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

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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 ($< 2\,Mg\,ha^{-1}$) 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.

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).

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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 (Dusserre 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 (Dusserre 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 of the experiment were 160 and 51 mg P kg^{-1} soil for field 1 and field 2, respectively. This P_{ox} and the soil pH predict 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 × 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 × 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^{-1} (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.

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)	

[a] Farmyard manure (FYM) expressed as Mg fresh weight/ha (36–56% moisture content), triple super phosphate (TSP) expressed as kg P ha^{-1}.
[b] N added as urea and K as K_2SO_4.

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^{-1} and 60 kg K ha^{-1} 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 × 1 m^2 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 HNO_3 65%