**Pronounced effect of farmyard manure application on P availability to rice for paddy soils with low total C and low pH in the central highlands of Madagascar**

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**ABSTRACT**

Farmyard manure (FYM) – mixtures of animal droppings, crop residues, and fodder that are piled nearby homesteads – is a major nutrient source for smallholder farmers in Sub-Saharan Africa. However, its application effect has not been fully understood on typical P-deficient soils in tropics and in particular under anaerobic conditions. This study assessed the effect of FYM on irrigated rice in relation to soil properties – oxalate-extractable P (P\text{Ox}) , pH, and total C (TotC) – that are important indicators of soil P deficiency in the region. The first pot experiment was conducted with a factorial combination of FYM (0 and 20 g kg\(^{-1}\)) and mineral P (0 and 100 mg kg\(^{-1}\)) applications using six paddy soils differing in the aforementioned soil properties. The second pot experiment was conducted in a factorial combination of FYM and mineral P using the isotope dilution technique. In both experiments, the effect of FYM application on biomass and P uptake of rice per P applied was nearly equivalent to that of mineral P and was greater in soils with lower TotC and lower pH with negligible effect of P\text{Ox}. The isotope tracing suggested that the FYM application might increase rice P uptake by solubilizing non-labile P pools in soils while mineral P was directly used by rice from labile P pools. The results indicated that the FYM should be most effective in soils with low TotC and low pH, and its application could enable the use of insoluble P pools in soils and enhance P uptake of rice under P-deficient and anaerobic conditions.

**ARTICLE HISTORY**

Received 9 November 2019  
Revised 26 January 2020  
Accepted 1 March 2020

**KEYWORDS**

Farmyard manure; isotope dilution; labile P; Madagascar; *Oryza sativa*; P deficiency

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**Introduction**

Rice is the second largest source of caloric intake after maize (*Zea mays*) in Sub-Saharan Africa (SSA, hereafter). However, rice yields in SSA have remained low because of several biotic and abiotic stresses. Among these various stresses, P deficiency is a major constraint for rice production in highly weathered soils in SSA (Dogbe et al., 2015; Saito et al., 2019). P deficiency to rice is commonly observed in Madagascar, the second largest rice producer in SSA, which is due to high levels of P-fixing iron (Fe) or aluminum (Al) oxyhydroxides in soils (Nishigaki et al.,...
and late P fertilizer inputs (Rabeharisoa et al., 2012; Tsujimoto et al., 2019). Our previous on-farm experiments demonstrated that the yield gap between P-fertilized and non-P-fertilized treatments could reach up to 2.5 t ha\(^{-1}\) in the central highlands of Madagascar (Andriamananjara et al., 2016).

To alleviate this P-deficient stress in highly weathered soils, more effective use of organic matter (OM) such as farmyard manure (FYM) is expected because OM is the major available nutrient source for smallholder farmers. The FYM can be defined as a mixture of organic materials such as animal droppings, crop residues, and fodder which are piled nearby the homesteads. A recent survey showed that 16.3% of agricultural households use organic fertilizer, mainly FYM, whereas only 0.5% use mineral fertilizer in the central highlands of Madagascar (Tsujimoto et al., 2019).

On-farm trials in the central highland of Madagascar showed large field-to-field variations in the effect of FYM application on increases in grain yield (0.11 to 1.10 t ha\(^{-1}\)) and P uptakes (0.26 to 2.92 kg ha\(^{-1}\)) of rice under irrigated lowland conditions (Andriamananjara et al., 2016). In the same study, the effect of FYM application tended to be high in soils with limited P availability in terms of pH and contents of oxalate-extractable P (PO\(_{\text{ox}}\), hereafter). These results suggested that soil characteristics should be further examined with respect to the effective use of OM or FYM in lowland rice production in severely P-deficient soils in tropics. Rabeharisoa et al. (2012), through a country-wide field survey in Madagascar, found that soil pH and PO\(_{\text{ox}}\) were useful indicators of P availability for lowland rice. Additionally, our previous incubation and pot experiments demonstrated that the application of OM or rice straw under submerged conditions increased the amount of anion exchange membrane extractable-P (AEM-P) in soils up to 4.4 mg kg\(^{-1}\), and the effect was particularly large in soils with low total carbon content (TotC, hereafter) (Rakotoson et al., 2014, 2015). The increase in labile P with OM application can be related to extended microbial Fe-oxide reduction while how OM application affects soil-plant P dynamics and its relationship with soil characteristics are yet to be clarified.

Based on these previous understandings, the current study aimed to identify the relationship between P-deficiency status of soils defined by PO\(_{\text{ox}}\), TotC, and pH and the effect of FYM and mineral P applications on P availability for rice plants under submerged conditions. Then, we determined their effects on isotopically exchangeable P (labile P or L-values) using the principle of isotope dilution (Larsen, 1952). This is based on the concept that the specific activity (ratio of radioactive P to non-radioactive P in plants) reflects the amounts of labile P pools in soils labeled with radioactive \(^{32}\)PO\(_4\) ions after the incorporation of mineral P or FYM. This technique is more accurate as compared with soil extraction tests because the P taken up by plants is more representative of the plant-available P as compared with the P measured in soil extracts. Such an analysis of OM by soil interaction on P availability for lowland rice has not been carried out. We hypothesized that FYM would affect the dynamics of P pools in soils and consequently P uptakes and biomass production of rice and that the effect would be related to the soil parameters of PO\(_{\text{ox}}\), TotC, and pH.

**Materials and methods**

**Experimental design**

Two pot experiments, i.e. Exp.1 and Exp.2, were conducted in a greenhouse at the Laboratoire des Radio-Isotopes in Madagascar (18°53'56.0"S, 47°33'01.2"E, 1,222 m altitude). The experimental design consisted of full factorial combinations of FYM application, mineral P application, and soil characteristics with three replications. The most common lowland rice variety in the central highlands of Madagascar, X265 was used for both experiments and was grown under continuously flooded conditions. The daily mean temperature throughout the growing periods during the two experiments was 28.1°C for Exp.1 and 25.1°C for Exp.2 (WatchDog 2475 Plant Growth Station, Spectrum Technologies, Inc.).

Prior to the experiments, soil samples from 0 to 20 cm depth were randomly collected from 60 lowland rice fields in the central highlands of Madagascar. Samples were subsequently analyzed for TotC, PO\(_{\text{ox}}\), and pH. Based on this extensive survey, samples of six soils of lowland rice fields were selected to have a wide range of TotC, PO\(_{\text{ox}}\), and pH (Table 1). The soils were also characterized by high contents of oxalate extractable iron (FeO\(_{\text{ox}}\), hereafter) which are composed of Fe associated with amorphous oxides. The selected six fields were continuously under rice cultivation once a year from Nov–Dec to Apr–May with or without off-season upland crops in rotation.

During this extensive soil survey, we interviewed to 42 farmers using FYM and identified that (1) the FYM was commonly produced in a pile nearby the homesteads by mixing organic materials and soils and left for 5–6 months during the off-season before rice cultivation and (2) cow dung was the most commonly used organic material followed by rice straw for developing FYM in the region. Additionally, we randomly analyzed the C:N ratio and P concentration of FYM collected from 14 farmers. Based on these sets of preliminary information, we selected...
Table 1. Soil characteristics and estimated P deficiency level of experimental soils.

| Soil ID | Location          | Cropping System      | Type*     | TotC (g kg⁻¹)² | ℘Ox (mg kg⁻¹)⁻ | pH¹ | FℓOx (g kg⁻¹)⁻ | Estimated P deficiency level² |
|---------|-------------------|----------------------|-----------|----------------|----------------|-----|----------------|-------------------------------|
| 1       | Antanetikely      | Rice-upland crop     | Gleysol   | 11.0           | 38             | 4.54| 9.7            | High                          |
| 2       | Sahalombo         | Rice monoculture     | Fluvisol  | 10.1           | 704            | 6.05| 14.2           | Low                           |
| 3       | Mandriankiheniheny | Rice monoculture     | Gleysol   | 28.1           | 56             | 4.31| 5.9            | High                          |
| 4       | Mandriankiheniheny | Rice-upland crop     | Gleysol   | 27.2           | 644            | 4.84| 16.9           | Medium                        |
| 5       | Mandriankiheniheny | Rice-upland crop     | Gleysol   | 36.4           | 81             | 4.84| 10.6           | Medium                        |
| 6       | Mandriankiheniheny | Rice monoculture     | Gleysol   | 39.3           | 654            | 5.35| 26.7           | Low                           |

*IUSS Working Group WRB. ¹Dry combustion by NC analyzer (Sumigraph NC-220F, SCAS, Japan). ²Extracted by ammonium oxalate (Courchesne & Turmel, 2008). ³Dry combustion by NC analyzer. ⁴Estimated from ℘Ox and pH (Rabecharisoa et al., 2012).

representative types of FYM from two farmers being composed of cow dung and rice straw and more or less on average in C: N ratio and P contents. Then, the FYM was air-dried, ground, and mixed in a 1:1 weight ratio to be used for the present experiments. The FYM contained 3.8 g kg⁻¹ of P as determined by hot acid digestion with the molybdenum blue colorimetric method (Murphy & Riley, 1962), 165.4 g kg⁻¹ of total C and 15.0 g kg⁻¹ of total N as determined by NC analyzer (Sumigraph NC-220F, SCAS, Tokyo, Japan), and 3.9 mg kg⁻¹ of NH₄-N and 51.0 mg kg⁻¹ of NO₃-N as determined by a flow injection analyzer (AutoAnalyzer3, BL-Tech, Tokyo, Japan) after extracting by 2M KCl solution (Mulvaney, 1996). The CN ratio and CP ratio of FYM were 11.0 and 48.8, respectively.

**Exp.1: effect of FYM application on biomass and P uptake of rice as affected by various soil characteristics**

One-liter plastic pots (13 cm in diameter, 15 cm in height) without drainage were filled with 1 kg of each of the six soils after air-drying and sieved at 4 mm. Each pot was afterward filled with distilled water until the soil was submerged (2 cm standing water) and was left to incubate in the greenhouse for 6 days prior to transplanting. The treatments consisted of two levels of FYM applications, no FYM or with FYM (20 g per pot which is equivalent to 30 t ha⁻¹), two levels of mineral P application as KH₂PO₄, no mineral P or with mineral P (100 mg of P per pot which is equivalent to around 150 kg P ha⁻¹), and their combination. The total applied P per treatment was 0 for the control (no FYM and no mineral P), 76 mg pot⁻¹ for FYM, 100 mg pot⁻¹ for mineral P, and 176 mg pot⁻¹ for their combination. Fertilizers were applied and uniformly incorporated into soils 2 days for the FYM and 1 day prior to transplanting for the KH₂PO₄. Nitrogen as NH₄NO₃ and K as KCl were applied to all treatments at a rate of 157 mg kg⁻¹ (equivalent to 235 kg ha⁻¹) to exclude the potential effects of N or K deficiencies. For the pots with mineral P application, the amount of KCl application was adjusted based on the amount of K from KH₂PO₄ to make the K application rate equal for all pots.

Three 15-day-old (3-leaf stage) seedlings of X265 grown in P-free sand were transplanted into each pot; the water level was adequately maintained by regularly adding distilled water throughout the experiment. At 24 days after transplanting, the plants were cut at the soil surface and their lower portions were washed with distilled water to remove any remaining soil. Then, the plants were dried at 70°C for 2 days to determine their aboveground biomass. The plants from each pot were ground to a powder, and 50 mg of each plant sample was digested in 1 mL 65% HNO₃ at 180°C and diluted to 10 mL with distilled water to determine the P concentrations with the molybdenum blue method (Murphy & Riley, 1962) with a UV-VIS spectrophotometer (SP-8001, Metertech Inc.) at 882 nm. Total P uptake (mg pot⁻¹) was calculated as the product of the aboveground biomass and the P concentration of the plants.

**Exp.2: determination of isotopically exchangeable P in soils (L-value)**

Based on the results from Exp.1, three soils that differed in their responses to the FYM and mineral P applications, i.e. Soil 1, Soil 2, and Soil 5 were selected for Exp.2 (Table 1). In Exp.2, FYM and mineral P as triple super phosphate (TSP, hereafter) were applied at an equal P dose of 47 mg pot⁻¹.
which made 94 mg of P per pot for the combined FYM and mineral P treatment. Then, the soil-exchangeable P was labeled with \( ^{32}\text{P} \)O\(_4\) ions (\( ^{32}\text{P} \) radionuclide delivered in 1M HCl, NEX011010MC, Perkin Elmer). Treatments were the same with Exp1 – control, FYM, mineral P, and FYM + mineral P in three replicates.

Both FYM and mineral P were incorporated and incubated at 25–30°C in soils for 12 days before adding \( ^{32}\text{P} \). After the incubation, N and K solutions were added at the same rates as Exp.1 and mixed thoroughly into soils using a big plastic tray. After that, a carrier-free solution of \( ^{32}\text{P} \) was sprayed onto the soils at a final rate of 11.1 MBq \( ^{32}\text{P} \) kg\(^{-1}\) soil. Then, the soils were thoroughly mixed again. An aliquot from the \( ^{32}\text{P} \) spike solution was stored and analyzed for total activity to know the exact activity added to each soil. After \( ^{32}\text{P} \) addition, 1 kg of soils for each of the three soils was transferred into a 1-L plastic pot, then filled with distilled water and left to incubate for 8 days before transplanting. 15-day-old seedlings of X265 were transplanted into each pot and grown in the same way with the Exp.1. The top of the pot was covered by a black plastic sheet – but with a hole of the stem size in the center so that rice plants grow normally – to control the development of green algae on the soil surface, therefore avoiding unwanted immobilization of added \( ^{32}\text{P} \) and \( ^{31}\text{P} \) (the non-radioactive P). Aboveground biomass and total P uptake were determined at 35 days after transplanting.

The L-value was determined at the end of the experiment. After the plant samples being digested in the same way with the Exp.1, the \( ^{32}\text{P} \) activity in the plant was analyzed with a liquid scintillation analyzer (Tri-Carb 2800TR, PerkinElmer Inc.) using Ultima Gold XR as the scintillation liquid. The \( ^{32}\text{P} \) activities in the aliquots of spiking (labeling) solutions were measured at the same time as plant digests where all radioactivity concentrations were decay corrected. The \( ^{31}\text{P} \) concentrations were determined as total P based on the molybdenum blue method as described above.

The L-value (mg P kg\(^{-1}\)), indicating isotopically exchangeable P or labile P in soils, was calculated with Equation (2). This equation is derived from the concept of isotope dilution in Equation (1) assuming that the specific activity (SA or \( ^{32}\text{P}/^{31}\text{P} \) ratio) in aboveground biomass is equal to the SA in the labile-P pools in soils (Larsen, 1952):

\[
SA_{\text{Plant}} = SA_{\text{Soil}} \frac{^{32}\text{P}_{\text{Plant}}}{^{31}\text{P}_{\text{Plant}}} = \frac{^{32}\text{P}_{\text{Soil}}}{^{31}\text{P}_{\text{Soil}}} \tag{1}
\]

\[
L = \frac{D}{SA} = \frac{^{32}\text{P}_{\text{Plant}}}{^{31}\text{P}_{\text{Plant}} – ^{31}\text{P}_{\text{Seed}}} \tag{2}
\]

where \( D \) is the concentration of radioactivity added to the soil (MBq \( ^{32}\text{P} \) kg\(^{-1}\) soil); \( SA \) is the specific activity in the aboveground biomass (MBq \( ^{32}\text{P} \) mg P\(^{-1}\)); \( ^{32}\text{P}_{\text{Plant}} \) is the activity in the aboveground biomass (MBq \( ^{32}\text{P} \) kg\(^{-1}\) soil); \( ^{31}\text{P}_{\text{Plant}} \) is the non-radioactive P in the aboveground biomass (mg P kg\(^{-1}\) soil); and \( ^{31}\text{P}_{\text{Seed}} \) is the \( ^{31}\text{P} \) in the seeds as determined with the molybdenum blue method (average P content of three seeds was 0.064 mg kg\(^{-1}\) soil).

**Statistical analyses**

For both experiments, the effects of FYM, mineral P fertilizer, and different soils on the aboveground biomass, total P uptake, and L-values were analyzed with multifactor ANOVA. Multiple comparisons by the Scheffe test were conducted to determine the mean differences between treatments. For Exp.1, the relationship between soil chemical proprieties and the increases in aboveground biomass (ΔBiomass) and total P uptake (ΔPup) resulting from fertilizer application was assessed by backward stepwise regression using Akaike’s information criterion (AIC). Statistical analyses were done with the R(x64) 3.4.0 program (https://www.r-project.org/) with significance set at \( P < 0.05 \).

**Results**

**Aboveground biomass and P uptake of rice plants in Exp.1**

Multifactor ANOVA detected significant effects of all individual factors, i.e. soil characteristics, mineral P application, and FYM application, on both aboveground biomass and P uptake (Table 2). There were significant interactions of FYM and mineral P applications with soil characteristics on the aboveground biomass, and significant interaction between

| Table 2. Treatment effects of the two experiments analyzed by multifactor ANOVA. |
|-------------------------------|-------------------|-------------------|
| Factor                        | Exp1 Biomass yield | Exp1 P uptake     | Exp2 L-value   |
|-------------------------------|-------------------|-------------------|----------------|
| Soil                          | ***               | ***               | ***            |
| Mineral P                     | ***               | ***               | ***            |
| FYM                           | ***               | *                 | ***            |
| Soil × Mineral P              | ***               | ***               | ***            |
| Soil × FYM                    | ***               | n.s.              | *              |
| Mineral P × FYM               | *                 | n.s.              | ***            |
| Soil × Mineral P × FYM        | n.s.              | n.s.              | n.s.           |
| f statistic                   | 41.08             | 25.73             | 150            |
| P-value                       | <0.001            | <0.001            | <0.001         |
| Degrees of freedom            | 44                | 48                | 20             |

The times symbol (×) refers to the interaction between different treatments.

***P < 0.001; *P < 0.05; n.s., not significant.
mineral P application with soil characteristics on plant P uptake.

On average, the mineral P application increased the aboveground biomass by 0.35–1.62 g pot⁻¹ and P uptake by 1.59–5.71 mg pot⁻¹ relative to the control treatment depending on the soil types (Figure 1). Likewise, the effects of FYM application largely differed among the six experimental soils. Significant increases in aboveground biomass production (ΔBiomass) with the FYM application were observed for Soil 1, Soil 3, Soil 4, and Soil 5 in the range of 0.11–0.77 g pot⁻¹, whereas the effect of FYM application was not significant for Soil 2 and Soil 6. The increases in plant P uptake (ΔPup) with FYM application relative to the control were significant for Soil 1, Soil 4, and Soil 5 in the range of 0.06–1.30 mg pot⁻¹. Interaction of FYM application and mineral P application was also significant (Table 2). Apparently, there was an additive effect of FYM application to the mineral P application on both biomass production and P uptake for Soil 1, Soil 4, and Soil 5, whereas the effect of FYM application was null or even negative when combined with mineral P application for Soil 2, Soil 3, and Soil 6 (Figure 1). The negative effect of FYM application when combined with mineral P was particularly significant for Soil 6.

Stepwise regression analysis indicated that TotC and pH were more important explanatory factors than POx for the variations in ΔBiomass and ΔPup (Table 3). The

Figure 1. Aboveground biomass and P uptake of rice plants as affected by mineral P and FYM applications for the six soils in Exp.1. Black-colored bars indicate treatment without FYM, and grey-colored bars indicate treatment with FYM. Data are shown as the mean ± standard error.
Table 3. Stepwise regression retained parameters related to increases in aboveground biomass (ΔBiomass) and P uptake (ΔPup) of rice plants as affected by FYM and mineral P applications in Exp.1.

| Parameter                      | Intercept | P<sub>OX</sub> | TotC | pH | AIC |
|--------------------------------|-----------|----------------|------|----|-----|
| ΔBiomass (FYM)                 | 2.22      | 0.0003         | -0.16 | -0.33 | -70.32 |
| ΔBiomass (mineral P)           | 1.39      | -0.0005        | -0.17 | n.r. | -32.09 |
| ΔBiomass (FYM + mineral P)     | 1.66      | -0.0078        | -0.18 | n.r. | -31.90 |
| ΔPup (FYM)                     | 3.76      | n.r.           | -0.24 | -0.55 | -21.25 |
| ΔPup (mineral P)               | 5.02      | n.r.           | -0.91 | n.r. | 11.40 |
| ΔPup (FYM + mineral P)         | 11.42     | n.r.           | -0.95 | -1.23 | 6.91 |

n.r., not retained in regression model; AIC, Akaike’s information criterion.

regression model indicated that the soils with lower TotC were more responsive to the FYM application, mineral P application, or their combined applications on both ΔBiomass and ΔPup. The soils with lower pH were also more responsive to the FYM application on both ΔBiomass and ΔPup and to the combined application of FYM and mineral P on ΔPup. Soil pH was not related to the differences in ΔBiomass and ΔPup with mineral P application. Based on the results in Exp.1, we selected three representative soils that differed in their response to application of FYM and mineral P, i.e. Soil 1 and Soil 5 that had low P-supplying capacity and significant responses to both mineral P and FYM application and Soil 2 that had high P-supplying capacity and no responses to either single FYM application or combined application of FYM and mineral P.

**Aboveground biomass, P uptake and L-values in Exp.2**

Responses of biomass production and P uptake to FYM or mineral P applications for the selected three soils mostly confirmed the results of Exp.1 (Table 4). Soil 2 consistently had the largest biomass and P uptake under the control, and its responses to the FYM and mineral P applications were small relative to Soil 1 and Soil 5. Both Soil 1 and Soil 5 significantly increased aboveground biomass and P uptake with the FYM and mineral P applications (difference in biomass between control and mineral P application was not statistically significant for Soil 5, though). For these two soils, the FYM application significantly increased the aboveground biomass and P uptake by 0.60–1.17 g pot<sup>-1</sup> and 0.65–2.03 mg pot<sup>-1</sup>, respectively. These increases were more or less equivalent to the values observed with mineral P applications that were 0.37–1.37 g pot<sup>-1</sup> for Δbiomass and 0.93–3.77 mg pot<sup>-1</sup> for ΔPup. The increase in P uptake tended to be slightly higher with TSP than FYM, but there were no significant differences.

The L-values in the control treatment were 49.0, 146.8, and 67.2 mg kg<sup>-1</sup> for Soil 1, Soil 2, and Soil 5, respectively (Table 4). These values reflected the estimation of the P deficiency level of these soils in Table 1 in which the soil P deficiency was severest in the order of Soil 1 > Soil 5 > Soil 2. Mineral P application significantly increased the L-values by more than 47 mg P kg<sup>-1</sup>, the amount applied to pot, in all three soils. Similarly, increases in L-values by combining FYM and mineral P applications were all greater than 94 mg P kg<sup>-1</sup> – the total amounts of P applied with FYM and mineral P – relative to the control. On the other hand, the increases in L-values with the FYM application were all below 47 mg P kg<sup>-1</sup>.

**Discussion**

Results of Exp.1 confirmed that the effect of FYM application on both P uptake and biomass production of rice largely differed among soils under flooded conditions. Our previous studies indicated that the effect of FYM application on rice production and P uptake was much clearer under the upland ecosystem relative to the lowland ecosystem (Andriamananjara et al., 2016, 2018), but the specific soil chemical factors that caused different responses to FYM application have not been fully understood. Our hypothesis was that FYM would have a greater effect on P uptake and consequently on biomass production for rice in soils with low available P based on soil P<sub>DW</sub>, TotC, and pH. The stepwise regression analysis in Exp.1 revealed that the effect of FYM application on ΔBiomass and ΔPup was significantly greater in soils with lower pH and lower TotC. These responses of rice corresponded to our previous incubation trials in which the largest increase of isotopically exchangeable P (measured by the anion exchange membrane or E<sub>AEM</sub> value) was observed in soils with a low TotC and low pH when rice straw was incorporated under submerged condition (Rakotoson et al., 2014).
The positive impact of FYM application under lower pH or acidic soil could be attributable to a temporary pH increase as affected by the FYM decomposition which should reduce the P sorption capacity and increase the soluble P contents in soils (Haynes & Mokolobate, 2001). Although the present study did not measure the pH changes, this assumption can be supported by earlier study by Amery and Smolders (2012) in which they observed the significant pH increases after the incorporation of organic materials under submerged condition using the same acidic soils (pH at 4.5–4.6) from paddy fields in Madagascar. A negative correlation between the effects of FYM application and soil TotC might be related to extended microbial reduction and solubilization of more Fe$^{2+}$ after incorporating FYM into high TotC soils under submerged conditions. Increased amounts of Fe$^{2+}$ in soil solution could (i) induce precipitation of P (Heiberg et al., 2012) and consequently prevent P absorption by plant roots or (ii) directly induce Fe toxicity for rice plants (Ponnamperuma, 1972). A slight reduction in biomass and P uptake by the FYM application observed in Soil 6 that was high in both TotC and oxalate extractable Fe or greater effect of FYM for Soil 1 than Soil 2 implies the possibility of such adverse effects of large amounts of easily reducible iron in soils in addition to their differences in pH (Table 1, Figure 1).

The results of Exp.2 confirmed the equivalent effect of FYM relative to mineral P at the same P application rates to increase P uptakes and biomass production of rice plants under the continuously flooded condition (Table 4). In addition, the low $L$-values in the control treatment confirmed that Soil 1 and Soil 5 are more P-deficient, i.e. the labile P pool is smaller than in Soil 2, corresponding to the estimated P deficiency status based on pH and P$_{Ox}$ (Table 1). However, there were large differences in $L$-values between FYM and mineral P applications. These differences might reflect the different dynamics of these fertilizer resources in supplying P to rice plants after being incorporated into the soils. Much lower $L$-values with FYM than the amounts of P applied imply that only a small fraction of FYM-borne P was mineralized and labeled with $^{32}$P during the 12-day incubation prior to transplanting, while the FYM was gradually mineralized or/and unlocked the insoluble P pools in soils – which were not labeled with $^{32}$P – during the rice growing period after transplanting. The unlocking insoluble P pools by the FYM application could be likely through tentative pH increases and extended reductive dissolution of P-bearing Fe-oxyhydroxides. Our previous study found that more soil P can be unlocked in P-deficient paddy soil with low pH and low TotC (Rakotoson et al., 2014). This result corresponds to the current study in which the FYM application might unlock the insoluble-P pools and was more effective in soils with low pH and low TotC. Opposingly, high $L$-values with the mineral P application imply that most of the added P was retained in a labile form – which was labeled with $^{32}$P – at the time of transplanting, and directly used by rice plants.

Conclusion

In this study, we confirmed that responses of rice to FYM have significant interactions with soil characteristics under flooded conditions. In tropical P-deficient paddy soils, the effect of FYM application on biomass production and P uptake can be equivalent to mineral P applications and can be large for soils with low TotC and low pH. In addition, the isotope dilution technique implied that FYM application could potentially utilize insoluble-P pools in soils. It should be noted that the results of the current study were based on the pot experiments with relatively short growth durations. Nevertheless, it is also true that rice plants can benefit from optimized P nutrition at their very early stage such as nursery stage and consequently impact the final grain yields under P-deficient conditions (Vandamme et al., 2018, 2016). Therefore, the mechanical understanding of the interaction between FYM application and soil characteristics in the current pot experiment should provide a certain knowledge for the management of locally available resources for rice production in SSA. Field-based trials on varying soil types should be further needed to make use of the results in the current study.

Acknowledgments

We are thankful to Dr. Tomohiro Nishigaki of Japan International Research Center for Agricultural Sciences for his technical advice in preparing the manuscript. We also thank Mr. Rakotonirina Mamimbola Elysé of the Laboratoire des Radio-Isotopes for technical assistance.

Disclosure statement

The authors declare no potential conflict of interest in this paper.

Funding

This research was partly supported by the Science and Technology Research Partnership for Sustainable Development (SATREPS), Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA) [Grant No. JPMUSA1608].
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