1 Farmyard manure application in weathered upland soils of
2 Madagascar sharply increase phosphate fertilizer use efficiency
3 for upland rice

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13 **Running Title:** Manure increase P availability to upland rice

Abstract

A vast upland area in Madagascar remains uncultivated because of erratic rainfall and because of the low fertility of the soils that are highly weathered and depleted in available phosphorus (P). This study was set up to identify to what extent farmyard manure (FYM) can overcome P deficiency and increase the use efficiency of mineral P (TSP). Rainfed rice was grown with soybean in rotation (two fields) in three subsequent seasons with factorial supplies of FYM and TSP (both applied in planting hole) with blanket N&K doses. The low and unresponsive rice grain yields ($<2 \text{ Mg ha}^{-1}$) in the initial year were contrasted with large treatment responses cumulating in a grain yield of 5.8 Mg ha^{-1} in year 3 at highest rates, 3.6-fold above the no P and no FYM control with N&K and 11-fold above the absolute control. The above ground P uptake responded to total P application (TSP and FYM derived) and its slope significantly increased with FYM application. The fertilizer (TSP) P use efficiency in the above ground biomass, was 14% for the zero FYM dose increasing to 22% for the highest FYM dose of 10 Mg ha^{-1} at year 3 of study. The FYM benefits were likely unrelated to nutritional factors as revealed from tissue analyses and it is speculated that FYM alleviates moisture stress or Al toxicity. Dosing FYM only with no TSP did not alleviate P deficiency. This study illustrates the agronomic potential of the uncultivated area provided that the soil nutrients are capitalized.

Key words: Phosphorus bioavailability, Upland rice, organic fertilizer, TSP

1. Introduction

Tropical soils are characterized by low nutrient status including P where P deficiency is known as a limiting factor for crop production (Pypers et al., 2007). Rice as staple food crop for the Malagasy people is widely cultivated across Madagascar. Irrigated rice systems, which ensure 87% of total rice production, occupy the lowland area while rainfed rice is mostly planted in

upland area (Rabeharisoa et al., 2012). Highland area offers possibilities for rainfed rice production by smallholder farmers considering the unavailability of lowland area.

However, previous field investigations conducted on acid Ferralsols in Madagascar reported that rainfed rice yield is mainly limited by P owing to P fixation on the Fe and Al oxyhydroxides (Rabeharisoa et al., 2012). Previous research on rainfed lowland rice in Cambodia, Thailand, and Laos also reported the low yields in rainfed rice yield due to water availability constraints, soil infertility including N and P deficiency and soil acidity (Kato et al., 2016; Haefele et al., 2006). Appropriate fertilizer management strategies are required to improve rice yield in this system.

Organic resources are the main accessible fertilizers for Malagasy farmers. Organic amendments such as farmyard manure enhance nutrient availability, either directly through nutrient supply or indirectly by improving soil physical properties (Palm et al., 1997). It has been reported that P availability in highly weathered tropical soils may be controlled by soil organic matter turnover (Nziguheba and Bünemann, 2005). Decomposing organic amendments provide a source of inorganic P from mineralization or increase soil P availability by producing organic anions which reduce P sorption by competition or enhanced pH (Six et al., 2014; Palm et al., 1997; Guppy et al., 2005; Eichler-Löbermann et al., 2007). Organic amendment also affect physical soil parameters including improvement of soil structure and soil moisture retention, bulk density, and aggregate stability, and improving furthermore the P availability (Cong and Merckx, 2005; Dorado et al., 2003). However, the use of organic amendments alone is unlikely to overcome P nutrient deficiency in strongly depleted soils (Six et al., 2014, Nziguheba et al., 2002). The available amendments in such areas do not contain large P concentrations, hence requiring unfeasible doses to match the P need of crops (Palm et al., 1997; Chivenge et al., 2009). The combination of organic resources with mineral fertilizers can offer a sustainable way for increasing soil fertility and crop production to smallholder farmers and

may reduce the use of inaccessible mineral fertilizer (Six et al., 2014, Chivenge et al., 2009). Positive interaction of organic fertilizers (farmyard manure or *Tithonia diversifolia*) and TSP on grain yields of maize crop after two years of experiment were indeed reported with 50% substitution effect from organic fertilizers (Aye et al., 2009). These positives interactions could be attributed to soil moisture improvement. Such interaction offer the possibility of a better agronomic and economic use efficiency of both nutrient resources. Triple super phosphate (TSP) is frequently used to overcome P deficiency in many tropical soils but the availability of inorganic P fertilizers on local markets is a challenge for smallholder farmers in developing countries and there is a need to increase its nutrient use efficiency to capitalize the soil in an economically acceptable way.

In Madagascar, research on upland crops has mainly focused on direct-seeding mulch based cropping systems (DMC) where soil is permanently covered by organic residue mulch and the legume-cereal cropping rotation is grown without tillage (Dusserre et al., 2010; Rabary et al., 2008; Gerardeaux et al., 2012). Some authors reported similar upland rice yields for DMC and conventional tillage approaches in the highland of Madagascar (Duserre et al., 2010; Henintsoa et al., 2012). In the DMC or tillage systems, dosing FYM only did not increase the rice yield compared to combined FYM and mineral NPK fertilizer (Duserre et al., 2010).

Most of smallholder Malagasy farmers use FYM in the rainfed rice and add very small doses of mineral fertilizers. To our knowledge, no field trials have focused on the interaction between mineral P and FYM, thereby testing the potential substitution effect or testing potential benefits of FYM on increasing the fertilizer use efficiency. The use of different P doses from FYM (P added via FYM) and from TSP fertilizer would be very useful for calculating P use efficiency as related to upland rice practice.

Therefore, this study aimed to investigate the P nutrient disorder in the upland area of Madagascar and to analyse to what extent the nutrient use efficiency of TSP might be enhanced by dosing with feasible rates of locally available organic amendments.

2. Materials and methods

2.1. Field experiment

The rainfed rice experiment was conducted on a Ferralsol with poor P status in Ivory, Mid-West Madagascar from 2011 to 2013. The oxalate extractable P in the soil at the start were 160 and 51 mg P kg⁻¹ soil for field 1 and field 2, respectively. This and the soil pH predicts that flag leaf P is below 2 g kg⁻¹, well indicating P deficiency as described before (Rabeharisoa et al., 2012). An annual rotation of rainfed rice- soybean was conducted on two sites, side by side during three consecutive years. In field 1, rainfed rice was planted in the first and third year in rotation with soybean. In field 2, rice was grown in the second year after soybean crop. Initial soil and site characteristics are given in Table 1.

The rice experiments used a split-plot arrangement of treatments in a randomized complete block design with two blocs. The FYM fertilizer was established as main plot and TSP fertilizer established as sub-plots. The 12 treatments, including the combination of FYM (0, 5, 10 Mg FW ha⁻¹ year⁻¹) and inorganic fertilizer TSP (0, 20, 40, 80 kg P ha⁻¹ year⁻¹) were replicated two times with blanket N and K application.

Each plot has a size of 5 m x 5 m. Field was ploughed at 20 cm depth prior to seeding. Rice cultivar (*Oryza sativa* L. cv. Nerica 4) was sown between November-December at a spacing of 20 cm x 20 cm with two or three seeds per hole. Farmyard manure was applied per hole. The FYM is a cattle manure mixed with straw and household green waste, composted and stored outdoor until the application. The total P content in the FYM was 0.23%, 0.24%, and 0.25%

respectively for year 1, 2 and 3. The total N content in FYM was 2.0%, 1.4%, and 1.1% for year 1, 2, and 3 respectively. Triple-super phosphate, TSP (46% of P_2O_5) was also located. The N and K fertilizers were broadcasted in each plot at equivalent rate of 80 kg N ha⁻¹ (as urea, 46 %N) and 60 kg K/ha (as K_2SO_4 , 50 % K_2O), respectively. Nitrogen and K doses were applied in two equal splits at sowing and tillering. Weed control and pest management were followed by farmers during the plant growth. Two additional plots were included as an absolute control (no TSP, no FYM). Growth durations of rice crops (*Oryza sativa* L. cv. Nerica 4) were 119 days, 127 days, and 130 days for year 1, 2 and 3 respectively.

For the soybean crop (*Glycine max* CD 206), similar rates of TSP and FYM treatments as for the rice crop (12 treatments of TSP x FYM) but with blanket application of 60 kg N/ha and 60 kg K/ha were applied for the two sites.

Following harvest, grain yields were determined by weighing all harvested grain from one whole plot. All grain yields were recorded at the standard moisture content of 13%.

Grain yield was assessed by measuring grain production from the whole plot while grain and straw biomasses were measured 3 sampled squares of 1 x 1 m² along the diagonal in rice plot. Grain and straw dry weights were measured after oven-drying at 60°C. Grain and straw yields at 0% moisture were estimated by averaging the 3 sampled squares and used to calculate the grain and straw P uptake. After grain harvest, straw biomass was returned on the soil surface of each plot.

2.2. Soil, manure and plant analyses

Soil samples from the three diagonal points were composited for each plot after the harvest, giving around 2 kg fresh weight of 0–20 cm of depth. Soil pH was measured with this fresh soil in a solution of 0.01 M $CaCl_2$ at a 1:5 soil:water ratio. Soils were thereafter air-dried and sieved through a 2 mm mesh for other chemical analyses. The measurements included oxalate-

extractable P, Fe, and Al, soil organic carbon. Oxalate-extractable P, Fe, and Al content was determined according to Schwertmann (1964). Soil organic carbon was determined using the Walkley and Black procedure (Allison, 1965). The FYM composition ranged from 6 to 7 kg P ha⁻¹ for 5 Mg FYM ha⁻¹ (on average 6.6 kg P ha⁻¹) and from 12 to 13 kg P ha⁻¹ for 10 Mg FYM ha⁻¹ (on average 12.6 kg P ha⁻¹). Plant samples of grain and straw were oven-dried at 60°C, ground and digested in HNO₃ 65% at 140°C. The P concentration of each sample in digested solution was analysed by inductively coupled plasma optical emission spectrophotometry (ICP-OES, Perkin Elmer 3300 DV). Details on chemical analyses were previously reported by Andriamananjara et al. (2016). Other nutrient concentrations (Mg, K, Ca, P, Cu, Fe, Zn, and Mn) in grain and straw were also measured.

2.3. Data analysis

Grain yield, total (straw + grain) P uptake and P use efficiency (PUE, see below) were subjected to two-way ANOVA with TSP and FYM entered as categorical variables. In addition, generalized linear modeling was used to analyse grain yield, grain P content, and total P uptake in relation to total annual P addition (TSP + P derived from FYM) and its interaction with FYM addition. Since data did not indicate that the FYM only affected these parameters via an effect on the slope, a multivariate model was fitted on Y (either, yield, P content or P uptake) as:

$$Y = \beta_0 + (\beta_1 + \beta_2 (5\text{FYM}) + \beta_3 (10\text{FYM})) \times (\text{Total P}) \quad (1)$$

where β_0 , β_1 , β_2 , β_3 are regression parameters; 5FYM and 10FYM are dummies (0, 1) where FYM is applied at 5 Mg ha⁻¹ and 10 Mg ha⁻¹; total P is the annual dose of P via TSP or FYM.

The nutrient (fertilizer) P use efficiency (PUE) was calculated according to Dobermann (2007) as the apparent recovery efficiency by difference, i.e. the fraction of nutrient applied taken up by the plant. This was calculated as the total aboveground P uptake (straw+grain) in a fertilizer

treated plot minus the mean value of the unamended plot (with N&K) divided by the TSP dose. This PUE was calculated per plot for the three years combined, i.e. total uptake summed over three years. The annual P balance was calculated as the difference in P fluxes between P inputs from P in fertilizers and P outputs from P in grain and straw. The cumulative P balance was calculated from the sum of the annual P balance. All statistical analyses were performed using R software version 3.1.2 (R Core Team, 2015). Levels of significance were 0.05 (*) or lower (**0.01, ***0.001).

3. Results

The rice yield, grain P content and total P uptake by plant under different treatments are shown in Figure 1. Grain yield was highly affected by total P application in year 3 but not in years 1&2. Application of TSP and FYM significantly increased grain yield only at year 3 (Table 2). The three years combined grain yield were neither affected by FYM nor by TSP. No interaction among these factors were found.

Soybean grain yield are shown in Figure 2. Soybean grain yield was highly affected by TSP and FYM in year 2 and in year 3 (Table 3). The three years combined soybean grain yield were also affected by TSP and FYM. Interaction among these factors were found only in year 3.

The total P uptake was always significantly affected by the total P application rate (Figure 1 and Table 4). A mere linear model with TSP and OM as continuous variables showed that total P uptake did respond to TSP, to TSP-FYM interaction but not to FYM only (Table 2). However, total P uptake response to FYM was observed at year 3.

The multivariate regression analysis (Equation (1) revealed that FYM application enhanced the slope of the relationship between P uptake and P application. Note that this analysis already corrects for the nutrient input via the organic amendment, i.e. the total P application is that of

TSP and FYM combined. The FYM-TSP interaction analysed via Equation (1) hence test for effects of FYM on soil and fertilizer P uptake, i.e. on increasing its bioavailability. Alternative models did not find a significant FYM effect on P uptake on the intercept of either parameters after correcting for the total P application. This indicates that FYM application increased the fertilizer use efficiency of added P, not of soil P. The Equation (1) also revealed a significant FYM-TSP interaction on grain yield ($P < 0.05$, year 3 and all years combined, data not shown) but not on P content. In the ensemble of the data, grain P concentration ranged between 0.1-0.3%. The comparison of FYM effect by TSP level showed that FYM application increase ($P < 0.01$) grain P content at year 3 at the highest dose of TSP (80 kg P ha^{-1}). The P application from FYM and TSP increased grain P content significantly in years 2 and 3.

The three year combined fertilizer P use efficiency (PUEs) was significantly affected by FYM application ($P = 0.01$) and by TSP application (Figure 3; Table 5). The PUE in year 3 only was larger than that in preceding years and was 22% at the highest FYM dose for the lowest TSP dose, decreasing to 14% at the zero FYM dose (Figure 3).

The residual P from FYM and TSP application was detectable in soil P after three years of rotation cropping system (Figure 4).

No significant differences in grain or straw nutrient concentrations were found between TSP and FYM treatments (whether TSP are combined or not with FYM; Table 6). Only a small difference was found for Ca but this element was higher in the TSP treatment compared to FYM, i.e. not explaining the beneficial effects on the PUE. In contrast, significant increases due to FYM were found in straw Mg and K, suggesting that FYM was a source of these elements. The straw K concentrations ($>1.3\%$) are likely adequate while Mg might be borderline deficient. Micronutrient deficiency was not suspected for this study using the critical values for rice (Reuter & Robinson, 1997).

4. Discussion

This study was set up to identify to what extent farmyard manure (FYM) can overcome P deficiency and increase the use efficiency of mineral P (TSP) for rainfed rice. The multivariate model shows that the application of FYM at 10 ton/ha increased the average total P uptake to 8 kg P ha⁻¹ across years and treatments, however that addition increased with TSP and cumulated in a very large benefit on grain yield and P uptake (Figure 1). This positive interaction effect confirms previous studies (Satyanarayana et al., 2002; Haefele et al., 2006), but this study might be first in showing such large benefits yielding to upland rice yields over 5 Mg ha⁻¹. The grain yields of the absolute unfertilized control in year 3 were only 0.53 Mg ha⁻¹, 11-fold that in highest input systems (details not shown). This large effect was only found after 3 years of treatment in the same plots suggesting that soil nutrients need to be capitalized first. It should be added that the FYM and TSP are both locally added which adds to a better use efficiency of the amendments (Buresh et al., 1997). The final yield at highest dose are exceptional for rainfed rice on weathered soils. These increasing rice yields were above the average values for northeast Thailand (Haefele et al., 2006), likely as a result of very depleted soils used here.

The rotation with soybean here may also have contributed to a better utilization of residual P (Medhi and De Datta, 1996; Nuruzzaman et al., 2005) and efficient control of striga (Rodenburg and Johnson, 2009) that is affecting rice yield in neighboring fields. Here, soybean production yielded up to 1.3 Mg ha⁻¹ in the first year. Analysis of rice grain yield from both field 1 and field 2 suggests a positive residual effect of soybean, i.e. the previous soybean crops was always followed by higher rice grain yield than the preceding rice yield at the same. Despite the significant effect of FYM and TSP fertilizers on soybean, no marked increasing soybean grain yield was found at the end of three years in field 2 compared to that at year 1 except at the highest dose of TSP (80 kg P ha⁻¹). This is in contrast with the substantial increase of the rice grain yield at the end of three years in field 1. The positive rotation effect of soybean on rice in

field 1 in year 3 might also be related to the biological nitrogen fixation of the soybean: all crops had been amended with 80 kg N/ha, a dose that is typically sufficient for a low yield of the upland crop but probably insufficient for the large yield observed here in year 3.

It is somewhat puzzling why three year applications of 5 Mg FYM ha⁻¹ FYM had more effect on P uptake than 2 year applications of 10 Mg FYM ha⁻¹ despite higher total doses in the latter (Figure1). First, that effect noted in Fig.1 is related to the slope of the relationship between P input and P uptake, i.e. the cumulative total P uptake is involved and is larger in year 3 than in year 2. Second rainfall data could also be involved. The total rainfall was 1816 mm in year 1, 998 mm in year 2, and 1454 mm in year 3. Lower water availability in February (corresponding to critical rice growth stage: flowering) was observed in year 2 compared to year 3 (132 mm vs 347.5 mm respectively). The low rainfall in year 2 may explain why the treatment effects of FYM are less pronounced than in year 3.

The positive FYM-TSP interaction effect can be due to (i) competition for P sorption sites of organic anions released during FYM decomposition and thereby improving availability of P from TSP (Hue, 1991; Nziguheba et al., 2000); (ii) reduction of Al-P precipitation after complexation or precipitation of soluble Al with these organic anions (Hoyt and Turner, 1975; Hue, 1991), (iii) temporary increases of soil pH during FYM decomposition reducing P sorption (Haynes and Mokolobate, 2001) and finally (iv) a higher soil moisture in the presence of FYM that increases the water holding capacity of the soils and, consequently, improves the P mobility (Rakotoson et al, 2016). Grain or straw elemental analysis did not identify marked effects of FYM on plant nutrients that explain the interaction, excluding K and Mg.

Considering the absence of FYM effect on grain and straw nutrient content, it is speculated that decreased moisture stress is involved after 3 years. It was reported that rainfed systems are limited by drought and poor soil fertility (Haefele et al., 2006). Farmers confirmed that seedling establishment was better in the presence of FYM added to the planting holes, probably by

reducing the formation of a soil crust after heavy rainfall or by increasing the water holding capacity. The local liming effect of FYM in this acid soils (Cong and Merckx, 2005) should be recalled as it allows better root proliferation and better use efficiency of the TSP granules located near the seedlings. The limited water stress resulted from FYM application favored higher significant average yields and P uptake at the highest applied TSP. The PUE values of TSP are all low (<25%) but are typical for low-input systems. The FYM effects on PUE repeat the strong FYM-TSP interaction.

Cumulative effect of repeated annual fertilizer application coupled sufficient water availability and soybean rotation was likely the cause of clear FYM effect on rice yield and P uptake in year 3 compared to years 1 and 2.

To conclude, this study revealed that FYM can enhance the use efficiency of mineral fertilizer-P in rainfed rice grown in weathered P deficient soils with continuous application for three years. The FYM has only a positive (but small) effect on P bioavailability where P bioavailability is very low. The lower %SOC in rainfed rice soils (Table 1) adds to the greater relative effects of FYM on soil fertility.

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TABLES

Table 1 Field locations, climatic data, selected initial mean soil properties and design of experiments.

Sites	Field 1	Field2
Duration (year)	3	3
Start year	2011	2011
Location	19°33'36.3"S ; 046°24'33.1"E	
Mean temperature (°C)	21	
Altitude (m)	929	
Soil classification (FAO)	Ferralsol	
Soil pH _{CaCl2}	3.7	4.0
P _{ox} (mg.kg ⁻¹)	160	51
Fe _{ox} (g.kg ⁻¹)	1.0	1.1
Al _{ox} (g.kg ⁻¹)	2.0	-
SOC (g.kg ⁻¹)	18	16
Preceding crop	maize	maize
Crop rotation	rice/soybean/rice	soybean/rice/soybean
Treatments ^a	0/5/10 FYM x 0/20/40/80 TSP	
Replicates	2	
N and K rates (kg/ha/yr) ^b	60 N + 60 K (rice)	
	30 N + 60 K (soybean)	

^aFarm yard manure (FYM) expressed as Mg fresh weight/ha (36-56% moisture content), triple super phosphate (TSP) expressed as kg P ha⁻¹. ^bN added as urea and K as K₂SO₄.

402 **Table 2** Rice grain yield (GY) and total P uptake (PU) responses to annual FYM and TSP application in the presence of blanket NK.

	All 3 years		Year 1		Year 2		Year 3		403
	GY	PU	GY	PU	GY	PU	GY	PU	404
TSP	n.s.	***	n.s.	**	n.s.	***	***	***	405
FYM	n.s.	**	n.s.	n.s.	n.s.	n.s.	***	***	406
TSP x FYM	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	407
R ²	0.08	0.45	0.09	0.42	0.16	0.58	0.64	0.88	408
<i>P-value</i>	0.14	<0.0001	0.581	0.010	0.326	<0.001	<0.001	<0.0001	409
									410

411 Statistical significance for treatment effects on grain yield and total P uptake ***P < 0.001; ** P < 0.01; n.s. = non-significant.

412

413

414 **Table 3.** Soybean grain yield responses to annual FYM and TSP application in the presence of blanket NK..

	All 3 years	Year 1	Year 2	Year 3
TSP	**	n.s.	***	***
FYM	*	n.s.	***	**
TSP x FYM	n.s.	n.s.	n.s.	*
R ²	0.14	0.20	0.78	0.79
<i>P-value</i>	0.04	0.267	<0.001	<0.001

422 Statistical significance for treatment effects on grain yield and total P uptake ***P < 0.001; ** P < 0.01; *P<0.05; n.s. = non-significant.

423

Table 4. Significance of the effects of total P applied and of FYM on the total P uptake in aboveground biomass by rice. The model reads: Total P uptake= $\beta_0 + (\beta_1 + \beta_2 (5\text{FYM}) + \beta_3 (10\text{FYM})) \times (\text{Total P})$ with Total P applied= annual dose of P via TSP + FYM; the variables 5FYM and 10 FYM are entered as a dummy (1) when that treatment (Mg FYM ha⁻¹) was applied and 0 when not applied.

	Effect of total P (β_1)	Interaction FYM-Total P at low FYM dose (β_2)	Interaction FYM-Total P at high FYM dose (β_3)	R ²
Year 1	*	n.s.	n.s.	0.34
Year 2	**	n.s.	n.s.	0.50
Year 3	***	n.s.	***	0.86
All Years	***	n.s.	*	0.56

n.s. = non-significant; ***P < 0.001; **P < 0.01 ; *P < 0.05.

431 **Table 5.** Significant effect of FYM and TSP on the phosphorus use efficiency (PUE) of rice for
 432 each year of cropping season.

	All 3 years	Year 1	Year 2	Year 3
TSP	**	***	***	***
FYM	*	n.s.	n.s.	*
TSP x FYM	n.s.	n.s.	n.s.	n.s.
R ²	0.58	0.90	0.90	0.71
<i>P-value</i>	0.029	<0.001	<0.001	<0.001

440 n.s. = non-significant; ***P < 0.001; **P < 0.01 ; *P < 0.05.

441

Table 6. Nutrient concentrations (mg kg⁻¹) in rice grain and straw fertilized with either TSP (0 FYM) or with FYM (with or without TSP). Data (means and SD in brackets) of plants in year 3.

Element (mg kg ⁻¹)	Only TSP	FYM/FYM+TSP
Grain		
Mg	1630 (259)	1543 (447)
K	5139 (508)	4383 (1095)
Ca	535 (60)	412*** (69)
P	1941 (372)	2018 (630)
Cu	6.4 (1.2)	6.2 (1.6)
Fe	45 (15)	40 (14)
Zn	28 (2)	28 (5)
Mn	248 (37)	221 (43)
Straw		
Mg	691 (230)	1013** (243)
K	13122 (1678)	14761* (1877)
Ca	4225 (861)	3974 (830)
P	308 (132)	251 (70)
Cu	6.8 (3.1)	6.1 (2.0)
Fe	161 (77)	144 (57)
Mn	1922 (392)	1965 (302)
Zn	25 (13)	24 (7)

*, ** significant at $P < 0.05$, $P < 0.01$.

FIGURE CAPTIONS

Fig. 1. Rice grain yield, grain P content and total aboveground P uptake as affected by FYM and TSP treatments with N&K added for each year of rice cropping in rice-soybean rotation, note the field numbers. The total P application is the sum of FYM-derived P and TSP-P. Error bars are standard error of mean (n=2). ** significant FYM effect at the highest total P dose ($P < 0.01$).

Fig. 2. Soybean grain yield as affected by FYM and TSP treatments with N&K added in rice-soybean rotations, note the field numbers. The total P application is the sum of FYM-derived P and TSP-P. Error bars are standard error of mean (n=2).

Fig. 3. The fertilizer P use efficiency (PUE: P uptake in fertilized minus that in unfertilized plot divided by TSP dose) as affected by FYM and TSP applications in field 1 (Years 1 and 3) and in field 2 (year 2). Error bars are standard error of mean (n=6).

Fig. 4. Relationship between soil oxalate extractable P (P_{ox}) and cumulative soil P balance after three years of cropping system in field 1 ($r = 0.57$; $P\text{-value} = 0.003$).

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