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PHOSPHORUS DYNAMICS IN SOILS UNDER SLASH AND BURN CULTIVATION IN THE SEMI-ARID NORTHEAST OF BRAZIL

DINÁMICA DEL FÓSFORO EN SUELOS CULTIVADOS BAJO SISTEMA DE CORTE Y QUEMA EN EL NORDESTE SEMIÁRIDO DE BRASIL

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ABSTRACT

A sequential extraction procedure for phosphorus (P) in ashes and soils was carried out on an Oxisol of the semi-arid Northeast of Brazil cultivated following the slash and burn method. Most of the P in ashes (60%) was held in Ca-P complexes, which dissolved and sustained the 5 years crop cycle. Total soil P (Pt) was low (120 μgP g^{-1} soil) and has not been substantially affected by cultivation. However, specific fractions of P were affected differently. Changes were small in magnitude within P fractions but quite dynamic in the 0 to 5 cm depth. The more biologically active sodium bicarbonate-extractable organic P (bi-Po) fraction was reduced by cultivation, whereas other Po fractions accumulated in depths from 5 to 20 cm, an indication of Po redistribution within the profile. There was a slight increase in inorganic P (Pi) fractions as resin- and sodium hydroxide-extractable Pi (Al and Fe-P) in depths from 5 to 20 cm. During cultivation, the more soluble or bioavailable organic and inorganic forms of P tended to be converted into more resistant forms (concentrated HCl-extractable Pi and residual P). Organic P represented 20% of the total P in the soil studied.

Key words: Phosphorus forms; phosphorus transformation; organic phosphorus; slash and burn; ashes.

RESUMEN

Se realizó una extracción secuencial de fósforo (P) en cenizas y suelo de un Oxisol de la zona semiárida del Nordeste de Brasil, cultivado bajo sistema de corte y quema. La mayor parte del P en las cenizas (60%) fue retenido en complejos Ca-P, los cuales permanecieron disueltos durante los 5 años del ciclo de cosecha. El P total del suelo (Pt) fue bajo (120 μgP g^{-1} suelo) y no resultó substancialmente afectado por el cultivo. Sin embargo, fracciones especificas de P fueron afectadas de manera diferente. Los cambios resultaron pequeños en magnitud dentro de las fracciones, pero bastante dinámico en la profundidad de 0 a 5 cm. La fracción de P orgánico extraíble en bicarbonato de sodio (bi-Po), que es biológicamente más activa, se redujo por cultivo, mientras que otras fracciones de Po se acumularon en profundidades de 5 a 20 cm, indicando la redistribución del Po en el perfil. Se produjo un ligero incremento en fracciones de P inorgánico como las extraíbles en resina-Pi hidróxido de sodio (Al y Fe-P) en la profundidad de 5 a 20 cm. Durante el cultivo, las formas de P orgánicas e inorgánicas más solubles o biodisponibles tendieron a convertirse en formas más resistentes (extraíbles en HCL concentrado y P residual). El P orgánico representó el 20% del P total en el suelo estudiado.

Palabras clave: formas del fósforo, transformación del fósforo, fósforo orgánico, corte y quema, cenizas.

INTRODUCTION

Phosphorus (P) is usually a limiting nutrient in natural and cultivated tropical ecosystems. Total P may be low in soils derived from sedimentary deposits (Udo and Ogunwale 1977). In highly weathered soils such as Oxisols, there exist a higher proportion of secondary inorganic forms of P, associated with iron (Fe) and aluminum (Al) oxides (Mattingly 1975) which are also complexed with soil organic matter (SOM) (Batsula and Krivonosova 1973, Mattingly 1975). Thus, the P forms in acid tropical environments are stable and are usually of little significance in terms of plant availability in the short term.

In the traditional slash and burn agricultural system usually practiced in subsistence farming in the tropics, crop growth depends on the release of nutrients, particularly P, from leaf litter and SOM mineralization (Mueller-Harvey *et al.* 1985). The

Table 1. Some properties of the 0 to 20 cm soil depth of the Araripina soil (average of 19 soil samples taken along three transects).

Sample	Org.C	N	Bulk density	pH	Al	Ca	Mg	K	ECEC	base saturation*
	---mg kg^{-1} ---		(Mg m^{-3})		----------cmol kg^{-1} ----------					(%)
mean	9000	626	1.4	5.0	0.5	0.7	0.2	0.1	1.5	67
CV (%)**	18	15	-	5	24	49	40	21	23	-

*Effective base saturation. **cv=coefficient of variation.

importance of organic P (Po) mineralization in supplying available P during cultivation of highly weathered soils has been well established (Acquaye 1963, Adepetu and Corey 1976). Besides Po mineralization, the addition of P in the ashes of plant biomass in slash and burn agriculture may contribute a considerable amount of P to the soil and sustain the usually short period of cultivation in such agricultural systems. Despite these facts research carried out in this area is still scarce, but an increasing effort has been made towards the understanding of P forms, transformations and cycling in tropical agriculture.

The objectives of this study were: a) to identify the forms and amounts of P in soils using a sequential extraction technique for P on an Oxisol cultivated with cassava through the slash and burn method; b) to examine the amount and fractions of P in the ashes originated from the burn of plant biomass; and c) to determine the changes in soil P fractions and availability due to cultivation.

MATERIALS AND METHODS

Description of the study area

The research site is located in the Experimental Station of the Institute of Agronomic Research (IPA) occurring on an uniformily gentle topography (<1% slope) referred to locally as "Chapada do Araripe" (40°20'W, 7°35'S), town of Araripina, in Pernambuco State, Northeastern Brazil, at an altitude of 820 m above sea level and 750 km west from the Atlantic coast. The region has a highly variable annual rainfall between 235 and 1,146 mm and a mean of 790 (50 years average). Most of the rainfall occurs between December and April. The average annual air temperature is 24°C, with a difference between mean summer and mean winter temperatures of less than 5°C. The local mean annual potential evapotranspiration is 1,127 mm.

The soils at the study site are Oxisols (Xanthic Haplustox, fine-loamy, kaolinitic, isohyperthermic) (Soil Survey Staff 1996), developed in situ from underlying Cretaceous sandstone of the Exu Formation (Buerlen 1962). The soils have a well developed fine granular structure, well drained and without evidence of soil erosion. They are also low in organic matter, present low pH values, not rich in exchangeable cations (Table 1) and belong to the association LVd9, widespread throughout almost 2,000 km^2 of the "Chapada do Araripe" (EMBRAPA 1972). The native vegetation community is transitional between dry forest and savanna. It is composed of dense deciduos shrubs (understory stratum) and a few trees reaching 10 m height (overstory stratum). The predominant plant families in decreasing order of abundance were constituted of Rutaceae, Verbenaceae, Bignoniaceae, Euphorbiaceae and Leguminosae. Some species were found in both the understore and overstore, suggesting that the vegetation was still in a successional stage and, it's been reported locally, last slash and burn ocurred more than 15 years ago. The usual type of soil management in cassava fields in slash and burn agricultural systems consists of non-mechanized operation with no addition of fertilizers and pesticides. A summary of the sequence of events in the field at the Araripina site is shown in Table 2.

Plot layout and sampling

Three adjacent plots having approximately of the same size (0.7 ha) were studied (Figure 1). Plot 1, was covered with the native vegetation in the beginning of the experiment. The vegetation was slashed and burned, the ashes collected from the soil surface with a spatula from eight randomly selected areas of 0.40 m x 0.40 m immediately after

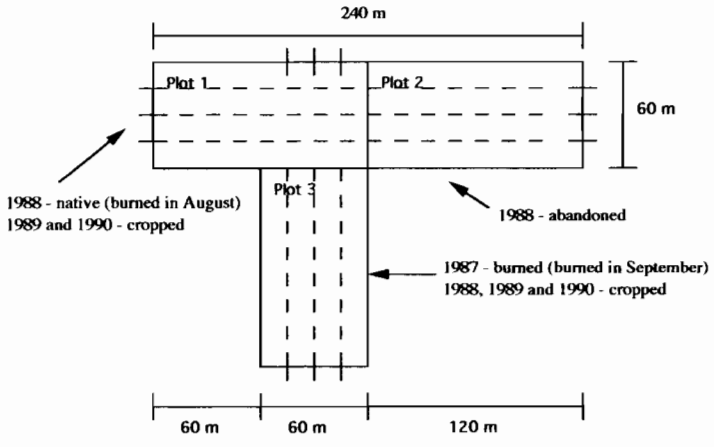

Figure 1. Plot map at Araripina Research Site.

the burning, placed in plastic bags, later sieved through 35 mesh (0.42 mm) and weighed without correction for moisture content. Plot 2, had been abandoned to natural fallow that same year, following the harvest of the third crop grown on that soil, completing a five-year cultivation cycle. Plot 3, had been burned the previous year, cassava and beans were growing together in the field at the first sampling, and the remaining ashes were still visible on the soil surface.

Soil samples were taken from 0 to 5, 5 to 20, and 0 to 20 cm depths at every 10 m along three parallel transects 10 m apart in each plot. Plots 1 and 3 were sampled in April of 1988, 1989 and 1990. The sampling in Plots 1 and 3 along the years allows for some overlapping, however did not quite represent replication, because Plot 3 was in a more advanced stage of the cultivation cicle in all sampling times. Actually they represented a sequence of events at different intervals of the cassava cicle. Plot 2 was sampled only once after been harvested in April of 1988 under the assumption that it represents the final stage of the cultivation cicle. The number of samples taken from each plot in

Table 2. Summary of the sequence of events in the adjacent plots at the Araripina Site.

Year	Month	Plots and events
1987	November	Plot 1: Native Site. Plot 3: Cassava and beans planted. Plot 2: Third crop of cassava in the field.
1988	April	Plot 1: Native Site. Characterization of plant species, sampling of litter, fine roots (0 to 20 cm depth), litter and soils below selected species (0 to 20 cm depth), fine roots (0 to 50 cm depth). Plots 1, 3, and 2: soil samples along transects (0 to 20 cm depth) and core samples for bulk density determinations. Plot 3: cassava and beans growing in the field. Plot 2: abandoned after the harvest of the third crop of cassava.
1988	June	Plot 1: Slashing of the vegetation, estimations of the vegetation compartments: trunks, branches, leaves+twigs.
1988	August	Plot 1: Burning of the vegetation debris and collection of ashes.
1989	April	Plots 1 and 3: soil samples (0 to 5 and 5 to 20 cm depth) taken along transects for analyses and separation of fine roots.
1990	April	Plots 1 and 3: soil samples (0 to 5 and 5 to 20 cm depth) taken along transects for analyses and separation of fine roots.

Table 3. Sample replicates and depth of sampling in plots 1, 2 and 3 in 1988, 1989 and 1990 at Araripina Site.

	Plot 1			Plot 2	Plot 3		
depth (cm)	0-5	5-20	0-20	0-20	0-5	5-20	0-20
Years							
1988	-	-	21	36	13	-	39
1989	36	36	-	-	18	18	-
1990	33	33	-	-	18	18	-

different years is reported in Table 3. Soil samples were air-dried, transported to the laboratory at the University of Saskatchewan (West Canada) and stored for analyses. All soil samples were sieved (<2 mm sieve) and had the fine roots (<2 mm) removed by hand picking. One time core samples were taken in 1988 to identify changes in bulk density on the basis of air dry soils (Table 4). Two approaches were used in the analysis of the data: a) a comparison of key soil properties in a particular plot in successive years, and b) a comparison of such key properties in different plots during the same year to determine the changes that occurred with time on the same soil.

Analytical methods

Total C in soil was estimated by dry combustion and the two-endpoint titration method (Tiessen *et al.* 1981). Total P in ash and total N and P in soils were determined on the concentrated H_2SO_4/H_2O_2 digestion system (Thomas *et al.* 1967) using an autoanalyser. The pH of soils and ash was determined in water (1:2 soil:water ratio). The cations (Al, Fe, Ca, Mg, K) were extracted using an unbuffered 1M NH_4Cl extractant (1:5 soil:solution ratio). The soil was shaken for 30 min with the extractant and centrifuged at 10,000 rpm for 10 min, before filtration of the supernatant (<0.45 μm). The extraction was repeated twice and the extracts were combined. The elements were determined by plasma emission spectroscopy. The sum of the exchangeable cations (except H^+ which was not determined) in the NH_4Cl extract was calculated without corrections for soluble cations, expected to be negligible.

Phosphorus in ash and soils was extracted sequentially by following the procedure developed by Hedley *et al.* (1982) with minor modifications (Figure 2). The basic differences from the original method were the exclusion of the microbial P fraction, and the incorporation of one additional step to the procedure: the extraction of P with concentrated HCl before the digestion of the final residual fraction with H_2SO_4. These modifications are related to: (a) the long sampling interval, which limits the significance of the microbial data because of the very dynamic nature of the microbial P and also due to the fact that the determination of microbial P as part of the fractionation procedure by the flush of $NaHCO_3$-extractable P following $CHCl_3$-fumigation seems erratic in highly weathered acid soils of high adsorption capacity for P (Potter *et al.* 1991), and (b) an attempt to increase the recovery of organic P (Po).

The P fractionation was carried out by sequentially extracting the resin inorganic P (Res-

Table 4. Soil bulk densities on Plots 1, 3 and 2 from single samples taken in 1988†.

Depth	Native (Plot 1)	Cultivated-1th yr (Plot 3)	Cultivated-5th yr (Plot 2)
		Mg m^3	
0-5	1.11	1.40	1.39
5-10	1.34	1.37	1.36
10-20	1.46	1.48	1.54

†refer to the plot map of the study site.

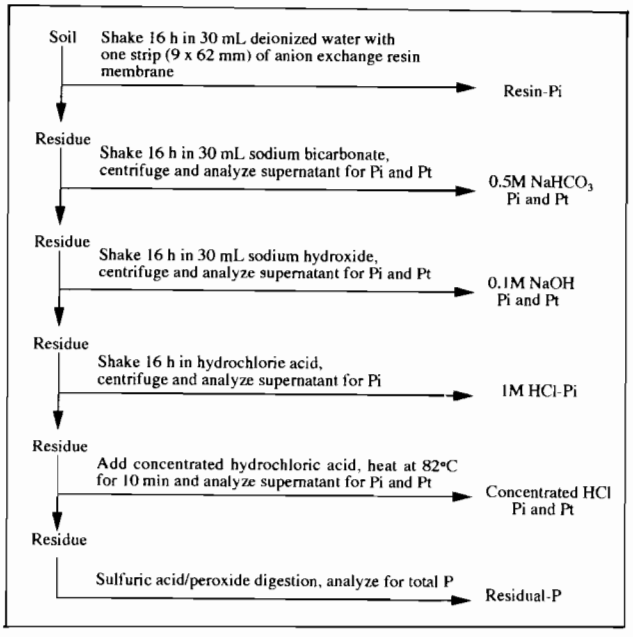

Figure 2. Flow chart of the sequential extraction procedure for P.

Pi) (anion exchange membrane BDH # 55164 - cut into strips 9 x 62 mm, converted to bicarbonate form). 0.5M bicarbonate-extractable inorganic and organic P (bi-Pi and bi-Po), 0.1M hydroxide-extractable P (OH-Pi and OH-Po), 1M HCl inorganic P (HCl-Pi), concentrated HCl (conc.HCl-Pi and conc.HCl-Po) and the Residual P (Rd-P). The resin-extractable P was recovered in a 0.5M HCl solution. Inorganic P in the sodium bicarbonate, sodium hydroxide and concentrated HCl extracts was determined after acidification of the proper aliquot to pH about 1.5 with H_2SO_4 to precipitate the organic matter and cooling for 30 min, followed by centrifugation at 10,000 rpm for 10 min at 0°C, and the supernatants were transfered to 50 mL flasks.

All phosphates were measured by the acid molybdate blue colorimetric method (Murphy and Riley 1962). Total P in the bi-P, OH-P and the conc.HCl-P extracts was determined by digestion of the proper aliquot on a hot plate after addition of 1 mL of 11N H_2SO_4 and 0.6 g of ammonium persulfate. The final step was a sulfuric acid/peroxide digestion to produce the Rd-P. The organic P in each extract was calculated by taking the difference between the values for total and inorganic P in each fraction.

The Res-Pi, bi-Pt and OH-Pt are the three fractions which constitute the portion of the total P that, in general, behave most dynamically in soils (Amer *et al.* 1955, Bowman and Cole 1978, Tiessen *et al.* 1992). They are related to the short-term P transformations (year or a few years) and are potentially available. The Res-Pi is the fraction that correlates well with the weak acid extractions generally used in more weathered tropical soils to determine the available or extractable P (van Raij 1986). These three first sequential fractions represent the sum of the solution P, probably some microbial P, and the labile P adsorbed with various energy strengths on surfaces of more crystalline compounds, sesquioxides and carbonates (Bowman and Cole 1978, Mattingly 1975, McLaughlin *et al.* 1977).

Since calcium phosphates are not stable in Oxisols, the fraction of P represented by the 1M HCl-P extraction may be included in the labile pool of P in this work. Due to the complexity of the constituents of the Rd-P, involving a mixture of organic and inorganic P in very stable forms, the residual fraction was not considered when estimating the ratios of organic to inorganic P.

Statistical analyses

The soil properties evaluated were treated as normally distributed due to the large number of samples taken in each plot, allowing the use of parametric methods. The large number of samples also compensates for the lack of replication of plots, which was not possible under the conditions of this

Table 5. Air-dry weight, P, Ca, Fe and Al content, pH and coefficients of variation (CVs) of the ash (<35 mesh) produced on Plot 1 at the Araripina Site after the slash and burn in 1988.

	Ashes*	P	Ca	Fe	Al	pH
		----------g kg^{-1} dry ash----------				
mean		1.1	30.8	15.8	30.7	10.2
CV (%)		88	125	17	19	10
	----------kg ha^{-1} ----------					
mean	11,294	12	348	178	347	
CV (%)	30	84	105	45	47	

*mean of 8 replications

study. In addition, the variability of many soil parameters at the site was not known and, hence, many samples were included in the evaluation. Analysis of variance (ANOVA) and t-tests where appropriated were carried out to segregate variances and test the hypothesis of no effect by checking for equality of the population means. All analyses were performed at the 5% of probability level, unless otherwise specified. The computer software Statview SE (1988) was used for the statistical analyses.

RESULTS AND DISCUSSION

Phosphorus in ashes

The ash resulting from the burn amounted to an estimated 11 Mg ha^{-1} (Table 5), contributed a considerable amount of nutrients and were the most important nutrient input to the soil (Lessa *et al.* 1996a). The concentration of total P in the ashes was 1.1 g kg^{-1}, which is low in comparison to the P concentration of 2.6 g kg^{-1} of the ashes produced after fire in the semi-arid zone of Sri Lanka (Andriesse and Schelhaas 1987). Because the Ca, Fe, and Al contents of the ashes were high (Table 5), and a strong possibility exists for these cations interacting with P, a sequential fractionation of the ash was carried out to clarify the importance of such P forms in relation to P availability. Furthermore, a generalized pattern of slow release of P after burning is reported in the literature (Ellis and Graley 1983, Khanna and Raison 1986, Stromgaard 1984).

Despite the high Fe and Al contents in ashes, a small portion of the ash-P was in the form of Fe-P and Al-P (6%) and extracted by the 0.1M NaOH (Figure 3). The lower interaction of P with Fe and Al constituents present in ashes was due to the high pH (about 10) of the ash material (Table 5). At high pH Fe and Al-oxyhydroxides become negatively charged and will not be able to adsorb P (Schwertmann and Taylor 1977).

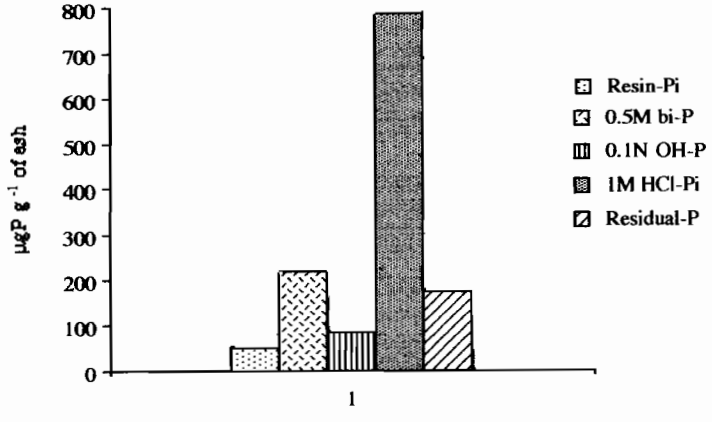

Figure 3. Phosphorus fractions in ashes.

Sixty per cent of the P in the ash was recovered in the 1M HCl-extractable Pi fraction (Figure 3), likely occurring in various forms of calcium-phosphate and, as for the Res-Pi, bi-P and OH-P, this P form can also be considered potentially available in the short term. It may be released upon mixing of the alkaline ashes with the acid soil and become quickly available. Otherwise, depending on the available moisture and the degree of mixing of ashes with soil, the formation of Ca-P compounds may be responsible for the delay in P dissolution and transformation to more available forms.

Phosphorus in soil. Total P

The amounts of Pt in the soils studied were low (Table 6), varying within and among the plots (Figure 4). Exception is for high values at points 2 and 5 of transect 1 on Plot 2. There are some statistically significant differences between the plots despite the similarity of figures and it appears that the large number of samples taken facilitated the segregation of variances thereby producing significant differences. No P was added to the plots as fertilizer and the slight increases in Pt upon cultivation may have come from nonestimated P contained in unburned vegetation debris.

Additions of P through wet and dry depositions of atmospheric inputs are generally considered negligible (Sanchez 1976). The slightly higher values for the average of Pt can not be explained by the additions of P in ashes and through fine root decomposition (Lessa 1995). Increases in Pt tended to occur in the inorganic P (Pi) and residual fractions (Table 6), which were a sink for P upon cultivation. The tendency for accumulation of P in the resistant pool during cultivation has been observed by other workers as well (Adepetu and Corey 1977, Tiessen *et al.* 1992) and is usually

Table 6. Phosphorous forms (μgP g^{-1} soil) and transformations with cultivation at the 0 to 20 cm soil depth.

	Plots		Years	
			1988	
	1,3,2	120^{b*}	112^{c}	130^{a}
Total P				
		1988	**1989**	**1990**
	1	120^{a}	119^{a}	122^{a}
	3	112^{b}	114^{b}	120^{a}
			1988	
	1,3,2	24.9^{a}	21.0^{b}	22.7^{ab}
Organic P				
		1988	**1989**	**1990**
	1	24.9^{a}	20.3^{b}	23.2^{a}
	3	20.9^{a}	19.1^{b}	18.5^{b}
			1988	
	1,3,2	77.2^{b}	78.0^{b}	88.9^{a}
Inorganic P				
		1988	**1989**	**1990**
	1	77.2^{a}	79.0^{a}	77.8^{a}
	3	78.0^{ab}	75.9^{b}	79.7^{a}
			1988	
	1,3,2	18.2^{a}	13.4^{b}	18.0^{a}
Residual P				
		1988	**1989**	**1990**
	1	18.2^{b}	20.0^{ab}	21.1^{a}
	3	13.4^{b}	18.9^{a}	21.4^{a}

*Values in horizontal rows followed by different superscripts differ significantly at 5% of probability.

Table 7. Organic phosphorus (μg P g^{-1} soil) forms and transformations with cultivation at the 0 to 20 cm depth.

	Plots		Years	
			1988	
0.5M $NaHCO_3$	1,3,2	4.9[a*]	3.6[b]	3.8[b]
		1988	**1989**	**1990**
	1	4.9[a]	3.8[b]	2.4[c]
	3	3.6[a]	3.5[a]	3.1[a]
			1988	
0.1M NaOH	1,3,2	17.0[a]	15.2[a]	16.3[a]
		1988	**1989**	**1990**
	1	17.0[a]	14.8[b]	17.7[a]
	3	15.2[a]	13.6[b]	14.0[b]
			1988	
Concentrated HCl	1,3,2	3.0[a]	2.1[a]	2.6[a]
		1988	**1989**	**1990**
	1	3.0[a]	1.7[b]	3.1[a]
	3	2.1[a]	2.0[a]	1.4[a]

*values in horizontal rows followed by different superscripts differ significantly at 5% of probability.

due to a higher mobilization of labile fractions, transformations of organic to labile inorganic P forms, and their subsequent reaction with Fe and Al oxyhydroxides, forming more stable or resistant constituents. Such events show that Pt is not very much affected by cultivation in traditional shifting cultivation agroecosystems, where yields are usually low.

Organic P

Organic P (Po) constituted between 21 and 15% of Pt and has slightly decreased during cultivation (Table 6), lowering the proportion of Po in relation to Pt, as demonstrated with the data from Plot 3, which represents more advanced phases of the cultivation cycle. The sodium bicarbonate-extractable Po fraction slightly decreased (Table 7), except in Plot 3, where soil pH is slightly higher than in the other two plots. It appears that conversion of P among fractions takes place as P taken up by plants is replenished from more resistant pools (Adepetu and Corey 1977, Tiessen *et al.* 1992). The bi-Po has been reported as a fair measure of labile Po in soil (Bowman and Cole 1978). It represented the largest pool of organic P and it also decreased upon cultivation.

The conc.HCl-Po represented the smallest Po pool and the least sensitive to the effects of cultivation. Decreases in the total Po fractions may have represented the release of about 10 kg P ha^{-1} during the cultivation cycle (Lessa 1995). Part of the Po may have reached lower horizons or either leached beyond the root's depth due to the higher mobility of these P forms in relation to its inorganic counterpart, as demonstrated in a laboratory experiment where the soil leaching potential was studied (Lessa and Anderson 1996). Experiments with the same soil have also indicated that carbohydrate components were the predominant structures in the water-dissolved organic carbon and this may be associated with the more mobile Po forms reported above (Lessa *et al.* 1996b).

Inorganic P

Inorganic P (Pi) tended to accumulate with cultivation, particularly in the resin- and concentrated HCl-extractable Pi fractions, true for both Plots 1 and 3 (Table 8), and represented the smallest and largest pools of Pi, respectively. The increase in these fractions with cultivation represented an accumulation of about 15 kg P ha^{-1} (Lessa 1995).

Table 8. Inorganic phosphorus (μg P g^{-1} soil) forms and transformations with cultivation at the 0 to 20 cm depth.

	Plots		Years	
			1988	
	1,3,2	2.5[a*]	1.8[a]	2.0[a]
Resin				
		1988	**1989**	**1990**
	1	2.5[b]	2.0[b]	3.5[a]
	3	1.8[b]	2.3[b]	3.4[a]
			1988	
	1,3,2	3.3[b]	4.3[a]	4.4[a]
0.5M $NaHCO_3$				
		1988	**1989**	**1990**
	1	3.3[a]	3.0[a]	2.8[a]
	3	4.3[a]	3.1[b]	2.3[c]
			1988	
	1,3,2	12.5[b]	13.9[b]	18.7[a]
0.1M NaOH				
		1988	**1989**	**1990**
	1	12.5[a]	12.3[a]	10.8[b]
	3	13.9[a]	12.1[b]	12.6[b]
			1988	
	1,3,2	2.2[ab]	2.0[b]	2.4[a]
1M HCl				
		1988	**1989**	**1990**
	1	2.2[a]	2.2[a]	1.8[a]
	3	2.0[a]	2.2[a]	1.7[b]
			1988	
	1,3,2	56.7[b]	56.0[b]	61.4[a]
Concentrated HCl				
		1988	**1989**	**1990**
	1	56.7[a]	59.5[a]	58.9[a]
	3	56.0[b]	56.2[b]	59.7[a]

*values in horizontal rows followed by different superscripts differ significantly at 5% of probability.

However, other Pi fractions appear to have decreased, such as the bi-, OH- and 1M HCl-Pi. The losses from these fractions into soils solution is calculated to be about 10 kg P ha^{-1} (Lessa 1995).

The several available and stable P fractions varied considerably in time and space and an example is showed for the resin-extractable Pi and total P along three transects in Plots 1, 2 and 3. The highest Res-Pi values were on sampling points 1 and 5 of transect 2 (Plot 2) (Figure 5) and did not coincide with high Pt values (Figure 4). Transect 1 of Plot 3 has higher values for both Pt and Res-Pi in sampling point 8, and point 10 of the same transect has lower Res-Pi than is expected from the Pt value, pointing out to no consistent relation between Res-Pi and Pt values.

The sequence of events on Plot 3

The results obtained in Plot 3 represent a more advanced stage of the cultivation cicle, a more complete set of data, and they are used to illustrate the changes in P fractions in the 0 to 5 and 5 to 20 cm soil depths during the more intense phases of cultivation (Tables 9 and 10). Changes in the P contents of the 0 to 5 cm depth are also more illustrative of cropping effects than the lower depths (Table 9). The Res-Pi (24 μg P g^{-1} soil) was unusually high in the 0 to 5 cm depth in 1988,

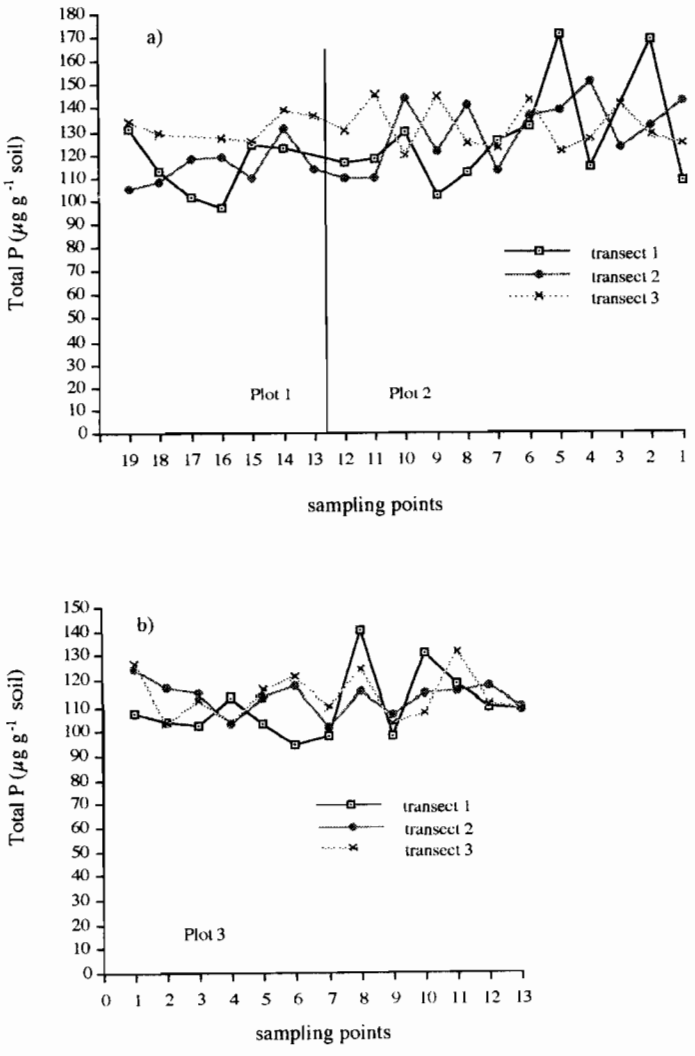

Figure 4. Total P along the transects of samples taken 10 m apart in 1988 in Plots 1, 2 (a) and 3 (b).

considering that this fraction is about 2 μg P g^{-1} soil in most soils studied, probably because of the addition of P in ashes, but then decreased substantially in 1989, with a slight increase in the 5 to 20 cm depth from 1989 to 1990 (Table 10). Values of such magnitude may be considered medium level for soil Res-Pi (van Raij 1986). Other factors may have also contributed to increased Res-Pi levels: the burning and heating effects on SOM resulting in P release and the increase in soil pH, which may increase P solubility.

Organic and inorganic bi- and OH-P decreased in the 0 to 5 cm depth from 1988 to 1989. In the 5 to 20 cm depth, bi-Pi decreased from 1989 to 1990, whereas OH-Pi slightly increased (Table 10). The release of Po and the more labile Pi forms, particularly in the 0 to 5 cm soil depth, appeared to be responsible for increases in Res-Pi and the more stable conc.HCl-Pi and Rd-P fractions in the 5 to 20 cm depth in 1990. Mineralization of Po is likely related to pH increase (Harrison 1982, Thompson *et al.* 1954), because of its effect on the microbial activity (Alexander 1977) and also hydroxyl competition with phosphate for organic or metal-organic bonding sites may release P into the soil solution (Hingston *et al.* 1972, Mattingly 1975).

All of the more labile or biologically available Po and Pi forms decreased in the 0 to 5 cm depth

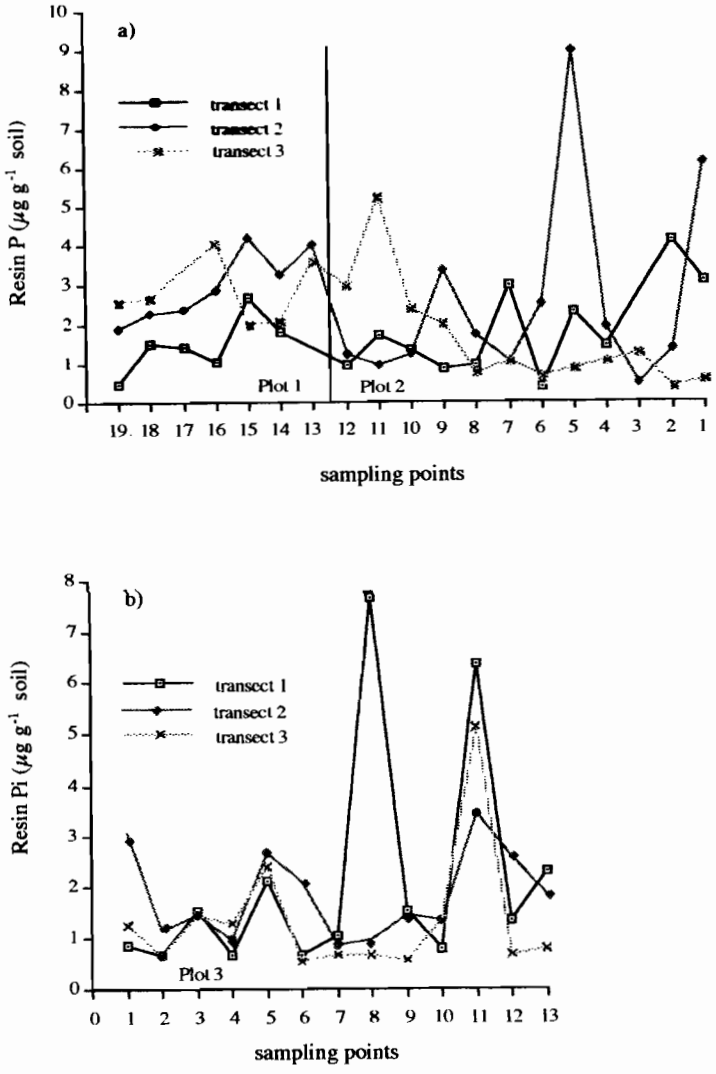

Figure 5. Resin Pi along the transects of samples taken 10 m apart in 1988 in Plots 1, 2 (a) and 3 (b).

between 1988 and 1989. Slight but statistically significant increases in some labile (Res-Pi and OH-Pi) and stable (conc.HCl-Pi and Rd-P) forms of P occurred in the 5 to 20 cm depth from 1989 to 1990. Stable forms of P increased in both soil depths. The resistant pool increased from 204 kg ha^{-1} (64% of total soil P) in 1988 to 220 kg ha^{-1} (68%) in 1989, and then 236 kg ha^{-1} (69%) in 1990, considered the 0 to 20 cm depth. These transfers caused changes in the ratio of labile to resistant pools, reducing it from 0.57 to 0.45 from 1988 to 1990. The ratio of organic to inorganic P pools was slightly reduced from 0.27 in 1988 to 0.23 in 1990, due mainly to the reduction in the Po pool. The Po constituted 19% of the total soil P in 1988 and 15% by 1990. It has been documented a contrary tendency in which the Rd-P pool has decreased along with Po pools during the cultivation of Alfisols in Africa, pointing to a possible reliese of Rd-P in the long term and with a substantial amount of Po in this particular P pool (Agbenin and Goladi 1998).

In the 0 to 5 cm soil depth (mean bulk density = 1.40 Mg m^{-3}), the amount of labile P was strongly reduced from 71 kg ha^{-1} in 1988 to 36 kg ha^{-1} in 1990, causing the ratio of labile to resistant pools to reduce from 1.29 to 0.57 during the period. The resistant pool increased from 55 (44% of the total P) to 63 kg ha^{-1} (64%). The ratio of organic to inorganic

Table 9. Changes in P fractions with cultivation in the 0 to 5 cm soil depth of Plot 3 from 1988 to 1990.

P fractions	Years 1988	1989	1990
		μgP g^{-1} soil	
Total P			
Σ (P_i + P_o + residual P)	179^{a*}	135^{b}	142^{b}
Organic P			
0.5M $NaHCO_3$	10.9^{a}	4.2^{b}	4.2^{b}
0.1M NaOH	29.0^{a}	16.8^{b}	17.4^{b}
Conc.HCl	2.3^{b}	1.6^{b}	3.9^{a}
Σ P_o fractions	**42.2^{a}**	**22.6^{b}**	**25.5^{b}**
Inorganic P			
Resin	24.2^{a}	4.8^{b}	5.4^{b}
0.5M $NaHCO_3$	8.0^{a}	5.1^{b}	4.2^{b}
0.1M NaOH	23.5^{a}	20.2^{b}	17.4^{b}
1M HCl	5.2^{a}	3.7^{b}	2.9^{b}
Conc.HCl	59.0^{b}	58.9^{b}	64.4^{a}
Σ P_i fractions	**119.9^{a}**	**92.7^{b}**	**94.3^{b}**
Residual P			
H_2SO_4/H_2O_2	17.1^{b}	19.4^{b}	22.0^{a}

*values in horizontal rows followed by different superscripts differ significantly at 5% of probability.

P decreased from 0.35 to 0.27 from 1988 to 1990. The organic pool constituted 24% of the total P in 1988 and 18% by 1990. Only small changes occurred in the amounts of labile and resistant P in the 5 to 20 cm soil depth (mean bulk density = 1.44 Mg m^{-3}) between 1989 to 1990. Both the labile and resistant pools increased, by 3 kg ha^{-1} and 8 kg ha^{-1}, respectively, keeping constant the labile/resistant ratio of 0.4. The ratio of organic (17% of the Pt in 1989) to Pi pools decreased slightly from 0.26 in 1989 to 0.22 in 1990. The Po pool was about 14% of the Pt in 1990. The smallest single soil P fraction was the Res-Pi (2 μg P g^{-1} soil), which was equal to 1M HCl-Pi (2 μg P g^{-1} soil), followed by bi-Pt (8 μg P g^{-1} soil), Rd-P (18 μg P g^{-1} soil), OH-Pt (30 μg P g^{-1} soil), and the conc. HCl-Pt (60 μg P g^{-1} soil).

Most of the P in both 0 to 5 and 5 to 20 cm soil depths are tied up in the more resistant fractions, thus being of less biological significance to plant growth in the short term. However, in the 0 to 5 cm depth, P behaves very dynamically and most probably, the transformations which occur at this particular soil depth are responsible for the supplying of available P during the cultivation cycle, determining the productivity of the crops usually growing at the site, and determining the duration of the cultivation cycle. Available P is one important soil fertility constraint, responsible for the usually low crop productivity at the site, which declines during the years of cultivation.

CONCLUSIONS

Total P in the study site was low and changed little over the cultivation cycle. The differences observed in 1988 between adjacents plots may be due to the initial P contents of the plots. The small gains of Pt in Plot 3 could be due to the residual effect of ashes. Nevertheless, slight but significant differences in the distribution of P among fractions occurred as a result of cultivation.

Organic P (Po), mainly in the 0 to 5 cm depth, decreased during early stages of the cultivation cycle, particularly the bicarbonate Po fraction, which is considered to be largely available to plants. The Pi fractions,which decreased during cultivation,were

Table 10. Changes in P fractions with cultivation in the 5 to 20 cm soil depth of Plot 3 from 1989 to 1990.

P fractions	Years 1989	1990
	μgP g^{-1} soil	
Total P		
Σ (P_i + P_o + residual P)	107[b]*	112[a]
Organic P		
0.5M $NaHCO_3$	3.3[a]	2.8[a]
0.1M NaOH	12.5[a]	12.8[a]
Conc.HCl	2.1[a]	0.6[b]
Σ P_o fractions	**17.9[a]**	**16.2[b]**
Inorganic P		
Resin	1.5[b]	2.7[a]
0.5M $NaHCO_3$	2.4[a]	1.7[b]
0.1M NaOH	9.3[b]	10.9[a]
1M HCl	1.7[a]	1.3[b]
Conc.HCl	55.2[b]	58.1[a]
Σ P_i fractions	**70.1[b]**	**74.7[a]**
Residual P		
H_2SO_4/H_2O_2	18.8[a]	21.2[a]

*values in horizontal rows followed by different superscripts differ significantly at 5% of probability.

the bicarbonate ($NaHCO_3$), hydroxide (NaOH) and 1M HCl-extractable Pi, all considered to be labile fractions. The resin-Pi fraction increased during cultivation, particularly in the 0 to 5 cm depth after the burn and its concentration decreased later upon cultivation. The initial increase in the resin-Pi may have resulted from the addition of P in ashes, mineralization of Po, and may also be due to the effect of the pH increase on P availability. The residual fraction accumulated slight amounts of P, acting as a reserve for P.

Most P is originally tied up in more resistant forms of less biological significance to the biota at least in the short term, and Po represents 20% of the total P in the area studied. Changes in P fractions and pool sizes were quite dynamic in the 0 to 5 cm depth, with little changes in the 5 to 20 cm depth. The magnitude of changes in the P fractions was less than 5 μg $P \cdot g^{-1}$ of soil, considered the 0 to 20 cm depth. However, the amounts of P required by low-yielding crops cultivated by the traditional slash and burn method during one crop cycle are seldom higher than such amounts of P (Adepetu and Corey 1977, Mueller-Harvey *et al.* 1985).

Part of the P reserves was transferred to the resistant pool (concentrated HCl-extractable and residual P fractions), decreasing the ratio of labile to resistant P in the cultivated soils. Transfer to resistant fractions represents an important mechanism of P retention against leaching and also limits P supply to crops. The downward migration of soluble Po may have enriched the hydroxide Po fraction of the 5 to 20 cm depth.

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