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Farmyard manure application has little effect on yield or phosphorus supply to irrigated rice growing on highly weathered soils

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ABSTRACT

It is well established that organic matter application can enhance soil phosphorus (P) bioavailability in acid, weathered soils. It is yet unclear to what extents this also holds for irrigated rice in flooded soils where, in principle, organic matter may unlock soil P due to reductive dissolution of Fe-(III) minerals. This study was set up to identify if farmyard manure (FYM) can enhance the use efficiency of soil-P and mineral fertilizer-P in irrigated rice after excluding N and K effects. Field trials with factorial supplies of FYM and banded mineral P fertilizer (Triple Superphosphate or TSP) were set up at three irrigated rice fields in Madagascar with equal annual applications during three consecutive years. All treatments received a blanket N and K application. The FYM rates were within local agronomic rates and TSP rates were maximally 80 kg P ha^{-1}. Total P application from FYM and TSP increased rice grain yields of 4.2 Mg ha^{-1} at the +NK-control to, on average for all years and fields, 5.5 Mg ha^{-1} at highest P doses. Grain yield generally responded to TSP but not to FYM. Total P uptake in grain and straw increased with total P application. Positive effects of FYM on P uptake were mainly related to its P application to irrigated rice soils. The soil P balances amended with FYM only, i.e. the common local farmers practice, were negative. At adequate N and K supply, effect of FYM application on increasing soil or fertilizer P use efficiency was not detectable in irrigated rice; it mainly recycles P.

1. Introduction

Phosphate deficiency is ubiquitous in the highly weathered acid soils in Sub-Saharan Africa due to the strong immobilization of PO_4 anions on the Fe and Al oxyhydroxides. The P use efficiency of added mineral fertilizers is very small and its residual value low. Different agricultural systems have been developed to improve the availability of soil- and fertilizer P. Rotations of grain crops with leguminous plants improve P-supply to the subsequent crop and increased organic matter (OM) applications to soil, either alone or in combination with mineral P can increase P availability (Ayaga et al., 2006; Nziguheba et al., 2000; Vanlauwe et al., 2000). The effects of OM application on increased soil P availability is indicated by higher soil P extractability, higher yield or higher crop P uptake in treatments with mixtures of OM-derived P and mineral P compared to mineral P only at equivalent total P application (Nziguheba et al., 2002, 2000). The increase of P availability due to OM addition can be related to various mechanisms: (i) organic anions released during its decomposition compete with P on soil binding sites; (ii) OM can locally increase the soil pH, thereby reducing the soil PO_4 binding (Haynes and Mokolobate, 2001; Hue, 1991); (iii) enhanced biological cycling of P in soil (Ayaga et al., 2006) and (iv) any other indirect physical or nutritional effect from OM applied to soils on plants that affects their P uptake potential, even after correcting (as well as possible) for other nutrients besides P in the OM.

The OM-P interactions are well studied in aerobic soils. Less is known if OM supply can also enhance P supply at P deficient conditions in waterlogged (flooded) soils where soil chemical conditions differ from aerobic soils. Upon flooding soils, anaerobic reactions release some PO_4 due to reductive dissolution of Fe(III) oxides, due to competitive adsorption of dissolved organic matter (DOM), and due to formation of aqueous ternary DOM-Fe-PO_4 or DOM-Al-PO_4 complexes (Kirk, 2004; Kirk et al., 1990; Peretyazhko and Sposito, 2005; Ponnamperuma, 1985). These reactions explain why, in general, irrigated (flooded) rice exhibits less P-deficiency than rainfed (upland) rice grown in corresponding soils (Huguenin-Elie et al., 2009; Rabeharisoa et al., 2012). In addition, waterlogging soils strongly increases the effective diffusion of P in soil due to mere

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water filling the soil pores. These processes are unlikely to be sufficient to overcome P deficiency in weathered soils since field trials worldwide show significant P-responses in irrigated rice, especially in ferralsols (IRRI, 1978). In principle, increasing supplies of OM or applications of OM just before soil flooding may increase the P availability in irrigated rice by promoting reductive dissolution of Fe(III)-oxides. Reduction reactions can indeed be promoted and chemical studies have shown increased P solubility in OM added soils. Soil chemical assays, i.e. extractions and isotope exchange studies showed that the addition of rice straw prior to flooding increased Fe reduction and increased plant-available P relative to aerobic or anaerobic soils without OM (Amery and Smolders, 2012; Rakotoson et al., 2014). The increase of P availability due to flooding increases with increasing concentrations of P associated with amorphous Fe(III)-oxides. In contrast, P solubility can also decrease by reducing soils with additional OM (Vadas and Sims, 1998). This is attributed to precipitation of Fe(II)-P compounds. The soil cation exchange capacity limits the release of P in flooded soils, probably because this capacity buffers the Fe^{2+} cation activity and modulates the precipitation of Fe(II)-P compounds (Amery and Smolders, 2012).

In general, the interaction of OM and P-supply on crop performance in P-deficient soils has received little attention in irrigated rice cultures. Dawe et al. (2003) reviewed 25 long-term trials and concluded that organic amendments did not improve rice yield. Organic amendments increased yields when the mineral NPK fertilizer rate was equal as in the no-OM control whereas, in contrast, yields were lower where mineral NPK was reduced or fully replaced (on a N-unit basis) by the organic amendments. Authors of these long-term trials do caution that the experimental designs in these 25 experiments do not allow estimating comparative fertilizer values between the mineral and organic because mineral fertilizer rates had not been corrected appropriately. Most importantly, these field trials tested macronutrient effects in intensive rice production systems at doses of P that are unlikely to be representative for low input systems with P-deficient soils. Higher applications of organic amendments in irrigated soils can have negative effects on yields due to stimulated release of soluble Fe^{2+} and increase iron toxicity. Iron toxicity occurs in acid soils with low cation exchange capacity (Becker and Asch, 2005).

In Madagascar, about 87% of rice (*Oryza sativa* L.) is grown as a fully irrigated crop. The P-deficiency is widespread (Rabeharisoa et al., 2012), hence this country offers possibilities to identify potential benefits of OM supply on availability of soil- or fertilizer P. A country-wide fertilizer project on irrigated rice concluded that crop response to P is ubiquitous in contrast with the response to N that is not found in soils with high OM supply (PEM, 1992). The P response (percentage yield increase) was significant and large in soils with high soil organic matter (SOM) content (PEM, 1992). Such an observation suggests that SOM or more generally, OM has a beneficial effect on fertilizer P use efficiency in irrigated rice. However, this interaction may have been related to N-supply of SOM as no corrections were made to have constant N-supply in the soil. These trials did not assess the interactions between residue management and NPK-fertilizer supply.

The objective of this study is to identify if organic matter application can enhance the use efficiency of soil-P and mineral fertilizer-P in irrigated rice grown in weathered, P deficient soils. Field trials were set up with farmyard manure (FYM) as amendment as an obvious and widely available source. The FYM doses were selected within the relevant (feasible) range based on a preliminary survey on small scale farms. In Madagascar, the application of OM is one of the components of the System of Rice Intensification (SRI), a method that includes OM application, only periodic flooding and lower plant density. The comparison of this SRI system with the conventional rice culture system was beyond the scope of this study, however field experiment on that system were set-up and are reported in the Supporting information (SI).

2. Material and methods

2.1. Field trials

Fertilizer trials were set up at three different fields that were suspected to be P deficient based on the low fertilizer input that is common in Madagascar. The trials with irrigated rice were set up with a split-plot design with FYM in the main plot and TSP in sub-plot with blanket N and K application and 2 replicates (plots). The 12 treatments included the combination of FYM (0, 5 and 10 Mg FW year^{-1}) and inorganic fertilizer TSP (0, 20, 40, 80 kg P ha^{-1} year^{-1}). Absolute controls with no fertilizer input (N0K0) were included as an additional treatment at two of the three fields. Details are given in Table 1. Duplication about two replicates and three consecutive years were repeated in same plots. This resulted in three trials over three years of rice harvest.

The FYM rates, mostly between 5 and 10 Mg FW ha^{-1} were selected to cover agronomically feasible rates. A survey preceding the trials identified annual FYM rates ranging 0.2–27 Mg FW ha^{-1}, on average 8.8 Mg FW ha^{-1}. The treatments were fully randomized per block with TSP treatments randomized per FYM block. Effects of this blocking of treatments on results will be discussed below. The plot sizes were 9 m × 5 m (Ambatondrazaka), 6.25 m × 5.9 m (Ambohinaorina A) and 5 m × 5 m (Ambohinaorina B).

The trials were conducted on land of small-scale farmers located within the highland zone at Ambohinaorina (A and B), and in Mid-East and Mid-West of Madagascar at Ambatondrazaka. The experiments were conducted during 3 years between October 2010 and April 2014 (detailed experimental schedule is reported in Table 2). Before the trials were installed, all fields were used for irrigated rice by farmers. After the onset of trials, all dry season cultures were suspended during the trials. Some irrigation was initiated before ploughing when rain did not occur. Soils were ploughed (about 30 cm) with the applied FYM two days before transplantation except at Ambohinaorina A and B during the two last years of trials, when ploughing was one month before transplanting. Soils were subsequently flooded and harrowed with motorized engine one to two days before transplantation.

Rice cultivar (*Oryza sativa)* cv. X265: Ambohinaorina A, B and cv. MK: Ambatondrazaka, was transplanted in the irrigated plots between October-January with spacing of 20 cm × 20 cm and harvested between March and May. Seedling nurseries were established on nearby nurseries by farmers. The transplantation was done with seedlings of 3 leaves (approximately 15–20-day old). The FYM was obtained from nearby farms, heaped and then uniformly mixed prior to plot application. The FYM is a mixture of cattle manure; straw and household green waste in various proportions and the quality varied over years but was always recorded (the NPK content of FYM is shown in Table SI1). Mineral fertilizer application just preceded the transplantation or sowing. Each plot received the equivalent of 80 kg N ha^{-1} (as urea, 46%N) and 60 kg K ha^{-1} (as K_2SO_4, 50%K_2O) but only half of N and K were applied at transplanting, the other half was spread at the end of stem elongation. The N and K applications were broadcasted on the plots. The mineral-P was provided as Triple Super Phosphate (TSP; 46% of P_2O_5 SEPCM) and applied in the seedling row except during the first year at Ambatondrazaka where it was located by hand where the seedling was subsequently planted.

Farmers were in charge of water management and control of weeds or rice pests during the plant growth. One or two monitoring passages of staff researchers ensured the right application of the second application of N and K fertilizers. At harvest, grain yield was