Residual Soil Phosphorus Under Sustained Cropping in the Humid Tropics[1]

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ABSTRACT

Residual P in river terrace soils of the West African humid uplands sustained satisfactory yields of Funk G-901 maize (*Zea mays* L.), Anethoda rice (*Oryza sativa* L.), and Mares groundnut (*Arachis hypogaea*) under a sequence of continuous cropping for 3 consecutive years. Up to 90 kg/ha soluble P applied at the inception of the cropping sequence failed to elicit a yield increase when other cultural parameters were maintained at levels recommended as adequate for satisfactory yields under these conditions.

At the start of the experiment the soil had already attained a residual P level of 55 kg/ha, the Ca + Mg concentration averaged 0.5 meq/100 g soil, and fresh crop and cover residues contributed 18 metric tons/ha of organic matter to the 15-cm soil depth each year.

Lime applied in the last year raised soil pH from 4.8 to 5.1, reduced Al base-saturation from 30% to 9%, and probably contributed to the increase in groundnut yield, although this effect was not experimentally tested. In the 3rd year a second application of the P treatments after liming did not induce a significant increase in yield over the check (0-P) or in those plots which had received only the P treatment initially.

In soils where exchangeable Al comprised 30% or less of the base saturation, the conversion of soluble P into insoluble Al and Fe phosphates apparently was not a yield-limiting reaction. Phosphorus fixation, particularly as Al phosphates, is a recalcitrant problem for soils in the humid tropics, but this is not true for soils under sustained cropping. By using the same crop varieties and soils similar to those used in this study, subsistence farmers could intensify their operations on selected sites utilizing residual P for extended periods without soil P becoming a yield-limiting factor.

Additional Index Words: phosphorus fixation, tropical soils, continuous cropping, subsistence farming, Al-P interactions.

IN THE forested and savanna upland soils of West Africa shifting agriculture, short cropping periods following long natural fallows, is the major mode of crop production (4). In Sierra Leone it is the prevalent practice on 96% of cultivated land (16). Where land is abundant, shifting agriculture is a reliable system that has served the people well, although not with abundance. It is a cultural system adapted to the vicissitudes of a harsh ecosystem and, for the most part, providing only subsistence.

Now a larger, better educated, healthier, and more materialistic population has brought irreversible change in the social mores, particularly of the youth (14). Shifting agriculture can neither meet the needs induced by change nor offer new generations the quality of life for which they strive. New agrarian systems, of which sustained cropping of selected sites is one, must and will slowly evolve (15).

In the humid tropics on selected sites, sustained cropping systems hold great promise to meet the food requirements of a nation involved in massive and rapid technological change (6, 15). It has been argued that such a system would create "isles of affluence" (18). This is not necessarily so. In Sierra Leone where this study was made, the fertile river terrace and alluvial soils comprise 10% of the best arable soils of the country and constitute a substantial resource for a large number of people (16).

If we accept the premise that sustained cropping is one of several main directions agriculture should take in the humid tropics, two factors of soil fertility are of crucial importance viz: (i) the cycling of organic matter (2), (ii) and a concentration of labile soil phosphorus at a sufficiently high level to meet the crop requirements throughout the growing season. The latter factor, the concern of this paper, depends in part on the P-fixing capacity of the soil and the availability to the plant of residual soil P. Sporadic fertilization during long cropping periods can maintain and possibly increase yields only if a residual pool of available soil P can be developed at a high enough potential to meet the plant requirements. These are important considerations for agricultural development in the humid tropics because as new systems evolve in an economy plagued with limited capital, every kilogram of phosphorus applied must induce an increase in yield or at least forstall a yield decline (17, 19, 20).

Investigators working in tropical areas have reported considerable influence of residual P on crop yields during rotations (3, 5). Others have demonstrated pronounced immobilization of P in highly weathered soils (1, 8, 19, 22). The problem has not been fully resolved and is the concern of agronomists working in agricultural development (12, 23, 25).

It is the purpose of this study to ascertain the magnitude of some of the forms of residual P in these soils and

Table 1—Physicochemical properties of soil in experimental site under secondary forest

Parameter	Identification	
Soil series	Bonjema fine sandy loam	
Classification	Aquic Plinthic Dystropept	
Drainage	Imperfectly drained	
	Surface 0–40 cm	Subsoil 40–80 cm
Particle-size, %		
2 mm (% of entire sample)	0	32
Sand	61.9	46.4
Silt	26.0	24.4
Clay	12.1	29.2
Clay types (in order of abundance)	K G CH†	K G CH
Exchangeable cations, meq/100 g soils		
Calcium	0.18	0.08
Magnesium	0.10	0.10
Potassium	0.01	0.01
Sodium	0.06	0.04
Aluminum	1.50	1.89
Cation exchange capacity, meq/100 g soil	5.8	5.6
Base saturation, %	6.0	4.1
pH, 1:1 in water	4.1	4.5
Organic C, %	1.2	0.30
Soil phosphorus, kg/ha		
P_1	11	2
P_2	2	4
Free Fe oxide, %	1.9	3.8

* From Soil Survey Report: J. C. Dykerman and H. Breteler, Njala U. C.
† K = Kaolinite, G = Gibbsite, CH = Chlorite.

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whether a pool of residual soil P can be maintained that could satisfactorily sustain yields of agronomic crops through several years of continuous cropping.

MATERIALS AND METHODS

This study was conducted in Sierra Leone, West Africa in an area which lies in the humid Tropical Belt with distinct wet (May–Oct.) and dry (Nov.–April) seasons. Yearly temperature averages 30C.

The experimental site was part of a 15-year-old oil palm (*Elaeis guineensis*) nursery on Bonjema fine sandy loam located on a river terrace soil bordering the River Taia near the Njala University College campus. The soil properties are given in Table 1. The site had received more intensive management during the 15 years as an oil palm nursery than similar sites under forest. However, the ground cover, root proliferation, and physical properties of the soil were essentially the same as the typical forest ecosystem that had once been cropped. Some chemical properties, however, have been altered and these will be noted later. The year prior to the trial, the site was cleared, fertilized with 24 kg of N/ha from ammonium sulfate and 19 kg of P/ha from ordinary superphosphate and planted to groundnuts (*Arachis hypogaea*). In early February 1968, 3 months after harvest, the site was disked and the groundnut residue and regenerative cover plowed under.

The experiment was designed to test the residual effects of soil P and the influence of an initial application of soluble phosphates on crop yields during 3 years of sustained cropping. The initial treatments considered here and in Tables 2 and 3 refer to the P applied at the inception of the experiment and not the P applied the year before the experiment or in previous years noted above. Four levels of applied P derived from ordinary superphosphate were tested; 0, 30, 60, and 90 kg P/ha were each replicated 6 times in a randomized block design. Each year regenerative cover and crop residues were worked into the 2 to 15 cm soil depth about 3 to 4 weeks before planting. This procedure was an integral part of the cultural system employed in this study.

The treatments were broadcast 3 weeks before planting and incorporated into the top 15 cm of soil. At planting, 24 kg of N/ha from ammonium sulfate, 70 kg of K/ha from potassium sulfate, 112 kg/ha of magnesium sulfate, and a micronutrient mix of the sulfates of Cu, Zn, Fe, Mn, and sodium borate in washed sand were broadcast to each plot and raked into the soil. The site was not limed. Irrigation water from the river was pumped into retaining ditches and directed through metal gates into shallow trenches 6 cm deep and 6 cm wide running the length of the site. Gypsum moisture sensors were buried at 15- and 45-cm depths to monitor soil moisture fluctuation *in situ*.

In late February 1968, the first year of the cropping sequence, maize 'Funk G-901' (*Zea mays* L.), a temperate hybrid, was planted on the irrigation ridges at a density of 35,000 plants/ha. In May the maize was harvested, and the shelled grain dried to 14% moisture and weighed.

The site was leveled in June 1968, and the maize residues and regenerative cover incorporated into the soil with native hoes. Fertilizer was applied as before with the exception of P and the micronutrient mix. Rice 'Anethoda' (*Oryza sativa* L.), an upland dry-land variety, was broadcast at 50 kg/ha. An additional 24 kg of N/ha from ammonium sulfate was side-dressed to the rice in the fourth week after emergence. The rice was harvested in October and dried to 10% moisture and weighed. The straw was returned to the plots.

In May 1969 of the second year, the plots were split into equal subplots and groundnuts 'Mares' (*Arachis hypogaea*) and rice were planted respectively in randomized subplots. Prior to planting, the plots received the same fertilizer application as the year before except the second N application was omitted. Rice was broadcast at 50 kg/ha, and the groundnuts were planted in 60-cm rows, 15 cm in the row without ridging. At harvest, rice straw and groundnut stems were chopped, mixed, and evenly distributed over the plots. Groundnuts were shelled, dried, and weighed.

To ascertain the magnitude of the residual P effect, the plots were split again into equal subplots as before, but to eliminate the effect of previous cropping, the subplots were aligned perpendicular to the arrangement previously employed. In March 1970, 3 weeks prior to planting, 560 kg/ha of lime was broadcast over each subplot and worked into 15 cm of the soil. The lime used tested 85% pure $CaCO_3$ and passed through a 40-mesh screen. In each plot, one subplot received a proportional amount of soluble P at a rate and source to that originally administered to the entire plot at the inception of the experiment. The other subplot did not receive the second P treatment. Fertilizer was applied to both subplots at a rate and kind as the previous year. Groundnuts were planted and harvested in both subplots, as previously described.

Soil samples were collected at the beginning and end of each growing season and taken from the 2- to 15-cm depth. They were air-dried and stored in plastic bags in a cool room. Soil P was determined in a Bray soil extract (.03*N* NH_4F + 0.025*N* HCl) by the molybdenum-blue method in a soil/solution ratio of 1:10. Soil organic matter was determined by the wet-oxidation method, and soil K was determined in a soil extract of unbuffered 1*N* NH_4Cl at pH 7.0 by flame photometry in a soil/solution ratio of 1:10.

RESULTS AND DISCUSSION

Soil analysis at the inception of the experiment indicated 55 kg/ha of residual P, a level 3-fold higher than the adjacent bush site (Table 2). This was attained through (i) a single application of basic slag at a rate of 200 kg/ha while the site was part of an oil palm nursery, (ii) recycling of natural cover and tree cuttings, and (iii) the application of 112 kg/ha of ordinary superphosphate 1 year prior to the experiment.

The initial P treatments applied at the inception of the experiment failed to increase crop yields or induce a diminution in yields during the cropping period (Table 3). The marked increase of rice yield in the second year (Table 3)

Table 2—Fluctuations of P, K, pH, (Ca + Mg), and Al in river terrace soil during course of experiment

Initial P treatments	Initial level (pretreatment)	1st year	2nd year	3rd year
kg/ha	P, kg/ha			
0	55	63	72	44
30	65	85	111	83
60	62	88	116	79
90	66	105	110	70
Bush†	18	--	22	18
	K, kg/ha			
0	72	85	149	--
30	75	111	145	--
60	77	108	150	--
90	97	117	125	--
Bush	113	117	125	--
	pH			
0	4.5	4.5	4.6	5.0‡
30	4.6	4.5	4.6	5.1
60	4.5	4.4	4.5	5.1
90	4.5	4.6	4.8	4.8
Bush	4.6	--	--	4.4
	Ca + Mg, meq/100 g soil			
0	0.5	--	--	1.7
30	--	--	--	--
60	--	--	--	--
90	--	--	--	--
Bush	--	--	--	--
	Al, meq/100 g soil			
0	1.6	--	--	0.4
30	--	--	--	--
60	--	--	--	--
90	--	--	--	--
Bush	--	--	--	--

* Average of 6 replicates per treatment.
† Bush samples taken from 20-year bush site in adjacent area of identical soil.
‡ Values of groundnut plots limed in the third year and taken 3 weeks after harvest and 4 months after lime application.

was attributable to the absence of blast infection (*Piricularia aryzae*) and severe lodging which affected the rice in the first year. The rice yields in the second year represent the production that is usually attained on these soils under the prevailing cultural systems. In the third and last year, lime applied to the entire site, plus a second application of P to respective subplots, did not elicit a significant increase in yields over the check (0-P) or those subplots which had received only the initial P treatments 3 years previously (Table 3).

It is postulated that two soil conditions had contributed to the lack of response to applied P. First, the concentration of residual P was adequate and potentially high enough to meet the crop requirements for good yields without further addition of soluble P. Secondly, applied soluble P was immobilized as insoluble Al, Fe, or Ca phosphate and made unavailable to the plant. Both conditions had probably contributed in varying degrees to the ultimate effect.

If the former condition predominated, then residual P, which averaged 55 kg/ha (Bray P_1) in the control plots, supplied sufficient labile P at a potentially high enough level to maintain satisfactory yields of plants under the conditions of this experiment. A study in Nigeria had also shown that a yield response in millet (*Pennisetum typhoideum*) and maize to applied P growing in upland soils having a level of 30 kg/ha of inorganic, residual P was not detected during 4 years of continuous cropping (24).

If the second soil condition postulated was primarily operative, the addition of lime in the third year should have increased yields by relieving the constraint imposed by the immobilization of inorganic nutrient P as Al, Fe phosphates. This however, was not the case. Before liming, the soil pH averaged 4.5 and the concentration of exchangeable Al averaged 1.8 meq/100 g soil, or 30% of the cation exchange sites. After lime was applied, the pH increased to 5.1 and the concentration of exchangeable Al dropped to 0.4 meq/100 g soil, or 9% of the exchange sites. Apparently, the concentration of exchangeable Al even in the more acid range was too low to precipitate sufficient quantities of residual or applied P and become a yield-limiting factor. Any beneficial influence of lime in this soil at higher pH levels would be very unlikely (22). Kamprath reported that when soils with high saturation of exchangeable Al were limed to neutralize the Al, only 50% as much applied P was required to give maximum growth (13). However, this was not the case in soils where 55 kg/ha of residual P had sustained crop yields equivalent to those crops growing in unlimed plots that had received up to 90 kg/ha of applied P (Table 3). Based on these results, Al saturation up to 30% of the exchange capacity did not reduce the potential of labile P in the soil to an extent where P became a yield-limiting factor under conditions of this experiment. It is also quite probable that application of P in excess of 90 kg/ha would not induce significantly higher yields under the cultural system and varieties employed in this trial or be acceptable to subsistence farmers at the present state of technological development in the country.

The free Fe oxides are also involved in P reactions and evidence is accumulating that Fe immobilizes P to a much greater degree than Al (10). However, Fe averaged only 1.9% in the surface soils, almost 95% less than Oxisols where P-fixation was evident (1), and within the concentration range of tropical soils that do not exhibit P-fixation (22).

Table 3—Crop response to residual P under sustained cultivation in river terrace soil of Sierra Leone, West Africa

Initial P treatments	1st year		2nd year		3rd year* Groundnut	
	Maize†	Rice	Groundnut	Rice	A	B
kg/ha	Yields, kg/ha‡					
0	4,593 a	1,592	837	1,780 ab	1,836	1,620
30	3,848 b	1,425	810	1,472 b	1,782	1,642
60	4,276 a	1,228	927	2,009 a	1,863	1,617
90	4,536 a	1,252	813	2,123 a	1,890	1,700

* Subplot A received only initial P treatment. Subplot B received repeat of initial P treatment in the third year. All subplots, (A and B), limed in the third year.
† Values with the same letter are not significant at the 0.05 level within respective columns.
‡ Average yields of 6 replications per treatment.

The usual marked response of groundnuts to lime in soils low in basic ions could be due to extensive proliferation of roots, increasing the total uptake of nutrients. However, the lack of any influence of lime to enhance P utilization with a subsequent increase in yields further substantiates the postulate that the residual P in the soil was already at a concentration and potential high enough to adequately supply the needs of the plant when P was applied. The significantly lower groundnut yields in plots receiving an additional application of P as against those under the initial P treatment (Table 3, subplots A and B) is unexplained.

Large amounts of lime to promote response to P fertilizer should be used with discretion and could depress yields in some soils (9, 11, 21). It is important, however, that the Ca + Mg levels are adequate for satisfactory yields. In the experimental site, the Ca + Mg levels prior to liming averaged 0.5 meq/100 g soil and groundnut yields averaged only 840 kg/ha. However, when lime was applied, the yield was doubled (not necessarily attributable to the effect of lime) and the concentration of (Ca + Mg) reached 1.7 meq/100 g soils, a relatively high value in the humid tropics (9). The Ca + Mg/K ratio of 7.0 was low enough to negate any antagonistic effects.

The concentration of extractable K at the start of the trial averaged 80 kg/ha, which is not considered adequate for good yields. There was, however, a gradual increase in K concentration up to 0.17 meq/100 g or 145 kg/ha during the cropping sequence, attributable to the application of K_2SO_4 before each planting (Table 2). Apparently, this level was adequate to sustain satisfactory yields above the absolute minimum level of 0.1 meq/100 g soil advocated by Forde (7). However, it is questionable whether this minimal level could support improved crop varieties or achieve greater yields from soils under subsistence farming.

The results clearly show that it was possible to build-up and maintain a pool of inorganic, residual soil P at a level great enough to meet the plant requirements for three consecutive years of continuous cropping. The increase in soil P in the second year however, (Table 2) cannot be explained with the data available. Apparently, the increased mineralization rate of organic matter after 2 years of cultivation contributed to the pool of inorganic P (2, 19). If P deficiencies should occur in these soils, the condition could easily be ameliorated by the addition of moderate amounts of soluble, inorganic phosphates prior to planting.

By attaining a concentration of 55 kg/ha of inorganic and residual P that may or may not be considered a "threshold level," a subsistence farmer practicing continuous cultivation on these soils need only to supply soluble P once every 3 years to sustain yields commensurate with his economic resources and technology. He would also need to supply enough lime to compensate for leaching and crop losses of Ca^{2+} unless the Al base-saturation exceeds the crop tolerance for this element. This situation would then require a larger application of lime, but the exact amount of lime could only be determined by further research ascertaining the relationship of crop tolerance to Al base-saturation levels for the soils under cropping.

The fact that residual P exerts an influence on yields of three major food crops is contrary to the often expressed opinion that phosphate ions are irreversibly fixed and have no residual value in soils of the humid tropics. This study has shown that P-fixation as a yield-limiting factor was not the recalcitrant problem associated with sustained cropping systems claimed to prevail generally in tropical soils. The results clearly indicate that sustained cropping is quite possible, at least with respect to available P, in these tropical soils for farmers of very limited resources and technology.

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