



COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
Vol. 34, Nos. 3 & 4, pp. 427–437, 2003

Long-Term Cropping Effect on Phosphorus Fractions in an Ultisol of the Humid Forest Zone in West Africa

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ABSTRACT

The nature of phosphorus (P) pools in soils after application of P fertilizers should be considered when designing management practices to raise P fertility. Five rates of P: 0(P₀), 45(P₄₅), 90(P₉₀), 135(P₁₃₅) and 180(P₁₈₀) kg ha⁻¹ in the form of triple superphosphate (TSP) were applied once in 1993 on a Typic Paleudult at Man in Côte d'Ivoire and the soil was cropped successively for five years (i.e., up to 1998) with four upland rice cultivators. At the end of the cropping season in 1998, soil samples were collected from the various P treated plots and the following P fractions were analyzed: resin-P, NaHCO₃-Pi, NaOH-Pi, HCl-P residual P and organic P. The P fractions were compared with those of

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stored soil samples collected in the field before the initiation of the experiment in 1993. Five years of cropping the soil reduced labile Pi (resin-P + NaHCO_3 -Pi) from $10.8 \text{ mg P kg}^{-1}$ in the uncultivated soil to $7.62 \text{ mg P kg}^{-1}$ in the control (P_0) and to $9.71 \text{ mg P kg}^{-1}$ in the P_{45} treatment. Labile Pi in P_{90} was the same ($10.7 \text{ mg P kg}^{-1}$) as in the uncultivated soil but in the P_{135} and P_{180} soils, labile Pi increased by 1.3 and 2.7 mg P kg^{-1} above that of the uncultivated one. The NaOH-Pi and residual P fractions of lower availability increased with increasing rates of P application. The results suggested that on the Ultisol studied, P applied once to a field, cropped successively over a period of time was not an adequate management option. Frequent P application at low rates at each cropping season is suggested and merits investigation on the Ultisol studied.

INTRODUCTION

In highly weathered soils of West Africa, P deficiency is a major constraint to rice production so that application of fertilizer P has become necessary.^[1] The soils are strongly acidic and will require either liming or an efficient P management strategy for optimizing P uptake and crop yields. Although liming increases soil pH, reduces P retention and hence increases available phosphorus content of the soil, liming materials are scarce and the price is unaffordable to local rice farmers.

A study was initiated for developing P management strategy for four upland rice cultivators grown on an Ultisol in the humid forest zone of Côte d'Ivoire. Phosphorus fertilizer was applied at different rates once in 1993 and the field cropped for five successive years (i.e., up to 1998). Yields of the four upland rice cultivars decreased considerably across the range of P fertilizer rates after the first crop, suggesting rapid decrease in the residual P effect on the rice crop. Determination of the P fractions in the soils may provide insight to the status of the applied P.

To assess P status and the residual effect of added phosphorus, the integration of a number of P pools such as available inorganic P (Pi) fractions and organic P (Po) and its potential mineralization should be known. Routine soil P tests designed to determine plant available P do not measure the less available inorganic and organic P pools. The study of P fractions in soils has largely relied on sequential extractions.^[2-4] The fractionation method developed by Hedley,^[5] however, permits the separation of Pi and Po into major chemical groupings, such as Ca-versus Fe-and Al-associated Pi and pools of differing chemical availability.^[6] Relationships between extractable P and plant availability have been inferred from many experiments.^[7,8]

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The objective of the present study was to determine the size and changes in soil P fractions in unfertilized and fertilized soils after a long-term continuous cropping experiment established on an Ultisol in the humid forest zone of Côte d'Ivoire. The effect of P application and continuous cropping was assessed by comparing changes in soil chemical properties between a stored uncultivated soil sampled from the plots at the beginning of the five-year experiment and those of the unfertilized/fertilized cropped soils.

MATERIALS AND METHODS

Site and Soil Used

A long-term field experiment was begun in 1993 at a site close to the Institut des Savanes (IDESSA) Station near Man (7.2°N, 7.4°W; 500 m altitude) in Côte d'Ivoire. The site is located in the humid forest zone with total annual rainfall of about 1,700 mm.

The soil is highly weathered, low-activity clay Typic Paleudult. Soil samples were collected from the surface (0–20 cm) layer before the beginning of the experiment (original uncultivated soil) and at the end of the 1998 growing season (unfertilized/fertilized and cropped soils). They were air-dried and ground to pass a 2-mm screen before analyses. Soil pH was determined in 1:2.5 soil: water and also in 1:2.5 soil: 0.01 CaCl₂ suspensions. Organic C was determined by Walkley and Black^[9] method. Bray 1 extractable P was determined using 1:7 soil:NH₄F-HCl solution as described in Olsen and Sommers.^[10] Exchangeable bases were extracted with 1.0 M NH₄OAc (pH 7.0), and exchangeable acidity was determined as described in Thomas.^[11] The cation exchange capacity (CEC) was calculated as the sum of the exchangeable bases and acidity. Dithionite-citrate Fe (Fe_d) was extracted by the method of Mehra and Jackson,^[12] and oxalate Fe (Fe_o) was extracted using 0.2 M (NH₄)₂C₂O₄, pH 3.0.^[13] Iron in both the dithionite-citrate and ammonium oxalate extracts was determined by atomic absorption spectrophotometry (AAS).

Phosphorus Fractionation

Soil P was fractionated using sequential extraction of Hedley et al.^[5] A separate soil sample (0.5 g) was analyzed for total P content by means of concentrated H₂SO₄ and H₂O₂ digestion to verify the total soil P determined by summation of all fractions.

For the purpose of this study, the Hedley P fractions were grouped into three discrete pools of differing availability.^[8] They are: resin P plus 0.5 M NaHCO₃ extractable inorganic P (NaHCO₃-Pi) as labile Pi, and the 0.1 M NaOH extractable inorganic P is considered moderately labile. The residual P is nonlabile and unavailable to plants over a long period of time. The organic P fraction (Po) refers to the sum of 0.5 M NaHCO₃-Po and NaOH-Po.

Field Experiment

Fertilizer P was applied at rates of 0(P₀), 45(P₄₅), 90(P₉₀), 135(P₁₃₅) and 180(P₁₈₀) kg P ha⁻¹ as triple superphosphate once in 1993 and the soil cropped successively with four upland rice cultivars in 1993, 1994, 1995, 1996 and 1998 to assess the direct and residual effects of the applied P. There were four replications. Before the P application, soil samples were collected from plots, bulked together and stored. At the end of the field experiment in 1998, soil samples were again collected from replicate plots of the cultivar WAB56-125 only, since there were no differences in yield and P uptake for the four upland cultivars for the entire five years. The soil samples from the replicate plots were also bulked for each P treatment. Chemical analysis and P fractions determination were carried out simultaneously for the stored uncultivated soil and the unfertilized/fertilized and cropped soils.

RESULTS

Chemical Properties

Cropping for five years with upland rice caused changes in the soil chemical characteristics (Table 1). Soil pH and, therefore, exchangeable acidity did not change significantly in the cultivated soils when compared to the uncultivated soil. Available P (Bray-1) was similar in all P treatments, and was far below the critical values of 12.5 to 15 mg kg⁻¹ needed for 90% upland rice grain yield for an Ultisol in the forest zone of Côte d'Ivoire.^[14] The difference between Bray-1 P in the uncultivated soil and that of the unfertilized cultivated soil (P₀) was strikingly small, despite cropping in the latter without P for five years. This conforms to the explanation that in highly weathered soils, organic P and less labile inorganic P fractions, not measured by common soil tests, contribute to plant P availability and that may have maintained available P in the P₀ treatment close to that of the uncultivated soil.^[15] The ratio of Fe_d/Fe_o in the cultivated soils increased compared to that

**Table 1.** Chemical properties of uncultivated and cultivated soils.

Treatment	pH		Bray-1 (mg P kg ⁻¹)	OC (g kg ⁻¹)	Ca (mmol _c kg ⁻¹)	Mg (mmol _c kg ⁻¹)	K (mmol _c kg ⁻¹)	Na (mmol _c kg ⁻¹)	Exch. acidity (mmol _c kg ⁻¹)	CEC (mmol _c kg ⁻¹)	Fe _d (g kg ⁻¹)	Fe _o (g kg ⁻¹)	Fe _d /Fe _o
	H ₂ O	CaCl ₂											
<i>Uncultivated soil</i>													
0	4.3	3.8	6.4	14.7	5.4	2.5	2.3	0.1	19.3	30.1	3.11	2.30	1.35
<i>Cultivated soils</i>													
P ₀	4.2	3.6	5.0	14.4	4.5	2.4	0.8	0.8	19.5	28.0	4.21	1.17	3.60
P ₄₅	4.5	3.6	4.9	14.2	6.7	1.9	0.7	0.6	19.5	29.4	3.95	1.10	3.60
P ₉₀	4.4	3.7	5.0	14.3	5.8	1.9	0.5	0.4	19.5	27.1	3.66	1.09	3.36
P ₁₃₅	4.3	3.8	5.5	14.0	6.2	2.0	0.6	0.3	19.5	27.6	3.86	1.09	3.54
P ₁₈₀	4.0	3.7	7.6	13.8	5.8	1.6	0.8	0.3	19.5	29.5	3.45	1.02	3.38

of the uncultivated soils because cropping reduced Fe_o , but Fe_d was not affected much.

Inorganic P Fractions

The reliability of the Hedley P fractionation procedure in accounting for the total P content of the soils studied was evaluated by a linear regression (Fig. 1). The sum of P fractions underestimated total P of the soils by 3% but the high r^2 (i.e., 0.997) obtained is an indication of the suitability of the method.

The order of abundance of the Pi forms in the soils, irrespective of P treatments was residual P (nonliable) \gg OH-Pi (moderately labile) > labile Pi > HCl-P (Table 2). Five years of cropping had reduced the magnitude of the labile Pi from $10.8 \text{ mg P kg}^{-1}$ in the uncultivated soil to 7.6 mg P kg^{-1} in the P_0 treatments. Cropping did not only reduce the labile Pi in the P_0 soil, but it also reduced the NaOH-Pi fraction which is consistent with the observation that this fraction is moderately available with time.^[7] The labile Pi content of the samples from the fertilized soils P_{45} and P_{90} was below the critical values of 12 to 15 mg P kg^{-1} and, therefore, may be limiting for subsequent cropping. In the P_{135} and P_{180} soils, labile Pi was within the P critical limit,

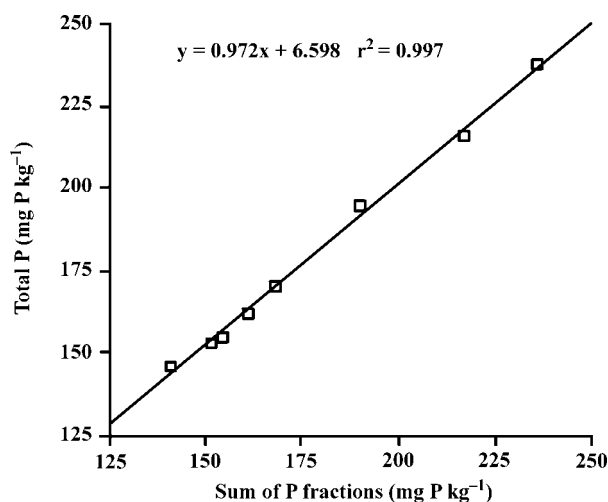


Figure 1. Relationship between the sum of P fractions and total P determined independently by concentrated H_2SO_4 - H_2O_2 digestion.

**Table 2.** Phosphorus fractions of uncultivated and cultivated soils that received different rates of P application and cropped for five years.

Treatment	Resin (mg P kg ⁻¹)	NaHCO ₃ -Pi (mg P kg ⁻¹)	OH-Pi (mg P kg ⁻¹)	HCl-P (mg P kg ⁻¹)	Residual P (mg P kg ⁻¹)	Σ P ₀ (mg P kg ⁻¹)	Σ P fractions (mg P kg ⁻¹)
	Labile Pi	Mod. labile Pi			Nonlabile Pi		
<i>Uncultivated soil</i>							
0	10.8	26.7		2.33	84.2	33.0	152
<i>Cultivated soils</i>							
P ₀	7.62	24.7		0.18	83.5	24.9	141
P ₄₅	9.71	34.4		0.20	99.1	25.0	168
P ₉₀	10.7	47.5		0.18	105	26.8	190
P ₁₃₅	12.1	56.4		0.18	109	39.2	217
P ₁₈₀	13.5	60.5		1.06	115	45.5	236

although, the agronomic data indicated low yields (data not shown). This suggested that the P pools were only indicators of availability and that it is the plant alone that can measure the amount of P available to it. The NaOH-Pi increased with increasing P rates and, therefore, acted as P sink under conditions of excess P fertilization. With time, the NaOH-Pi could have either of the following two pathways: it may become available in soils that have low amounts of Fe/Al sesquioxides and thus replenish the labile Pi pool or it may react further with Fe/Al oxides in the soil and is transformed into nonlabile P fraction which becomes unavailable to plants.

The HCl-P, a Ca-bound P, was very low which is in conformity with the highly weathered status of the soil. Calcium phosphates are the main P forms in young soils, and with progressive weathering, Al-P and Fe-P become important.^[6,16] The HCl-P content declined considerably from a level of 2.3 mg P kg⁻¹ in the uncultivated soil to traces in all the cultivated ones (Table 2). Reports from greenhouse studies indicate that the HCl-P is available to plants in slightly weathered soils, but its availability in highly weathered soils is not certain.^[8,15] However, the large decrease in the HCl-P observed in the present study suggests that it is a potential source of available P to crops under field conditions in a highly weathered Ultisol.

Most of the P left in the soil was in the residual nonlabile form and represented between 49 and 54% of the total P. The residual P of the uncultivated soil and that of the P₀ remained the same, despite long-term cultivation (Table 2), indicating that this P fraction is not easily available to plants. The progressive increase in the moderately labile Pi and the nonlabile P pools in the soils is an indication that more P has been transformed to these fractions as the rates of P application increased. This is of relevance to local agriculture where application of heavy doses of P may not necessarily be beneficial to the rice crop.

Organic P Fraction

Organic P represented, on the average, 17% of the total P in the cultivated soils and 21% in the uncultivated one. Although mineralization of organic P or organic C was not measured, the decrease in organic P in the P₀, P₄₅, and P₉₀ soils compared to that of the uncultivated soil is assumed to be due to mineralization. This mineralized P could come predominantly from the native organic matter because all plant residues were removed from the plots before P application in 1993.

Only traces of NaHCO₃-Po were extracted in the soils (data not shown), probably because of rapid mineralization of soil organic matter that occurs in

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tropical soils.^[17,18] Consequently, most of the organic P was in the NaOH-Po form. Soil samples from P₁₃₅ and P₁₈₀ treatments accumulated Po in the form of NaOH-Po which represents an additional sink but may be biologically dynamic and, therefore, is expected to mineralize to supply P to crops in the long-run.^[19]

DISCUSSION

The idea of applying P once to the field and cropping the soil for several years is under the assumption that residual benefits will be derived with subsequent cropping. Although some studies have demonstrated long-lasting residual benefits from large additions of P to soils^[20,21] the present one showed that most of the P applied to the soil especially at higher rates (135 and 180 kg ha⁻¹) was transformed into moderately labile and nonlabile P forms, which may not be easily available to the rice crop. The soil studied has high P adsorption capacity due to the presence of Fe oxides that react with the added P and render it unavailable to the rice crop.^[22] For soils similar to the strongly weathered Ultisol in the study, P applied once and cropped for several years may not be good P management strategy.

To sustain crop productivity frequent small applications of P may, therefore, be more cost-effective than applying large amounts of P to the soil. By this means, P transformations in the soil would be minimized and more P would be made available to the crop. Sahrawat et.al.^[1] have demonstrated in an earlier study on upland rice on an Ultisol of the humid forest zone of Côte d'Ivoire that there was no further response in grain yield at higher rates of P than 60 kg ha⁻¹. Thus, low rates of P applied frequently would be beneficial to the rice crop.

Furthermore, management options such as leaving crop residues in the field to decompose and release P for plant uptake or to reduce P adsorption capacity would increase P fertility for farmers cultivating this type of soil. The use of moderately reactive rock phosphate deposits in some West African countries and breeding for acid tolerance and P efficiency are suggestions that might offer effective means of achieving a successful rice cultivation on this tropical acid soil.

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