 30% of the newly available P was fixed every year. Subsoil P was ignored. There is no experimental basis for any of these assumptions.

Table 8. Dry matter production and phosphorus uptake and % recycling of an upland rice-cowpea rotation in Yurimaguas.

	Dry matter production				P accumulated				P recycled	
Crop Sequence	Grain	Straw[1]	Roots[2]	Total	Grain	Straw	Roots	Total		
	Mg ha^{-1}				kg ha^{-1}					%
Year 1										
1. Upland rice	1.9	2.3	0.8	5.0	4.4	1.6	0.7	6.7	2.3	34
2. Upland rice	1.2	1.4	0.5	3.1	2.8	1.0	0.5	4.3	1.5	35
3. Cowpea	0.6	1.2	0.7	2.5	2.1	1.5	0.9	4.5	2.1	53
Total	3.7	4.9	2.0	10.6	9.3	4.1	2.1	15.5	6.2	40
Year 2										
4. Upland rice	1.6	1.9	0.7	4.2	3.7	1.3	0.6	5.6	1.9	34
5. Upland rice	1.2	1.4	0.5	3.1	2.8	1.0	0.6	4.4	1.6	36
6. Cowpea	0.3	0.6	0.4	1.3	1.1	0.7	0.4	2.2	1.1	50
Total	3.1	3.9	1.6	8.6	7.6	3.0	1.6	12.2	4.6	38

[1] Based on grain/straw ratios of 0.82 and 0.52 for rice and cowpea respectively. Cowpea pods ignored (from Benites and Sanchez 1989).

[2] Based on grain/fine root biomass ratio at anthesis of 2.27 for rice and 0.83 for cowpeas (Scholes and Salazar, 1989).

[3] Calculated from mean P contents of 0.23, 0.07 and 0.09% P for rice grain, straw and roots and 0.35, 0.13, 0.12% for cowpea grain, stover and roots, respectively (Benites and Sanchez, 1989).

Hypothetical calculations shown in Table 9 suggest a net input of 11.7 and 5.8 kg P ha^{-1} for the first and second year, respectively. The initial available P_i pools for year 1 and year 2 were 7.4 and 11.0 kg ha^{-1} respectively. Grain removal left a balance of 11 and 9.3 kg P ha^{-1}, respectively which closely coincides to measured available P data (Table 9). Such a close match may be a coincidence, but illustrates a depletion pattern of annual P additions to the system, which in the second year are less than removal. It also shows why no responses to P fertilization occurred in the second year; inputs from other sources appear sufficient.

No firm conclusions can be drawn from such calculations, except to suggest that these different P pools and their fluxes should be determined. In other instances where higher yields were produced, there is a clear evidence of P depletion and response (Gichuru and Sanchez, 1988).

The fallow period. Contrary to commonly held beliefs, the fallow period of the shifting cultivation system does not improve the (inorganic, ed.) fertility status of the soil. Available P_i levels in the topsoil are almost always lower than those found under a mature forest (Ramakrishnam and Toky, 1981, Szott and Palm, 1986; Sanchez et al., 1985). In fact, there is a marked decline in available P levels during the first few years of fallowing. Golley et al., (1974) attributed this effect to the transfer of P from the soil to the rapidly growing vegetation. Evidence of such buildup in above-ground biomass P is shown in Table 4 with examples from Colombia, Peru, Zaire and Côte d'Ivoire.

Table 9. Hypothetical calculations of topsoil (0-15 cm) available P_i inputs and outputs for the first and second year of the cropping phase of shifting cultivation with an upland rice-cowpea rotation without external nutrient inputs after slashing and burning an 11-year old secondary forest fallow in Yurimaguas, Peru. (Smyth, Palm and Alegre, unpublished)

Source of P	Year 1			Year 2		
	Pool size kg ha^{-1}	Turnover %/year	Flux kg ha^{-1}	Pool size kg ha^{-1}	Turnover %/year	Flux kg ha^{-1}
Ash P_i	10	100	10.0	0	-	0
Unburned biomass	23	10	2.2	19.8	10	1.9
Forest roots P_o	7	10	0.7	6.3	10	0.6
Total Soil P	173	0.01	0.02	173	0.01	0.02
Crop recycled						
straw	2.6	100	2.6	3.8	100	3.8
roots	1.2	100	1.2	2.0	100	2.0

	Year 1	Year 2
Subtotal inputs	16.7	8.3
Less net 30% P fixation of inputs	5.0	2.5
Net inputs	11.7	5.8
Initial available P_i[2]	7.4	11.0
Total Input	19.1	16.8
Grain harvest removal[3]	9.3	7.6
Balance (calculated)	9.8	9.2
Actual Available P[4]	9.4	10.0

[1] Crop 1 and 2 for year 1; crops 3, 4 & 5 for year 2
[2] Pre-burn for year 1; after 3rd crop for year 2
[3] Crop 1-3 for year 1; crop 4 and 6 for year 2
[4] After 3rd crop for year 1; after 5 crop for year 2

Where is this P coming from? It is hard to deplete topsoil available P much below 10 kg P ha^{-1} (5 µg g^{-1}) in soils such as those of Yurimaguas at the levels of cropping intensity reported. Szott's (1987) study of several fallow species suggest that biomass P is accumulating at the expense of a decrease in available P_i levels in layers as deep as 45 cm, where roots are active.

Which P pools contribute to this effect is also an interesting question. Rates of P uptake by fallow vegetation, suggested in Table 4, appear slower than P uptake by crops shown in Table 8. Time and a slower rate of P uptake by trees during fallow vs. short-term crops, plus nutrient cycling through the establishment of an effective litter layer in fallows may explain these differences. Furthermore, little if any P is extracted from a forest fallow as opposed to crop harvest removals. Consequently P, extracted from soil pools at a rate too slow to support crop growth, is accumulated in the forest fallow biomass as a savings account ready to be tapped by the shifting cultivator in the next cycle.

The problem of paramount concern is many areas of the humid tropics is that the length of the fallow period is rapidly shortening due to population pressures. Farmers, therefore are tapping this nutrient savings account before it can build up much capital in forest fallow.

Conclusions

This review outlines the cycle of P under shifting cultivation in the Amazon, and raises questions concerning rates and magnitudes of P transfers between soil and vegetation pools during the shifting cultivation cycle.

Phosphorus accumulated in the biomass of primary forest or tall secondary forest fallows in Oxisols and Ultisols of the humid tropics is about two orders of magnitude lower than the P in the soil to an average rooting depth of 50 cm. Due to the incomplete burning common in humid tropical areas with a short dry season, only about 20% of the above-ground biomass P is converted to ash, another 50% remains unburned and the remainder is apparently lost to the atmosphere (as fly ash). The remaining biomass decomposes slowly into available and unavailable inorganic P, microbial P, and slow and passive organic soil P pools. Phosphorus fixation by soil minerals is an important control on P availability in Oxisols and Ultisols. Weatherable and occluded inorganic P pools, although very slowly reactive, may play a major role in the long term. Quantitative determinations of these pools are fraught with methodological difficulties. Estimates of the various soil P pools vary with the extraction method used, depth interval considered and the bulk density conversion factor used.

Within this framework, several questions need to be answered to provide a basis for improved management of a degrading agricultural system. What is the long-term role of the inorganic P pools? What are the interactions between inorganic and organic pools? How does nutrient depletion during the cropping cycle proceed and from where does the P accumulated in the biomass during the fallow period come? Regardless of the answers to these questions, crop plants do extract more P from the system than are recycled back and P fertilization is likely to be needed in most Oxisols and Ultisols in the Amazon in order to sustain crop production under current land pressures.

References

Adedeji, F.O. 1984. Nutrient cycles and successional changes following shifting cultivation practice in moist semi-deciduous forests in Nigeria. Forest Ecology and Management. 9:87-99.

Alegre, J.C., D.K. Cassel, D.E. Bandy and P.A. Sanchez. 1986. Effect of land clearing on soil properties on an Ultisol and subsequent crop production in Yurimaguas, Peru. p 163-180. In: R. Lal, P.A. Sanchez, and R.W. Cummings, J.r (eds.). Land clearing and development in the tropics. A.a. Bakema, Boston, USA

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Andriesse, J.P. and T. Th. Koopmams. 1984/85. A monitoring study on nutrient cycles in soils used for shifting cultivation under various climatic conditions in tropical Asia. I. The influence of simulated burning on form and availability of plant nutrients. Agriculture, Ecosystem and Environment, 12: 1-16.

Bartholomew, W.J., J. Meyer, and H. Laudelout. 1953. Mineral nutrient immobilization under forest and grass fallow in the Yangambi (Belgian Congo) region. Congo Belge. Inst. Natn. Etude Agron. (Serie Scientifique, 57). 27p.

Benites, J. and P.A. Sanchez. 1989. TropSoils Technical Report, 1986-1987.

Buol, S.W., P.A. Sanchez, R.B. Cate, and M.A. Granger. 1975. Soil fertility capability classification: a technical soil classification systems for fertility management. In: E. Bornemisza and A. Alvarado (eds.). Soil Management in Tropical America. N.C. State University, Raleigh, N.C. pp 126-145.

Cochrane, T.T., L.G. Sanchez, L.G. de Azevedo, J.A. Porras, and C.L. Garver. 1985. Land in Tropical America. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia; Empresa Brasileira de Pesquisa Agropecuária dos Cerrados (EMBRAPA-CPAC), Planaltina, D.F., Brasil. 444p.

Cochrane, T.T. and P.A. Sanchez, 1982. Land resources, soils and their management in the Amazon region: A state of knowledge report p. 137-209. In: S. Hecht (ed.) Amazonia: Agriculture and land use research. CIAT, Cali, Colombia.

De las Salas, G. 1978. El sistema forestal Carare-Opón. CONIF. Ser. Tec. 8 Corporación Nacional de Investigación y Fomento Forestal. Bogotá, Colombia.

Elliott, E.T., 1986. Aggregate structures and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50:627-632.

Ewel, J., C. Berish, B. Brown, N. Price and J. Raich. 1981. Slash and burn impacts on a Costa Rican wet forest site. Ecology. 62(3):816-29.

Falesi, I.C. 1976. Ecosistema de pastagem cultivada na Amazonia brasileira (CPATU Bol. Tec. 1). Belém (Brazil): Centro de Pesquisa Agropecuaria do Trópico Umido, EMBRAPA.

Fox R.L., and E.J. Kamprath. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soils. Soil Sci. Soc. Am. Proc. 34:902-907.

Gichuru, M. and P.A. Sanchez. 1988. Phosphate rock fertilization in tilled and no-till low-input systems in humid tropics. Agron. J. 80:943-947.

Golley, F.G., J.T. McGinnis, R.G. Clements, G.I. Child and M.J. Duever. 1974. Mineral cycling in a tropical moist forest ecosystem. University of Georgia, Athens.

Hedley, M.J., J.W.B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46:970-976.

Jordan, C.F. 1985. Nutrient Cycling in Tropical Forest Ecosystem. John Wiley and Sons, New York.

Jordan, C.F. (ed). 1989. An Amazonian rainforest. Parthenan, New Jersey. 176 p.

Klinge, H., W.A. Rodrigues, E. Brunig, and E.J. Fittkau. 1975. Biomass and strcutre in a Central Amazonian rainforest. pp 115-122. In Golley, F.B. and E. Medina (eds.) Tropical Ecological Systems. Springer-Verlag. New York.

Le mare, P.H. 1982. Sorption of isotopically exchangeable and non-exchangeable phosphate by some soils of Colombia and Brazil, and comparisons with soils of Sourthern Nigeria. J. Soil Sc. 33:691-707.

Lopes, A.S., J.T. Smyth and N. Curi. 1987. the need for soil fertility reference base and nutrient dynamic studies. In: O.A. Sanchez, E.R. Stoner and E. Pushparajah (eds.): Management of acid tropical soils for sustainable agriculture. IBSRAM. Proceedings 2: 147-166 Bangkok, Thailand.

Lopes, A.S. and F.R. Cox. 1979. Relação de caracteristicas, fisicas, quimicas e mineralógicas com fixação de fósforo em solos sob Cerrados. R. Bras. Ci. Solo 3:82-88.

Marbut, C.F. and C.B. Manifold. 1926. The soils of the Amazon basin in relation to agricultural possibilities. Geogr. Rev. 16:414-442.

Marin, G. 1977. Fertilidad de suelos con énfasis en Colombia. Instituto Colombiano Agropecuario, Bogotá. 299p.

Nye, P.H. and D.J. Greenland. 1960. The soil under shifting cultivation. Harpenden, England Commonwealth Bureau of Soils. 156 p (Technical Communication 51).

Olson, R.A. and O.P. Engelstad. 1972. Soil phosphorus and sulfur. pp 82-101. In Soils of the Humid Tropics. National Academy of Sciences. Washington.

Parton, W.J., J.W.B. Stewart and C.V. Cole. 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5:109-131.

Ramakrishnan, P.S. 1989. Nutrient cycling in forest fallows in north-eastern India. p 337-352. In J. Proctor (ed.). Mineral nutrients in tropical forest and savanna ecosystems. Special Pub. No. 9. British Ecological Society Blackwell Scientific Publications.

Ramakrishnan, P.S. and D.P. Toky. 1981. Soil nutrient status of agro-ecosystems and recovery patterns after slash-and-burn agriculture (jhum) in northeastern India. Pl. Soil 60:41-64.

Ruiz, P. 1989. TropSoils Technical Report, 1986-1987.

Russell, C.E. 1983. Nutrient cycling and productivity in native and plantation forests in Jari Florestal, Para, Brazil. Ph.D. thesis, Institute of Ecology, University of Georgia, Athens.

Sanchez, P.A. and J.R. Benites. 1987. Low -input cropping for acid soils of the humid tropics. Science 238:1521-1527.

Sanchez, P.A. 1976. Properties and management of soils in the tropics. Wiley, New York.

Sanchez, P.A., W. Couto and S.W. Buol. 1982b. The fertility capability soil classification system: interpretation, applicability and modification. Geoderma, 27:283-309.

Sanchez, P.A., C.A. Palm, L.T. Szott, E. Cuevas and R. Lal. 1989. Organic input Management in Tropical Agroecosystems. In: D.C. Coleman, J.M. Oadas and G. Uehara (eds.). Dynamics of soil organic matter in tropical ecosystems. NIfTAL Project, University of Hawaii Press.

Sanchez, P.A., J.H. Villachica, and D.E. Bandy. 1983. Soil fertility dynamics after clearing a tropical rainforest in Peru. Soil Sci. Soc. Am. J. 47:1171-1178.

Sanchez, P.A. C.A. Palm, C.B. Davey, L.T. Szott and C.E. Russell. 1985. Tree crops as soils improvers in the humid tropics? In: M.G.R. Cannell and J.E. Jackson (eds.): Attributes of Trees and Crop Plants. pp 327-358. Institute of Terrestrial Ecology, Huntingdon, U.K.

Scholes, R. and A. Salazar. 1989. TropSoils Technical Report, 1986-1987.

Seubert, C.E. P.A. Sanchez and C. Valverde. 1977. Effects of land clearing methods on soil properties and crop performance in an Ultisol of the Amazon jungle of Peru. Trop. Agric., Trin., 54:307-321.

Sfredo, G.J., C.M. Borkert, D.S. Cordeiro, J.B. Palhano, and D.C. Dittrich. 1979. Comparação de cinco extratores de fósforo do solo, considerando-se o tempo de incorporação de tres adubos fosfatados.

Silva, L.F. 1981. Manejo del ecosistema tropical húmedo y sus consecuencias en el complejo suelo-planta-organismos. Suelos Ecuatoriales, 12:316-324.

Smyth, T.J. and J.B. Bastos. 1985. Abudação fosfatada para milho e caupi em latossolo amarelo alico do tropico úmido. Pesquisa Agropecuaria Brasileria 20:1259-1264.

Smyth, T.J. and M.S. Cravo. 1990a. Phosphorus management for continuous corn-cowpea production in a Brazilian Amazon Oxisol. Agronomy Journal 82:305-309.

Smyth, T.J. and J.B. Bastos. 1984. Alteraçãoes na fertilidade de um latossolo amarelo alico pela queima da vegetação. Rev. Bras. Cienc. Solo 8:127-132.

Smyth, T.J. and M.S. Cravo. 1990b. Critical phosphorus levels for corn and cowpea in a Brazilian Amazon Oxisol. Agronomy Journal 82:309-312.

Stromgaard, P. 1984. The immediate effect of burning and ash fertilization. Pl. Soil 80:307-320.

Szott, L.T. and C.A. Palm. 1986. Soil and vegetation dynamics in shifting cultivation fallows. Ministerio da Agricultura. ANAIS Proceedings, Vol. 1. Clima e Solo. Belém, Brasil.

Szott, L.T. 1987. TropSoils Technical Report, 1985-1986.

Toledo, J.M. and E.A.S. Serrao. 1982. Pasture and animal production in Amazonia. In: Amazonia: agriculture and land use research, edited by S.B. Hecht, 281-310. Cali, Colombia.

Valverde, C.S. and D.E. Bandy. 1982. Production of annual food crops in the Amazon, p. 243-248. In S.B. Hecht (ed.) Amazonia: Agriculture and land use research. CIAT, Cali, Colombia.

Van Reuter, H. and B.J. Janssen. 1989. Nutritional constraints in secondary vegetation and upland rice in south-west Ivory Coast p. 371-382. In: J. Proctor (ed.). Mineral nutrients in tropical forest and savanna ecosystems. Special Pub. No. 9. British Ecological Society. Blackwell Scientific Publications.

van Raij, B. 1978. Seleçãc de métodos de laboratorio para avaliar a disponibilidade de fósforo em solos. R. Bras. Ci. Solo 2:1-9.

Vitousek, P.M. and R.L. Sanford Jr. 1986. Nutrient cycling in moist tropical forest. Annual Review of Ecology and Systematics 17:137-167.

Westin, F.C. and J.G. de Brito. 1969. Phosphorus fractions of some Venezuelan soils as related to their stage of weathering. Soil Sci. 107: 194-202.