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Rice Yields Enhanced through Integrated Management of Cover Crops and Phosphate Rock in Phosphorus-deficient Ultisols in West Africa

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Abstract: The relatively low solubility and availability of phosphorus (P) from indigenous phosphate rock could be enhanced by legumes in the acid soils of humid forest agroecosystems. *Crotalaria micans* L. was grown in a screenhouse without P or with P from triple superphosphate (TSP) and Malian Tilemsi Rock P. The P response of 20 cover crops was field-evaluated using TSP and Rock P. In both experiments, the fertilized cover crops were followed by upland rice without mineral N or P application. Mean rice grain yield and agronomic residual P-use efficiency were similar for both P sources. In the field, 1-year fallow treatment of *Canavalia ensiformis* (velvet bean) supplied with Mali Rock P gave the highest rice grain yield of 3.1 $Mg\,ha^{-1}$, more than 180% that of 2-year continuous unfertilized rice (cv. 'WAB 56-50'). Among continuous rice plots, 'NERICA 2' (interspecific rice) supplied with Rock P produced the highest yield (2.0 $Mg\,ha^{-1}$), suggesting that 'NERICA 2' might have greater potential to solubilize rock P. Results indicate that when combined with an appropriate legume, indigenous rock-P can release sufficient P to meet the P requirement of the legume and a following upland rice crop in rotation.

Keywords: Cover crops, legume rotation, NERICA rice, phosphate rock, Ultisols, velvet bean

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INTRODUCTION

The upland rice-based systems of West Africa consist of 2.3 million hectares that are subsistence oriented and characterized by limited use of purchased external inputs. These systems rely on extended periods of bush-fallow to regenerate soil fertility and prevent the buildup of weeds and other pests. However, this practice of shifting cultivation is no longer a viable option for farmers because of the increasing pressure on land from the rapidly growing populations in the region. Becker and Assigbé (1995) reported a reduction from 12–15 years of forest fallow in the 1980s to 3–7 years in the 1990s in upland rice-based systems of seven countries in West Africa. This constraint has forced West African farmers to intensify their rice production systems, resulting in continuous cropping of the same piece of land over several years.

Land-use intensification associated with low use of external inputs and reduction in fallow length has led to a steady depletion of the already limited soil nutrient reserves (Buresh, Smithson, and Hellums 1997). The studies of Becker and Johnson (1999) showed that intensification has led to 26% decrease in soil N-supplying capacity and a significant upland rice yield loss of 35% in the forest agroecosystem where about 70% of the West African upland rice is being cultivated. It appears, therefore, that the productivity of upland rice is no longer sustainable under the current levels of land-use intensification. The identification of low-cost technologies to improve soil fertility and increase rice productivity while preventing the buildup of weed infestation could be an attractive proposition that could be readily adopted by a majority of the resource-limited smallholder rice farmers.

Legume cover crops offer an alternative for reducing dependency on purchased external mineral inputs. Becker and Johnson (1998, 1999) reported that the use of nitrogen $(N)_2$–fixing legumes including *Mucuna spp.*, *Stylosanthes guianensis*, and *Canavalia ensiformis* grown as a preceding fallow crops increased upland rice productivity and suppressed weed growth under intensified land use in Côte d'Ivoire, West Africa. They also showed that rice yield strongly correlated with the legume P uptake. Similarly, a synergy between legume fixed N and P supply has been reported (Cassman, Singleton, and Linquist 1993). Kirk et al. (1998), therefore, suggested that this synergy should be exploited to maximize the yields of crops grown in rotation with N_2-fixing legumes. Furthermore, Tian, Carsky, and Kang (1998) reported a 900% phosphorus (P)–induced increase in N accumulation of tropical leguminous cover crops grown on Alfisols in Nigeria. In an acidic Oxisol deficient in P, biomass (193%) and N accumulation (295%) in *Centrosema spp.* increased in response to added P (Cadisch et al. 1993).

Application of P from locally available phosphate rock (rock P) to N_2-fixing legumes can be another low-cost technology to produce large amounts of N-rich biomass of improved legume fallows, which have the potential through biological nitrogen–fixation (BNF) to contribute to improving soil fertility and increasing crop productivity. Large deposits of rock P exist in sub-Saharan Africa (Buresh, Smithson, and Hellums 1997). The use of rock P in the strongly weathered and P-deficient acidic soils (Oxisols and Ultisols) of the humid forest agroecosystems of West Africa is agronomically responsive (Mokwunye 1995) and economically profitable because the unit price of P from the rock P can be as little as one third the price of a unit of P from commercially available superphosphates (Nye and Kirk 1987). However, rock P is sparingly soluble and thus has limited potential as a P source for direct application. Some legumes have been reported to enhance rock P solubilization under acidic soil conditions (Somado et al. 2003).

Limited studies are available on the effect of rock P application on solubilization of rock P, biomass production, and P and N accumulation in prerice legume cover crops and the benefits to rice following in a cropping sequence. The adoption of legume with rock P by farmers would, however, imply that farmers have to grow the legume cover crops for one season and then follow up with an upland rice crop. It is hypothesized that the succeeding rice crop will benefit from the residual P effects, derived from enhanced solubilization of the rock P by the previous legume cover crop. The legume cover crop will also contribute fixed N to the succeeding rice crop, a win–win situation. However, it is not known which cover crops under the influence of sources of applied P will contribute the most residual P and N and enhance the yield of the succeeding upland rice under P-deficient Ultisols.

The objectives of this study were to evaluate the effects of added P sources on cover crops, and the contribution of the residual P and cover crops to the yield of the succeeding upland rice grown in rotation sequence.

MATERIALS AND METHODS

Location and Site Characterization

Two separate experiments were carried out in Côte d'Ivoire in 2001 to 2002, including a pot experiment at the main research center of Africa Rice Center (WARDA) at Mbé [(screen-house trials, 7.5° N, 5.1° W, 280 m above sea level (derived savanna)] and a field experiment at Danané [7.3° N, 8.2° W, 336 m above sea level; annual rainfall of 1100 mm (bimodal)] in the humid forest agroecosystem. The site at Danané had repeatedly been planted to upland rice by the local farmers where soil samples were taken from 0 to 20 cm for soil characterization and screen-house experiment. The experimental soils had earlier been described by Somado, Sahrawat, and Kuehne (2006) as Ultisols with pH 4.7–5.2 (acidic) and Bray 1 P of 4 mg kg^{-1} (P deficient).

Screen-House Experiment: Influence of Two Sources and Two Rates of Applied P to *Crotalaria Micans* used as Green Manure on Yield of Subsequent Rice

Experimental Design and Treatments

Topsoil samples (0–20 cm) were collected from an upland field under long-term natural fallow vegetation at Danané, transported to Mbé, dried, sieved (<10 mm) and used for the screen-house experiment. A root nodulating N_2-fixing legume, *Crotalaria micans* Link (Syn. *C. anagyroides* Kunth), native to southeast Asia and reported to be a promising green manure legume in parts of West Africa (Becker and Johnson 1998), was used for the study.

In the screen house, concrete boxes measuring 2 m × 1 m × 0.6 m were filled with the sieved soil samples to a depth of 40 cm. A 10-cm gravel layer underneath the soil and a lateral outlet to the drainage canal enhanced drainage to avoid water logging. The experiment was a 2 × 2 factorial consisting of two sources of applied P [triple superphosphate (TSP) and Mali (Tilemsi rock P) rock P] and two rates of application [60 kg P ha^{-1} and zero P (control)]. The experiment was laid out in three replications in a randomized complete block design. In screen-house experiments, 60 kg P ha^{-1} was recommended for upland rice (Sahrawat, Jones, and Diatta 1995; Somado, Sahrawat, and Kuehne 2006). Because most farmers do not apply fertilizer, an absolute control without P was included as a treatment. The total P content of the finely ground (<0.3 mm) Mali rock P used for the study was 0.14 g P kg^{-1} rock P, with an available P of 0.42 g kg^{-1} P_2O_5 as measured in neutral ammonium citrate (Somado, Sahrawat, and Kuehne 2006). Water-soluble TSP was used as a reference P source. No mineral N fertilizer was applied, but uniform dose of 100 kg potassium (K) ha^{-1} as potassium chloride (50% K) was supplied. Before sowing of the legumes, both P sources and K fertilizer were applied basal and manually incorporated onto the top 5- to 10-cm soil layer. Soil moisture in each of the nine concretebased microplots was kept at field capacity throughout the experiment.

The legume seeds were first scarified for 30 min in concentrated sulfuric acid (commercial grade) to break dormancy and achieve a high germination rate and uniform crop establishment. The seeds were then rinsed with tap water and air dried. Seeds were dibble seeded at a density of 100 seeds m^{-2} (0.10 × 0.10 m) in each of the nine concrete boxes. The seedlings were thinned down to three per box at 14 days after sowing. Nine additional concrete boxes were similarly filled with the sieved soil, supplied with P sources but no legume seeds were sown to serve as bare fallow (control).

At 8 weeks after sowing (WAS), corresponding to the time available for a short-duration preceding green manure crop grown in the transition period between the dry and wet seasons, in the absence of food or cash crops in the field, the biomass was slashed and incorporated onto the soil. Rice (*O. sativa* cv. 'WAB-56-60') was sown in each of the previous legume and bare-fallow boxes at a seed rate of $50\,kg\,ha^{-1}$. Three plants were maintained per box. No chemical fertilizer was applied. Boxes were kept weed-free throughout the experiment.

Sampling and Measurement

Samples were collected for measurement of P concentration in the legume shoots. Rice was harvested at maturity from whole boxes. Rice straw was oven dried at 80 °C for 72 h and weighed. Grain weight was recorded at $140\,g\,kg^{-1}$ moisture content.

Field Experiment: Influence of P Supplied to Cover Crops on the Response of Succeeding Rice in the Sequence

Experimental Design and Treatments

This experiment was conducted based on the promising results from the screen-house experiment. The aim was to identify cover crops with potential to solubilize P from phosphate rock as an affordable alternative source of P for upland rice production in the humid forest agroecosystems. The treatments were 20 cover crops (14 legumes and 6 nonlegumes) and three levels of P supply: (1) no added P (control, farmers' practice); (2) unlimited soluble P with $100\,kg\,P\,ha^{-1}$ as TSP (potential production); (3) $100\,kg\,P\,ha^{-1}$ as Mali rock P arranged as split plots in a randomized complete block design, with three replications. Ninety $kg\,P\,ha^{-1}$ as TSP is recommended for field upland rice production in the humid forest agroecosystem (Somado, Sahrawat, and Kuehne 2006). Because of the slow release of P from phosphate rock, $100\,kg\,P\,ha^{-1}$ of each source of applied P was used in this study.

The cover crops were in the main plots while levels of P supply were in the subplots ($9\,m^2$). The seeds of small seeded-cover crops (e.g., *Aeschynomene histrix*, *Stylosanthes guianensis*) were first scarified using the same procedure as in the screen-house experiment. Seeds were dibble seeded at a density of 100 seeds m^{-2} for small seeded cover crops, 25 seeds m^{-2} for large seeded (e.g., *Canavalia* and *Mucuna*), and 60 seeds m^{-2} for other cover crops.

Basal application of the P sources and K at 100 kg ha^{-1} as potassium chloride (50% K) was done just before sowing of the cover crops as described for the screen-house experiment. No mineral N fertilizer was applied. All plots were kept weed-free by manual weeding throughout the experiment.

Sampling and Measurement

The cover crops were allowed to grow into the dry season until the beginning of the wet season of year 2. Plants (aboveground and roots) were periodically sampled at 28, 56, and 84 days after sowing (DAS) and at the beginning of the following wet season for the determination of final biomass production and N and P uptake. Plants were harvested from 0.25 m^2 at each sampling time. Total fresh weight was taken and the stalk and leaves were cut into pieces, mixed thoroughly, and subsampled for fresh weight. The dry weight of these subsamples was measured after oven drying at 80 °C for 72 h. Dry biomass was expressed in kg ha^{-1}. Root samples were extracted using an Eijelkamp root auger of 8 cm diameter to a depth of 0.15 m (750 cm^3) from three cores within the 0.25-m^2 sampling area. Samples were washed and root nodules were teased out from the roots, counted, dried separately from the roots in the oven at 80 °C for 72 h, and weighed.

Phosphorus concentration in the plant samples was analyzed by digesting the plant samples with a 2:1 (v/v) mixture of concentrated nitric and perchloric acid. The P concentration in the digests was analyzed by colorimetry following the vanado-molybdate yellow method. Total N concentration in the plant parts was determined by adapting the method described by Novozamsky et al. (1983).

Root mass density (RMD, mg cm^{-3}) was calculated as root mass per unit of soil volume (750 cm^3). Phosphorus and N accumulation in the plant was calculated from the products of concentrations of these nutrients and aboveground dry biomass, and P-use index (PUI) was expressed as total dry biomass production at the respective sampling periods in unlimited P supply relative to zero P.

Response of Upland Rice to Residual P Supply and Cover Crops

To assess the contribution of the residual P supply and cover crops to succeeding upland rice in the rotation sequence, at the end of the dry season all cover crops were slashed, dried, and burnt according to the local farmers' practices. Before burning, plant samples were collected for biomass determination and nutrient analyses.

All plots were then prepared with hand hoeing and dibble seeded (50 kg ha^{-1} seed rate) to the 115-day upland rice variety ('WAB-56-60'), a popularly-grown *O. sativa*, at a spacing of 25 × 25 cm. Plots did not receive any mineral N, P, or K fertilizer and were kept weed-free throughout the experiment. Plant height was measured at maturity. Rice was harvested at maturity from a 6-m^2 harvest area. Straw and grain weight were recorded. Grain yield data were corrected for 140 g kg^{-1} grain moisture content. Numbers of tillers and panicles were recorded. Harvest index for dry matter was calculated as the ratio of grain yield to total aboveground dry-matter yield. Agronomic residual P-use efficiency was calculated as grain yield in increase because of P divided by P applied to the previous cover crops. Grain and straw samples were collected for N and P analyses. However, soil samples collected at rice seeding and rice straw and grain samples were abandoned because of the civil war that broke out in Côte D'Ivoire in 2002.

Statistical Analyses

The screen-house rice grain and total dry biomass yield data were analyzed as a $2 \times 2 \times 2$ factorial experiment (2 levels of fallow management, 2 levels of P sources, 2 P rates) using the general linear model procedures of SAS (SAS Institute 2000). Mean comparison was done using single degree of freedom contrast (Table 1). Field data were analyzed as split plot using the mixed model procedures of SAS with the restricted maximum likelihood method (REML) for variance components estimates (SAS Institute 2000). Phosphorous supply levels and cover crops were considered as fixed effects, whereas replications were random effects. Total aboveground dry biomass of the cover crop at the beginning of the wet season, before the sowing of succeeding rice, was used as a covariate in the analyses of plant height at harvest, rice yield, and yield component data.

Furthermore, grain yield was sorted and analyzed by previous P supply to identify which legume best contributed to rice grain yield from previous Mali rock P treatment. Pearson's correlation coefficients were calculated among traits of biomass, N and P accumulation in cover crops supplied with Mali rock P, and rice agronomic traits using PROC CORR of SAS (SAS Institute 2000).

RESULTS

Screen-House Experiment

Rice Grain Yield and Total Dry Biomass Accumulation as Influenced by Fallow Management, and Sources and Rates of Applied P to Crotalaria Micans (Green Manure)

Independent of the fallow management strategies, previous application of 100 kg P ha^{-1} enhanced ($P < 0.001$) rice grain yield and total dry biomass by 23 to 24% over previous zero-P treatment (Tables 2 and 3). When

Table 1. Summary of single degree of freedom contrast used to compare treatment effects on rice yield as influenced by *C. micans* fallow management and sources and rates of applied P on P-deficient acid soil under screen house

Treatment no.	Treatment details	Contrasts of interests	Treatment contrasts	Questions answered[a]
1	Legume GM alone	Response to P (0P vs. TSP + PR)	1 + 6 vs. 2 + 3 + 4 + 5	i
2	TSP alone	TSP vs. PR	2 + 3 vs. 4 + 5	ii
3	TSP + legume GM	GM vs. Bare fallow	1 vs. 6	iii
4	Mali Rock P alone	(TSP + GM) vs. TSP	3 vs. 2	iv
5	Mali Rock P + legume GM	(PR + GM) vs. PR	5 vs. 4	v
6	Farmer control (no P & no legume GM)			

[a]Questions answered based on contrast of interest:

i. Was there a response to P application? That is, did P fertilizers (TSP & Mali Rock P) have any influence on rice yields (mean averaged over treatments)?

ii. Was the average response of rice to the water-soluble TSP greater than that of the sparingly soluble Mali Rock P?

iii. Without P application, was the legume green manure (legume GM) effect on rice superior to that of bare fallow management?

iv. Did the addition of TSP to legume GM grown as preceding crop increase the subsequent rice crop yield, as compared to TSP applied alone to rice?

v. Did the addition of Mali Rock P to legume GM grown as preceding crop increase the following rice crop yield, as compared to a sole application of Mali Rock P to rice?

Table 2. Grain yield and total aboveground dry biomass of upland rice as influenced by sources of applied P and *C. micans* green manure fallow management on P-deficient acid soil in the screen house

Phosphate sources	Grain yield ($Mg\,ha^{-1}$)			Total biomass ($Mg\,ha^{-1}$)		
	Bare	Legume	Mean	Bare	Legume	Mean
Zero P	3.3	2.7	3.0	5.5	4.4	5.0
Mali Rock P	3.5	3.5	3.5	6.0	5.8	5.9
TSP	3.7	3.9	3.8	6.3	6.6	6.5
Mean	3.5	3.4		5.9	5.6	
Mean applied P	3.6	3.7	3.7	6.2	6.2	6.2
S. E. (D.F. = 1) fallow			0.06			0.11
S. E. (D.F. = 1 P source			0.07			0.14
S. E. (D.F. = 1) P source × fallow			0.10			0.19

Table 3. Single degree of freedom contrast for above means of grain yield and total aboveground dry biomass of upland rice as influenced by sources of applied P and *C. micans* green manure fallow management on P-deficient acid soil in the screen house

Source of variation	F significance[a]	
	Grain yield ($Mg\,ha^{-1}$)	Total biomass ($Mg\,ha^{-1}$)
Non vs. applied P (Rock P + TSP)	***	***
TSP vs. Rock P	Ns	*
No legume vs. unfertilized legume	***	**
(TSP + legume) vs. TSP alone	*	Ns
(Rock P + legume) vs. Rock P alone	Ns	Ns

[a]ns means not significant at $P = 0.05$; *, **, and *** mean significant at $P = 0.05$, 0.01, and 0.001, respectively. Details on the contrast used are described on Table 1.

averaged across fallow management strategies, there was no significant difference in grain yield between water-soluble TSP and the sparingly soluble Mali rock P, but total dry biomass was increased by 0.6 $Mg\,ha^{-1}$ with application of soluble TSP over that with Mali rock P (Table 2). On average, when P was not applied, *C. micans* legume green manure fallow management depressed rice grain yield by 22% over bare fallow management (Table 2). The addition of TSP or Mali rock P to the legume green manure did not significantly influence grain yield or total biomass compared with sole application of Mali rock P or TSP directly to the rice (Table 3). The P concentration of the *C. micans* residues used as green manure in the experiment was 1.6 for the unfertilized control, 1.8 for rock P, and 2.5 $g\,kg^{-1}$ DM for TSP treatment. The standard error (S.E.) was 0.27.

Field Experiment

Biomass Accumulation and Root Nodule Production in Cover Crops as Influenced by P Supply

There were significant interactions in aboveground dry biomass yield between P supply and cover crop genotypes (Tables 4 and 5). The highest aboveground dry biomass yields were obtained, at all sampling periods, with application of Mali rock P at 100 $kg\,ha^{-1}$ to *Canavalia ensiformis* (Figure 1). At the end of the dry season, the final dry biomass was significantly different among cover crop genotypes (data not shown). Phosphorus deficiency reduced the final biomass by more than 30% compared with biomass produced when P was supplied, but there was no significant difference in the final biomass produced between soluble TSP and Mali rock P as P source.

Table 4. Significance of cover crops, phosphate sources, and interactions on biomass accumulation, root mass density, nodule formation, shoot N and P accumulation, and P-use index under field conditions in the humid forest agroecosystem, West Africa

Source of variation	NDF	DDDF	Probability level of F[a]							
			Total dry biomass ($Mg.ha^{-1}$)			Root mass density ($mg.cm^{-3}$)			Root nodules (no. $plant^{-1}$)	
			28 DAS	56 AS	84 DAS	28 DAS	56 DAS	84 DAS	28 DAS	56 DAS
Cover crops (CC)	19	38	<0.001	<0.001	<0.001	0.01	0.001	0.01	<0.001	<0.001
Phosphate supply (PS)	2	80	<0.001	<0.001	<0.001	0.09	0.19	0.01	0.01	0.75
CC × PS	38	80	0.01	<0.001	0.06	0.39	0.06	0.54	<0.001	0.99
-2 Res Log likelihood			1652	1807	2174	237	362	418	808	808

[a]Probability levels are test of fixed effects; NDF, numerator degree of freedom; DDF, denominator degree of freedom.

Table 5. Significance of cover crops, phosphate sources, and interactions on shoot N and P accumulation, and P-use index under field conditions in the humid forest agroecosystem, West Africa

Source of variation	NDF	DDDF	Probability level of F[a]								
			N uptake ($kg\,ha^{-1}$)			P uptake ($kg\,ha^{-1}$)			P-use index		
			28 AS	56 DAS	84 DAS	28 DAS	56 DAS	84 DAS	28 DAS	56 DAS	84 DAS
Cover crops (CC)	19	38	<0.001	<0.001	<0.001	<0.001	<0.001	0.35	0.11	<0.001	0.15
Phosphate supply (PS)	2	80	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	<0.001	<0.001	<0.001
CC × PS	38	80	0.12	<0.001	0.01	0.19	<0.001	0.84	0.02	<0.001	0.15
-2 Res Log likelihood			837	945	1278	601	793	1315	434	411	585

[a]Probability levels are test of fixed effects; NDF, numerator degree of freedom; DDF, denominator degree of freedom.

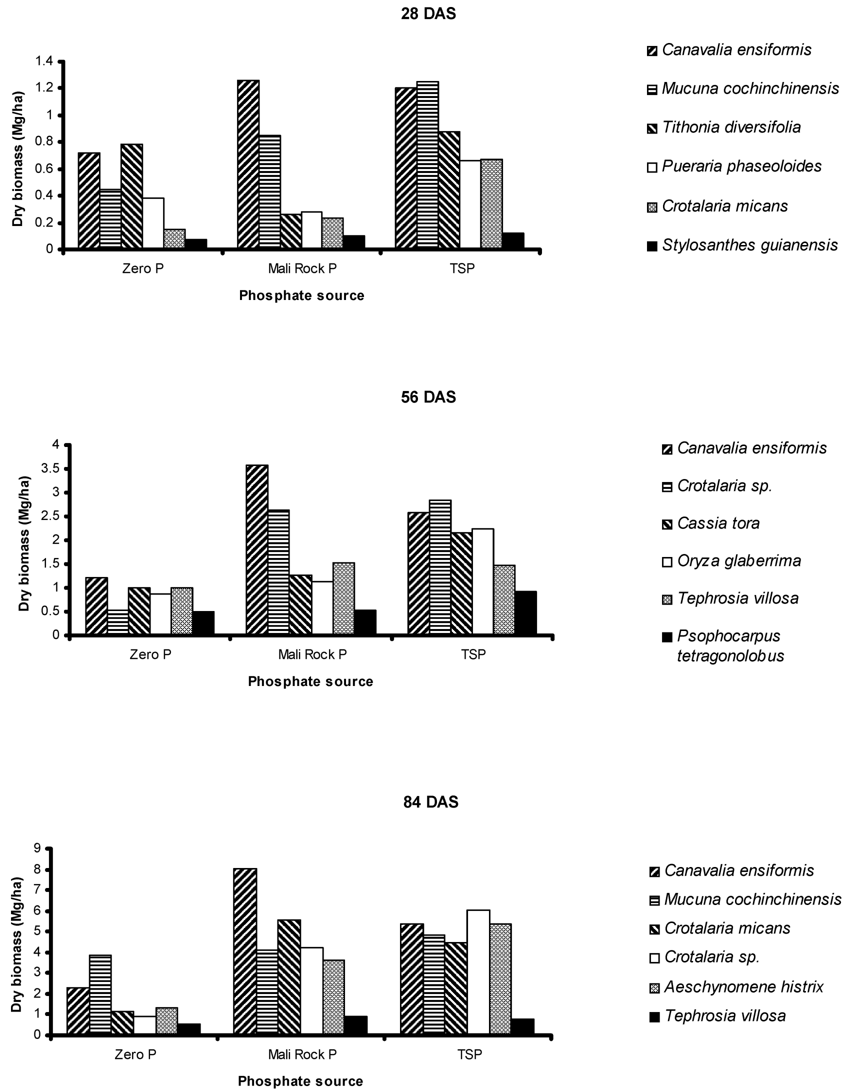

Figure 1. Biomass production of selected best cover crops as influenced by previous sources of applied P at 28, 56, and 84 DAS under field conditions in the humid forest agroecosystem, West Africa.

The ranking of the cover crops on the basis of belowground dry biomass density varied with sampling period (Table 6). At the initial growth stage (28 DAS), *Mucuna cochinchinensis* ranked highest (1.14 mg cm^{-3}), but at 56 DAS, *C. ensiformis* and two nonlegumes (*Oryza glaberrima* cv. 'CG14' and *Oryza sativa* cv. 'Locale') gave higher

Table 6. Influence of cover crop fallow and levels of P supply on root mass density, N and P accumulation in the shoots, and P-use index under field conditions in the humid forest agroecosystem, West Africa

Cover crops	Root mass density ($mg\,cm^{-3}$)			Nitrogen uptake ($kg\,ha^{-1}$)			Phosphorus uptake ($kg\,ha^{-1}$)			P-use index		
	28 DAS	56 DAS	84 DAS	28 DAS	56 DAS	84 DAS	28 DAS	56 DAS	84 DAS	28 DAS	56 DAS	84 DAS
Aeschynomene histrix	0.3	0.7	0.8	5.8	34.9	106.7	1.5	8.8	19.6	2.2	2.3	2.6
Cajanus cajan	0.4	1.1	2.4	4.2	28.4	79.7	1.0	8.8	15.1	1.3	1.7	3.7
Canavalia ensiformis	0.5	2.0	2.9	30.5	58.0	116.7	6.0	15.2	14.7	1.9	2.6	3.9
Cassia tora	0.3	1.0	1.9	4.7	29.1	31.7	1.5	10.0	23.9	1.6	1.6	1.4
Eupatorium odorata	0.1	0.9	1.4	6.0	18.3	31.9	3.2	4.4	17.3	2.3	2.3	1.8
Crotalaria micans	0.3	0.7	1.7	7.1	30.3	74.0	3.3	5.8	24.5	2.4	1.7	3.5
Crotalaria sp. (Cameroun)	0.1	1.4	1.5	5.9	43.7	95.7	1.3	14.5	25.5	2.3	4.0	4.2
Dolichos lablab	0.3	1.5	1.1	12.0	27.7	53.9	2.8	10.2	11.3	1.3	2.4	4.3
Mucuna cochinchinensis	1.1	1.1	Na[a]	23.5	40.1	137.1	5.5	9.1	30.5	2.5	1.3	1.2
Oryza glaberrima (CG 14)	0.7	2.1	2.6	9.8	26.7	54.2	4.2	17.1	38.4	2.2	1.6	2.6
Oryza sativa (local variety)	0.3	2.1	2.3	5.6	19.9	42.7	1.4	16.1	37.4	2.6	2.5	3.5
Oryza sativa (WAB 56-50)	0.6	1.8	1.8	2.6	26.1	35.5	1.3	8.1	34.5	1.9	2.4	1.9
NERICA 2 (interspecific rice)	0.2	1.2	3.1	2.3	26.1	55.2	0.6	9.3	23.1	1.5	5.8	2.6
Psophocarpus tetragonolobus	0.2	0.7	0.8	4.2	15.0	66.4	1.4	6.8	14.1	1.0	1.4	2.4
Pueraria phaseoloides	0.3	0.6	0.6	12.5	27.9	69.7	3.8	14.5	18.2	1.2	3.4	3.8

Sesbania pachycarpa	0.3	0.7	1.2	6.3	25.2	69.4	2.9	12.0	22.2	1.2	1.1	1.4
Stylosanthes guianensis	0.1	0.3	1.5	3.3	15.4	47.5	1.1	13.0	37.9	1.6	2.3	3.1
Tithonia diversifolia	0.0	0.9	3.2	14.1	17.6	46.7	6.2	11.8	30.3	0.8	2.1	1.1
Tephrosia purpurea	0.1	0.5	0.6	6.3	30.2	Na[a]	2.1	17.3	9.5	2.2	1.4	Na
Vigna radiate	0.2	1.3	1.8	6.1	24.1	46.7	1.9	8.6	18.2	3.5	3.2	3.8
Mean	0.3	1.1	1.7	8.6	27.2	64.0	2.7	11.1	26.2	1.9	2.4	2.7
S. E. (D. F. = 19)	0.17	0.28	0.47	1.92	3.26	11.88	0.75	1.64	14.56	0.33	0.31	0.61
Phosphate supply												
Zero P	0.2	1.2	1.2	5.8	14.6	32.9	1.5	2.8	12.2	1.0	1.0	1.0
Mali Rock P	0.4	0.9	1.9	8.3	31.4	77.5	2.3	15.3	34.8	1.9	2.8	3.3
TSP	0.4	1.2	2.0	11.8	35.6	81.5	4.2	8.3	31.5	2.8	3.2	3.9
Mean	0.3	1.1	1.7	8.6	27.2	64.0	2.7	8.8	26.2	1.9	2.4	2.7
S.E (D.F. = 2)	0.06	0.11	0.18	0.75	1.26	4.60	0.29	2.82	5.64	0.13	0.12	0.24

[a]Na, not available.

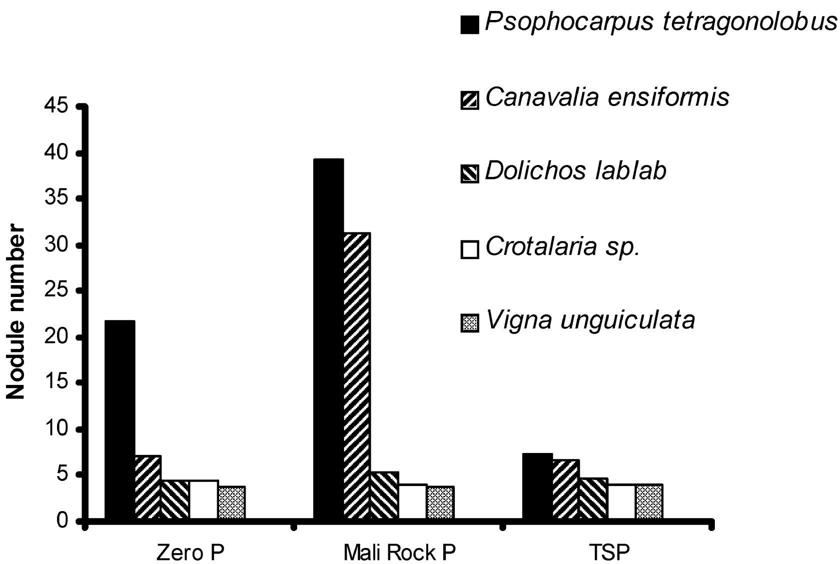

Figure 2. Root nodules production in selected best legume cover crops as influenced by previous sources of applied P at 28 DAS under field conditions in the humid forest agroecosystem, West Africa.

root mass densities (2.0 mg cm^{-3}) compared to the other cover crops. At 84 DAS, root mass densities of the interspecific cultivar ('NERICA 2') and *Tithonia diversifolia* were 10–400% higher than root mass densities of the other cover crops.

Root mass density at 84 DAS was significantly increased by more than 50% with supply of either TSP or Mali rock P compared with the control, zero P (Table 6). Root mass density was similar with both sources of P supply. However, at other sampling periods, there were no significant differences in root mass densities among levels of P supply (Table 4).

At 28 DAS, root nodule production was higher (31–39 $plant^{-1}$) with application of Mali rock P to *Canavalia ensiformis* and *Psophocarpus tetragonolobus* TPT3 than other combinations of P supply and cover crops (Figure 2). At 56 DAS, there was no significant interaction between P supply and cover crops on root nodulation (Table 6).

Nitrogen and P Accumulation, and P-Use Index in Cover Crops as Influenced by P

Canavalia ensiformis accumulated the highest amount of N in the shoots at 28 DAS (31 kg ha^{-1}), 56 DAS (58 kg ha^{-1}) and the second best at 84 DAS (117 kg ha^{-1}) after *Mucuna cochinchinesis* (Table 6). Mean N accumulation in the legume cover crops ranged between 32 and 137 kg ha^{-1} at 84 DAS.

Nitrogen accumulation was similar among the nonlegume cover crops at 56 DAS (18–27 kg ha^{-1}) and at 84 DAS (31–54 kg ha^{-1}).

Mean N uptake by the cover crops was 1.4 to 2.4 times higher with P supply than without P at all sampling periods (Table 6). At the initial growth stage (28 DAS), TSP gave 46% higher N uptake than Mali rock P, but at other sampling periods, there were no statistical differences in N uptake between the two sources of P supply.

At 28 DAS, P uptake was higher ($P < 0.001$) in *C. ensiformis* and *T. diversifolia*, each with 100 kg P ha^{-1} compared with the other cover crops (Table 6). *O. glaberrima* and *Tephrosia purpurea* accumulated greater amounts of P in the shoots (17 kg ha^{-1}) at 56 DAS than the other cover crops. There were no significant differences in P uptake among cover crops at 84 DAS (Table 4). The influence of P supplied as Mali rock P or TSP on P accumulation in the shoots followed a trend similar to N uptake at various sampling periods (Table 6).

Results on P-use index (Table 4) showed that there were no significant differences among the cover crops at 28 and 84 DAS, but at 56 DAS, the index was the highest (5.8) in rice cv. 'NERICA 2,' a nonlegume cover crop (Table 6). At 28 and 56 DAS, P-use index was 33–47% higher ($P < 0.001$) with TSP as P source than with Mali rock P, but at 84 DAS the P-use index was similar for both sources of P (Table 6).

Influence of Residual P and Cover Crops on Succeeding Rice in Rotation Sequence

Plots supplied with TSP or Mali rock P gave 44% more grain yield and 10% more straw yield compared to zero-P plots. There was no significant difference in yields between TSP and Mali rock P treatments (Tables 7 and 8). Number of tillers and panicles produced per unit area and harvest index for dry-matter production followed a trend similar to that of yields (Tables 7 and 8). Plant height at maturity and agronomic residual P-use efficiency were not significantly affected by the supply of either TSP or Mali rock P (Table 8).

When averaged across previous P supply, previous *Canavalia ensiformis* plots gave the highest rice grain yield of 2.7 Mg ha^{-1} (Tables 7 and 8) among the legume cover crops evaluated. When grain yield of the succeeding rice was analyzed by previous Mali rock P supply, previous *Canavalia ensiformis* also gave the highest grain yield of 3.1 Mg ha^{-1}, more than 180% greater than the yield from 2-year continuous unfertilized rice (cv. 'WAB 56-50') (Figure 3). Among the nonlegume cereal cover crops averaged across P supply, previous plots of 'NERICA 2' (interspecific rice) and *Oryza glaberrima* (African rice) gave 43% higher grain yield in the succeeding rice over that from plots previously sown to *Oryza sativa* (exotic Asian rice) supplied with rock P

Table 7. Significance of plant height, yield and yield, components of upland rice as influenced by previous cover crops and levels of P supply under field conditions in the humid forest agroecoystem, West Africa

Phosphate source	Num DF	Den DF	Probability level of F[a]						
			Aboveground dry biomass ($Mg\,ha^{-1}$)			Height at maturity (cm)	Tillers (no. m^{-2})	Panicles (no. m^{-2})	Agronomic residual P-use efficiency
			Grain	Straw	Total				
Previous cover crop (PCC)	19	38	0.02	0.60	0.08	0.36	0.37	0.27	0.94
Phosphate source (PS)	2	80	<0.001	0.01	<0.001	0.81	0.01	0.002	0.89
PCC × PS	38	80	0.38	0.23	0.49	0.76	0.29	0.50	0.68
PCC dry biomass ($kg\,ha^{-1}$) burnt before sowing rice (covariate)	1	79	0.001	0.08	0.001	—	0.40	0.67	—
-2 Res Log likelihood			1943	1905	2037	892	1107	1097	30

[a]NDF, numerator degree of freedom; DDF, denominator degree of freedom.

Table 8. Mean plant height, yield, and yield components of upland rice as influenced by previous P supply and cover crop fallow under field conditions in the humid forest agroecosystem of West Africa

Previous cover crops	Aboveground dry biomass ($Mg\,ha^{-1}$)			Height at maturity (cm)	Tillers (no. m^{-2})	Panicles (no. m^{-2})	Agronomic residual P-use efficiency
	Grain	Straw	Total				
Aeschynomene histrix	2.2	2.3	4.5	121	107	102	0.46
Cajanus cajan	2.2	2.5	4.8	122	117	106	0.24
Canavalia ensiformis	2.7	2.5	5.2	117	117	104	0.22
Cassia tora	2.3	2.7	5.0	121	115	106	0.18
Eupatorium odorata	2.5	2.3	4.8	124	112	102	0.10
Crotalaria micans	2.1	2.2	4.2	119	104	95	0.37
Crotalaria sp. (Cameroun)	2.1	2.5	4.5	122	117	106	0.38
Dolichos lablab	2.0	2.3	4.3	119	110	99	0.40
Mucuna cochinchinensis	2.3	2.4	4.7	126	107	105	0.44
Oryza glaberrima (CG 14)	1.9	2.2	4.1	120	114	106	0.25
Oryza sativa (local variety)	1.4	2.0	3.4	120	98	90	0.23
Oryza sativa (WAB 56-50)	1.4	1.8	3.1	116	102	91	0.21
NERICA 2	2.0	1.9	3.8	119	97	88	0.26
Psophocarpus tetragonolobus	2.2	2.5	4.8	124	123	114	0.29
Pueraria phaseoloides	2.2	2.3	4.5	122	115	103	0.30
Sesbania pachycarpa	2.1	2.4	4.4	119	113	104	0.14
Stylosanthes guianensis	2.0	2.2	4.1	120	115	103	Na[†]
Tithonia diversifolia	1.9	2.2	4.1	127	111	103	0.31
Tephrosia purpurea	2.4	2.2	4.6	124	108	100	0.43
Vigna radiate	1.6	2.1	3.7	124	101	94	0.46
Mean	2.1	2.3	4.3	121	110	101	0.30
S.E. (D.F. = 19)	0.19	0.14	0.25	2.43	6.00	5.98	0.06

(*Continued*)

Table 8. Continued

Previous cover crops	Aboveground dry biomass ($Mg\,ha^{-1}$)			Height at maturity (cm)	Tillers (no. m^{-2})	Panicles (no. m^{-2})	Agronomic residual P-use efficiency
	Grain	Straw	Total				
Phosphate supply							
Zero P	1.7	2.1	3.8	121	103	94	–
Mali Rock P	2.3	2.4	4.6	122	115	105	0.30
TSP	2.3	2.3	4.6	121	113	104	0.29
Mean	2.07	2.3	4.3	121	110	101	0.30
S.E. (D. F. = 2)	0.08	0.06	0.11	0.97	2.40	2.38	0.020

[a]Na, not available.

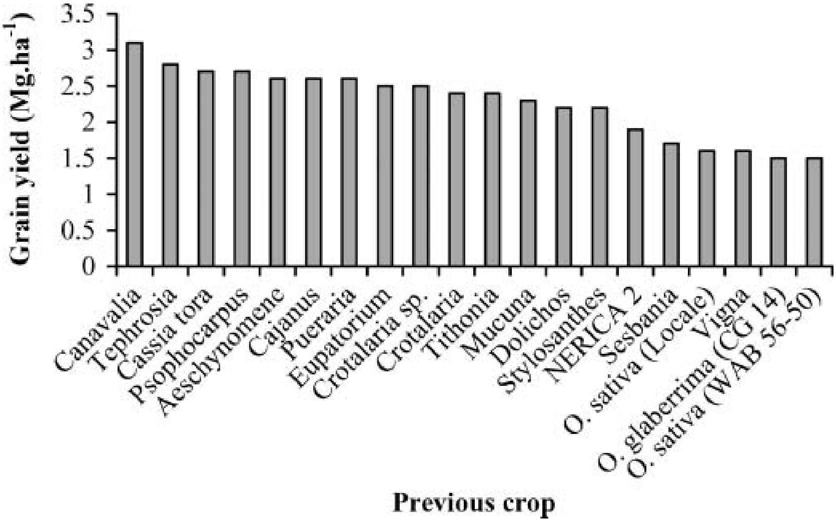

Figure 3. Grain yield of upland rice as influenced by previous cover crop fallow supplied with Mali Rock P under field conditions in the humid forest agroecosystem, West Africa. Vertical bar is standard error of means.

(Table 8). A combination of previous Mali rock P and 'NERICA 2' gave 27% higher grain yield compared to previous rock P plots of *Oryza sativa* (cv. WAB 56-50) and 72% higher grain yield over previously unfertilized cv. 'WAB 56-50' (farmers' practice) (Figure 3).

Correlations of Rice Agronomic Traits with Previous Cover Crop Biomass, N, and P Accumulation under the Influence of Mali Rock P

At all sampling periods, there were significant correlations between N and P uptake of the cover crops (Table 9). Root mass density at 28 and 56 DAS significantly correlated with N and P uptake in the cover crops at these sampling periods. Also, there were significant positive correlations among biomass, N, and P accumulated in the cover crops with grain yield of the succeeding rice (Table 9).

DISCUSSION

Integrated management of legume cover crop fallow and phosphate rock (locally available source of P) can provide complementary sources of N and P to enhance upland rice productivity in legume-rice based systems under acidic P-deficient soil conditions. In this study, genotypic differences in biomass and in N and P uptake into the shoots of the

Table 9. Correlation coefficients and probability of significance (n = 60) among biomass, Naccumulation, and P accumulation in cover crops and upland rice yield following in a rotation under field conditions in the humid forest agroecosystem, West Africa[a]

	BM28	Nup28	Pup28	RMD28	BM56	Nup56	Pup56	RMD56	BM84	Nup84	Pup84	RMD84	BMF	Yldkgha
Nup28	0.96													
	<.001													
Pup28	0.77	0.80												
	<.001	<.001												
RMD28	0.34	0.32												
	0.009	0.014	0.031											
BM56	0.523	0.477	0.007	0.056										
	<.001	0.001	0.959	0.672										
Nup56	0.46	0.42	−0.06	0.07	0.91									
	<0.001	<0.001	0.67	0.61	<.001									
Pup56	0.19	0.11	0.07	0.11	0.47	0.34								
	0.150	0.384	0.602	0.417	<.001	0.007								
RMD56	0.25	0.24	0.22	0.16	0.27	0.29	<.001							
	0.053	0.061	0.094	0.211	0.039	0.027	0.979							
BM84	0.57	0.60	0.12	0.22	0.51	0.49	0.00	0.11						
	<.001	<.001	0.360	0.085	<.001	<.001	0.996	0.422						
Nup84	0.57	0.58	0.34	0.31	0.40	0.42	−0.09	0.16	0.77					
	<.001	<.001	0.009	0.015	0.002	0.001	0.510	0.226	<.001					
Pup84	0.05	0.07	−0.02	0.02	0.07	0.01	−0.06	−0.11	0.50	0.28				
	0.705	0.615	0.866	0.851	0.580	0.930	0.674	0.424	<.001	0.030				
BMF	−0.07	−0.04	−0.17	−0.09	−0.04	−0.01	−0.17	−0.02	0.17	0.03	0.21	0.05		
	0.615	0.766	0.196	0.489	0.781	0.914	0.191	0.878	0.184	0.803	0.103	0.700		
Yldkgha	0.34	0.28	0.07	−0.03	0.29	0.22	0.18	−0.06	0.34	0.26	0.13	0.03	0.30	
	0.008	0.031	0.584	0.796	0.025	0.087	0.160	0.635	0.007	0.046	0.308	0.824	0.019	

[a]BM, dry biomass; Nup, N uptake; Pup, P uptake; RMD, root mass density; BMF, final biomass before rice crop in year 2; Yldkgha, grain yield in kg ha^{-1}. The numbers 28, 56, and 84 indicate that samplings were done at these periods in days after sowing.

cover crops were observed as early as 28 DAS from the field experiment. The high rooting capacity (RMD) and nodule production by *Mucuna cochinchinensis* and *Canavalia ensiformis* observed at this growth stage may have enhanced biological nitrogen fixation and thus uptake of N and P, as previously reported (Cassman, Singleton, and Linquist 1993; Somado, Sahrawat, and Kuehne 2006). Also, the production of more roots per unit surface area by these legumes compared with the others implied that a larger soil volume is available for the extraction of nutrients including N and P (Oikeh et al. 1999). Furthermore, the rapid uptake of N and P by both legumes at the initial growth stage indicates that both legumes, in addition to being used as cover crop fallow legumes in rice-based systems, will be the most suitable candidates from among the legumes evaluated for use as legume green manure. They can contribute 20 to 30 N kg ha^{-1} and organic matter of 0.48 to 0.71 Mg ha^{-1} to the production systems when grown for 1 month and incorporated prior to the upland rice crop.

On average, the superior performance in biomass production and in N and P uptake of the forage legume *Canavalia ensiformis* compared with the other cover crops may be attributed to the improvement in the solubilization of rock P compared with the other cover crops. Unfortunately, this could not be confirmed from the soil samples because they were abandoned when civil war broke out in Côte D'Ivoire in 2002.

Previous studies showed that N derived from the air correlated positively with legume nodulation and P uptake from the use of phosphate rock (Cassman, Singleton, and Linquist 1993; Somado, Sahrawat, and Kuehne 2003). In the present study, even though we did not assess N fixation, there was a synergy between N and P uptake in the cover crops as indicated by the strong positive correlation between both traits under the influence of Mali rock P (Table 9).

Because the soils used for the experiments are highly P deficient, there was a great response to P application by the cover crops. Among the legume cover crops, the application of P may have stimulated their growth, nodule number, and nitrogenase activities to enhance N uptake compared with plots without P as previously reported by Israel (1987) and Somado et al. (2003). Even though at the initial growth stage (28 DAS) the Mali rock P was slow in releasing P to the cover crops as indicated by the significantly lower N and P uptake compared with the soluble TSP, over time the acidic nature of the soil, in addition to the process of N fixation among the legumes, may have stimulated the dissolution of the rock P sufficiently to meet the P need of the cover crops. Hence, the similar response observed with both sources of P supply at 56 DAS. Similarly, Savini, Smithson, and Karanja (2006) reported a greater release of P from water-soluble TSP compared with Minjingu rock P in Kenyan Oxisol at the initial stage of incubation, although P released from the two sources later was not significant. Earlier studies reported by Anguilar and van Diest (1981) had attributed the enhanced dissolution of phosphate rock to the acidification of the rhizosphere of legumes as a result of the process of nitrogen fixation.

In the screen-house experiment, the dramatic depression in rice yields observed in the unfertilized legume plots (Table 2) may have been caused by low P concentration of the *C. micans* residues incorporated into the soil prior to rice planting. The low P concentration of *C. micans* residues might have resulted in temporary immobilization of P by soil microbes. Reports have consistently shown that the quality of the legume residues determines the mineralization–immobilization turnover of most nutrients in the residues and can lead to periods of immobilization that aggravate deficiencies relative to crop demand (Oikeh et al. 1998; Mafongoya, Barak, and Reed 2000; Somado et al. 2007). Palm (1995) suggested a critical value of P concentration of 2.5 g kg^{-1} in legume residues above which there will be net P release. Organic materials with less than 2 g kg^{-1} total P have been reported to show little or no P mineralization (Mafongoya, Barak, and Reed 2000). In the present study, the mean P concentration of *C. micans* green manure supplied with Mali rock P was less than 2 g kg^{-1}, which may have constrained the net release of P, causing grain yield depression of the succeeding rice in the rotation sequence.

In contrast to the screen-house experiment, grain yield of upland rice following a previous *Canavalia ensiformis* cover crop in the field experiment was twice the yield obtained from a 2-year continuous rice system, possibly because of the high residual effects of P and fixed N from this legume compared with other cover crops. Becker and Johnson (1998) also reported a similar increase in upland rice yield following previous N_2-fixing legume (*Crotolaria mican*) under intensified land use in the humid forest of West Africa. Furthermore, they reported a significant positive correlation between rice grain yields after legume crops with legume P uptake as observed in our study (Table 9). However, a minimal impact on lowland rice yield following a combined use of *Aeschynomene afraspera* as green manure and P application under similar soil conditions as used in the present study has been reported (Somado et al. 2003). The authors attributed the limited response to asynchrony in nutrient released from the green manure and the demand by the succeeding rice crop.

The adoption of *Canavalia ensiformis* (velvet bean) as a cover crop fallow or green manure may be attractive to the smallholder farmers in West Africa because of the food value derived from the seeds. Farmers in West Africa are often reluctant to adopt legume cover crops that are not for human consumption in spite of the positive impact on improving soil fertility (Oikeh et al. 1998).

Among the preceding nonlegume cover crops (rice varieties) evaluated, 'NERICA 2' (interspecific rice) was superior to the popular *O. sativa* (exotic Asian rice) in influencing grain yield of the succeeding rice. Thus, 'NERICA 2' may have greater potential to solubilze rock P. Moreover, 'NERICA 2' had better rooting capacity, which may have played a greater influence in the recycling of nutrients (including N and P) from the soil compared with the Asian rice and to the benefit of the succeeding crop in rotation.

Both the screen-house and field experiments showed that the residual effect of P supplied either as rock P or the more soluble TSP significantly enhanced upland rice yield over zero-P treatment as earlier reported for upland rice in the humid forest agroecosystem by Sahrawat, Jones, and Diatta (2001). Rice grain yield was similar with application of rock P and TSP, suggesting that the locally available rock P can successfully replace imported TSP in smallholder farming systems under acidic P-deficient soil conditions, provided P availability is enhanced by using preceding appropriate cover crops.

The contribution of the previous cover crop fallow to the succeeding rice could have been greater than observed in this study had the cover crop biomass been incorporated and not burnt. However, under resource-limited farming systems, the most viable option available to manage the bulky biomass produced by the cover crops before cropping of the succeeding rice in the sequence is by burning, thus limiting the benefits of the cover crops in improving soil fertility. Environmental consequences of burning are recognized as a limiting factor to the adoption of the technology by the smallholder farmers.

CONCLUSIONS

Differences among cover crops in biomass production and N and P uptake into the shoots of the plants were observed as early as 28 DAS. *Mucuna* and *Canavalia* would be the preferred candidate cover crops for use as green manure at early growth stage. Both legumes possess seeds with food value. Grain yield of rice succeeding *Canavalia* cover crop fallow supplied with Mali rock P almost tripled the yield obtained from a 2-year continuous unfertilized rice. The benefit was attributed to better biomass production and accumulation of N and P in the shoot during the fallow year, possibly due to enhanced solubilization of rock P. Among the cereal cover crops, previous 'NERICA 2' (interspecific rice) plots supplied with rock P gave 72% higher grain yield in the succeeding rice compared with previous unfertilized *Oryza sativa* (cv. 'WAB 56-50') plots. In both the screen-house and field experiments, Mali rock P was as efficient as the soluble TSP as a P source for both the production of the cover crop fallow and the rice following the cover crops in the rotation sequence.

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