Farmyard manure application increases spikelet fertility and grain yield of lowland rice on phosphorus-deficient and cool-climate conditions in Madagascar highlands

Hidetoshi Asai, Michel Rabenarivo, Andry Andriamananjara, Yasuhiro Tsujimoto, Tomohiro Nishigaki, Toshiyuki Takai, Tovohery Rakotoson, Njato Mickaël Rakotoarisoa and Tantely Razafimbelo

ABSTRACT
Phosphorus (P) deficiency is a major yield constraint for lowland rice production in the tropics. As P-fertilizer resources are finite, alternative fertilizer management is needed for sustainable rice production. We examined whether farmyard manure (FYM), a major nutrient source for small-holder farms, can overcome issue in typical P-deficient lowlands in the central highlands of Madagascar. A multi-location trial in sites varying in altitude and soil P availability, clarified that the effect of both FYM and mineral P fertilizer application on grain yield greatly increased at higher elevation and when the soil oxalate-extractable P content was <100 mg kg⁻¹. The yield increase was attributable to improved grain fertility, probably because FYM and mineral P applications decreased days to flowering and avoided low temperatures at late growth stages. Nutrient uptake assessment clarified that despite its relatively low P content, FYM had an equivalent effect on plant P uptake to those of mineral P fertilizer. We concluded that FYM application was effective in low-P availability soils at high altitude, as alternative of mineral P fertilizer. Further monitoring is required to assess the effect of consecutive FYM use on grain yield and plant nutrient uptake in the context of cold stress induced by P deficiency.

Introduction
Poor soil fertility and low fertilizer inputs are major causes for yield stagnation and the yield gap in rice cultivation in Sub-Saharan Africa (SSA) (Balasubramanian et al., 2007; Saito et al., 2019; Tsujimoto et al., 2019). Thus, many countries in SSA are dependent on rice imports to meet their increasing domestic consumption (Otsuka & Kalirajan, 2006). This is especially the case in Madagascar, where rice self-sufficiency has not yet been achieved despite of the largest rice cultivation area (1.8 million ha) and the highest annual rice consumption per capita in SSA (105.5 kg per capita) (Maclean et al., 2013). Most of Madagascar’s rice cultivation occurs in irrigated lowlands (80% of total area). Half of the lowland rice cropping area is located in the valleys and plains of the highland region, at an altitude of 800–1800 m (Balasubramanian et al., 1995). In the central highlands, rice is generally grown in highly weathered soils, most of...
which are Ferralsols, without sufficient fertilizer inputs. Thus, national average of rice yield stagnated at 2.0–2.6 t ha\(^{-1}\) during the 1995–2010 period (Maclean et al., 2013).

Soil P deficiency is the major nutrient constraint for most lowland rice production systems in Madagascar. In the Ferralsols of this region, most P is bound to iron and aluminum oxyhydroxides and therefore has a very low availability (Balasubramanian et al., 1995; Nishigaki et al., 2019). Thus, plant P uptake is severely inhibited even under flooding conditions (Rabeharisoa et al., 2012). Previous on-farm experiments have 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). Moreover, yield responses to P fertilizer were found to be greater than responses to any other macro nutrients (Balasubramanian et al., 1995).

Plant P deficiency can also lead to delayed phenological development and flowering (Doerrenmann & Fairhurst, 2000). Tsujimoto et al. (2019) found that pheno-logy changes in relation to P deficiency may have an interaction with climate-induced stress. In the central highlands of Madagascar, cold stress is another major abiotic constraint. Low temperatures at flowering stage can result in reduced spikelet fertility (Raboin et al., 2014; Van Oort, 2018). Therefore, delayed flowering induced by soil P deficiency could often exacerbate the cold stress damage in high altitudes (Rakotoarisoa et al., 2020).

In these regards, appropriate P fertilizer management is important to increase grain yields by addressing low P-supplying capacity of soils and P-deficiency-induced cold stresses. Mineral fertilizers, such as triple superphosphate, are preferable, but their use is limited by economical and logistical constraints in SSA (Croppenstedt et al., 2003; Liverpool-Tasie et al., 2017). On the other hand, farmyard manure (FYM) – a mixture of animal droppings, crop residues, and fodder – can be produced on-farm and is a potential P source for smallholder farmers. However, in the central highlands of Madagascar, FYM is poorly utilized in lowland rice farming (used by 18% of lowland rice farmers) (Tsujimoto et al., 2019).

To date, laboratorial studies have demonstrated that FYM can improve P uptake by rice plants due to the release of mineral P from organic matter under flooded conditions (Rakotosona et al., 2014; Rakotosona & Tsujimoto, 2020; Seng et al., 2004; Willett, 1989; Zhang et al., 1994). However, few on-farm studies have been established to verify the benefit of FYM to lowland rice farms. Moreover, little is known about the field conditions under which FYM application improves grain yield. Liniquist et al. (2007) reported an improvement in yield following FYM application, but did not find the evidence of P uptake improvement and also identified a large year-to-year variation in rain-fed lowlands in Laos. On the other hand, Andriamananjara et al. (2016) reported no effect of FYM on grain yield and plant P uptake in a P-deficit soil in the central highlands of Madagascar. These studies demonstrated the contrasting results. Moreover, their findings have been limited to a specific location with limited environmental variation. These call for the multi-location trial that allow us to assess to the FYM effect on grain yield and P uptake under a wide range of environments and to identify the key factors controlling the FYM performance.

In this study, we assessed the effect of FYM, in comparison with a mineral P fertilizer, on grain yield and nutrient uptake on lowland rice farms in the central highlands of Madagascar, where yield performance is constrained by soil P deficiency and cold stress. A multisite trial was designed to identify the field conditions that enhance or suppress FYM performance, with sites varying in altitude (i.e. air temperature) and soil bioavailable P content.

**Materials and methods**

**Site description**

In the cropping season from December 2017 to April 2018, on-farm trials were conducted at eight lowland sites located in the communes of Antohobe (19° 46’ S, 46° 41’E) and Behenjy (19° 10’ S, 47° 29’ E) in the central highlands of Madagascar. Before the trial, all sites were used for the monocropping of rice cultivation without mineral fertilizer inputs. The altitude at the sites ranged from 1238 to 1247 m in Antohobe and from 1375 to 1381 m in Behenjy (Table 1). Air temperature was relatively constant during the vegetative stage (December to February), decreasing in March when rice starts flowering (Figure 1). Air temperature was generally one-to-two degrees lower in Behenjy than in Antohobe throughout the cropping season. Mean annual rainfall in both communes is 1300–1400 mm, with most rain occurring during the rainy season between November and April.

Soils were mostly Ferralsols, with a yellow-reddish color and low fertility. The soils were moderately acidic, with pH ranging from 5.1 to 6.0 (Table 1). Soil textures were categorized into loam, sandy clay loam, and clay loam soil; clay content ranged from 25.6% to 38.4%. Soils ranged in bioavailable P content, with Olsen-P (Pol) content ranging from 4.8 to 6.4 mg kg\(^{-1}\) (coefficient variation (c.v.) = 9%), and oxalate-extractable P (Pox) content ranging from 43.9 to 149.3 mg kg\(^{-1}\) (c. v. = 42%). Other soil parameters also exhibited large variations, with total carbon (C) ranging from 1.1% to
Table 1. Description of experimental sites, including soil textual and chemical properties, and rice grain yield in control in the central highlands, Madagascar.

| Site Code | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|-----------|----|----|----|----|----|----|----|----|
| Commune   |    |    |    |    |    |    |    |    |
| Elevation (m.a.s.l.) | 1238 | 1246 | 1247 | 1260 | 1375 | 1375 | 1376 | 1381 |
| Transplanting date | 8-Dec. | 9-Dec. | 7-Dec. | 08-Dec. | 13-Dec | 14-Dec | 14-Dec | 15-Dec |
| Clay (%) | 32.5 | 32.6 | 27.5 | 26.4 | 37 | 31.9 | 38.4 | 25.6 |
| Silt (%) | 15.4 | 23.3 | 11.6 | 28.5 | 26.6 | 31.8 | 19.6 | 29.3 |
| Sand (%) | 52.1 | 44.1 | 60.9 | 45.1 | 36.4 | 36.3 | 42 | 45.1 |
| Soil type | SCL | CL | SCL | L | CL | CL | CL | L |
| pH | 5.6 | 6.1 | 5.7 | 5.2 | 5.5 | 5.7 | 5.4 | 5.3 |
| Total Carbon (%) | 2.3 | 1.4 | 1.3 | 1.1 | 1.4 | 1.5 | 2.8 | 1.2 |
| Total Nitrogen (%) | 0.19 | 0.13 | 0.12 | 0.1 | 0.11 | 0.12 | 0.19 | 0.11 |
| Olsen P (mg kg⁻¹) | 5.3 | 6.4 | 4.8 | 6.2 | 6.1 | 5.4 | 5.8 | 5.3 |
| Oxalate-extractable P (mgkg⁻¹) | 85 | 120 | 44 | 107 | 149 | 50 | 95 | 52 |
| Grain yield in control (t ha⁻¹) | 3.6 | 3.73 | 2.68 | 2.83 | 2.84 | 1.16 | 1.46 | 1.56 |

Notes: Soil samples (0–15 cm) were collected at after second ploughing. Soil type was categorized following USDA soil classification methods. L: loam soil, SCL: sandy clay loam, CL: clay loam. Soil particle size distribution was determined with the wet sieving and pipet method (Gee & Or, 2002). Soil pH was determined in a 1:2.5 ratio of soil-water. Total C and N were determined by the combustion method with an organic elemental analyzer (Sumigraph NC220F, Sumika Ltd.). Soil P was extracted following the Olsen method (Kuo, 1996) and the acid ammonium oxalate method (Courchesne & Turmel, 2008).

Experiment design and crop management

The effect of FYM and P fertilizer on grain yield was investigated at all eight sites (S1 to S8). The experimental design consisted of three P source treatments, (1) no application, (2) P fertilizer application (basal application of 50 kg ha⁻¹ of P₂O₅, which was equivalent to 21.8 kg ha⁻¹ of P, applied as triple superphosphate) and (3) FYM application (8 t ha⁻¹ on a fresh mass basis). The FYM application rate was the amount available to farmers in the area, determined based on the intensive survey by Ozaki and Sakurai (in press). To maintain FYM quality across the eight sites, all FYM, mixture of cattle manure, rice straw, green waste and soil, was obtained from a single farmer in Antohobe. The FYM was carefully mixed with soils at ploughing. The moisture content of FYM was 49.5%. Total C and total N contents, measured via combustion, were 14.5 and 0.873% on dry basis, respectively. Total P content, measured with HNO₃ /HClO digestion, was 1.24 g-P kg⁻¹. The nutrients supplied by the FYM application were estimated to be 0.58 t ha⁻¹ of C, 35.2 kg ha⁻¹ of N, and 4.9 kg ha⁻¹ of P, which is equivalent to only 23% of the P supplied in the P fertilizer treatment.

Experimental plots were established in a randomized complete block design with three replicates at each site. Individual plot size was 3.2 m × 1.6 m with a hill spacing of 20 cm × 20 cm, in which 128 hills were grown in each plot. An improved variety of rice (Oryza sativa L., cv. X265), which is widely grown in the central highlands (Diagne et al., 2015), was cultivated in each plot. Each plot was separated by a 40-cm-wide bund. Soils of 0–15 cm layer were...
hand-ploughed twice, at one month and two weeks before transplantation, and were subsequently hand-puddled at one day before transplantation. Seedlings (21 days old, 3–4 leaves) were transplanted from the 7th to 9th December for Antohobe, and from the 13th to 15th December for Behenjy. Harvesting was done in the period from early April to late May. Each plot was irrigated in order to maintain flooded conditions throughout the cropping season. Weeds were controlled by hand when necessary.

**Measurements**

At maturity, grain yield was determined for each plot after removing one border row on each side of the plot. Grain yield was expressed as the filled grain weight, corrected with grain filling ratios. Grain yield was corrected to 14% moisture using a grain moisture sensor (Riceter f, Kett Electric Laboratory, Tokyo, Japan). Within each plot, ten hills were sub-sampled to determine yield components (panicle number per m2, grain number per panicle, grain filling ratio, and grain weight). Grain filling ratio was determined by counting the number of submerged and floating grains in distilled water. Then, the submerged grains were weighed after oven drying at 65°C for 48 h to determine the filled grain weight.

P concentration was measured for each grain and straw sample after dry ashing using the vanadate-molybdate method with a UV-visible spectrophotometer (UV-1800, Shimazu, Japan). P uptake in grain and straw was calculated by multiplying the grain and straw weight with the plant P concentration. Total P uptake was estimated by summing the grain P uptake and straw P uptake.

**Statistics**

An analysis of variance (ANOVA) was conducted for grain yield, yield components, P concentration for grain and straw, and total P uptake using JMP 10 software (SAS Institute Inc., USA) with data from all eight sites. In the models, P source, Site, and their interaction were fixed effects, while the replicates nested within sites were random effects. For each site, one-way ANOVA was performed to test the effect of P source on grain yield.

Yield responses to P fertilizer and FYM were calculated with the yield difference between control and P fertilizer or FYM plots. To determine which yield components contributed most to grain yield, the relative grain yield response associated with either FYM or P fertilizer were regressed against the relative increase in each yield component. Similarly, P uptake responses to P fertilizer and to FYM were calculated with the difference in total P uptake between control and P fertilizer or FYM plots, respectively.

**Results**

**Yield and Yield components**

Grain yield varied considerably among the eight sites. The yield in control was the lowest at S6 (1.16 t ha⁻¹) and the highest at S2 (3.73 t ha⁻¹) (c.v. = 39%) (Table 1). Similarly, large variations were observed for soil total C, total N and Pox (c.v. = 28–42%). However, there was little variation in Pol (c.v. = 9%). Soil Pol and Pox were both low at S3 (4.8 and 44 mg kg⁻¹) in Antohobe, and S8 (5.3 and 52 mg kg⁻¹) and S6 (5.4 and 50 mg kg⁻¹) in Behenjy. Grain yield in control was not significantly correlated with any of the soil properties measured.

Flowering started in early March at Antohobe and the middle of March at Behenjy (Figure 1). It was visually observed that flowering delayed in control plots compared with FYM and P fertilizer plots. The delay was most prominent at low-P availability sites of high altitude – it was delayed by approximately four weeks in S6 and S8 (Behenjy).

Grain yield across the eight sites was significantly affected by P source treatment (p < 0.001; Table 2). Both P fertilizer and FYM application significantly increased yield; the average yield response across the eight sites was 0.40 t ha⁻¹ (16% increase) for FYM and 0.43 t ha⁻¹ (18% increase) for P fertilizer (Table 3). For yield components, P source treatment significantly affected grain filling ratio, while the other components were not significantly affected (Table 2).

The effect of Site × P source interaction on grain yield was significant. One-way ANOVA clarified that both of FYM and P fertilizer were significantly effective for yield improvement at three of four sites in Behenjy (S6, S7 and S8). The other two sites in Antohobe (S1 and S3) also exhibited the positive effects of FYM on grain yield, but not at significant level.

Yield response to P fertilizer was significantly correlated with soil Pox content (r = −0.67 at p < 0.05, Figure

| Site    | Grain Yield | Panicle number | Grain number per panicle | Grain filling ratio | Grain weight |
|---------|-------------|----------------|--------------------------|---------------------|--------------|
| P source | 15.8 **     | 3.5 *          | 11.5 ***                 | 20.0 ***            | 1.7 ns       |
| Site × P source | 3.6 **     | 0.8 ns         | 2.4 *                    | 2.4 *               | 3.2 *        |

**Notes**: Values are F ratios, while asterisks represent significant probability. ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001.
2), but not with soil Pol content ($r = -0.47$, $P = 0.32$, data not shown). The yield response to P fertilizer was greatest at sites with low Pox, but it was minimized or disappeared at sites where Pox was above 100 mg kg$^{-1}$. Yield response to P fertilizer was also related to site location, with greater yield responses in Behenjy sites compared with Antohobe sites, even for the Antohobe sites with low Pox content.

The trend in yield response to FYM was similar to the response to P fertilizer. Yield responses were significantly correlated with Pox content ($r = 0.70$ at $P < 0.05$) and larger yield responses were observed in the low-Pox sites of Behenjy compared with other sites (Figure 2). Consequently, there was a strong correlation between yield response to FYM and yield response to P fertilizer ($r = 0.88$, $P < 0.005$, data not shown).

Both yield response to P fertilizer and yield response to FYM were positively correlated with grain filling ratio ($r = 0.97$ and 0.80, data not shown). In control, grain filling ratio was lower at low-Pox sites, particularly in Behenjy sites (Figure 3). In the low-Pox sites of Behenjy, both P fertilizer and FYM drastically increased grain filling ratio, from 62.4% in the control to 81.8% and 80.4% in S6 (Pox = 52 mg kg$^{-1}$) and from 54.2% in the control to 85.6% and 72.3% in S8 (Pox = 50 mg kg$^{-1}$) (Figure 3). On the other hand, in Antohobe sites, grain filling ratio in control was higher than in Behenjy sites and the increase in grain filling ratios associated with P fertilizer and FYM was smaller even at low-Pox sites (e.g. S3, Pox = 44 mg kg$^{-1}$). The difference in the recovery of grain filling ratio between two communes can explain well why the yield response to P fertilizer and FYM was more prominent in Behenjy than Antohobe.

**P uptake assessment**

Plant P uptake assessment indicated that the significant effects of Site and P source treatment were identified for P concentration of grain and straw and total P uptake (Table 4). P fertilizer application increased P concentration of grain and straw and total P uptake. Similar trends were observed for FTM treatment, though not significant at straw P concentration. But, total P uptake in FYM plots (5.6 kg ha$^{-1}$) was significantly lower than that of P fertilizer plot (6.3 kg ha$^{-1}$), because of lower P concentration of grain and straw and lower biomass accumulation.

The effect of Site on total P uptake was significant and total P uptake in the control ranged from 2.04 kg ha$^{-1}$ at S6 to 8.42 kg ha$^{-1}$ at S2 (Figure 4a). The large variation in total P uptake among the eight sites was well explained by soil Pox contents ($r = 0.87$, $P = 0.01$). This relationship clearly indicated that low Pox content constrained the plant P uptake.

The P uptake response to P fertilizer was significantly correlated with Pox and was considerably improved under low Pox conditions. A similar site-specific trend was observed for the P uptake response to FYM. The result suggested that the use of FYM, as well as

### Table 3. Rice grain yields in control, FYM and P fertilizer plot at eight sites in the central highlands, Madagascar.

| Site | Control | FYM | P fertilizer | Probability |
|------|---------|-----|--------------|-------------|
| S1   | 3.6     | 4.29| 4.14         | 0.09        |
| S2   | 3.73    | 3.88| 3.6          | 0.81        |
| S3   | 2.68    | 3.00| 3.06         | 0.46        |
| S4   | 2.83    | 2.94| 2.41         | 0.09        |
| S5   | 2.84    | 2.87| 2.79         | 0.91        |
| S6   | 1.16    | 1.75| 2.43         | **          |
| S7   | 1.46    | 2.1 | 2.38         | *           |
| S8   | 1.52    | 2.23| 2.61         | **          |
| Average | 2.48 | 2.88| 2.91         | -           |

**Notes:** Probability is a result of one-way ANOVA for each site; *$p < 0.05$, **$p < 0.01$. Within each site, lowercase letters indicate significant differences based on Student’s t-tests at $p = 0.05$.  

![Figure 2](image-url)  
**Figure 2.** The relationship between Pox and rice yield response to P fertilizer (left) or to FYM (right) across eight sites in Antohobe and Behenjy, Madagascar.
Fertilizer, was effective for enhancement of plant P uptake under low Pox conditions.

**Discussion**

The effect of FYM on grain yield was studied across sites varying in soil P availability and altitude. We found that the effect of FYM application was highly effective for improving grain yield at low Pox soils of high altitude. This information is key for resource-poor farmers who need to efficiently use limited organic fertilizer resources for lowland rice production.

**Table 4.** Main effect of P source treatment on P concentration and Total P uptake and F ratios from ANOVAs showing the effect of Site, P source, and their interactions on each parameter.

| P concentration (mg g⁻¹) | Total P uptake (kg ha⁻¹) |
|--------------------------|--------------------------|
| Grain                    | Shoot                    |             |
| Control                  | 1.39 c                   | 0.59 b      | 4.92 c       |
| FYM                      | 1.44 b                   | 0.63 b      | 5.6 b        |
| P fertilizer             | 1.5 a                    | 0.82 a      | 6.3 a        |
| Site                     | 78.3 ***                 | 84.6 ***    | 27.5 ***     |
| P source                 | 15.2 ***                 | 15.3 ***    | 18.7 ***     |
| Site × P source          | 4.8 ***                  | 0.5 ns      | 1.8 ns       |

Notes: Within each column, lowercase letters indicate significant differences based on Student’s t-tests at p = 0.05. ns: not significant, * ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001.
Soil P deficiency is a major cause of yield stagnation, but accessibility to mineral P fertilizers is highly limited for smallholder farmers in Madagascar (Tsujimoto et al., 2019). Our results clearly demonstrate that the use of FYM is a practical alternative to mineral P fertilizers, leading to enhanced P uptake, to increased grain filling ratio and to improved grain yield, as were similarly observed in P fertilizer plots. These results are consistent with previous laboratory and pot studies that reported the P supplying potential of FYM (Rakotoson et al., 2014; Seng et al., 2004; Willett, 1989; Zhang et al., 1994). However, the positive effects of both FYM and P fertilizers on grain yield were highly site-specific. High yield responses were greatest at low-Pox sites, particularly those in high altitudes where Pox content was below 100 mg kg⁻¹. This suggests that both soil P availability and altitude can interactively influence the effect of FYM on grain yield in the central highlands of Madagascar.

Both soil P availability and altitude affected yield responses by strongly influencing the grain filling ratio (Figure 3). When soil Pox content was low, high-altitude sites had lower grain filling ratios in control treatments, and both FYM and P fertilizer had stronger effects on grain filling ratio than at low-altitude sites. This interaction between soil P and altitude may be related to phenology development and cold stress. It is well known that the risk of cold stress exponentially increases when rice experiences temperatures below 20–22°C during the booting and flowering stages, resulting in increased spikelet infertility (Horie et al., 1995; Yoshida, 1981). In our study, flowering was delayed in the low-Pox sites, especially in high altitudes, where control plots required approximately four more weeks for flowering than FYM and P fertilizer plots. Based on the observed trend in temperature at Behenjy, temperatures at flowering stage fell below 19°C in control treatment due to the delayed flowering (Figure 1). This likely resulted in the declined grain filling ratio in the control and its recovery at FYM and P fertilizer treatments in S6 and S8. Rakotoarisoa et al. (2020) observed in the central highlands of Madagascar that P fertilizer input resulted in fewer days to flowering and alleviated the cold stress, leading to increased rice yield. These results imply that the use of FYM, as well as P fertilizer also could alleviate the cold stress by avoiding the flowering delay. Further monitoring is required to assess the relationship FYM application and cold stress under P-deficiency condition of high-altitude.

Both yield responses to P fertilizer and FYM were correlated with Pox content (Figure 2), but not with Pol content, even though Pol is the standard soil P metric for flooded rice ecosystems (Dobermann & Fairhurst, 2000). In addition, Pox can well explain the variation in total P uptake at in the control and in the P uptake response to P fertilizer and FYM (Figure 4). These results are consistent with those of previous studies in Madagascar, which reported that soil Pox content was correlated with flag leaf P concentration and total P uptake (Andriamananjara et al., 2016; Rabeharisoa et al., 2012). This suggests that Pox content is an appropriate measurement of soil P availability for lowland rice ecosystems in the central highlands. According to Nishigaki et al. (2019), Pol content represents readily-available inorganic P, whereas Pox content represents all inorganic P – both readily-available and resistant forms. Taken together with our results, this implies that flooding induced mobilization of resistant P forms, which constitute most of the inorganic P in Madagascan lowland soils. This could be a key P process in highly weathered lowland soils. Our empirical results indicate that a Pox content of 100 mg kg⁻¹ is the indicative threshold value, at which severe P deficiency symptoms are avoided. Soil Pox can be rapidly and accurately measured using visible and near-infrared

Table 5. Altitude, Pox content, grain yield of P fertilizer and FYM treatments of farmer’s fields of four locations in the central highlands of Madagascar.

| Year | 2011 | 2012 | 2012 | 2018 | 2018 |
|------|------|------|------|------|------|
| Altitude (m) | 779 | 1400 | 1400 | 1651 | 1119 |
| Pox (mg kg⁻¹) | 51 | 100 | 150 | 1551 | 201 |
| Location name | Amباتondrazaka | Ambohinaorina | Ambohibary | Ankazo-miriotra |
| Grain yield (t ha⁻¹) | 6.7 | 3.4 | 5.5 | 2.0 | 2.0 |
| P | 7.7 | 5.3 | 5.3 | 3.6 | 2.8 |
| FYM | 8.3 | 4.2 | 5.9 | - | - |
| FYM+P | 8.9 | 5.3 | 5.9 | - | - |
| (P input (kg ha⁻¹)) | 20 | 20 | 20 | 25.8 | 25.8 |
| P from TSP | 12 | 6 | 6 | - | - |
| P from FYM | n.s. | n.s. | n.s. | s. | s. |
| Probability TSP* | n.s. | n.s. | n.s. | - | - |
| Probability FYM* | n.s. | n.s. | n.s. | - | - |

Notes: *s. significant at p = 0.05, n.s.: not significant at p = 0.05

References: Andriamananjara et al. (2016) Rakotoarisoa et al. (2020)
diffused reflectance spectroscopy (Kawamura et al., 2019), making it easy to adopt site-specific FYM management plans based on soil P analysis in the region.

This study identified soil Pox content and altitude as the key factors to determine the performance of FYM as well as P fertilizer. However, there are still contradictions among this study and the previous studies in Madagascar (Andriamananjara et al., 2016; Rakotoarisoa et al., 2020, summarized in Table 5). In these studies, the use of FYM and P fertilizer did not result in significant yield improvement even under low Pox site (Ambatondrazaka, Pox = 51 mg kg\(^{-1}\)). In contrast, P fertilizer improved the grain yields of volcanic soils in Ambohibary and Ankazo-miriotra, where soil Pox values were far above 100 mg kg\(^{-1}\). These results implied that diagnosis of soil P deficiency based on Pox value might be site-specific, highlighting the need to verify the effectiveness of this criterion under different soil types.

**Conclusions**

Our field trial provides information on the optimum use of FYM in the context of soil P deficiency and cold stress that characterize the majority of lowland rice farms in the central highlands of Madagascar. The results indicate that in sites with less than 100 mg kg\(^{-1}\) Pox, especially in high-altitude areas with a risk of late-season low temperature stress, FYM can be a practical alternative for mineral P fertilizers, which are unaffordable for many local farmers. This technical implication may be applicable not only to the central highlands of Madagascar, but also to other lowland ecosystems of tropical highlands, where yield performance is constrained by soil P deficiency at high-altitude. Our multi-site trial will continue for three more years. Further work will focus on the effect of consecutive applications of FYM, not only on grain yields but also on yield response to other macronutrients such as nitrogen. This will provide a better understanding of optimum site-specific soil management practices.

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**Disclosure statement**

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**ORCID**

Hidetoshi Asai http://orcid.org/0000-0003-0125-1234
Andry Andriamananjara http://orcid.org/0000-0001-5372-7359
Yasuhiro Tsujimoto http://orcid.org/0000-0001-7738-9913
Tomohiro Nishigaki http://orcid.org/0000-0002-6669-803X
Toshiyuki Takai http://orcid.org/0000-0002-6498-610X

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