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Application of low-phosphorus-containing legume residues reduces extractable phosphorus in a tropical Ultisol

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Summary

Application of legume green manure (GM) is suggested to be effective in increasing the availability of native soil phosphorus (P) and the dissolution and utilization of phosphate rock (PR)-P by food crops.

Experiments were conducted to study the dynamics of extractable P (P extracted by Bray-1-extracting solution) of an Ultisol amended with or without GM residues of contrasting P concentrations in the absence of growing plants. In two separate experiments, GM residues of *Aschynomene afraspera* (a flood-tolerant legume) and of *Crotalaria micans* (upland) with varying P concentrations were added to an acidic soil amended with PR-P or triple superphosphate (TSP) in plastic bottles. Soil moisture was brought to field capacity of the soil in the upland experiment and saturated with distilled water in the lowland setup. This was done to simulate aerobic upland and anaerobic lowland soil conditions in the relevant plastic bottles. Only P concentration of the residues added varied, while lignin and C : N ratios were similar. A temperature of 25°C was maintained throughout the experiment. Changes in soil extractable Bray-1-P were measured at the end of the incubation period (60 or 80 d). In the aerobic soils, extractable P in the combined PR+GM or TSP+GM treatments was significantly lower than in the PR- or TSP- treated soils. The amendment with GM residues alone significantly increased Bray-1-P over the unamended control in the case of the inorganic P-fertilized GM residues. The trend in extractable P was similar in the soils incubated under anaerobic conditions. However, in the case of PR, concentrations of P extracted by Bray-1 solution did not significantly change in the presence or absence of GM.

The results suggest that the incorporation of GM residues with low P concentration does not lead to a net P release in upland or lowland soils. These results have implications for nutrient cycling in farming systems in W Africa as most of the soils are poor and very low in available P.

Key words: acid soils / *Crotalaria* / *Aeschynomene* / green manure / phosphate rock / extractable Bray-1-P / W Africa

1 Introduction

Subsistence farmers in W Africa rely on organic inputs, including green manure (GM) to sustain soil fertility. Studies have shown that GM residues incorporated into the soil are effective in increasing the availability of native soil phosphate and the dissolution and utilization of phosphate rock (PR-P) by subsequent crops (*Kamh* et al., 1999; *Somado* et al., 2003). It is hypothesized that organic acids produced during decomposition of the residues by the microfaunal population prevent precipitation of phosphate by iron (Fe) and Aluminum (Al) oxides out of the soil solution (*LeMare* et al., 1987), and as a result, phosphorus (P) concentration in the equilibrium solution increases. Competition for P-sorption sites between P and the released organic acids as well as complexation of Fe and Al oxides/hydroxides by organic acids have been suggested as the key factors controlling reduction of soil P-sorption capacity and P availability in soil solution (*Singh* and *Jones*, 1976; *Nziguheba* et al., 1998). The latter author reported that decomposition of *Tithonia diversifolia* residues reduced the P sorption and increased the available-P pools of an acid soil over a 16-week period. However, plant P availability does not always increase following GM incorporation. The magnitude of the effect of GM on soil test P availability may depend on the organic residues quality, especially the C : P ratio (*Zaharah* and *Bah*, 1997).

This soil incubation study was undertaken to determine the effects of GM residues varying in P content on extractable P in the soil amended with plant residues under simulated aerobic upland and anaerobic flooded conditions.

2 Materials and methods

The experiment was conducted in January–April 1999 in the laboratory of the Agronomy Division of the Africa Rice Center (WARDA) at Mbé (7.5° N, 5.1° W, and 280 m asl) in Côte d'Ivoire (W Africa).

2.1 Soil used and its characteristics

A subsample of an acidic Aquults (Ultisol) (pH 5.2), deficient in P (4 mg kg^{-1} Bray-1 P) was used in the study. A bulk surface sample (0–20 cm) from a natural fallow field was transported in sufficient quantity to Mbé; the soil was air-dried, sieved (<2 mm), and homogenized.

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Subsample of the soil was analyzed for pH in water or 1N KCl (1:2.5), Bray-1-P (0.03 M NH4F + 0.025 M HCl in a 1:7 soil to solution ratio; *Olsen* and *Sommers*, 1982), organic C (Walkey-Black method; *Nelson* and *Sommers*, 1982) and total N (Kjeldahl; *Bremner*, 1965), cation-exchange capacity (CEC) and exchangeable base cations (1N NH4OAc, pH 7) (*Chapman*, 1965), and total P (colorimetrically after digestion of soil with nitric and perchloric acid). Exchangeable acidity (Al^{3+} + H^+) was measured by the titration method using nonbuffered, neutral salt (KCl). Some physical and chemical characteristics of the experimental soil are summarized in Tab. 1.

2.2 Fertilizer P and green manures

The Tilemsi (Mali) PR-P (finely ground <100 μm, 13.7% P) was used in the experiments. The chemical composition of the PR is given in Tab. 2. Triple superphosphate (TSP) in the granular form was used as a reference for comparison. Triple superphosphat is manufactured by treating PR with phosphoric acid (H_3PO_4); the TSP used had 19.6% water-soluble P.

Table 1: Some physical and chemical properties of soil used in the study.

Soil parameters	
Texture	Loam
pH H_2O (1:2.5)	5.2
pH KCl	4.4
Organic C (%)	1.10
Total N (%)	0.08
Available P (Bray 1) (mg kg^{-1})	4.0
Exch. Ca (cmol (+) kg^{-1})	1.26
CEC (cmol (+) kg^{-1})	3.86
Exch. acidity (cmol (+) kg^{-1})	0.06
%(Al^{3+} + H^+) of CEC	1.55

The GM residues used in the study were shoot biomass (stem + leaves) of *Crotalaria micans* Link (upland legume) and *Aeschynomene afraspera* J. Leonard (flood-tolerant legume); before use, the residues were cut into small pieces (<0.25mm).

2.3 Chemical analyses of GM residues

Subsamples of the biomass were oven-dried (70°C) for 72 h, ground, and analyzed for total N (Kjeldahl procedure; *Bremner*, 1965), total P (by digesting the 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-color method. Lignin content was measured using the acid detergent fibre-permanganate method (*Van Soest* and *Wine*, 1968). The residues varied in P content, but lignin and C : N ratios were similar (Tab. 3).

2.4 Experimental procedure

2.4.1 Incubation study

Green-manure legume residues (air-dried, <0.25 mm) with varying P contents were added at a rate of 5% (w/w) to 25 g sample of air-dried soil in 100 mL plastic bottles. Phosphorus fertilizer as TSP (granular) or ground (<100 μm) PR was added to the mixture at a rate of 5% of soil (w/w). Soil moisture in the plastic bottles was adjusted to field capacity of the soil (Experiment 1) or saturated with distilled water (Experi-

Table 2: Selected characteristics of the Tilemsi (Mali) phosphate rock used in the study.

P	**Neutral ammonium citrate solubility (P_2O_5)**	**CaO**	**MgO**	**CO_2**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**Molar ratio PO_4^{3-} : CO_3^{2-}**
				%				
13.7 (30% P_2O_5)	4.2	44	0.35	2.2	6.1	2.0	6.1	4.8

Table 3: Chemical composition of legume residues used in the incubation study.

Legume residues characteristics	**N** (g kg^{-1})	**Total P** (g (kg plant)$^{-1}$)	**C : N**	**Lignin** (%)
***Crotalaria micans* (upland)**				
No P fertilizer applied	26.2	1.4	17.0	8.0
Phosphate rock	33.3	1.7	16.8	7.9
Triple superphosphate	30.4	2.2	16.8	8.3
***Aeschynomene afraspera* (Lowland)**				
No P fertilizer applied	25.6	1.5	14.2	9.7
Phosphate rock	25.5	2.3	13.9	10.0
Triple superphosphate	28.8	2.7	13.9	9.8

ment 2) to simulate aerobic upland and anaerobic flooded conditions, respectively. The plastic bottles in the simulated upland condition were loosely covered, whereas those in the anaerobic system were capped air-tight. The bottles were regularly weighed to maintain constant moisture condition throughout the incubation period. Distilled water was added as required, to maintain the moisture levels. Treatments in either experiment included:

Treatment 1: control (no GM and no P added to soil in plastic bottles); Treatment 2: GM1 (fertilized with PR) added alone to soil in plastic bottle (no P added); Treatment 3: GM2 (fertilized with TSP) added alone to soil in plastic bottle (no P added); Treatment 4: GM1 (fertilized with PR) + PR added to soil in plastic bottle; Treatment 5: PR-P added to soil in plastic bottle (no GM added); Treatment 6: GM2 (fertilized with TSP) + TSP added to soil in plastic bottle; Treatment 7: TSP added to soil in plastic bottle (no GM added).

In either experiment, all plastic bottles replicated three times and containing each of the seven treatments above were placed in an incubator at constant temperature (25°C) using a randomized complete block design. The incubation period was 60 and 80 d under aerobic and flooded anaerobic conditions, respectively, and coincided in each case with the average time to maximum tillering in rice crop, corresponding to the peak in nutrient uptake.

2.4.2 Production of GM biomass with varying P contents

Green-manure biomass with different P contents was previously obtained (Tab. 3) by growing separately *Crotalaria micans* (upland legume) and *Aeschynomene afraspera* (lowland) in pot in screenhouse, using various P-fertilizer sources. In the upland setup, *C. micans* plants were fertilized with three P sources (no P and TSP, PR applied at 60 kg P ha^{-1}) to obtain GM biomass with different P contents. In the flooded pots, *A. afraspera* was grown using the same sources and rates of P fertilizers. The shoots of the legume plants grown in upland and lowland soils were harvested separately 8 weeks after sowing, at the onset of flowering.

2.5 Statistical analysis

Data were subjected to ANOVA using the SAS General Linear Model (GLM) (*SAS*, 2001). Least significant differences (LSD) were calculated to discriminate means, and means were declared as significantly different at $p < 0.05$.

3 Results

At the end of each incubation period, soil was extracted by a solution which composition was 0.03 M in NH_4F and 0.025 M HCl. This extraction technique is referred to as the Bray-1 method and most suitable to assess P availability in acidic soils. The soil used in the present study was acidic (Tab. 1).

Significant treatment effects were observed in the extractable Bray-1 P at the end of each incubation period (60 or 80 d of incubation) (Tab. 4). The results indicated a significant reduction in extractable Bray-1 P, when P fertilizers regardless of the source were combined with GM residue of low P contents. The changes in extractable Bray-1 P measured at the end of each incubation period are shown in Fig. 1.

Under the aerobic upland soil condition, soil Bray-1-extractable P in the combined PR+GM or TSP+GM was significantly lower than that in treatments with PR or TSP applied alone. Further, soil amendment with GM residues alone significantly increased Bray-1 P over the unamended control only in the case of TSP-fertilized GM residues (Fig. 1). Similarly, in the flooded anaerobic flasks, addition of GM in combination with TSP significantly decreased extractable P, as compared with sole application of P. In the case of PR, concentrations of P extracted by Bray-1 solution did not significantly change in the presence or absence of GM. In addition, soil amended only with residues from PR- or TSP-fertilized GM had a higher Bray-1 P than the

Table 4: Single degree of freedom contrast of means of P (mg (kg soil)$^{-1}$) extracted by Bray-1 solution in soil amended with P fertilizers and green manure legume (GM) under aerobic and anaerobic conditions in incubation flask.

	Aerobic (upland) **(*Crotalaria micans*)**	**Anaerobic (lowland)** **(*Aeschynomene afraspera*)**
Treatment contrast	F-significance	
TSP *vs.* PR	**	**
GM1 *vs.* GM2	*	n.s.
(PR+GM) *vs.* PR	**	n.s.§
(TSP+GM) *vs.* TSP	*	*
$LSD_{0.05}$ (GM main effects)	n.a.	n.s.
$LSD_{0.05}$ (P main effects)	n.a.	n.s.
$LSD_{0.05}$ (P × GM interaction)	*	n.s.µ

TSP, triple superphosphate PR, phosphate rock

*, **, significant at 0.05 and 001 probability levels; n.s.§, $p < 0.10$; n.s.µ, $p < 0.06$

n.a., not applicable (P × GM is significant)

GM1 and GM2, green-manure legume fertilized with PR or TSP, respectively

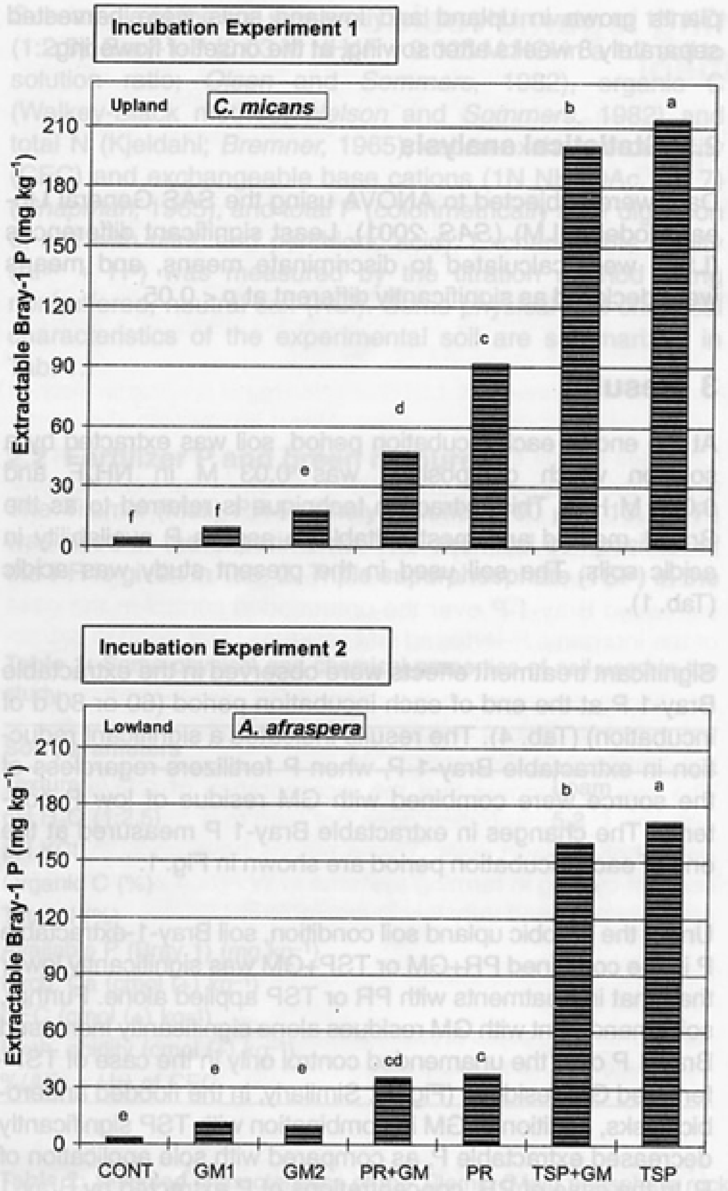

Figure 1: Extractable soil Bray-1 P in various treatments following incubation of the soil with GM under upland (60 d) and lowland (80 d) conditions. Bars capped with the same letters are not significantly different ($LSD_{0.05}$). GM1 and GM2: GM fertilized with PR and TSP, respectively, and solely applied. CONT. (control): no GM and no P were added to soil in plastic bottle.

unamended control. However, no significant differences were observed between the two sources of P.

4 Discussion

On average, extractable Bray-1 P was higher in the upland than in the lowland soil (Fig. 1), reflecting differences in P behavior under aerobic and anaerobic conditions (*Narteh* and *Sahrawat*, 1999). Bray-1 P was chosen as the available P in acidic soil is better assessed by Bray-1 reagent (*Sahrawat* et al., 1997).

Assessment of the P status of the reduced soil by a chemical test conducted on air-dried soil may not provide a reliable estimate of soil P availability after submergence (*Diamond*, 1985). However, it is noteworthy that though the availability of P is influenced by flooding (*Narteh* and *Sahrawat*, 1999), yet most of the practical aspects of P availability are done in air-dried state for practical application of the results.

On the other hand, in the case of PR, a rise in pH upon submergence was possibly an additional factor that did not favor dissolution of the apatite in PR under reduced soil conditions. Nonetheless, the similarity of the responses under upland and lowland soil conditions clearly indicated that application of GM residues adversely affected soil extractable P regardless of P source and soil water regime.

Other studies (*Nziguheba* et al., 1998) also reported little evidence of beneficial effects on resin-P of combined application of TSP with GM residues, as compared with sole application of TSP. Using the ^{32}P-isotope dilution technique, *Zaharah* and *Bah* (1997) showed depressing effects of GM residues on P derived from the more reactive PR and the water-soluble TSP. Using a broad range of PRs of variable reactivity characteristics and GM residues of contrasting chemical properties, these workers showed that the extent of the influence of GM in improving the solubility of PR and soil P availability was associated with the GM quality, especially its P concentration. Thus, whether net mineralization of P occurs in legume plant residues depends at least partly on the P content of the incorporated plant material.

Our results could also be explained by examining the chemical composition of the GM residue used in the incubation study (Tab. 3). The P concentration in the residues was less than the critical level of 2.5 g (kg dry matter)$^{-1}$ (DM) suggested by *Palm* (1995) or the critical P concentration of 3 g (kg DM)$^{-1}$ proposed by *Singh* and *Jones* (1976) for net P release in soils amended with GM. It is noteworthy that the P concentration of GM residues used in the experiments reported by *Zaharah* and *Bah* (1997) ranged between 0.9 and 2 g (kg DM)$^{-1}$. *Iyamuremye* et al. (1996) reported net P immobilization in soils amended with organic materials of P concentration as low as 0.9 g kg^{-1}. *Somado* et al. (2003), on the other hand, reported increase in extractable soil Bray-1 P in potted soil planted to rice under flooded conditions with the combined application of P fertilizer and residues of *A. afraspera*. In the present study, Bray-1 P was used to monitor the changes in available P without effects of plants. *Narteh* and *Sahrawat* (1999), using similar soils, reported soil-solution P concentrations in soil solution were too low unless fertilized with high P. It is then easy to pick-up small changes in Bray-1-extractable P.

The results reported by *Somado* et al. (2003) contradict the results obtained in present study (Fig. 1). The discrepancy between the two experimental conditions (incubation tubes in the absence of growing plant roots *vs.* pots in the presence of rice plant roots) might be attributed to the P-mobilizing capacity of the rice plants grown under anaerobic soil conditions. In fact, *Kirk* et al. (1991) and *Kirk* and *Saleque* (1995) suggested that rice plants growing in reduced soil, acidify their rhizosphere through the following mechanisms: (1) production of H^{+} during oxidation of Fe^{2+} by root-released O_2 and (2) direct root release of H^{+} to balance excess uptake of cations due to the predominantly NH_4^{+} supply in N nutrition.

Such acidification of the soil would then mobilize further PR-P and bring about additional P into the soil solution in flooded soils. Likewise, rice grown in P-deficient aerobic soil is efficient in mobilizing P from soil through a different mechanism: excretion of organic anions by the roots (*Kirk* et al., 1999). The organic anion is considered to chelate metal ions (Fe, Mn, and Al), which would otherwise immobilize P by precipitation of soluble P.

5 Conclusions

Under upland or flooded soil conditions, addition of GM residues to soil amended with PR and TSP did not increase extractable Bray-1 P. This was attributed to the low P concentration of the incorporated residues. The general contention that GM application increases the availability of native soil P and promotes the dissolution and utilization of PR, should be taken with caution. This study suggests that the soil P cycling is determined by the quality of the incorporated plant residues, especially their P concentration.

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