Output3 Introduction

Fertilizer management techniques using genetic resources for nutrient-efficient rice production are developed

Output 3 aimed to develop efficient fertilizer management practices based on the nutrient characteristics of the fields using locally available nutrient resources and nutrient-efficient genetic resources. For this, we set three targets:

1. Develop fertilizer management practices that improve nutrient use efficiency by 20%.
2. Select at least two varieties that show high performance in the field nutrient conditions.
3. Transfer the developed fertilizer management techniques to at least 20% of extension services in the target regions of Madagascar.

Throughout the project, Output 3 has scored several key achievements corresponding to the targets. The highlights included the development and dissemination of the P-dipping technique. The technique involves dipping the seedling roots into phosphorus (P)-enriched slurry at the P concentration of 1.8–2.6% for < 2 h before transplanting. Repeated on-farm trials and pilot-scale tests under a range of edaphic-climatic and farmers' management conditions in the target regions identified that fertilizer use efficiency can be nearly doubled compared with the conventional P application via broadcast. The effect of P-dipping was particularly large under cool climate conditions because the technique quickens heading and prevents low temperature stress. Additional experiments also showed that the effect of P-dipping can be enhanced by combining it with a small dose of NP application to the nursery bed and a shallow root genotype. The manual and small-dose fertilizer sac for P-dipping (containing 3 kg of triple superphosphate) were developed, and the technique has been already disseminated to > 3,000 farmers in collaboration with JICA technical cooperation Project (Papriz), extension officers of MINAE, and private fertilizer company Agrivet in Madagascar.

The cumulative and specific effect of farmyard manure (FYM) application to P-deficient lowlands together with key data on the functional mechanism and appropriate type of FYM was a novel and practical finding to enable more efficient use of locally available nutrient resources for rice production. The FYM is more commonly used than mineral fertilizer for lowland rice production in the target regions. The manual of effective FYM application was developed for both extension officers and farmers. The field-based evidence about the interaction between phosphorus deficiency that delays phenological development and climate-induced stresses is important for sustainable rice production against depleting P fertilizer resources and climate change.

We published two review papers regarding the N and P management practice for rice production in SSA. The information obtained in this output should contribute to improved fertilizer management and increased rice production under low-input and poor soil conditions in the target regions and elsewhere in SSA. The publications and manuals developed in this output have been compiled.

A memory of Output3 activities

Voka-tsoa azo avy amin'ny teknika P-dipping

1. Manatsara ny voka-bary amin'ny tany manta tsy ampy zezika

Fambolena tsotra **P-dipping**

Ny fampiasana zezika TSP 3kg dia hahazoana tombom-bary akotry manodidina ny 40~50 kg (45,000~60,000 Ar).

2. Manafaingana ny fitombon'ny vary mba tsy hahatratrarany ny fotoanan'ny hatsiaka

Fambolena tsotra **P-dipping**

Aiza ny toerana afaka hampiharana ny P-dipping?

1. Tanimbary tsy ampy zezika ary ambany ny voka-bary
2. Tanimbary tsy ampy kasinga faosifaoro
3. Toerana mangatsiaka, tara ny fanetsana sy/na ny fijinjana

Ahoana no ahafantarana fa tsy ampy faosifaoro ny tanimbary?

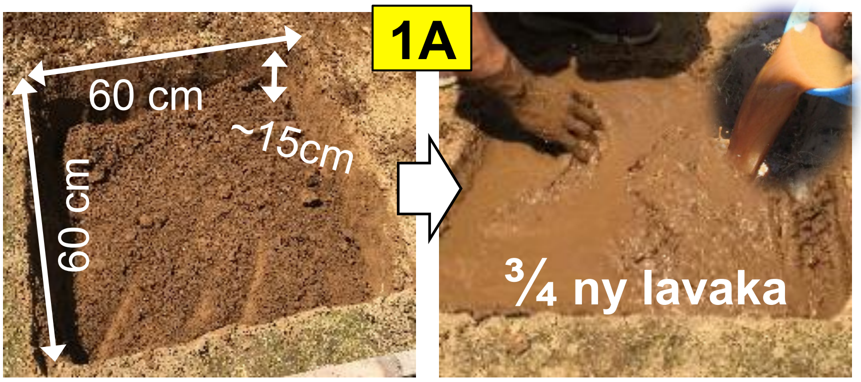
1. Vitsy ny zana-bary.
2. Miadana ny fanirin'ny vary.
3. Ambany ny vokatra azo na nahazo rano tsara sy voaava tsara ary ny vary.

Torolalana momba ny Teknika P-dipping

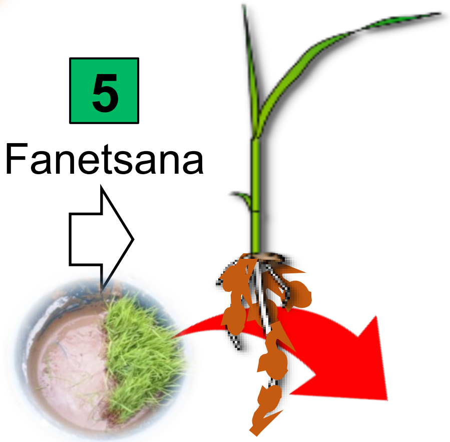
Levonina ao anaty rano 5~10L; alina iray mialohan'ny fanetsana ny TSP 3kg.

1. Arotsaka ary afangaro tsara ao anaty **A. Lavaka** (60 cm x 60 cm x 15 cm) na **B. Koveta** ny fotaka avy ao an-tanimbary sy ny rano.
2. Arotsaka ao ary afangaro tsara amin'ny fotaka ny ranon-jezika.
3. Azo ampiana tany maina malemy avy eny ivelany, ary afangaro tsara mba hahazoana fotaka marihitra.
4. Alona ao ny ketsa mba hampiraikitra tsara ny fotaka amin'ny fakany.
5. Fanetsana: tandremana mba tsy hiendaka ny fotaka amin'ny fakam-bary*

*Tohizana ny fanetsana mandra-pahalanin'ny fotaka (Mahavita 5 ara eo ho eo)

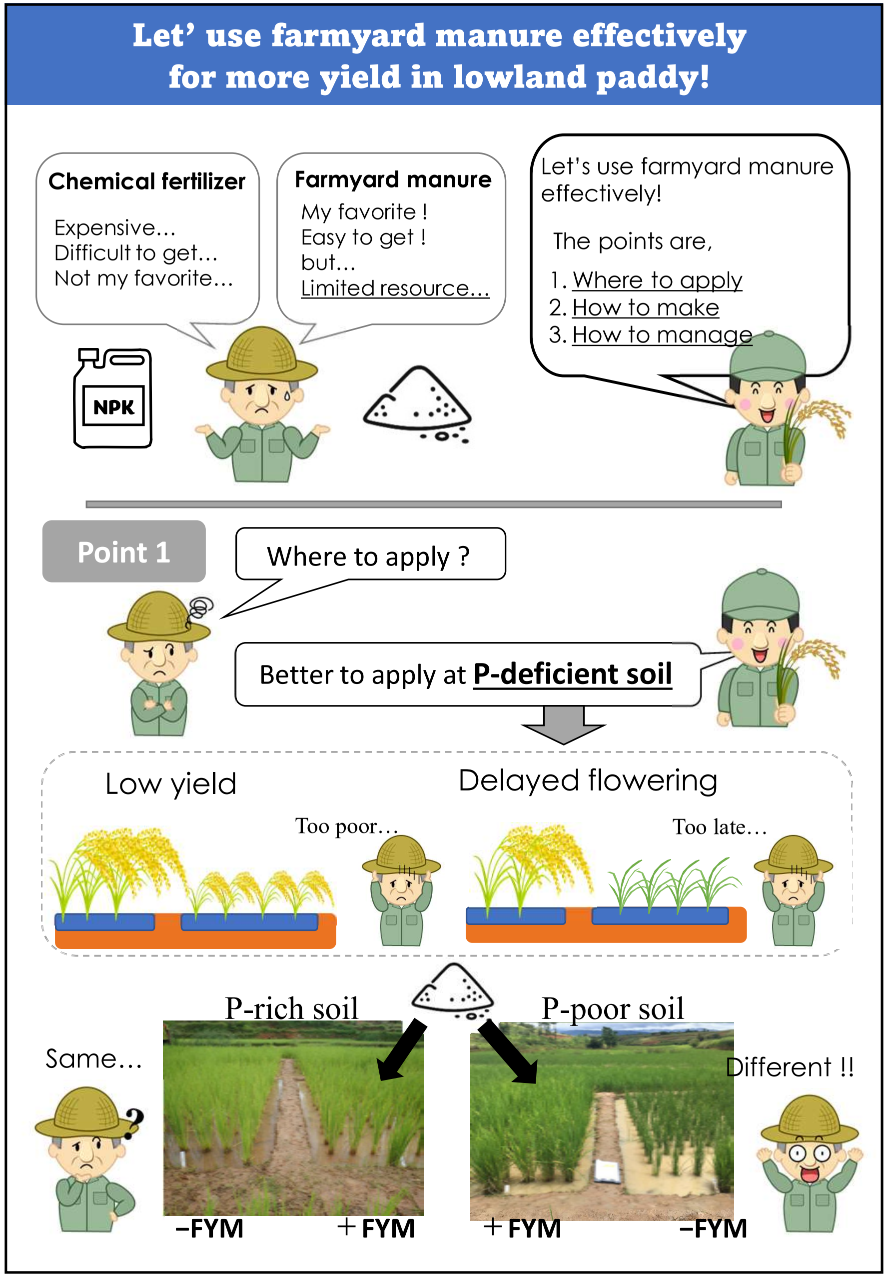


Raha koveta mahazaka:
40L=> ampiasaina daholo ny ranon-jezika
20L=> ny antsasaky ny ranon-jezika ihany aloha no ampiasaina (TSP 1,5 kg levonina ao anaty rano 5~10 L)



Afaka mampiasa koveta hitaomana ny ketsa sy ny fotaka.

Zezika TSP ihany no azo ampiasaina amin'ny fangaro fa tsy zezika hafa!



Let' use farmyard manure effectively for more yield in lowland paddy!

Chemical fertilizer

Expensive…
Difficult to get…
Not my favorite…

Farmyard manure

My favorite !
Easy to get !
but…
Limited resource…

Let's use farmyard manure effectively!

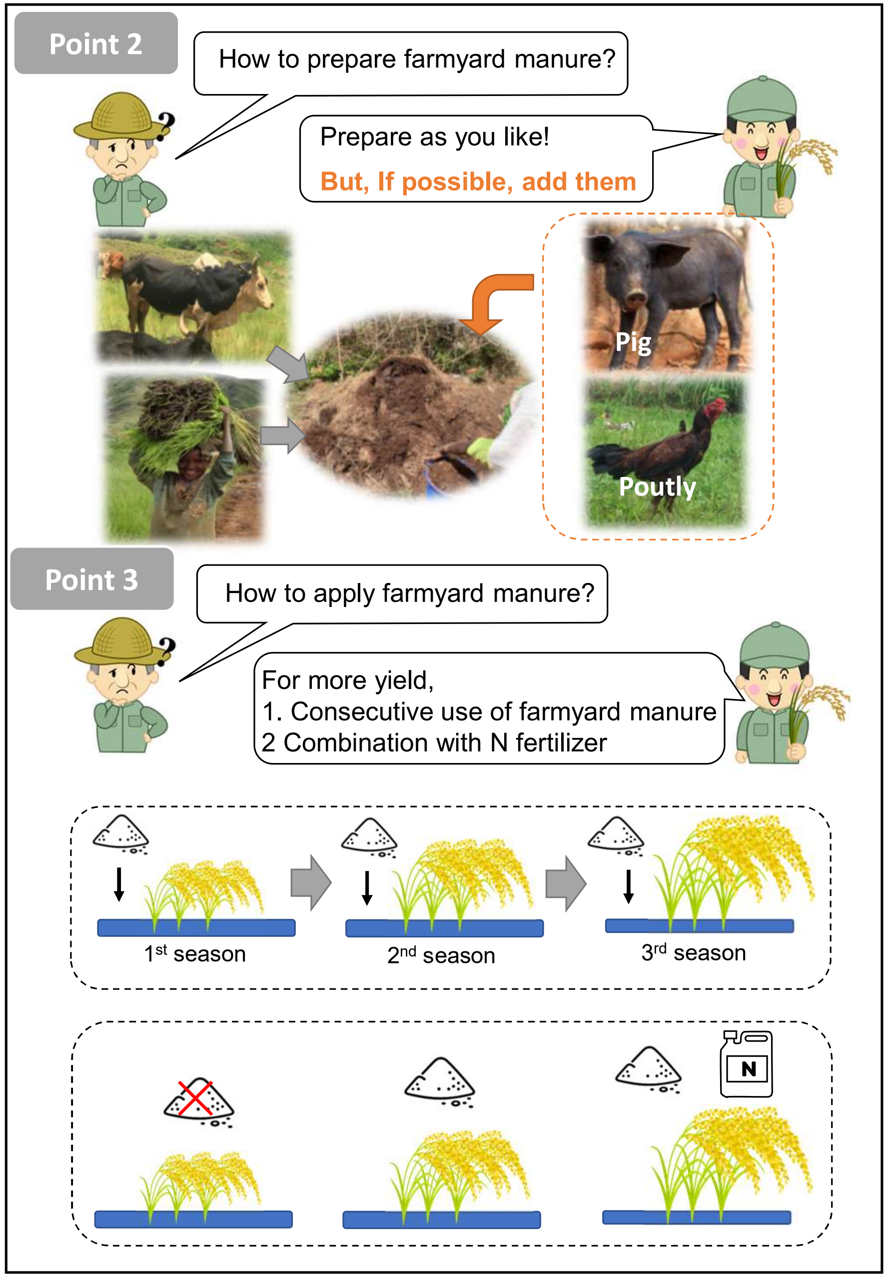
The points are,

1. Where to apply
2. How to make
3. How to manage

Point 1

Where to apply ?

Better to apply at **P-deficient soil**



Point 2

How to prepare farmyard manure?

Prepare as you like!
But, If possible, add them

Point 3

How to apply farmyard manure?

For more yield,
1. Consecutive use of farmyard manure
2 Combination with N fertilizer

Fampiasana zezi-pahitra (FYM) mahomby ho fanatsarana ny voka-bary an-tanimbary.

Zezika simika

Lafo…
Sarotra hita…
Tsy mahazatra…

Zezi-pahitra

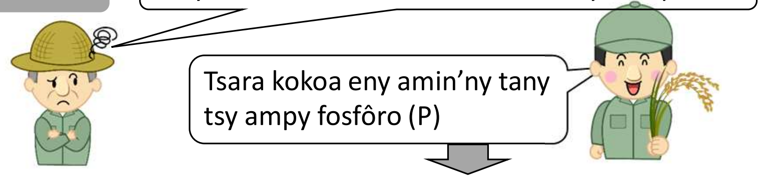
Mahazatra!
Mora azo!
kanefa…
<u>Voafetra ny akora…</u>

Andao hampiasa zezi-pahitra amin`ny fomba mahomby!
Ireo dingana 03 :

1. <u>Tanimbary manao ahoana no hitondrana azy</u>
2. <u>Fanamboarana ny zezika</u>
3. <u>Fitantanana ny zezika</u>

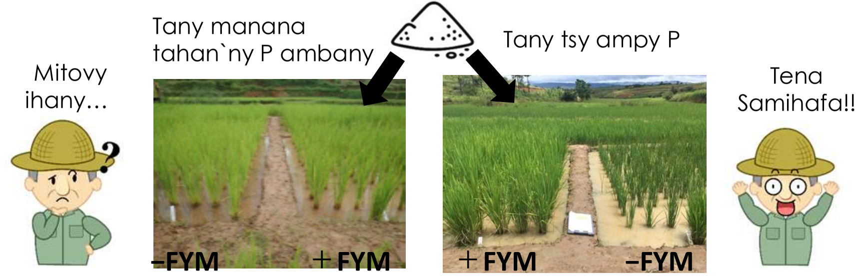
Dingana 1

Tany manao ahoana no hitondrana ny zezi-pahitra



Tsara kokoa eny amin'ny tany tsy ampy fosfôro (P)

<u>Rehefa nasiana zezi-pahitra</u>

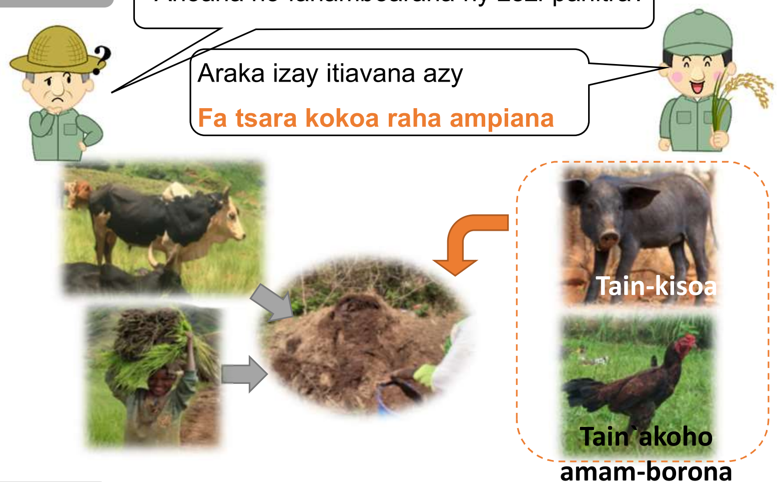


Dingana 2

Ahoana no fanamboarana ny zezi-pahitra?

Araka izay itiavana azy

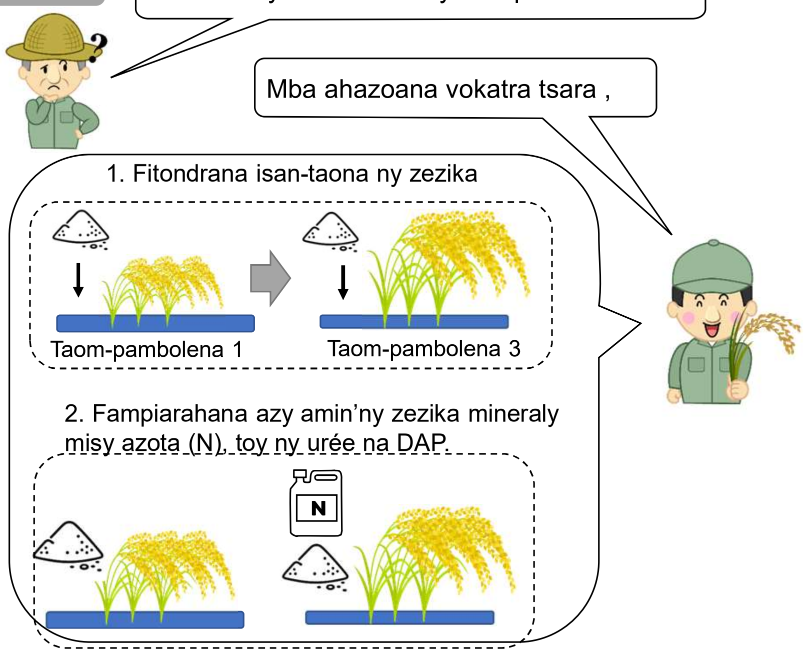
Fa tsara kokoa raha ampiana



Dingana 3

Ahoana ny fitantanana ny zezi-pahitra?

Mba ahazoana vokatra tsara ,



1. Fitondrana isan-taona ny zezika

2. Fampiarahana azy amin'ny zezika mineraly misy azota (N), toy ny urée na DAP.

Optimum use of Farmyard Manure (FYM) in paddy lowlands of central highlands

Keywords | P-deficiency, N fertilizer, FYM quality, Consecutive use

Summary

FYM is effective to improve the grain yield under P-deficient soils. In addition, under low P condition, we recommend the consecutive FYM application and/or the combined application with N fertilizer for further yield improvement. Since higher P content of FYM result in greater yield improvement, a high P materials such as pig or poutry dungs are recommended to be added for FYM preparation

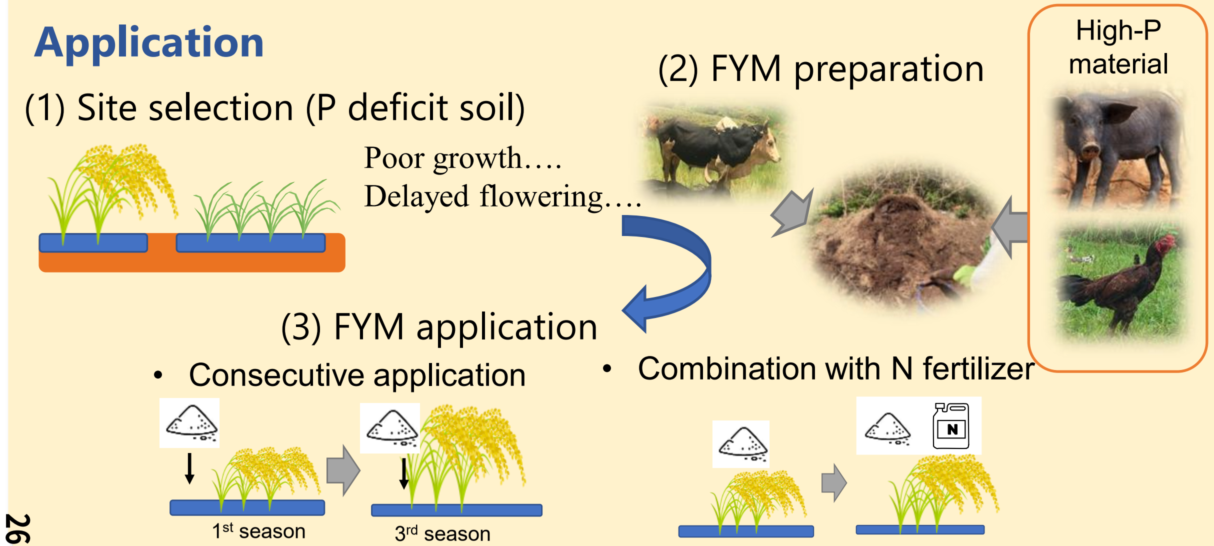
Background & Objective

FYM is an accessible materials for local farmers. However, due to the limited resource availability for FYM, optimum use of FYM is inevitable for farmer's livelihood. Here, we describe (1) where to apply, (2) how to apply, and (3) how to make FYM.

Contents & Characteristics

- FYM is effective to overcome the P deficiency (Fig. 1 and 2).
- Consecutive use of FYM with combination of N fertilizer is highly effective for yield improvement in low P soil. (Fig. 1 and 2).
- Pig or poutry dungs is recommended for FYM preparation. (Fig. 3)

Application



Supporting Data

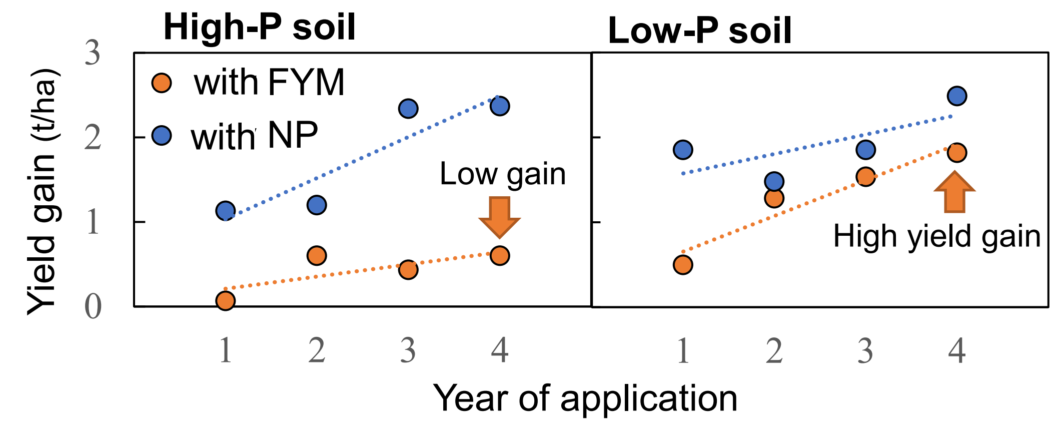


Figure 1. Comparison of yield gain with consecutive use of FYM and NP fertilizer under different soil P availability.

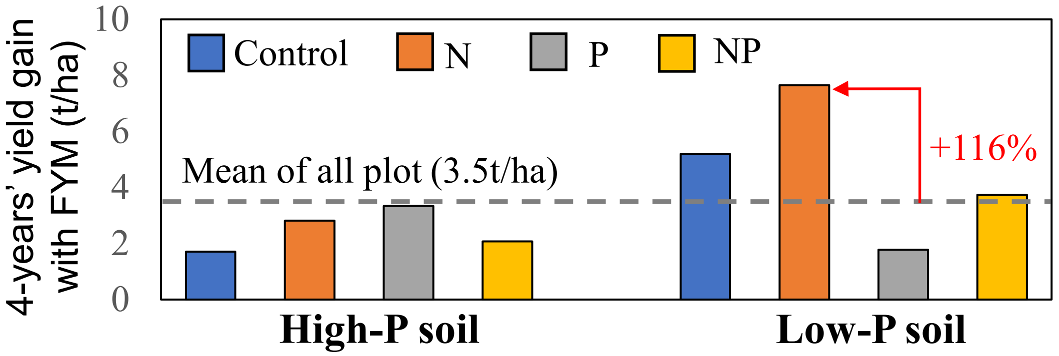


Figure 2. 4-years' yield gain with FYM application under different fertilizer management in low-P and high-P soils.

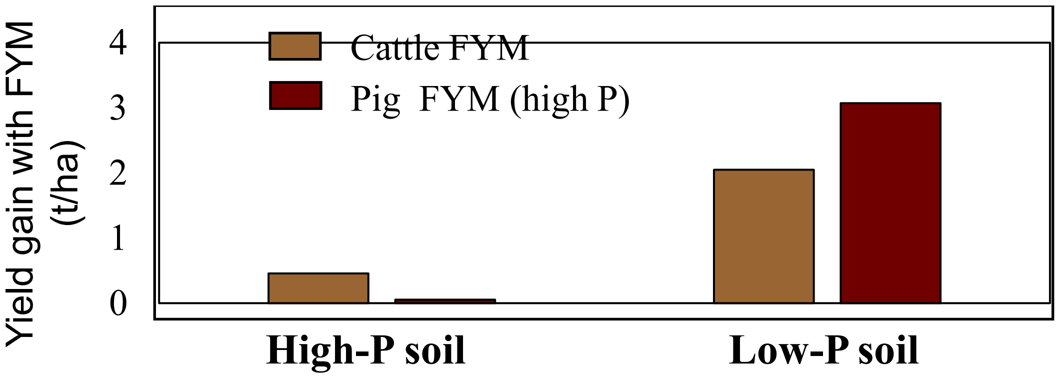


Figure 3. Yield gain with different FYM materials (cattle vs pig) under low-P and high-P soils

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References | Asai et al. (2021) DOI:10.1080/1343943X.2021.1908150
Rinasoa et al. (2022) DOI: 10.1002/jpln.202100266

Utilisation optimisée de fumier de ferme (FYM) dans les rizières de hautes terres

Mots clés | P-déficience, fertilisant N, qualité FYM, Utilisation continue

Résumé

FYM est efficace pour améliorer le rendement en riz dans les sols P déficients. Par ailleurs, sous faible condition phosphatée, nous recommandons l'application continue de FYM et/ou l'application combinée avec le fertilisant azoté pour une amélioration supplémentaire de rendement. Etant donné l'importante amélioration de rendement suite à une forte teneur en P du FYM, des ressources riches en P telles que fumiers de porc ou de volaille sont hautement recommandées comme substrats pour être utilisées dans la preparation de FYM

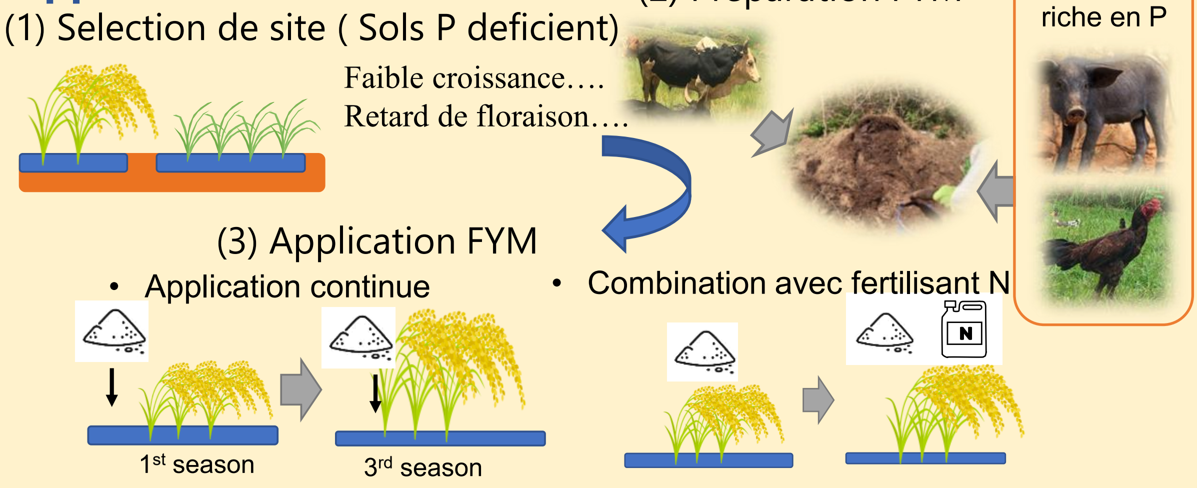
Contexte & Objective

FYM est un materiel accessible pour les agriculteurs locaux. Cependant, à cause de la disponibilité limitée de FYM, une utilisation optimale de FYM est importante pour la vie des agriculteurs. Ici, nous allons voir (1) Où et (2) Comment l'appliquer, (3) Comment le préparer.

Contenus & Caractéristiques

- FYM est efficace pour pallier la déficience P (Fig. 1 and 2).
- L'utilisation continue de FYM en combination avec le fertilisant N est hautement efficace pour l'amélioration de rendement dans les sols pauvres en P. Les fumiers de porcs ou de volailles sont recommandés dans la préparation de FYM (Fig.3)

Application



(1) Selection de site (Sols P deficient)

Faible croissance….

Retard de floraison….

(2) Préparation FYM

Matériels riche en P

(3) Application FYM

- Application continue
- Combination avec fertilisant N

Principales données

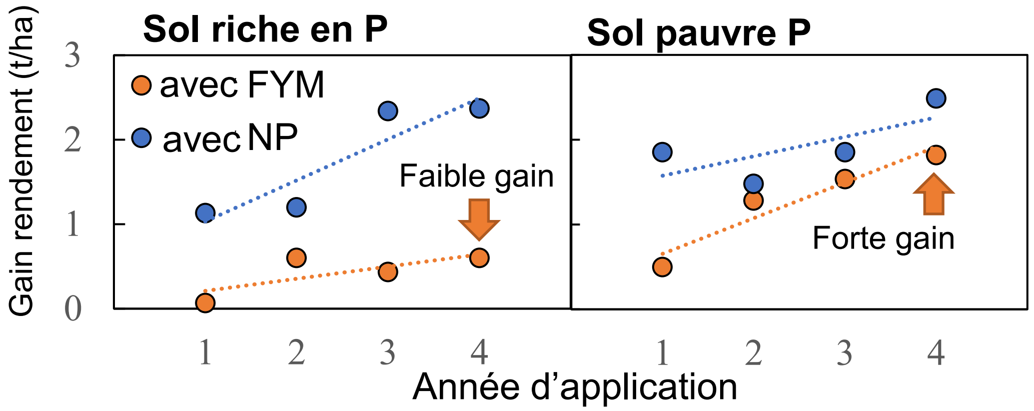


Figure 1. Comparaison de gain en rendement avec l'utilisation continue de FYM et fertilizer NP dans des sols à disponibilité P différentes.

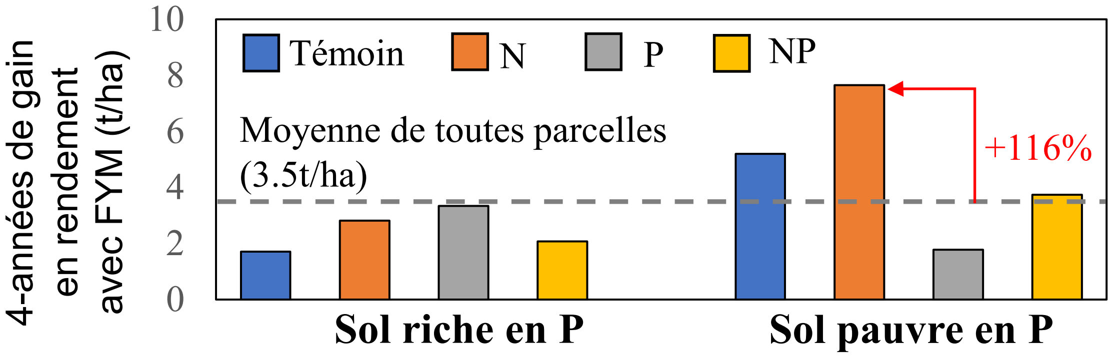


Figure 2. Gain de rendement après 4-années de culture avec l'application de FYM sous différents modes de gestion de fertilisant dans les sols pauvres et riches en P.

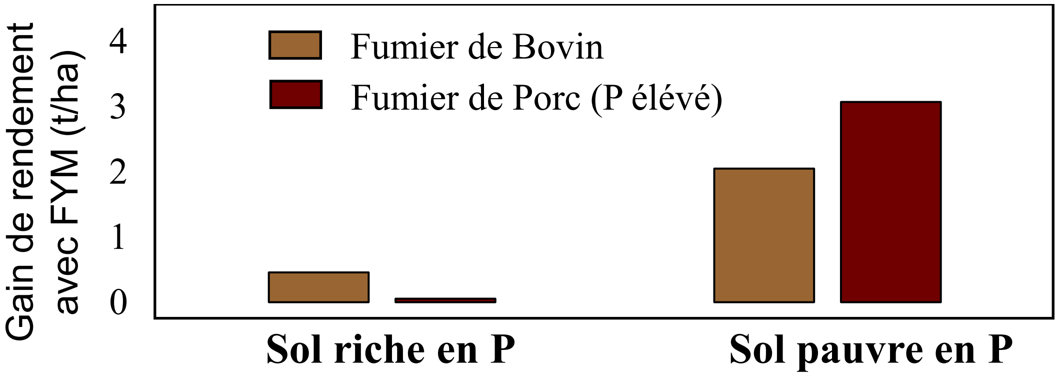


Figure 3. Gain en rendement avec les différents matériels de FYM (bovin vs porcin) dans les sols pauvres et riches en P.

Authors | Asai,H[1]., Andriamananjara, A[2]., Rakotoson T[2]., Rabenarivo, M[2]., Rinasoa, S[2]

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REVIEW

Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa

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ABSTRACT
In sub-Saharan Africa (SSA), rice production from smallholder farms is challenged because of a lack of fertilizer inputs and nutrient-poor soils. Therefore, improving nutrient efficiency is particularly important for increasing both fertilizer use and rice yield. This review discusses how to improve the return from fertilizer input in terms of agronomic N use efficiency (AE_N), that is, the increase in grain yield per kg of applied N, for rice production in SSA. The AE_N values we summarized here revealed large spatial variations even within small areas and a certain gap between researcher-led trials and smallholder-managed farms. Experimental results suggest AE_N can be improved by addressing spatial variations in soil-related factors such as P, S, Zn, and Si deficiencies and Fe toxicity in both irrigated and rainfed production systems. In rainfed production systems, differences in small-scale topography are also important which affects AE_N through dynamic changes in hydrology and variations in the contents of soil organic carbon and clay. Although empirical evidence is further needed regarding the relationship between soil properties and responses to fertilizer inputs, recent agricultural advances have generated opportunities for integrating these micro-topographical and soil-related variables into field-specific fertilizer management. These opportunities include UAV (unmanned aerial vehicle) technology to capture microtopography at low cost, database on soil nutrient characteristics at high resolution and more numbers of fertilizer blending facilities across SSA, and interactive decision support tools by use of smartphones on site. Small-dose nursery fertilization can be also alternative approach for improving AE_N in adverse field conditions in SSA.

ABBREVIATIONS: AE_N: agronomic nitrogen use efficiency; FISP: farm input subsidy program; VCR: value cost ratio; SOC: soil organic carbon; SSA: sub-Saharan Africa; UAV: unmanned aerial vehicle

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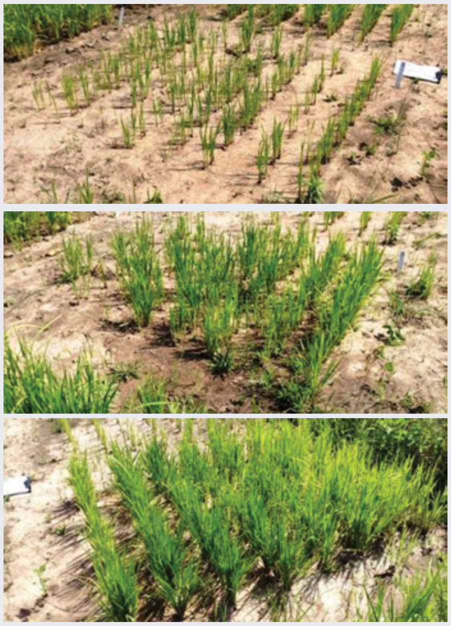
KEYWORDS
Rice; sub-Saharan Africa (SSA); decision support tool; field-specific fertilizer management; agronomic nitrogen use efficiency (AE_N); nutrient-poor soils; small-dose nursery fertilization

Field-specific fertilization is a key to improve N use efficiency in rice on heterogeneous and nutrient-poor soils in SSA



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Rice is the most rapidly expanding food commodity both in consumption and production in sub-Saharan Africa (SSA). Rice consumption (milled grain) was more than tripled from 9.2 Mt to 31.5 Mt during the period of 1990 to date in SSA (USDA, 2018). Currently in SSA, rice is the second largest source of caloric intake after maize, and it is anticipated that rice demand will increase continuously given the high rate of population growth and rapid urbanization in the region, which has resulted in a shift in consumer preference in favor of rice (Balasubramanian, Sie, Hijmans & Otsuka, 2007; van Oort et al., 2015).

In response to this growing demand, total rice production in SSA has gradually increased. In the past, this increase was mainly attributed to the expansion of harvested areas (Otsuka & Kalirajan, 2006), although recently it has been attributed to increased yield (Seck, Touré, Coulibaly, Diagne & Wopereis, 2013). Seck et al. (2013) pointed out that the relative contribution of yield to the increase in total production rose to 71% with the high yield growth rate at 108 kg ha^{-1} per year during the period 2007 to 2012, which was equivalent to that achieved by Asian countries during the Green Revolution period (Saito, Dieng, Toure, Somado & Wopereis, 2015a).

However, the average rice yield in SSA is still around 2.1 t ha^{-1}, and a recent database showed that yield growth tended to become stagnant again in the period of 2012–2018 (USDA, 2018). The current yield is far below the potential productivity for rice in the region. The Global Yield Gap and Water productivity Atlas (GYGA) simulated the potential yield of rice (modeled yields with water and nutrients non-limiting and biotic stress effectively controlled) at 7.5–10.8 t ha^{-1} for irrigated lowland production system and water-limited potential yield of rice (modeled yields restricted by solely water supply) at 4.1–8.5 t ha^{-1} for rainfed production systems in major rice-producing countries of SSA (accessed at http://www.yieldgap.org/on Mar13, 2019). Moreover, the gaps between regional rice consumption and production in SSA have continuously widened. The increasing dependency on rice imports has created an economic burden and food insecurity in SSA, and this insecurity became particularly apparent when food riots occurred in several major capitals during 2007–2008 (Berazneva & Lee, 2013). Therefore, further increases in regional rice production remain an urgent priority to ensure food security in SSA.

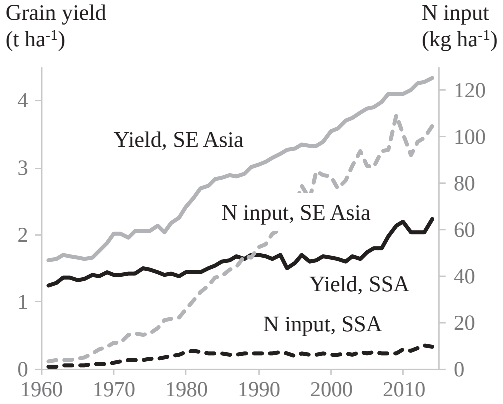

Figure 1. Changes in rice grain yield and mineral N input in southeast Asia (SE Asia) and Sub-Saharan Africa (SSA) from 1961 to present (FAOSTAT).

Previous studies have provided various socioeconomic and biophysical constraints for rice yields in SSA (e.g., Diagne, Amovin-Assagba, Futakuchi & Wopereis, 2013; Kajisa, 2016; Nakano, Bamba, Diagne, Otsuka & Kajisa, 2011; Saito et al., 2013) while it is generally agreed that inadequate fertilizer input and poor soil fertility are major limiting factors to production of not only rice but also other crops in SSA (e.g., Diagne et al., 2013; Haefele et al., 2013; Tittonell & Giller, 2013). Figure 1 compares the annual trends of mineral N application rate, as calculated by dividing total N consumption by total arable land area between Southeast Asia and SSA. Although the N application rates per arable land areas were not equal to those rates per rice harvested area, they were similar in Southeast Asia in 2001 (the N application rates to rice was 76.8 kg ha^{-1}) and in SSA[1] in 1995 to 1998 (the N application rates to rice was 8.9 kg ha^{-1}) (FAO, 2002). The N application rate in Southeast Asia has increased 20-fold, that is, from 5 to 105 kg N ha^{-1}, since 1971, during which time the region achieved substantial increase of rice yield. On the other hand, the N application rate in SSA has remained at less than 10 kg N ha^{-1} until recently, in parallel with the consistently low yield level of rice. These trends are the same for other major nutrient inputs, that is, P and K (data not shown).

Increasing use of fertilizer inputs by local farmers can be only possible if they are available, affordable, and profitable for rice production. The gain in profitability from fertilizer use is often measured by the value cost ratio (VCR), which is calculated as the additional revenue from the fertilizer application divided by its application cost. A VCR of two is the typical benchmark for reliably projecting an increase in profitability for local farmers using mineral fertilizers in SSA (e.g., Xu, Guan, Jayne & Black, 2009; Yanggen, Kelly, Reardon & Naseem, 1998). However, VCR values tend to be low in SSA compared to the other regions worldwide because the fertilizer is more expensive and less accessible owing to the relatively poor development of market and road infrastructures (Minten, Randrianarisoa & Barret, 2007). As many papers pointed out (e.g., Druilhe & Barreiro-Hurlé, 2012), the relatively high fertilizer price and lack of physical access are significant constraints for low mineral fertilizer input in SSA.

Subsidy programs that are geared toward lowering the net cost of fertilizers are one effective means of increasing the VCR for local farmers. Koussoubé and Nauges (2017) argued that subsidy programs can lower a framer's stake in mineral fertilizer, particularly for farmers who are averse to risk and who are uncertain about the best use of fertilizer. For instance, the Farm Input Subsidy Program of Malawi (FISP) has often been cited as a successful case (e.g., Sanzhez, 2015). Dorward and Chirwa (2011) reported that FISP more than doubled the national average yield of maize from less than 1 t ha^{-1} to more than 2 t ha^{-1} as well as the amount of mineral fertilizer input from approximately 0.05 to 0.13 million tons during the period 2005–2006.

However, excessive subsidies can be a burden on the national economies of SSA countries, and hence the cost may outweigh the benefits over the long term as funding for subsidies is typically directed away from other agricultural investments that may have more potential to contribute to sustainable agricultural development (Fan, Gulati & Thorat, 2008; Jayne, Mather, Mason & Ricker-Gilbert, 2013). Zhang et al. (2015) found that excessive subsidies can reduce the efficiency of N use by overdosing N, such as the case in China, or by using fertilizer application into less responsive fields or with inefficient fertilization techniques. Moreover, Marenya and Barret (2009) pointed out that subsidy programs ultimately may not favor poorer farmers because they often cultivate less-fertile soils where crops have a lesser response to applied fertilizer. Ricker-Gilbert and Jayne (2012) reported that households in the bottom 10th percentile of the total crop production value did not have any statistically significant yield increase from the application of fertilizer acquired by FISP. They attributed these low returns for poorer households to their limited landholdings, poor soil fertility, and lack of fertilizer management knowledge. For rice production, Estudillo and Otsuka (2013) pointed out the important role of fertilizer-responsive varieties to enhance fertilizer inputs by local farmers. These arguments strongly suggest that appropriate fertilizer management practices and knowledge should be also provided to enhance yield gains from fertilizer inputs under nutrient-poor soils in SSA rather than only focusing on lowering the cost factor of the VCR.

Therefore, in this paper, we review technical approaches and recent progress toward improving rice responses to fertilizer input. A certain number of studies have been accumulated regarding technical approaches for the improved fertilizer management practices for rice production in SSA, whereas no studies have provided an overview of their quantitative effects and relationship with different production systems and soil conditions. For our purposes, we consistently use agronomic N use efficiency (AE_N), that is, the increase in grain yield per kg of applied N, as an indicator of fertilizer use efficiency because the yield gain from N fertilizer input is the most available dataset and economically meaningful for farmers. First, we review current fertilizer use in terms of the amounts and use efficiencies, that is, AE_N in the major rice-producing regions and for different rice production systems in SSA. Here, we describe rice production in Madagascar to represent low-yield farms with limited fertilizer input and poor soil fertility. Second, we show experimental evidence for how AE_N could be improved by addressing hydrological and soil-related constraints such as phosphorus (P), sulfur (S), and silica (Si) deficiencies, iron toxicities, and low soil organic carbon (SOC) and sandy soils. Third, we discuss plausible technical countermeasures for smallholder farmers to enhance AE_N by giving examples of field-specific nutrient management practices using decision support tools and small-scale fertilizer application in nursery beds.

Genetic improvement that can be adopted to nutrient-deficient conditions is another approach. For example, identification of a P starvation tolerance gene (*PSTOL1*), which enhances early root growth and promotes P uptake (Gamuyao et al., 2012), or of certain QTLs related to internal P use efficiency (Wissuwa et al., 2015), may contribute to the development of rice cultivars that optimize yields from farms with highly P-deficient or P-fixing soils in SSA. Genetic progress in improving root morphological traits, such as steep root angle (Ramalingam, Kamoshita, Deshmukh, Yaginuma & Uga, 2017; Uga et al., 2013), deep rooting (Obara et al., 2010), shallow rooting (Uga et al., 2012), and root plasticity (Owusu-Nketia et al., 2018a, 2018b) can be also applied to nutrient-deficient environments by cultivating rice with root systems that are tailored to the nutrient availability of the local soil profiles. These genetic resources may contribute to higher and consistent returns from N inputs by mitigating other nutrient stresses. However, this approach is not a focus of our review. Further information concerning the progression of these genetic studies can be obtained in recent reviews (e.g., Heuer et al., 2017; Wissuwa, Kretzschmar & Rose, 2016).

Improvement of AE_N in different rice production systems and soil conditions in SSA

Amounts of fertilizer applied

Generally, mineral N use is more prevalent in West Africa compared with East and Southern Africa, which are the two major rice-producing regions in SSA (Saito et al., 2017). A recent cross-sectional survey of 1368 rice fields in 11 countries of West Africa reported that mineral N fertilizer was used in 81% of irrigated lowland fields (average application: 100 kg ha^{-1}), 56% of rainfed lowland fields (65 kg ha^{-1}), and 38% of rainfed upland fields (37 kg ha^{-1}) (Niang et al., 2017). The average N application rate for the irrigated lowland fields in this survey is comparable with the average value for countries in Southeast Asia (FAO, 2002). Other studies have also reported relatively high N application rates in irrigated lowland fields in West Africa, for example, in a range of 72–112 kg ha^{-1} in Benin (Tanaka, Saito, Azoma & Kobayashi, 2013), 134–139 kg ha^{-1} in the Senegal River Valley (Tanaka, Diagne & Saito, 2015), 37–251 kg N ha^{-1} in Mauritania (Haefele, Wopereis, Donovan & Maubuisson, 2001), and 73–147 kg ha^{-1} in Burkina Faso, Mali, and Senegal (Wopereis, Donovan, Nebié, Guindo & N'Diaye, 1999).

Statistically, the percentage of irrigated rice production areas are greater in East and Southern Africa than West Africa, for example, 58% versus 10% in HarvestChoice (2015), whereas mineral fertilizer use remains low even in irrigated lowlands in East and Southern Africa, including Madagascar and Tanzania, which are the second and third largest rice producers in SSA (Haefele et al., 2013; Nhamo, ROdenburg, Zenna, Makombe & Luzi-Kihupi, 2014). In a series of surveys on large-scale irrigation schemes, significantly low N application rates were identified in Uganda (~2 kg ha^{-1}), Mozambique (13–23 kg ha^{-1}), and Tanzania (15–22 kg ha^{-1}) compared to the rates in Burkina Faso, Mali, Niger, and Senegal (>100 kg ha^{-1}) (Nakano et al., 2011; Nakano & Kajisa, 2013; personal communication to Dr. Yuko Nakano on 18 January 2019). For Madagascar, an apparent mistrust of the use of mineral fertilizers for lowland rice production diminished fertilizer use (personal communication to Mr. Ranarivelo Lucien, the Director General of Agriculture in the Ministry of Agriculture and Livestock Madagascar on 5 July 2018). Consequently, mineral fertilizer for rice production in Madagascar is extremely low. Nhamo et al. (2014) also reported that fertilizer application rates were commonly 5–20 kg ha^{-1} for lowland rice production in East and Southern Africa. At least, the yield gap analysis verified equal or slightly greater yield potential and greater yield gaps of irrigated rice production, that is, large opportunities of yield increases with fertilizer inputs still remain in both Madagascar and Tanzania than most areas in West Africa (Saito et al., 2017; Tanaka et al., 2017; van Oort et al., 2015; GYGA at http://www.yieldgap.org/on Mar13, 2019). Therefore, further technical and institutional support may promote fertilizer inputs and yield increases in lowland rice production of these countries.

AE$_N$ in different rice production systems

As observed in surveys across West African countries (Niang et al., 2017), it is logical that farmers prefer to apply mineral fertilizer in irrigated lowlands where more stable returns can be expected relative to drought-prone, rainfed fields. In researcher-led trials in irrigated lowlands in West Africa, AE$_N$ values were in the range of 10–23 kg kg^{-1} (Wopereis et al., 1999), 15–27 kg kg^{-1} (Becker, Johnson, Wopereis & Sow, 2003), and 14–27 kg kg^{-1} (Saito, Azoma & Sié, 2010)—by adopting split N application, adequate weed management, and modern cultivars (Table 1). AE$_N$ data for rice are scarce by reflecting the low adoption of mineral fertilizer inputs in East and Southern Africa. A few studies have reported a range of AE$_N$ at 15–33 kg kg^{-1} in northwest Tanzania (Meertens, Kajiru, Ndege, Enserink & Brouwer, 2003) and 9–31 kg kg^{-1} in the central highland of Madagascar (Nabhan & Rakotomanana, 1990). It should be noted that N application rates in these two studies were relatively low at 30 kg ha^{-1}. AE$_N$ is usually higher at low N rate than at high N rate. Based on experimental results in tropical Asia, Dobermann and Fairhurst (2000) indicated that, with proper crop and water management, AE$_N$ should be typically in the range of 20–25 kg kg^{-1}. The observed AE$_N$ indicated that—at least as reported for researcher-led trials under adequate water management conditions across SSA—the average values were comparable to this range. However, it should be noted that there were large variations in AE$_N$ from location to location within and across these studies.

AE$_N$ values are generally low in rainfed production systems mainly because unstable hydrology restricts the grain yield and response of rice to fertilizer input. Niang et al. (2018) reported that AE$_N$ varied from 7 to 9 kg kg^{-1} as determined by their regression analysis of field surveys and experiments under farmers' management practices in rainfed fields of central Benin. Becker and Johnson (2001) showed even lower AE$_N$ at 3–5 kg kg^{-1} under farmers' management practices and at 6–17 kg kg^{-1} with researcher-led improved management practices in rainfed lowland fields in West Africa. Furthermore, experimental results have clearly demonstrated that AE$_N$ are greater with improved field hydrology in rainfed production systems in West Africa (see *with specific techniques to improve AE$_N$* in Table 1): Becker and Johnson (2001) reported that the presence of bunds increased AE$_N$ from 4 to 12 kg kg^{-1} in rainfed lowland fields across a range of agro-ecological zones; Touré et al. (2009) reported similar increases in AE$_N$

Table 1. AE_N values for researcher-led and smallholder-managed farms in different rice production systems in SSA.

Location	Ecology[a]	Operation[b]	N rate (kg ha^{-1})	Treatments for AE_N calculation[c]	AE_N (kg kg^{-1})	Specific management	Specific soil condition	Reference
Multilocational on-farm trials and reports to indicate typical AE_N range in SSA								
Senegal, Mali, Burkina Faso	IL	RM	73–143	NP& none, NPK & none	10–23	Split N		Wopereis et al. (1999)
Côte d'Ivoire, Senegal	IL	RM	60–138	NP& none, NPK & none	15–27	Split N		Becker et al. (2003)
Benin	IL	RM	50–86	NPK & none	14–27	Split N		Saito et al. (2010)
Madagascar	IL	RM	30	NPK & none	9–31	-		Nabhan and Rakotomanana (1990)
Across SSA	IL	FM	120–200	NPK & PK	−1–15	Split N		Saito et al. (2019)
Côte d'Ivoire, Senegal	IL	FM	17–104	NP& none, NPK & none	5–11	-		Becker et al. (2003)
Across SSA	IR, RU, RL	FM	0–191	Regression coefficient	9	-		Tsujimoto et al. (unpublished)
Tanzania	RL	RM	30	N & none	15–33	-		Meertens et al. (2003)
Across SSA	RL	FM	110–200	NPK & PK	3–19	Split N		Saito et al. (2019)
Across SSA	RU	FM	110–160	NPK & PK	5–9	Split N		Saito et al. (2019)
Benin	RU, RL	RM, FM	13–94	Regression coefficient	7–9	-		Niang et al. (2018)
With specific technique to improve AE_Nd								
Côte d'Ivoire	IL	RM	100	NPK (+Zn) & none	6 vs. 11	*Zn supply*	Fe toxicity	Audebert and Fofana (2009)
Madagascar	IL	FM	50	N (+Si) & none	8 vs. 12	*Si supply*		Tsujimoto et al. (unpublished)
Ethiopia	IL	RM	36–105	N (+S) & none	6–10 vs. 14–21	*S supply*		Habtegebrial et al. (2013)
Côte d'Ivoire	RL	RM	60	NPK & PK	1–8 vs. 5–23	*Bunding*		Touré et al. (2009)
Côte d'Ivoire	RL	RM, FM	23–89	N & none	3–5 vs. 6–17	*Bunding*		Becker and Johnson (2001)
Ghana	RL	RM	60	N (+S) & none	1–9 vs. 4–15	*S supply*	Low SOC, sand	Tsujimoto et al. (2017)
Ghana	RL	RM	60	N (+S) & none	11–24 vs. 28–33	*S supply*	High SOC, clay	Tsujimoto et al. (2017)
Ghana	RL	FM	60	N (+S) & none	7 vs. 14	*S supply*		Tsujimoto et al. (unpublished)
Madagascar	RU	FM	50	N (+Si) & none	5 vs. 10	*Si supply*		Tsujimoto et al. (unpublished)
Estimated AE_N with microdose application technique[e]								
Benin	IL	RM	5	NPK & none	110–150	*NPK to nursery*	P deficient	Vandamme et al. (2016)
Cambodia	RL	RM	2.7	NP & none	67–119	*NP to nursery*	Sandy, water-stressed	Ros et al. (2015)
Cambodia	RL	RM	2.7	NP & none	33–78	*NP to nursery*	Sandy, well-watered	Ros et al. (2015)
India	RL	RM	10	NPK &PK	40–211	*N to nursery*	Flood-prone	Panda et al. (1991)
India	RL	RM	4.1	NPK & PK	243	*N to nursery*	Salinity-stressed	Sarangi et al. (2015)

[a] IL: irrigated lowland; RL: rainfed lowland; RU: rainfed upland

[b] RM: researcher-led management; FM: farmer-led management

[c] AE_N was calculated by the yield difference between A & B.

[d] AE_N values are compared without to with specific management.

[e] AE_N are calculated by estimating the equivalent N rate to the main field from the ratio of seeding density to the transplanting density.

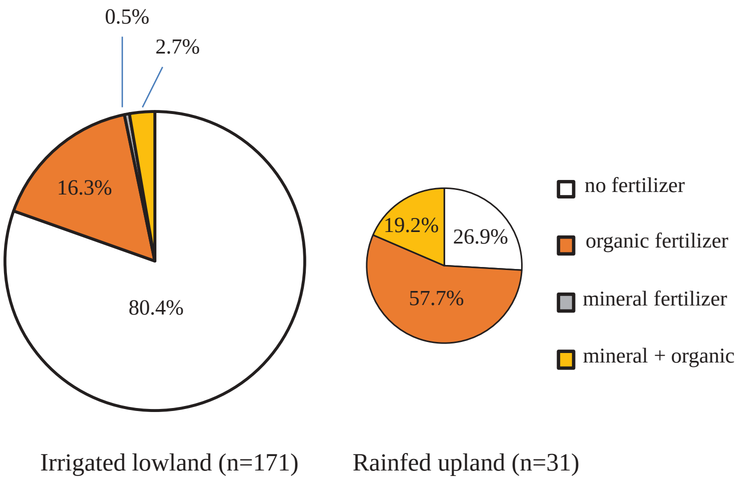

Figure 2. Proportion of farmers applying mineral fertilizer and organic fertilizer for rice production in irrigated lowlands and rainfed uplands in the central highland of Madagascar.

upon bund construction, with a greater effect near the bottom of valleys versus near the top, with a maximum AE_N of up to 22–23 kg kg^{-1} in rainfed inland valleys. The low and unstable AE_N have led farmers away from fertilizer input in rainfed production systems.

AE_N under smallholder-managed fields

Despite a general understanding about low and unstable AE_N in rainfed production systems, one interesting case has been observed in the central highland of Madagascar, where local farmers preferably apply mineral fertilizer for rainfed upland rice rather than irrigated lowland rice (Figure 2). The NPK complex fertilizer was applied to 19% of rainfed upland fields (n = 31) whereas it was applied to merely 3% of lowland fields (n = 171). Farmers explained that this selective application was because the yields of upland rice are too low without fertilizer application whereas they can expect adequate yields without fertilizer in irrigated lowlands. For the upland production systems, their conventional practice of placing a micro-dose mineral and organic fertilizers in each planting hole at seed dibbling may be high in fertilizer use efficiency. Yet, no experimental data exist to compare differences in benefits of fertilizer application between rainfed upland and irrigated lowland fields in the central highland of Madagascar.

This observation implies that agronomic researchers or extension officers should further accumulate empirical evidence for quantitative effect of fertilizer input on rice yields under different farmers' management conditions. Apparently, there is a gap in AE_N between researcher-led trials and smallholder-managed fields (Table 1). Our regression analysis of field surveys, which included 20 irrigated lowland fields, 69 rainfed lowland fields, and 14 rainfed upland fields all under adequate water conditions across SSA, implied relatively low AE_N at 9 ± 3 kg kg^{-1} under farmers' management conditions (unpublished). A recent extensive nutrition trial in a total of 1037 farmers' fields across 30 sites in 17 SSA countries also demonstrated that AE_N values were relatively low even in irrigated lowlands under farmers' management practices (Saito et al., 2019). The average yields with and without N application (NPK vs. PK) were 4.8 t ha^{-1} and 3.4 t ha^{-1} for irrigated lowlands, and for 3.9 t ha^{-1} and 2.5 t ha^{-1} rainfed lowlands, and 3.1 t ha^{-1} and 2.2 t ha^{-1} for rainfed uplands across experimental sites. It should be noted that the N application rates were high in this study which might have lowered AE_N. Nevertheless, the results revealed large variations in AE_N among locations and fields irrespective of rice production systems: the AE_N means were 9 kg kg^{-1} for irrigated lowlands (range—1 to 15 kg kg^{-1}, 12 locations), 10 kg kg^{-1} for rainfed lowlands (range—3 to 19 kg kg^{-1}, 15 locations), and 7 kg kg^{-1} for rainfed uplands (range—5 to 9 kg kg^{-1}, 3 locations). Relatively low AE_N in farmers' fields can be partly caused by suboptimal management practices, e.g., limited weeding frequency, delayed planting, inappropriate timing of fertilizer application, lack of access to fertilizer-responsive varieties, while this tendency can be also attributed to less favorable field conditions, for example, occurrence of micro-nutrient deficiencies and toxicities, poor drainage, extremely sandy or degraded soils that are often avoided from researcher-managed trial sites.

In this regard, identification of factors affecting spatial variation in AE_N at different levels (from location to location or field to field) particularly under farmers' management conditions remains as an important research task. Smallholder farmers require specific information on returns from fertilizer input based on the characteristics of their own fields, that is, as opposed to information pertaining to the average return for the region or for relatively favorable research experimental fields. For example, concerning the irrigated lowlands in the central highland of Madagascar, Nabhan and Rakotomanana (1990) found one field-specific indicator for the AE_N variations, namely that soils having a high content of Fe^{2+} (>200 mg kg^{-1}) tend to have low AE_N. A similar result was observed in the inland valleys of northwest Benin (Worou, Gaiser, Saito, Goldbach & Ewert, 2013). Variations in iron toxicity between fields constitute one soil-related parameter that decreases fertilizer use efficiency in SSA. As exemplified in these studies, soil characteristics are important factors to understand spatial variations in AE_N. In the following sections, we discuss how soil-related factors affect AE_N variations and can be managed to improve AE_N for rice production in SSA.

Considerations of how soil characteristics can be integrated in field-specific fertilizer management in SSA

Spatial characterization and the distribution of rice soils were studied both worldwide (Haefele, Nelson & Hijmans, 2014) and within SSA (Haefele et al., 2013; Saito et al., 2013). Haefele et al. (2014) and Saito et al. (2013) both pointed out that rice-producing soils in SSA are generally poor compared with those in Asia, as represented by the small nutrient-holding capacity or low effective cation exchange capacity, high P fixation, and potential Fe and Al toxicities. Saito et al. (2013) further concluded that these 'very poor rice soils' were dominant particularly in rainfed production systems and from sub-humid to humid environments in East Africa compared with the irrigated lowlands in semiarid to arid regions of West Africa. Tsujimoto, Muranaka, Saito and Asai (2014) also reported that the Si-supplying capacity of soils is poor in SSA, particularly in the sub-humid to humid environments of East Africa.

Efforts to link spatial soil variations to specific fertilizer management practices have been carried out for rice production in SSA since 1990s. First, diagnostic nutrition trials were conducted to assess indigenous N, P, and K supply from soils and responses of rice to fertilizer inputs for irrigated lowlands in West Africa (e.g., Haefele & Wopereis, 2005). The empirical results and mechanistic understanding of soil-plant nutrient dynamics have been integrated into simulation models to determine variety-, site-, and season-specific fertilizer management practices (Haefele & Wopereis, 2004; Haefele, Wopereis, Ndiaye & Kropff, 2003; Segda, Haefele, Wopereis, Sedogo & Guinko, 2005). These research achievements contributed to the implementation of efficient fertilizer management practices at national or subnational scales and to increases in fertilizer input and rice yields in irrigated lowlands in West Africa. However, these studies did not allow for field-specific fertilizer recommendations for individual farmers nor did they address rainfed production systems in which field-to-field variations in both soils and hydrology are much greater than in irrigated lowlands.

Recent progress in field-specific fertilizer management has included development of decision support tools by integrating farmers' individual information on their fields with crop models for calculating fertilizer requirements using their smartphone or tablet. RiceAdvice is one such decision support tool for lowland rice production in SSA (Saito & Sharma, 2018; https://www.riceadvice.info/en/). Using such decision support tool, Saito, Diack, Dieng and N'Diaye (2015b) demonstrated significantly greater fertilizer use efficiencies and economic returns by tailoring fertilizer recommendations to the needs of individual farmer's fields in irrigated lowlands of the Senegal River valley. They attributed these improvements to K application and to the timing and number of N applications.

However, a challenge has remained how to integrate individual soil characteristics with field-specific fertilizer management practices. In reality, the relationship between soil properties and responses to fertilizer input in the field is not straightforward. This is particularly true for lowland rice production systems because biological and chemical reactions of soils are complex under flooded conditions. Hence, there is a need to conduct time-consuming and costly nutrient omission trials for a period of 1–2 years to calculate the nutrient-supplying capacity of soils for regions in which the tools have been newly introduced. Haefele and Wopereis (2005) pointed out that installation of omission plots in each field would not be feasible for most small-scale farmers in SSA and might offset the possible gains from field-specific fertilizer management practices.

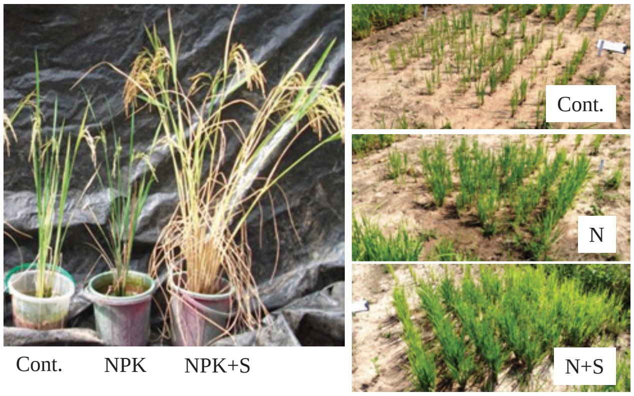

Figure 3. Significant responses to S application in S-deficient soils in the rainfed lowland of northern Ghana.

In this regard, quickly measurable and reliable soil properties or other environmental factors correlating with the responses of rice to fertilizer inputs can extend the model applicability. Our recent study identified large field-to-field variations in responses to N input as a function of the amounts of oxalated-extractable Al and Fe in soils, even among nearby fields of the typical P-deficient lowlands in the central highland of Madagascar (Nishigaki et al., 2019). This result implies that the benefits and applicability of decision support tools can be extended by integrating individual soil variations within a small area even in irrigated lowlands. Further analysis from a systematic nutrient omission trials on N, P, and K across SSA (totaling 1037 farmers' fields in 17 countries, Saito et al., 2019) is expected to improve the understanding on the relationship between soil properties and responses to these macro-nutrients in different farmers' management practices and different rice production systems.

Deficiencies in macro- and micro-nutrients apart from N, P, and K

Deficiencies in other macro- and micro-nutrients—apart from those included in commonly applied fertilizers or tested in nutrient omission trials, that is, N, P, and K—should also be considered when optimizing field-specific fertilizer management practices. Many investigators have noted that various types of macro- and micro-nutrient deficiencies, such as S, Si, and zinc (Zn), can inhibit AE_N for rice production in the 'very poor soils' of SSA (e.g., Bado, Djaman & Valère, 2018; Tsujimoto et al., 2013, 2014; Buri, Masunaga & Wakatsuki, 2000; Figure 3, Table 1). Three-year field experiments demonstrated that AE_N could be nearly doubled, that is, from 13 to 23, by simply applying S to floodplain lowlands in northern Ghana (Tsujimoto et al., 2017). In subsequent on-farm trials under farmers' management practices, AE_N values were also largely increased from 7 to 13 by applying S fertilizer (unpublished). These experiments further verified that greater economic returns are possible if urea (a cheap N source) is mixed with ammonium sulfate (source of S) compared with the application of urea or ammonium sulfate alone. This selective S-added fertilizer management can be to some extent beneficial for rice production in West Africa where such S-deficient soils are widely reported (e.g., Buri et al., 2000). Application of S also significantly improved AE_N, that is, from 8 to 17, in irrigated lowlands in Ethiopia (Habtegebrial, Mersha & Habtu, 2013). Audebert and Fofana (2009) reported significant increases in AE_N from 6 to 11 with Zn application in their 5-year trial in irrigated lowlands of Côte d'Ivoire. They attributed the effect of Zn to the alleviation of iron toxicity. As noted above, Si deficiency can be another AE_N-restricting factor in highly weathered soils in SSA, particularly in the sub-humid to humid environments of East Africa (Tsujimoto, Homma & Shiraiwa, 2010; Tsujimoto et al., 2014). On-farm trials under farmers' management practices in the central highland of Madagascar revealed that Si application as a silica gel significantly increased AE_N, on average, from 5 to 10 in the rainfed uplands and from 8 to 12 in the irrigated lowlands. These empirical evidences imply the AE_N can be improved by understanding spatial variations in these macro- and micro- nutrient deficiencies in SSA soils.

Currently, an increasing number of SSA soil database for N, P, K, and other macro- and micro-nutrients are available in continent-wide and high-resolution scales. Iron toxicity map for rice production across SSA is one of those and recently developed (van Oort, 2018). This is attributable to international initiatives such as the Africa Soil Information Service (http://africasoils.net/) and the development of simplified evaluation technologies using spectrometry and remote-sensing data along with machine learning (Forkuor, Hounkpatin, Welp & Thiel, 2017; Hengl et al., 2017; Kawamura et al., 2019, 2017; Towett, Shepherd, Sila, Aynekulu & Cadisch, 2015). Of course, more empirical evidence must be obtained to correlate specific soil properties with agronomic responses to fertilizer input for rice at different scales to confirm the applicability of these spatial soil information. Then, the information can contribute to accessibility and profitability for smallholder farmers to apply field-specific fertilizer management practices on their own fields and to the improvement of AE_N for rice production in SSA.

Effects of SOC and soil texture in rainfed production systems on AE_N

SOC content and clay content can be another specific soil properties that can be correlated with AE_N for rice particularly in rainfed production systems. In general, the SOC content of croplands tends to be low in SSA, particularly in West Africa compared with the other tropical soils as attributed to high temperature, prevailing coarse-textured soils, low fertilizer input, and low annual biomass production (Zomer, Bossio, Sommer & Verchot, 2017).

Previous studies that mostly focused on upland crops indicated that both SOC and soil texture play essential roles in not only biomass production but also the enhancement of fertilizer use efficiency in the poor soils of SSA (Vanlauwe et al., 2011; Wopereis et al., 2006; Zingore, Murwira, Delve & Giller, 2007). These authors argued that a certain minimum level of SOC and clay content is required for crops to respond well to fertilizer input even under adequate soil moisture conditions. A greater content of SOC and clay increases both soil aggregation and total porosity which contributes to the improvement of field hydrology (e.g., Weil & Magdoff, 2004), and thus increase AE_N in rainfed production systems. In addition, both SOC and clay enhance the nutrient-holding capacity of soils. As a result, higher SOC and clay contents can help supplying other macro- and micronutrients, then improve AE_N.

These positive functions of SOC or clay content for improvement of fertilizer use efficiency have also been observed for rainfed lowland rice production. In the rainfed and floodplain ecosystem of the White Volta River in Ghana, we confirmed a higher AE_N trend for rice in the range of 4.0 to 32.6 kg kg^{-1}, particularly when the content of SOC and clay was above 13.3g kg^{-1} and 18.7%, respectively, by conducting 3-year trials in fields of varying topography (Tsujimoto et al., 2017). This tendency—greater AE_N for soils with higher SOC and clay contents—was also observed when rice was grown in continuously irrigated pots (Tsujimoto et al., 2013). Similarly, Mochizuki et al. (2006) demonstrated a doubling of AE_N from 14 to 31 kg kg^{-1} by simply incorporating clay-rich pond sediment into the sandy fields of gradually sloped rainfed inland valleys of Northeast Thailand: soil amendment with this clay-rich pond increased the clay content from 9% to 19%. Niang et al. (2018) also indicated that sandy soils could be an indicator for low response of rice to N fertilizer input in rainfed production systems.

The content of SOC or clay can differ even among adjacent fields depending on topography and farmers' management practices. Topography-dependent differences in soil properties can be suitable for integration into field-specific fertilizer management practices because geographical information for individual fields can now be collected rapidly and accurately at relatively low cost using an unmanned aerial vehicle, in comparison with conventional soil chemical analysis or on-farm nutrition trials. A simplified SOC estimation method using a soil color sensor can also be used onsite, for its applicability to lowland soils has been demonstrated in Japan (Moritsuka, Matsuoka, Katsura, Sano & Yanai, 2014) and northern Ghana (Katsura et al., 2018). Moreover, there is the opportunity to integrate farmers' perceptions of the color and texture of their soil into field-specific fertilizer management practices (Saito, Linquist, Keobualapha, Shiraiwa & Horie, 2006). The benefits of field-specific fertilizer management based on these farmers' perceptions and topographical information should be further investigated.

Socioeconomic opportunities for increases in fertilizer use and efficiencies

Recent investments in fertilizer blending facilities to tailor nutrient formulations to specific applications should be a positive aspect of realizing the goal of effective and specific fertilizer management practices for rice production in SSA. According to AfricaFertilizer.org (available at https://africafertilizer.org/wp-content/uploads/2018/02/2018_AFO_SSA_Fertilizer_Plants_Register-min-ilovep.pdf), 25 new fertilizer blending facilities have opened or are expected across SSA countries during the period 2017–2019, in addition to the 53 facilities as of 2016. In Madagascar, domestic production of ammonium sulfate has started as the by-product of the nickel-cobalt metal production process and provided a relatively cheap source of both N and S fertilizer since 2015. Therefore, selective application of ammonium sulfate into S-deficient fields should be more cost-effective than blanket application of urea in Madagascar. Secondary-nutrient blended compound fertilizer such as NPK+S and NPK+Zn are yet costly but getting more available in some SSA countries. Foliar fertilizers are less available while the evidence for its cost-effectiveness relative to the direct application into soils has been reported such a case to alleviate Zn deficiency for crop production including rice in SSA (de Valença, Bake, Brouwer & Giller, 2017; Joy et al., 2015).

Effective use of organic resources, for example, crop residue, farmyard manure, animal dropping, can be another option for smallholder farmers to increase AE_N by replenishing SOC and soil nutrient balances such as Si deficiency in a sustainable manner. For the lowland rice production systems, the SRI (System of Rice Intensification)-practicing farmers in the central highland of Madagascar could be regarded as a successful case of organic fertilizer management (Tsujimoto, Horie, Randriamihary, Shiraiwa & Homma, 2009). Barison and Uphoff (2011) observed greater physiological N use efficiency (grain yield per unit N uptake) in SRI-practicing fields relative to conventional fields by comparing 109 farmers in Madagascar who applied both techniques in their different fields. Barison and Uphoff (2011) implied that balanced macro- and micro-nutrient supplies improved physiological N use efficiency in the SRI-practicing fields.

These chemical fertilizer and organic inputs combined with aforementioned soil and hydrologic information should increase opportunities and profitability to apply field-specific fertilizer management practices and contribute to the improved AE_N for rice production in SSA. Cost-benefit analysis should be further needed because the costs and accessibility for both fertilizer options and field information largely differ among sites, countries, and regions.

Improvement of AE_N with small-dose fertilizer supplementation

Development of effective fertilizer application techniques is another key component to improve AE_N and fertilizer profitability. Small-dose and localized fertilization techniques could potentially be adopted by resource-limited smallholder farmers particularly in the areas of SSA where intensive labor inputs are available. These techniques include P dipping to seedling roots at transplantation (De Datta, Biswas & Charoenchamratcheep, 1990) and inclusion of P in planting holes at seed dibbling (Vandamme et al., 2018). As noted above, the latter technique has been practiced by farmers in upland rice production in the central highland of Madagascar. In this section, we focus on the applicability of small-dose fertilizer application to a nursery bed and its effectiveness to improve AE_N under different soil conditions.

Previous studies suggest that the application of small-dose nutrient resources to a nursery bed increases rice yields, especially for nutrient-deficient soils (Ros, Bell & White, 1997; Ros, White & Bell, 2015; Vandamme, Wissuwa, Rose, Ahouanton & Saito, 2016). Ros et al. (2015) demonstrated that fertilizer application to nurseries increased rice yield in the low-fertility, sandy lowlands of Cambodia, reporting yield gains of 0.09–0.21 t ha^{-1} under well-watered conditions and 0.18–0.32 t ha^{-1} under water-stressed conditions. The amount of fertilizer applied to the nursery bed was equivalent to merely 2.7 kg N per hectare in the main field, which resulted in substantially high AE_N (33–78 kg kg^{-1} and 67–119 kg kg^{-1} in well-watered and water-stressed conditions, respectively), as estimated from the ratio of seeding density to the transplanted density (see *Estimated AE_N with microdose application technique* in Table 1). For the typical P-deficient irrigated lowlands of West Africa, Vandamme et al. (2016) reported yield increases of 10–14% with small-dose application to nursery beds at the corresponding rates of 5 kg N ha^{-1}, 3 kg P ha^{-1}, and 5 kg K ha^{-1} in the main field. They also reported an even more pronounced effect of small-dose fertilizer application when soil P deficiency was severe, with yield increases of 30–40%, which provided AE_N at 110–150 kg kg^{-1} as a result of mitigation P-deficiency stress. The results imply that the small-dose NPK application to nursery beds could be more profitable when combined with information on P-deficiency status. It should be noted that these AE_N values are rough estimates from the ratio of seeding density to transplanting density and that AE_N values can widely fluctuate when N application rates are low. Yet, these studies demonstrate that large opportunities exist for increasing AE_N by adopting small-dose application in nurseries, particularly in the nutrient-deficient soils of SSA.

Rice cultivation in SSA is seriously undermined not only by nutrient-deficient soils but also by abiotic stresses at the initial growth stage (Seck et al., 2013). In this respect, the improvement of seedling quality by optimizing nutrient management in the nursery has been documented as an effective measure to overcome abiotic stresses such as submergence (Bhowmick, Dhara, Singh, Dar & Singh, 2014; Ella & Ismail, 2006; Jackson & Ram, 2003; Ram et al., 2009; Singh, Hong, Sharma & Dhanapala, 2004), salinity (Sarangi et al., 2015), and drought stress (Ros et al., 2015). Panda, Reddy and Sharma (1991) demonstrated the large yield gains by 0.4–2.1 t ha^{-1} and AE_N at 40–210 kg kg^{-1} with the nursery application of 100 kg N ha^{-1} (roughly equivalent to 10 kg N ha^{-1} in main field) at submergence-prone fields in the initial growth stage. In the case of high-salinity soils in coastal areas, Sarangi et al. (2015) reported a yield gain of up to 1.0 t ha^{-1} with nursery application of 50 kg N ha^{-1} (equivalent to 3.5 kg N ha^{-1} in main field). These facts also suggest that small-dose fertilizer application to nurseries can benefit resource-limited smallholder farmers in SSA.

Further agronomic studies on nutrient management practices under climate change

Further studies are needed concerning the effects of nutrient management practices on yield and AE_N under different regional climate conditions. The impact of both climate change and suboptimal nutrient management practices on rice production in SSA has been studied intensively, but each separately (e.g., van Oort, 2018; van Oort & Zwart, 2018; and many studies cited in

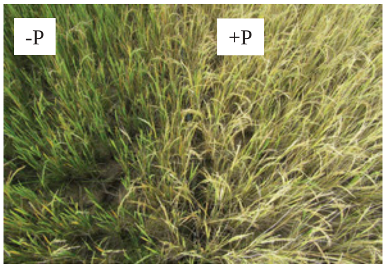

Figure 4. Significant effect of P application on phenological development in an irrigated lowland area of the central highland of Madagascar.

our current review). Nonetheless, some of the experimental results imply a significant effect of nutrient management practices on the risks of climate-induced stress with respect to rice production. For instance, Njinju et al. (2018) carried out three-season field experiments in the highlands of Kenya, where the daily minimum temperature was below 18ºC in the middle-to-late growth stages. They consistently observed that N application of >75 kg ha^{-1} linearly reduced rice grain fertility and resulted in significant yield reductions of up to 60% for certain varieties such as IR64 and Basmati370. The results imply that AE_N can be negative when overdose N and cold-induced stress are combined. These field-based results, demonstrating significant impacts of N management on climate-induced stresses, should attract further attention with respect to considering improved AE_N for rice production in SSA.

Interaction between P deficiency and climate-induced stresses may also affect AE_N for rice production. Our preliminary field trials demonstrated significant delays in phenology development under P-deficient conditions in the central highlands of Madagascar—heading was delayed by more than 3 weeks in P-deficient plots (Figure 4). This phenological response of rice to P deficiency could potentially have a positive effect on grain yield, that is, by extending the growth period. However, delayed heading may also increase the risk of cold-induced sterility later in the growth stage, which is the case for the main cropping season in the highlands of East and Southern Africa, and waste N inputs. The increased risk of environmental stress that can be attributed to P deficiency-induced delay in phenological development can also be presumed in regions where late-season drought is common. These assumptions imply that appropriate N and P management should not be based solely on field nutrient characteristics; rather, climate conditions, planting period, and duration of varietal growth should also be considered. These interactions between P deficiency and environmental stress have not been considered in any field experiments or model predictions.

Conclusion

By referring to the fact that the ratio of the price of grains to fertilizer has been fairly constant over 20 years in many countries of SSA, Jayne, Mason, Burke and Ariga (2018) noted 'only changes in agronomic response to fertilizer inputs can drive meaningful change in fertilizer profitability', while 'this response is lower than expected under smallholder-managed fields'. In this regard, a key task for agronomic researchers is to address improvements in fertilizer use efficiency in SSA. Evidence is scarce concerning rice production in SSA, whereas the AE_N values we have reported here imply that large gaps remain between researcher-managed and farmer-managed trials even in irrigated lowlands and that there were large spatial variations in different levels from location to location and field to field (Table 1). This review corroborates the general perception that fertilizer management practices must account for variations in soil characteristics and geography to fill this gap in SSA, where smallholder farmers still rely on inherent and heterogeneric field characteristics for their rice production. Accumulated experimental results suggest that AE_N values for rice production could be increased by adjusting not only N, P, and K nutrient status but also other micro- and macro-nutrient deficiencies such as S, Si, and Zn and iron toxicity even under conditions of adequate water management. Our recent observation of highly variable P-deficiency status even among adjacent lowland fields suggests the importance of optimizing site-specific nutrient management practices at a relatively small scale. Geographic parameters in relation to SOC content and field hydrology may be additional key factors for improving field-specific fertilizer management in rainfed production systems. Interactive decision support tools through smartphones/tablets can play a pivotal role in translating soil and geographic information into field-specific fertilizer management practices.

Note

1. FAO (2002) is to our knowledge most recently available data source for fertilizer use by crop and by nutrient element worldwide, but included merely 7 countries in SSA; Kenya, Madagascar, Malawi, Tanzania, Guinea, Mauritania, and Togo.

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Phosphorus management strategies to increase lowland rice yields in sub-Saharan Africa: A review

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ABSTRACT

Phosphorus (P) deficiency is one of the major yield-limiting factors for lowland rice production in sub-Saharan Africa (SSA). Therefore, improved P management could be an effective strategy to increase lowland rice yields in SSA. The study reviews on historical and recent efforts for improving P management for lowland rice production in SSA together with their limitations and prospects for future research. Special focuses are on following three aspects: (1) suitable soil tests to assess the indigenous soil P supply and the yield response to P application in lowlands; (2) organic inputs and localized P application to the nursery bed (nursery P) and to the seedling roots at transplanting (P-dipping); (3) the interaction between P application and climate-induced stresses via its impact on phenological development. For the first aspect, we demonstrate the importance of considering the P adsorption and desorption kinetics in SSA soils, where large amounts of insoluble P complexes are bound to iron and aluminum oxides while these insoluble P pools are solubilized under submerged soil culture. We propose using the oxalate-extractable P, which extracts insoluble P pools bound to amorphous iron-oxide minerals, as a reliable test for measuring the indigenous soil P supply for lowland rice production. With respect to the second aspect, the efficient use of organic inputs—an important nutrient resource for smallholder farmers in SSA—can be reconsidered not only as a source of P but also as a substance to accelerate the chemical reaction and P solubilization in soils for lowland rice production. Several studies have demonstrated significant effects of nursery P and P-dipping to increase rice yields and agronomic P use efficiency (AE_P) as the yield gain per unit of P applied. Excess yield gains with a micro-dosing nursery P may have a risk of P mining from soils. The P-dipping retains the P input-output balance and achieves a consistently high AE_P at 74–152 kg kg^{-1}. The third aspect has received little attention in the previous studies, although recent observations indicate that P management affects rice yields via its impact on phenological development. The time to heading under P deficiency can extend beyond three weeks, which allows plants to accumulate more biomass production while increasing the risk of biotic and abiotic stresses at the reproductive and ripening stages. Further attention should be paid to changes in phenological development and their interactions with climate-induced stress to develop improved P management practices in SSA.

1. Introduction

Rice is mostly grown in lowlands under rainfed or irrigated production systems in Sub-Saharan Africa (SSA) (Africa Rice Center, (AfricaRice), 2011). These two rice production systems contribute to 77% of the total rice production in the region (JICA/AGRA, 2008). Nutrient deficiency is one of the significant yield-limiting factors, which is attributed to the highly weathered soils that are prevalent in SSA in combination with the limited economical and physical access to mineral fertilizers by most farmers. In SSA, the mineral fertilizer inputs for agricultural production are merely 9.2 kg ha^{-1} of nitrogen (N) and 1.5 kg ha^{-1} of phosphorus (P); which are far below the values observed in the other regions of the world (Fig. 1).

Previous studies have indicated that the yield gap (actual yield as a percentage of attainable yield) can be narrowed by applying appropriate nutrient management practices (Dossou-Yovo et al., 2020; Saito et al.,

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Abbreviations: AE_P, agronomic P use efficiency; FYM, farmyard manure; PFP_P, partial factor productivity of P; P_{Ox}, oxalate extractable phosphorus; SSA, sub-Saharan Africa.

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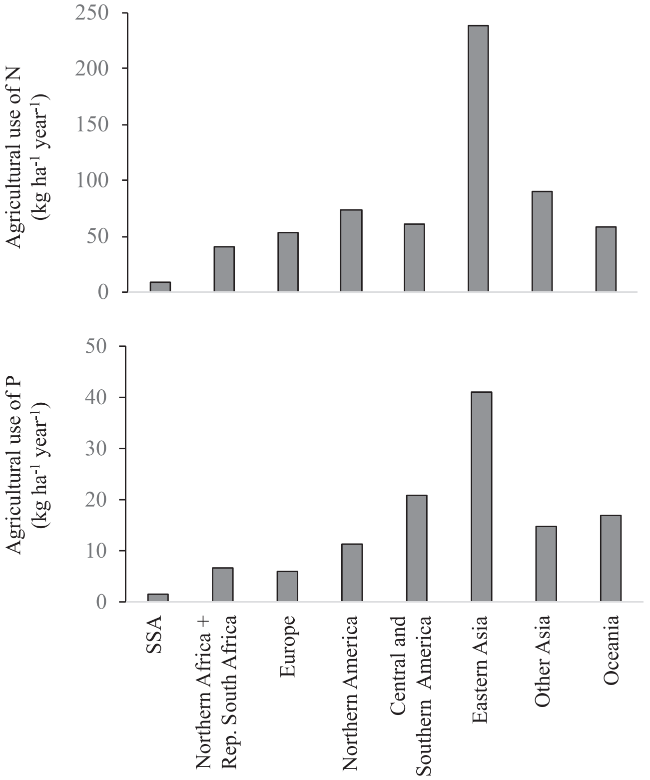

Fig. 1. Regional differences in agricultural use of N and P. The value was calculated by dividing the total use of N and P per year by arable land area, and averaged over the period from 2014 to 2018 (data is accessed at http://www.fao.org/faostat/en/ on Dec 17, 2020).

2019, 2017; Tsujimoto et al., 2019). These previous studies mainly focused on improved N management as the primary nutrient element for crop growth. However, there is minimal research addressing the potential impact of improved P management practices on rice production. A recent on-farm trial performed across SSA countries detected an average 17% yield reduction of rice (n = 372) with large site-to-site variations when P was omitted relative to the fully NPK-applied treatment for irrigated lowlands (Saito et al., 2019). A similar on-farm nutrient trial performed across south Asian and southeastern Asian countries (n = 531) detected a smaller average yield reduction of 9% and less field-to-field variations in its effect (the correlation between NPK and NK plots in rice yield was quite linear) (Buresh et al., 2010). Several studies performed in SSA also demonstrated significant yield reductions of lowland rice when P was omitted as equivalent to or more than that of N in Mauritania (Haefele et al., 2001), Senegal (Haefele et al., 2002), and Madagascar (Andrianary et al., 2021; Rakotoarisoa et al., 2020). These empirical results indicate that improved P management by considering spatial variations can be important for increasing lowland rice production in SSA. In addition, improved P management may concomitantly address the issues of Fe toxicity, i.e., another soil-related constraint for rice production in SSA (Audebert and Fofana, 2009; van Oort, 2018). Iron toxicity is often associated with low levels of P in soils (Kirk, 2004). Rakotoson et al. (2019) indicated that Fe uptake and Fe toxicity of rice plants can be mitigated by P application in P-deficient lowlands in the central highlands of Madagascar.

The objective of this study is to review the historical and recent efforts for improving P management for lowland rice production in SSA together with their limitations and prospects for future research. Therefore, we firstly conducted a systematic literature search on Web of Science from May to June 2021 to overview the effect of P application on grain yields in lowland rice production systems by retrieving publications with the yield response to P fertilizer application in field trials (Table 1). The search strings “Rice” AND “Phosphorus” AND “Africa” NOT “upland”; “Rice” AND “Phosphorus” AND “Asia” NOT “upland”; “Rice” AND “Phosphorus” AND “Efficiency” AND “Africa” OR “the country names in Africa”; ”Rice” AND “Phosphorus” AND “Efficiency” AND “Asia” OR “the country names in Asia”, which returned 589 articles (Supplementary Table). We included the results implemented in Asian countries as the major lowland rice-producing areas worldwide. Based on review of these articles and authors’ recent observations in Madagascar where P deficiency stress is widely found for lowland rice production, we focused on the following three points that have not been overviewed and potentially bring forward new insights regarding the improved P management practices in SSA.

The first point of discussion is the consideration of the P adsorption and desorption kinetics for soil tests to assess the P-supplying capacity and responses of rice to P application under flooded soil culture. The soil testing is a conventional research approach used to identify the contents of available P in soils but not yet adequately integrated into the current site-specific nutrient management. This is because most of soil tests do not account for the P sorption/desorption kinetics, resulting in the weak relationship with yield responses to P fertilizer. While the cost of site characterization at scale is reducing due to the advanced remote sensing and machine learning (Saito et al., 2021), the understanding of yield responses to soil properties should attract continuous attention to make most use of these advanced technologies for the improved P management.

The second point of discussion is the effect of organic inputs and micro-dosing localized P application to the nursery bed and to the seedling roots at transplanting. Use of organic inputs and micro-dosing localized mineral fertilizer application have been discussed to overcome P deficiency limitations for upland crop production in East Africa (Nziguheba, 2007) and in the Sahel (Aune and Bationo, 2008). Similarly, an increasing number of field observations have been reported regarding the significant effects of these approaches for lowland rice production under P deficiency in SSA (Asai et al., 2021; Rakotoarisoa et al., 2020; Vandamme et al., 2016) whereas they are yet to be overviewed in their prospects and limitations in previous studies. This paper discusses the agronomic nutrient use efficiency or AE_P (yield gain per unit of P applied) to assess the impact of the micro-dosing localized P application approach in a comparison of conventional P applications (Table 1). Although the calculation of AE_P requires laborsome nutrient omissition trials with and withput P-applied plots, the values reflect the direct production impact or economic return (Fixen et al., 2015), which is firstly important for smallholder farmers in SSA to start using P fertilizer. In addition, we also discusse the sustainablity of these micro-dosing localized P applicatons by analyzing the input and output balance of P. Saito et al. (2021) recently reported that the nutrient balance as estimated by the partial factor productivy (total grain yield harvested per unit of nutrient applied) is one of the most important parameters to standardize the knowledge of agronomic gain for sustainable intensification. Nakamura et al. (2013) provided a comprehensive review on the effect of direct application of local rock phosphate for lowland rice production in SSA, and therefore this issue was not extended in the present study. Finally, the third point of discussion is the interaction between P management and climate-induced stressors via the impact of P on the phenological development of rice. Although the third aspect has received minimal focus in previous studies, its importance has been highlighted in recent observations in the central highlands of Madagascar where both P-deficiency stress and low-temperature stress at the end of the rainy season are prevalent.

2. Necessity of a reliable soil P test for improved P management

A core problem of P deficiency in SSA is attributed to the predominant soil types that are low in available P contents or P-supplying capacity due to their long-term weathering processes and continuous cultivations with little external inputs and high in P retention capacity

Table 1
Effect of conventional P application and of localized P application to the nursery bed (nursery P) and to the seedling roots at transplanting (P-dipping) in various nutrient trials across Asian and African countries.

Location	Number of site or field	Rice production system*	Number of seasons or years * *	Treatments to calculate P effect* **	P apply rate* ** * (kg ha^{-1})	Yield gain (t ha^{-1})	AE$_P$ (kg kg^{-1})	PFP$_P$ (kg kg^{-1})	Shortened days to heading	Reference
Effect of conventional P applications as estimated from the single or multiple-season omission trials										
Across SSA	372	IL	–	NPK vs. NK	20–30	1.2	48	189	NA	Saito et al. (2019)
Across SSA	517	RL	–	NPK vs. NK	20–30	1.2	54	170	NA	Saito et al. (2019)
Mauritania	1	IL	–	NP vs. N	29	2.8	108	364	NA	Haefele et al. (2001)
Madagascar	4	RL	–	NP vs. N	21.8	0.6	27	182	NA	Asai et al. (2021)
Madagascar	7	RL	–	NP vs. N	21.8	1.4	62	145	14	Andrianary et al. (2021)
Nigeria	2	RL	–	NP vs. N	22.5	0.2	10	227	NA	Daudu et al. (2018)
Senegal	2	IL	20	NPK vs. N	26	2.1	81	204	NA	Haefele et al. (2002)
India	144	IL	–	NPK vs. NK	26	0.9	33	186	NA	(Singh et al., 2017)
Cambodia	4	RL	–	NPK (K at 3 kg ha^{-1}) vs. N	10.9	0.2	17	241	NA	Kong et al. (2020)
China	862	IL	–	NPK vs. NK	25–31	0.9	29	–	NA	Xu et al. (2017)
China	5556	IL	–	NPK vs. NK	30–48	0.9	15	–	NA	Xu et al. (2019)
Philippines	138	RL	4	NP vs. N	13	0.3	24	279	NA	Angus et al. (1990)
India	1	IL	4	NPK vs. NK	17.5	0.3	18	240	NA	Srivastava et al. (2014)
India	1	IL	6	NP vs. N	26	0.7	28	240	NA	Dwivedi et al. (2003)
China	1	IL	8	NPK vs. NK	25	1.5	59	226	NA	Zhang et al. (2006)
India	152	IL	8	NPK vs. NK	20–60	1.1	49	197	NA	(Panwar et al., 2019)
Philippines, Vietnam, China, India, Indonesia	11	IL	> 10†	NPK vs. NK	17–25	0.9	47	290	NA	Dobermann et al. (1996)
China	1	IL	14	NPK vs. NK	32	1.1	34	244	NA	Shen et al. (2004)
Vietnam	1	IL	16	NPK vs. NK	17.5	1.5	85	264	NA	Tan et al. (1995)
Nepal	1	IL	60	NPK vs. NK	26	2.1	82	106	NA	Regmi et al. (2002)
China	1	IL	70	NPK vs. NK	39.2	1.9	48	145	NA	Lu et al. (2021)
Location	Number of site or field	Rice production system*	Number of seasons or years * *	Treatments to calculate P effect* **	P apply rate* ** * (kg ha^{-1})	Yield gain (t ha^{-1})	AE$_P$ (kg kg^{-1})	PFP$_P$ (kg kg^{-1})	Shortened days to heading	Reference
Effect of localized P application to the nursery bed (nursery P)										
Madagascar	3	RL	–	NPK vs. Ct (NPK vs. Ct)	0.6 (25)	1.0 (2.3)	1650 (95)	6130 (232)	11–13	Rakotoson et al. (2020)
Cambodia	9	RL	–	NP vs. Ct (NPK vs. Ct)	2 (40, 8.8)	0.2 (0.9, 0.3)	114 (23, 33)	1145 (57, 372)	NA	Ros et al. (2015)
Benin	2	IL	–	NPK vs. NK	3	0.6	195	930	2–8	Vandamme et al. (2016)
India	1	RL	–	NPK vs. N	1.1	0.5	475	NA	NA	Sarangi et al. (2015)
Madagascar	3	RL	–	NP & N	0.6	0.4	680	4830	4–10	(Tsujimoto et al., 2021)
Effect of localized P application via seedling root dipping (P-dipping)										
Madagascar		RL	–	P-dipping (P broadcast) vs. Ct	13 (13–26)	1.7 (1.2)	124 (61)	244 (149)	14 (6)	(Rakotoarisoa et al., 2020)
India	1	IL	–	P-dipping (P broadcast) vs. Ct	13 (26)	1.1 (0.5)	85 (19)	400 (180)	NA	Ramanathan and Kothandaraman (1984)
India	1	IL	–	P-dipping vs. Ct	13	1.9	74	310	NA	Raju et al. (1980)
Madagascar	3	RL	–	NP-dipping vs. N-dipping	7.2	1.2	152	288	10–11	(Tsujimoto et al., 2021)
Madagascar	20	RL	–	P-dipping (P broadcast) vs. Ct	13 (13)	1.1 (0.5)	86 (39)	295 (245)	13 (7)	Oo et al. (unpublished)
Madagascar	1	RL	4	P-dipping (P broadcast) vs. Ct	13 (13)	1.2 (0.6)	93 (49)	240 (190)	NA	(Balasubramanian et al., 1995)

*IL: Irrigated lowland; RL: Rainfed lowland

* *The treatment difference was compared as a mean over the continuous nutrient omission trials in multiple seasons or years. "-" is the single season trial.

* **Ct: no fertilization. For the localized P application, the effect of conventional P application treatment is shown if available in bracket.

* ** *The P rate for the nursery P is estimated from the ratio of sowing density in the nursery bed to the transplanting density in the main field.

* ** *The P rate for P-dipping was estimated from the amount of P-enriched slurry being transferred with the seedlings.

AE$_P$ is the yield gain or yield difference between P-applied and non-P applied plots divided by the P apply rate. PFP$_P$ is the yield of P-applied plot divided by the P apply rate.

†The treatment difference was compared in a single-season trial but after the continuous and multi-season omission trials.

NA: data not available.

(Bationo, et al., 1998; Batjes, 2011; Buresh et al., 1997). Batjes (2011) estimated the P-retention capacity of soils based on the FAO Digital Soil Map and identified that > 25% of SSA soils are classified as having “moderate to very high” P retention capacities. These soils are predominant in > 75% of the areas in the central highlands of Madagascar. This high affinity to fix P is caused by an abundance of Fe-oxide and aluminum (Al)-oxide minerals in the soil (Kirk et al., 1998) and restrict the crop response to applied P even when the available P content is low in soils. The low use efficiency of applied P, i.e., little yield gain per unit of P applied, leads to a low return per investment, which has driven smallholder farmers away from using mineral P fertilizer. Consequently, the market is less developed, and the price of mineral P remains high (Razanakoto et al., 2018), leading to low yields. However, this soil P status can differ from field to field. For instance, Nishigaki et al. (2019) found that the forms and amounts of P in soils and the responses of rice to P application differed even among nearby lowland fields within the same valleys in the central highlands of Madagascar. Therefore, cost-effective and reliable methodologies to assess the indigenous soil P supply and response of rice to P application are needed by which farmers can selectively and efficiently apply P fertilizers. Identification of P-responsive fields increases the returns from minimal P inputs, whereas for less P-responsive fields, integrated and sustainable P management is needed. As described in the following section, organic inputs and P-dipping are potential approaches to address the challenge of highly P-fixing and less-P-responsive soils.

In contrast to the nutrient omission trials, soil P tests are a relatively simple means to assess the P-supplying capacity of soils and requirement of fertilizer P for crops (Jordan-Meille et al., 2012; Rosen et al., 2014). In addition, the cost-effectiveness of a soil P test has increased with advances in remote-sensing techniques and machine learning (Kawamura et al., 2019; 2020; Hengl et al., 2021). A soil database of available P (Mehlich-3) is currently available at a 30 m resolution for SSA (Hengl et al., 2021). To evaluate P availability or its predisposition to be taken up by plant roots, numerous soil tests have been developed using different extractants (Kuo, 1996). The amounts of extracted P vary depending on the types of extractants since they have different extracting capacities of the P pool in soils (Fig. 2). As shown in Fig. 2, extractions with water and CaCl$_2$ only tap the P in soil solution with immediate availability for root uptake. Meanwhile, the other tests often used as available contents of P in soils, e.g., Resin, Olsen, Mehlich, Bray, Truog, additionally encompass the readily available forms, which can be a P source as buffering soil solution. However, available P contents measured by these methodologies alone are often poor predictors of crop responses to P application in both uplands and lowlands (Dobermann et al., 2003; Nawara et al., 2017) except that the case is being applied in the same fields with different P fertilizer treatments (Bado et al., 2008). This is partly attributable to the fact that P uptake by crops and the response of crops to P application are associated not only with the quantities of available P in soils but also with the fluxes of available P governed by the soil P retention capacity (sorption-desorption kinetics) in soils (Nziguheba et al., 2016; Smolders et al., 2020). The importance of sorption-desorption kinetics in soils was highlighted for estimating the P uptake of perennial ryegrass (Smolders et al., 2020) and maize (Kuo, 1990) in glasshouse studies. A recent study showed that the P retention capacity of soils needs to be considered to predict the responses of rice to P fertilizer in the central highlands of Madagascar (Nishigaki et al., 2021).

Another difficulty in developing an appropriate soil P test for lowland rice production is attributable to a complex change in the physical and chemical properties of soils under the flooded condition. Generally, flooded rice culture systems are considered to suffer less from P deficiency because of increased physical diffusion (Rakotoson et al., 2014b; Turner and Gilliam, 1976) and increased solubilization of insoluble P complexes in the redox processes (Liptzin and Silver, 2009; Rakotoson et al., 2014a). Taking the latter aspect into account, Nanzyo et al. (1996) proposed using a reducing agent (ascorbic acid) prior to the general soil P test to Japanese paddy soils; however, the applicability of this method to tropical soils has not yet been examined. Oxalate extractable P (P$_{Ox}$) in soils is one of the suggested indices to determine the degree of P deficiency for lowland rice production under flooded and highly weathered soils with abundant Fe (Guo and Yost, 1999; Rabeharisoa et al., 2012; Rakotoson and Tsujimoto, 2020; Rakotoson et al., 2014a). For instance, country-wide surveys from typical P-deficient and flooded lowlands of Madagascar indicated that P$_{Ox}$ had relatively high correlation with rice yield (R^2 = 0.45) (Rabeharisoa et al., 2012). Asai et al. (2021) observed a significant correlation of P$_{Ox}$ with the magnitude of

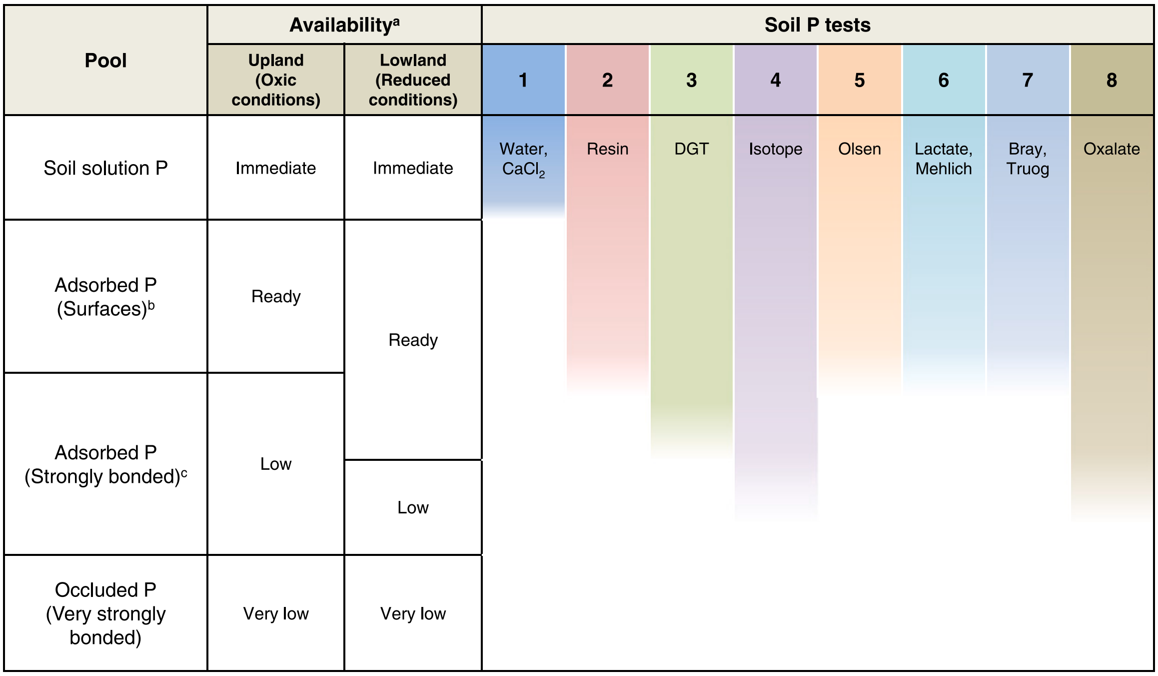

Fig. 2. Various soil P tests and their targeting P pools with different availabilities in soils
Adapted from Kuo (1996), Rakotoson et al. (2014a), Wuenscher et al. (2015), Wright (2018).

yield differences between P-applied and non-P-applied plots (R^2 =0.45). The main advantage of P_{Ox} over other soil P tests is the extraction of P associated with amorphous Fe-oxide minerals (Schwertmann, 1964). This form of P, which cannot be extracted with the other soil P availability tests (except for the isotope technique whereas this method requires more expensive equipment, consumables, and safety measures than P_{Ox}; Fig. 2), has increased solubility upon waterlogging via microbial reduction (Kirk, 2004; Moorman and van Breemen, 1978).

Recently, Kawamura et al. (2019) developed a P_{Ox} prediction model using visible and near-infrared diffuse reflectance spectroscopy with a genetic algorithm-based partial least squares regression analysis, which may provide a rapid and extensive evaluation of P_{Ox} in lowland soils. Although further empirical evidence should be accumulated to confirm the applicability of P_{Ox} to predict the degrees of rice responses to P fertilizer application, these findings indicate a potential opportunity to integrate the results of soil P tests into field-specific P fertilizer management practices, which can ultimately increase lowland rice production via P use. Notably, the P_{Ox} is considered to be a poor indicator of soil available P for upland crops (Nawara et al., 2017).

3. P management options for low input rice production systems

3.1. Potential of organic inputs in P-fixing soils

Locally available organic fertilizer remains an important nutrient source for rice production in SSA. A recent survey involving 357 rice farmers in Ethiopia, Madagascar, Rwanda, Tanzania, and Uganda revealed that 48% of farmers apply organic fertilizer for lowland and upland rice production (Senthilkumar et al., 2020). Likewise, Tsujimoto et al. (2019) showed that farmyard manure (FYM)—mixtures of animal excreta, crop residues, and fodder that are piled nearby homesteads—is used in 19% of lowland fields and 77% of upland fields for rice production in the central highlands of Madagascar, whereas these values are merely 3% and 20%, respectively, for mineral fertilizer. An extended survey involving 2263 rice fields in the same region of Madagascar confirmed the use of FYM in 24% of lowland fields and 34% of upland fields (Ozaki and Sakurai, 2021). In West Africa, data on organic inputs for lowland rice is very limited relative to data related to the use of mineral fertilizer. A few past studies observed that 7% of surveyed rice farmers in Ghana (Kranjac-Berisavljevic' et al., 2003) and 76% of rice famers among 17 different states for Nigeria (Longtau, 2003) reported using organic inputs. As such, organic input remains an important practice for rice production in SSA given its relatively low use of mineral fertilizer in the region.

Previous studies have demonstrated the potential beneficial effects of organic inputs such as FYM and green manure on rice yields and soil nutrient availability in the long term in Tanzania (Kwesiga et al., 2020a, 2020b). Kwesiga et al. (2020a) observed that sole FYM and green manures (cowpea, lablab, and *Stylosanthes guianensis*) increased rice yields from 0.7 to 3.1 t ha^{-1} over the non-amended control with more than an additive effect when the two were combined. Similarly, in a follow-up study, Kwesiga et al. (2020b) reported a reduction of the yield gap by > 50% following application of FYM and green manures in smallholder systems in Tanzania. However, the experimental design of these studies does not allow to single out the effects of these organic inputs to improve the P use efficiencies. In fact, very few studies have focused on the role of organic inputs in addressing P deficiency in the tropics because of a general perception that the P contents in these organic inputs are generally low. However, some studies indicate a potential role of organic inputs not as a P source but rather as a substance to enhance P solubilization and mobilization and to facilitate plant P uptake under flooded soil culture (Amery and Smolders, 2012; Rakotoson et al., 2014a; Rakotoson and Tsujimoto, 2020).

As discussed earlier, the flooded condition increases the soluble P content via microbial reduction and increased pH levels (Kirk, 2004; Liptzin and Silver, 2009; Ponnamperuma, 1972; Rabeharisoa et al., 2012). The fresh organic inputs accelerates such P solubilization by acting as an electron donor under the flooded condition, which intensifies the microbial reductive dissolution of P-bearing Fe-oxides. Rakotoson et al. (2014a) reported that rice straw addition almost doubled the soil labile P as *E*-values (measured using the isotope dilution technique and soil extraction with an anion exchange membrane), which reflect the potentially accessible P pool in soil. Furthermore, using isotope (^{32}P) tracing, Rakotoson and Tsujimoto (2020) demonstrated that FYM application can increase the labile P contents in soils and P uptake by rice plants. Recent field experiments demonstrated that FYM application greatly increased lowland rice yields, specifically on soils with low available P contents (Asai et al., 2021). These authors reported large yield differences by up to 2.7 t ha^{-1} with and without 3-year continuous FYM application under these lowland fields in the central highlands of Madagascar. Given the relatively low P contents in FYM [< 0.5% in Andriamananjara et al. (2016) and between 0.2% and 1.6% in (Sanginga and Woomer, 2009)], this result may attract more attention for FYM application to address P deficiency stress for lowland rice production in terms of solubilizing P bound to Al- and Fe- oxides and buffering high P-retention capacity of SSA soils. Our systematic literature search also confirmed that this aspect has been little mentioned in reviews or experimental studies investigating the effect of organic inputs for lowland rice production in the tropics despite a general perception of its role in supplying various nutrients and improving soil fertility (e.g., Cassman et al., 2008; Bijay-Singh et al., 2008). A similar effect of increased pH and P availability by liming has been reported mainly for upland conditions in acidic soils (Terman et al., 1970; Chang and Sung, 2004), whereas field-based evidence of liming to increase lowland rice yields under P deficiency remains scarce.

Future studies are warranted to clarify what types of organic inputs (e.g., with respect to the contents of P and carbon (C)) are most effective to solubilize P in soils and to alleviate P-deficiency stress for lowland rice production in SSA. Economic assessment is also a key aspect for the use of organic fertilizer amendment, whereas there are limited studies in this regard for rice production in SSA. Such assessments should consider not only the costs of purchasing organic resources but also the extra labor costs of transportation and application to the fields. A few studies have reported that the amounts of organic inputs are limited to cover an extensive area of rice production, suggesting that its widespread use might not be feasible (Morris et al., 2007; Otsuka and Muraoka, 2017). In Asia, an example in the Philippines showed that organic inputs cost more per unit of nutrient content compared to mineral fertilizers and their widespread use can be cost-ineffective, particularly for materials with a high moisture content and low nutrient contents (Mamaril et al., 2009; Timsina, 2018). In this regard, the effective strategy to use organic inputs is needed. The prioritized use to fields with low available P contents and abundant Fe- and Al-bound P in soils may be one such strategy to accelerate chemical P reactions and to solubilize more P in soils.

3.2. Localized and micro-dosing fertilizer application

Another potential approach to increase applied P use efficiency for lowland rice production is localized and micro-dosing P application to the nursery bed or to the seedling roots at transplanting via dipping. Several field experiments have identified that rice yield, applied P use efficiency (AE_P) as a yield increase per unit of input, or both, can be substantially increased by micro-dosing application to the nursery bed, as summarized in Table 1 (Rakotoson et al., 2020; Ros et al., 2003; Sarangi et al., 2015; Tsujimoto et al., 2021; Vandamme et al., 2016). The AE_P in these studies ranged between 114 and 1650 kg kg^{-1}, much greater than those of conventional P applications observed within the same study and in the other studies. Dobermann (2007) reported that the typical range of AE_P for cereal crop production ranged from 20 to more than 50 kg kg^{-1} on responsive soils and under favorable growth conditions. The AE_P with conventional P applications in Table 1 is similar to this range at 48 kg kg^{-1} for irrigated lowlands and 54 kg kg^{-1} for rainfed lowlands across SSA (Saito et al., 2019), and slightly lower at 15–33 kg kg^{-1} in single-season and multi-location trials in India, Cambodia, and China (Kong et al., 2020; Singh et al., 2017; Xu et al., 2017; 2019). The AE_P are slightly high when calculated from multi-season trials because the yield differences between P-applied and P-omitted plots are mostly enlarged, but the values remain much lower than those achieved by micro-dosing application to the nursery bed. A key mechanism of this approach is to produce vigorous and P-enriched seedlings that facilitates quick recovery from transplanting shock and accelerates initial growth, which in turn improve grain yields. Some studies have reported that the combination of N and P is more effective at developing vigorous seedlings and increasing grain yields than single nursery bed applications of P or N (Rakotoson et al., 2020; Sarangi et al., 2015). Ella and Ismail (2006) demonstrated that enrichment of seedlings with micro-dosing N and P applications improved their submerge-stress tolerance after transplanting. It should be noted that the P application rates to the nursery bed are marginal compared with normal P application to the main field, and thus the yield gain is also relatively small even with high AE_P.

Another drawback of this technique is the potential risk of nutrient mining or P depletion from soils if not applied with field fertilization because the amount of P introduced from the seedlings to the field is negligible compared with that exported by plant uptake at harvest (Vandamme et al., 2016). For instance, Vandamme et al. (2016) estimated that of the 3 kg P ha^{-1} applied in the nursery bed, merely 0.07–0.24 kg P ha^{-1} was transferred to the main fields via P-enriched seedlings (>90% of applied P is retained in the nursery bed) while an additional 2 kg P ha^{-1} was mined due to the increased grain production in response to nursery P application. This drawback is reflected by the extremely high partial factor productivity (PFP_P) —kilogram yield per kg applied P— at 930–6130 kg kg^{-1} (Table 1). Based on the survey of smallholders' rice production systems across six Asian countries, Devkota et al. (2019) categorized PFP_P into too high (soil mining, >350), desirable range (150−300), and too low (wasteful application, < 150) as an index of sustainable nutrient management. Based on this category, micro-dosing application to the nursery bed is regarded highly soil mining compared to the conventional P applications within the same study and in the other studies whose PFP_P ranges are mostly in the desirable range (Table 1). Vandamme et al. (2018) suggested that the micro-dosing application technique should be the first step before a more integrated and sustainable nutrient management strategy.

Dipping seedling roots in P-enriched slurry at transplanting (P-dipping) is another localized P application method, which allows ample P addition to the main field in the form of slurry attached to seedling roots at transplanting (see Table 1 for a comparison of the amount of P applied and the PFP_P values between micro-dosing P application to the nursery bed and P-dipping). The P-dipping technique itself has been conventionally examined in lowland rice production systems in Japan, India, China, and Madagascar (Obata and Arakaki, 1953; Lu et al., 1982; Ramanathan and Kothandaraman, 1984; Balasubramanian et al., 1995). However, as pointed out in Rakotoarisoa et al. (2020), the technique has been mostly reported in institutional documents/newsletters or partially cited in book chapters that provided little information on the methodologies in details, mechanism of the effect on rice growth, and its interaction with field environments. A recent study identified that the key function of this technique is not to develop P-enriched seedlings but rather to transfer ample amounts of P close to the root zone at transplanting (Oo et al., 2020a). Therefore, the dipping duration into the P-enriched slurry can be instant if the slurry is attached to the seedling roots, which minimize time- and labor-cost. However, it should be noted that a prolonged dipping duration > 4 h may increase a risk of salt stress to the seedlings. Further, we identified that the P-dipping creates soluble P hotspots near the root zone and develops vigorous surface root systems, which in combination facilitate the P uptake of rice plants even under highly P-fixing soils in SSA (Oo et al., 2020b).

Several studies including our recent observations mostly conducted in the central highlands of Madagascar confirmed that the P-dipping consistently had great yield gains (1.1–1.9 t ha^{-1}) and high AE_P (74–152 kg kg^{-1}) relative to those obtained with conventional P applications (Table 1). In addition, P-dipping enables large amounts of P inputs into the main field, whereby a positive P balance between the external inputs and removals by harvest can be retained. The PFP_P is in the desirable range as per Devkota et al. (2019). Thus, the concern of negative P balance by a continuous and single application of micro-dosing nursery bed fertilization can be mitigated by combining with the P-dipping technique. However, further empirical evidence is needed to assess the long-term effect of these P-efficient management practices. Numerous studies on long-term fertilizer management practices indicate reducing trends in yields, soil available P contents, or both with continuous P-omitted or P-reduced treatments for lowland rice cultivation (Dobermann et al., 1996; Regmi et al., 2002; Haefele et al., 2004; Ibrahim et al., 2021; Lu et al., 2021). In addition, further studies are needed to assess farmers' interest in using the technique and potential constraints for adoption, such as acceptable costs of labor and materials relative to the benefits and how to prepare the P-enriched slurry in a greater scale.

4. Importance of the interaction between P-fertilizer management and climate-induced stresses

Another important, but rarely studied, aspect for improved P management is its effect on phenological development. It is well known that P deficiency delays the flowering and maturity of rice and other annual plants (Chauhan et al., 1991; Datnoff et al., 1991; Dobermann and Fairhurst, 2000; Nord and Lynch, 2008; Rossiter, 1978; Ye et al., 2019). Some studies have reported delays in the flowering time of rice due to excess N application (Ye et al., 2019) or have indicated that flower initiation is dependent on the balance of P and N contents in plants (Kant et al., 2011). However, the effects of other minerals on phenological development are considered marginal when compared with that of P. In severely P-deficient and historically non-P-applied fields in Tanzania, Vandamme et al. (2018) observed that the time to heading of upland rice was shortened by around 20 days (relative to the control) by placing small amounts of P into the planting holes. Similarly, a survey in the central highlands of Madagascar revealed that P deficiency can delay the number of days to heading in rice by more than three weeks (Andrianary et al., 2021).

Our systematic review confirmed that there has been limited focus in the literature on the effect of P on phenological development (Table 1). A few studies recorded prolonged days to heading on P-omitted plots (Sahrawat et al., 1995; Gautam et al., 2015), but did not analyze its effect on plant growth. Tan et al. (1995) observed a declining yield trend with a high percentage of unfilled grain when P was omitted (NPK vs. NK) in a 16-season continuous nutrient trial. They stated that the reduced grain fertility under P deficiency may be attributed to the delayed ripening, whereas there were no data related to phenological development or climatic conditions. A quantitative study was found only in *Arabidopsis thaliana* grown in a climate-controlled greenhouse, in which the phenological delays in P deficiency were concluded to be adaptive and lead to increased P uptakes and biomass production with extra days to maturity (Nord and Lynch, 2008). However, the effects of such phenological changes need to be evaluated under variable environments.

Extra days to heading and maturity can be beneficial for biomass production in constantly favorable growing conditions, as reported in Nord and Lynch (2008) but may increase the risk of biotic and abiotic stresses under open-field environments. For instance, Rakotoarisoa et al. (2020) reported that prolonged days to heading under P deficiency increased the degree of low temperature stress and reduced grain fertility in the central highlands of Madagascar. Andrianary et al. (2021) more clearly demonstrated dual impacts of P deficiency-induced delays in phenological development on rice production in the central highlands of Madagascar. In this paper, the extra time to heading by more than three weeks under P deficiency allowed for more biomass production and increased grain yields when low-temperature stress was negligible at the reproductive and ripening stages (when plants were transplanted sufficiently early). In contrast, the phenological delay in P deficiency increased the cold-induced sterility from 21% (the mean of P-applied plots) to 45% (the mean of non-P-applied plots) when transplanting was delayed. Consequently, the effect of P application on grain yields was much greater when the risk of low-temperature stress was higher at the reproductive and ripening stages. This interaction between P application and climate-induced stresses via the impact of P on phenological development was clearly observed because the central highlands of Madagascar had a risk of both P deficiency and late-season low--temperature stress for rice production. A similar type of interaction can be presumed to occur in the highlands of eastern and southern Africa where decreasing temperatures and water shortages both commonly occur at the end of the main rice-growing wet season (Raboin et al., 2014; Samejima et al., 2020; van Oort, 2018).

These observations and presumptions imply that appropriate P management may play an important role in enabling plants to simultaneously cope with climate-induced stresses and suboptimal soil nutrient conditions. Recent experiments have suggested that the number of days to heading or phenological development can be shortened to a greater extent by altering the application methods. Both P-dipping and localized P application to the nursery bed (see Section 3.2) significantly shortened the days to heading by one to two weeks compared to P broadcasting or to no P application to the nursery bed (Rakotoarisoa et al., 2020; Rakotoson et al., 2020). In addition, a recent trial identified that the number of days to heading can be cumulatively shortened by combining P-dipping and micro-dosing P application to the nursery bed (Tsujimoto et al., 2021). Significantly shortened growth durations by these P application management practices may reduce the risks of biotic and abiotic stresses, as noted above, and allow for wider “safe sowing windows” (Dingkuhn, 1995) without changing varieties. This also benefits farmers to reduce the labor intensity at the time of transplanting (Dingkuhn, 1995). Shorter growth durations may increase the opportunity to intensify land use by enabling double- and triple-cropping of rice or rotations with vegetable crops in some areas (van Oort et al., 2016).

More empirical results and modeling studies are expected to accurately assess the impact of P fertilizer management practices on rice production by integrating data of its effect on phenological development. van Oort and Dingkuhn (2021) recently reviewed that the interaction between phenological development and climate-induced stresses (thermal spikelet sterility) is one of the most extensively studied areas in which crop models were applied to rice production in SSA, whereas none of these crop modeling approaches has focused on P deficiency as a factor to affect phenological development. Toward this end, the following questions need to be answered: 1) Is there any quantitative relationship between the degree of P deficiency stress of rice plants and the P-deficiency-induced delay in phenology development; and 2) Are there any genotype differences associated with the phenological changes that occur in response to the P deficiency stress?

5. Conclusions

Given the finite nature of the P fertilizer resource (i.e., rock phosphate) and increasing environmental concerns in the excessive use of P in agricultural systems, improving P management practices is a critical issue not only for lowland rice production in SSA but also for sustainable food production worldwide. This review reconfirmed the importance of this issue and provides options to improve the P use efficiencies for increasing lowland rice yields in SSA. A soil test to assess yield responses to mineral P and organic inputs can be refocused by considering the P adsorption and desorption kinetics because soils with high P-retention capacity prevail in SSA and large amounts of insoluble P complexes are bound to Fe- and Al-oxides. An appropriate assessment related to the effect of flooding and organic inputs on the chemical reactions or solubilization of P in soils may guide the more efficient use of these insoluble P pools. Both micro-dosing P application to the nursery bed and P-dipping at transplanting were confirmed to have high agronomic P use efficiencies relative to those of conventional P applications. These options should provide incentives to smallholder farmers to start using P fertilizer in the currently low-input and low-yielding production systems to increase lowland rice yields. However, for the options that can expect high yield gains with minimal inputs, the input and output nutrient balance should be carefully monitored. In addition, this review first captures the importance in understanding the interaction between P management and climate-induced stresses via its impact on phenological development. Both suboptimal nutrient management and climate-induced stresses have been intensively but separately studied as major yield constraints for rice production in SSA. Studies on improved P management practices may require a more integrated approach with respect to these factors.

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Tovohery Rakotoson, Yasuhiro Tsujimoto: Conceptualization, Methodology, Investigation, Dada analysis, Writing original draft, **Tomohiro Nishigaki**: writing the revised manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2021.108370.

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Optimizing the Phosphorus Concentration and Duration of Seedling Dipping in Soil Slurry for Accelerating the Initial Growth of Transplanted Rice

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Abstract: Given the finite nature of P fertilizer resources, it is imperative to investigate effective P management practices in order to achieve sustainable rice production. This study was conducted (1) to assess the effect of dipping rice seedlings in P-enriched slurry before transplanting (P-dipping, hereafter) on initial plant growth and (2) to determine the optimum P concentration and dipping duration. In the P-dipping treatments, four P_2O_5 concentrations in the slurry (4.3%, 5.0%, 6.0%, and 7.5%) and four dipping durations (0.5 h, 2 h, 4 h, and 8 h) were investigated. After the treatments, the seedlings were transplanted into 1/5000 Wagner pots and grown under flooded conditions for 42 days and they were compared with plants under conventional P incorporation at the rate of 300 mg P_2O_5 pot^{-1} and with plants under no P application. The amount of P_2O_5 attached to P-dipped seedlings, or locally applied in the rhizosphere at transplanting, increased with higher P concentrations in the slurry, ranging from 87.5 to 112.2 mg pot^{-1}. Shoot biomass at 42 days after transplanting (DAT) was greatly increased in plants under the P-dipping treatments, compared to that in plants with no P application and was comparable to or greater than that in plants under conventional P incorporation, even when P levels were 2.5 to 3 times lower. Among the P-dipping treatments, we observed some significant effects of P concentrations and dipping durations on seedling P uptake and shoot biomass, without any interaction between these variables. Seedling P uptake and biomass tended to be higher with higher P concentrations in slurry and longer dipping durations. Conversely, the shoot biomass at 42 DAT was significantly lower in plants under the highest P concentration treatment (7.5% P_2O_5) compared to that in other plants and tended to be lower with longer dipping durations (4 h and 8 h). These negative effects can be attributed to the slow recovery from transplanting shock because of the chemical damage of seedlings exposed to higher salt concentrations for longer durations. The present study highlights that (1) P-dipping could be an effective approach to increase transplanted rice production with minimal P inputs, and (2) this effect could be higher with a low P-concentration in the slurry (4.3% P_2O_5) and a short dipping duration (0.5 h). Based on the obtained results, further on-farm trials are expected to assess farmers' appreciation and the potential constraints of adopting this technique.

Keywords: localized application; *Oryza sativa* L.; P-dipping; P use efficiency; salt stress

1. Introduction

Phosphorus deficiency is one of the main constraints for rice production in many parts of the world [1–3]. In order to overcome this problem, recommended or even excess amounts of P fertilizer are usually applied to obtain high grain yields. However, world resources of P are finite and thus, P should be used as efficiently as possible in order to conserve the base resources [4]. Efficient P fertilizer management is also key to improving rice yield for smallholder farmers who use few external inputs, such as in the case of Sub-Saharan Africa [5]. Therefore, it is necessary to find appropriate strategies for the effective use of P fertilizers in rice production systems.

In this respect, micro-dosed and localized P applications were examined in several crops by applying P fertilizer in root zones where P is readily accessible to the plants, instead of conventional application via broadcasting or incorporation. Studies reported that this technique increases rice yield and improves P fertilizer use efficiency, particularly in P-deficient soils in the tropics, e.g., placement of P in a planting hole for the upland rice production system [3,6–8] and application to a nursery bed for the lowland rice production system [9,10].

Likewise, dipping seedling roots into P-enriched slurry just before transplanting (P-dipping) may also improve P fertilizer use efficiency in transplanted lowland rice production systems. Previous studies on P-dipping reported an increase in grain yield by 10%–50% with the same P application rates, or plants achieving the same yield levels with 40%–60% reductions in P application rates, relative to broadcasting or incorporating P at transplanting [11–15]. These empirical observations suggest that P-dipping should attract further attention as a considerable approach for sustainable yield increases with minimal P inputs. However, most of these studies were reported in institutional documents/newsletters or were partially cited in book chapters which provided little information on treatment aspects such as durations of dipping and P concentrations in enriched slurry. Such information is critically important to farmers who apply the P-dipping technique in their fields. The only study which assessed the application rate and duration of dipping was by Kalidas-Singh and Thakuria [15]. Their assessments were based on the P concentrations in seedlings after dipping, but not on biomass growth after transplanting. We consider that it is important to assess the P-dipping technique, based not only on its effect on the seedling nutrient status, but also on the initial biomass production after the treatment. Therefore, this study aimed (1) to confirm the effect of the P-dipping technique relative to P broadcasting and (2) to identify the optimum P concentrations in slurry and the optimal dipping durations, in terms of the biomass production and P uptakes at the early growth stages after transplanting.

2. Materials and Methods

2.1. Preparation of P-Enriched Slurries and Dipping of Rice Seedlings

The experiment was conducted in a greenhouse at the Japan International Research Center for Agricultural Science (JIRCAS, Tsukuba, Japan). The temperature inside the greenhouse was controlled by an automatic ventilation system in a basic manner, i.e., windows opened at the temperature >30 °C and closed at the temperature <25 °C. The daily mean temperature in the greenhouse ranged from 25.6 °C to 32.9 °C during the pot experiment (Thermo Recorder TR-50U2, T&D Corporation, Nagano, Japan). The volcanic soil was collected from the forest subsoil (20 to 40 cm layer) within the experimental farm of JIRCAS in order to ensure the absence of the potential effects of P-fertilization records. The soils were first air-dried and passed through a 2.0 mm sieve, and then used to prepare P-enriched slurry and to grow rice in pots. The experimental soil was sandy loam with a high P retention capacity of 99%. The other properties of the experimental soils are summarized in Table 1.

Based on the application rates in the previous P-dipping studies [13,14], 6.52 g of triple super phosphate (TSP) was mixed with different amounts of soil (70, 60, 50, and 40 g of air-dried soil) in order to obtain different P concentrations in the soil slurry (4.3% P_2O_5 (S1), 5% P_2O_5 (S2), 6% P_2O_5 (S3), and 7.5% P_2O_5 (S4), respectively). Water was added in the ratio of 2.5:1 (air-dried soil:water) and thoroughly mixed in to make a P-enriched slurry.

Table 1. Physicochemical properties of soil.

Parameters	
pH (1:2.5 H_2O)	5.7
EC (dS m^{-1})	0.04
Total N (g kg^{-1}) [a]	1.8
Total C (g kg^{-1}) [a]	45.5
P retention (%) [b]	99.0
$P_{oxalate}$ (g kg^{-1}) [c]	4.0
$Al_{oxalate}$ (g kg^{-1}) [c]	46.1
$Fe_{oxalate}$ (g kg^{-1}) [c]	25.7
Sand (%) [d]	83.4
Silt (%) [d]	10.5
Clay (%) [d]	6.1
Texture	Loamy sand

a: NC analyzer, Sumigraph NC-220F (SCAS, Tokyo, Japan). b: The proportion of absorbed P amounts after shaking 5 g of soil and 25 mL of 1000 ppm P solution for 24 h. c: Inductively coupled plasma mass spectrometer (ICPE-9000, Shimazu, Japan) after oxalate extraction. d: Sieving and pipetting method.

After the preparation of soil slurries with different P concentrations, the roots of 50 rice seedlings (21 days old, *Oryza sativa* L. var. IR64) were dipped in the slurry for four dipping durations (0.5 h, 2 h, 4 h, and 8 h). All treatment combination experiments were done in quadruplicate. At transplanting, any soil slurries naturally attached to two seedlings were sampled twice and carefully collected into an aluminum cup by washing off the seedling roots. Then, the amounts of soil slurry and P transferred with two seedlings per pot were estimated by oven-drying the slurry samples at 105 °C for 24 h and by multiplying the slurry amount by the P concentration for each replicate.

The rice seedlings were separately sampled in order to determine the dry weights at transplanting after oven-drying at 80 °C for two days. The seedling's P concentration was determined with the molybdate blue method [16], after dry ashing at 550 °C for 2 h and digesting with 0.5 M HCl. The seedling's P uptake (mg pot^{-1}) was calculated by multiplying the P concentration and the dry weight.

2.2. Pot Experiment

The treated seedlings were transplanted into pots (two seedlings per hill, one hill per pot). The pots were filled with 3 kg of air-dried volcanic soil and watered (1:5000 Wenger pot, height 20 cm, diameter 16 cm). P was incorporated ($P_{inco.}$) at the rate of 300 mg P_2O_5 pot^{-1} and control (Cont.—no P application) treatments were prepared in the same manner. For the $P_{inco.}$ treatments, all of the applied P was thoroughly mixed with soils in pots just before transplanting. In total, there were 72 pots and 18 treatments (four levels of P concentrations in the slurry combined with four dipping durations, $P_{inco.}$ and Cont.) with four replications. In all the treatments, NH_4NO_3 and K_2SO_4 at the rates of 300 mg N pot^{-1} and 300 mg K pot^{-1}, respectively, were applied to the soil before transplanting in order to exclude the potential effects of N and K deficiencies.

The rice plants were grown in submerged conditions and harvested 42 days after transplanting (DAT). At harvest, the biomass and P concentrations of the shoots were determined using the same procedure as described above for the seedlings.

2.3. Statistical Analysis

The data were analyzed by a two-way analysis of variance (ANOVA) in order to assess the single and interaction effects of P concentrations in the slurry and dipping durations using STAR software (Statistical Tools for Agricultural Research, International Rice Research Institute, IRRI, Los Baños, the Philippines). The mean comparisons of the treatment were ascertained using Tukey's HSD test at 5% and 1% probability levels. Then, the mean values of the P-dipping treatments were compared with single and interaction effects of P concentrations in the slurry and dipping durations using STAR software (Statistical Tools for Agricultural Research, International Rice Research Institute, IRRI, Los Baños, the Philippines). The mean comparisons of the treatment were ascertained using Tukey's HSD test at 5% and 1% probability levels. Then, the mean values of the P-dipping treatments were compared with those of the Cont. and $P_{inco.}$ treatments using Tukey's HSD test. In this comparison, the S4 and long dipping durations (4 h and 8 h) were excluded because of apparent salt stresses.

3. Results

3.1. *Effect of P-Dipping Treatments on the Seedlings*

The amount of P transferred with seedlings, or P concentratedly applied in the rhizosphere at transplanting, was significantly affected by the P concentrations in the slurry, but not by dipping durations (Figure 1). The amount of P_2O_5 transferred with seedlings ranged from 87.5 mg to 112.2 mg per pot, and it was the highest in the slurry S4, followed by S3, S2, and S1 in the order of P concentrations in slurry. The amounts of P applied in the P-dipping treatments were 167.4% to 242.9% lower than that of the $P_{inco.}$ treatment (300 mg P_2O_5 pot^{-1}).

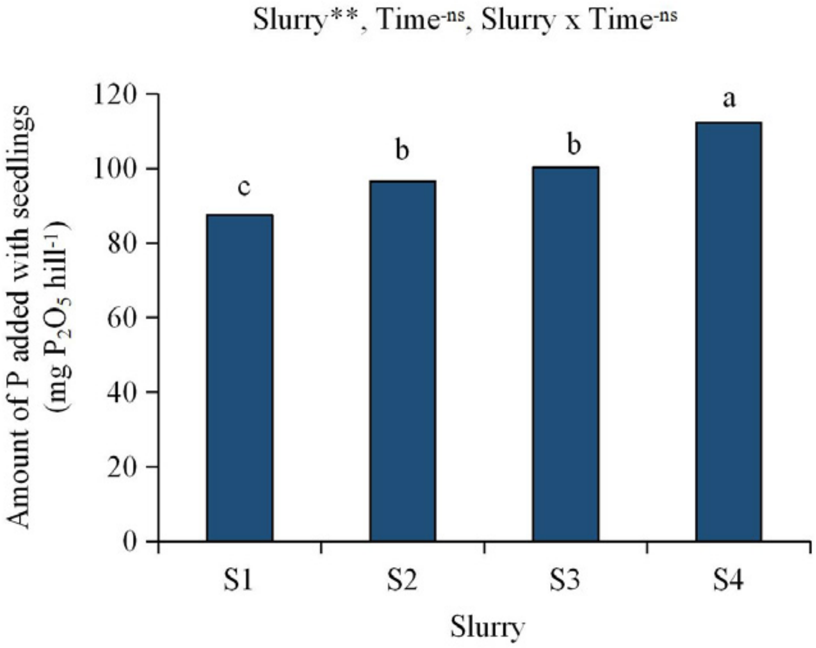

Figure 1. Effect of phosphorus concentration in slurry on the amount P added with seedlings at transplanting. ** $p < 0.01$, ns = not significant. The different letters within a column indicate significant differences between treatments at $p < 0.05$ using Tukey's HSD test.

The seedling P concentration and seedling P uptake were significantly affected by both the P concentrations in the slurry and the dipping durations, with no interaction between the two (Table 2). The seedling P concentration increased with the increasing P concentrations in the slurry from 0.43% in S1 to 0.59% in S4, and these values were 48.3%–103.5% higher, respectively, than those in the seedlings without P-dipping treatment. Accordingly, seedling P uptake was the highest in S4, followed by S3, S2, and S1, and these values were 83.3%–150% greater than those in the seedlings without P-dipping treatments. Both seedling P concentration and uptake were significantly lower with the dipping durations of 0.5 h and 2 h than those of 4 h and 8 h. The dipping duration of 4 h led to the highest P concentration and P uptake of seedlings.

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Table 2. Effect of P concentration in slurry and dipping duration on seedling P concentration, seedling P uptakes, and shoot biomass and P uptakes at 42 DAT in comparison with Cont. and P_{inco}. treatments.

	Seedling P Concentration (%)	**Seedling P Uptake (mg plant^{-1})**	**Shoot Biomass (g pot^{-1})**	**Shoot P Uptake (mg pot^{-1})**
P conc. in slurry				
S1	0.43 c	0.11 b	11.62 a	8.81 ab
S2	0.47 bc	0.12 b	11.48 a	9.87 a
S3	0.53 b	0.14 a	11.26 a	9.81 a
S4	0.59 a	0.15 a	9.71 b	8.15 b
Dipping duration (h)				
0.5	0.42 c	0.10 c	12.13 a	9.22 ab
2	0.43 c	0.10 c	11.88 a	10.13 a
4	0.61 a	0.17 a	9.00 b	8.24 b
8	0.54 b	0.15 b	11.06 a	9.04 ab
Analysis of variance				
P conc. in slurry	**	**	*	*
Duration	**	**	**	*
P conc. × duration	ns	ns	ns	ns
Mean comparison among P-dipping, Cont., and $P_{inco.}$				
P-dipping †	0.50 A	0.13 A	11.51 A	9.48 A
Cont.	0.29 B	0.06 B	0.49 C	0.21 C
$P_{inco.}$	–	–	9.00 B	6.69 B

* $p < 0.05$, ** $p < 0.01$, ns = not significant. In each column, different small letters within a column indicate significant differences between treatments at $p < 0.05$ using Tukey's HSD test. † The mean value over P-dipping treatments except 4 h and 8 h dipping durations in S4 was compared with Cont. and $P_{inco.}$ Different capital letters indicate significant differences among these treatments at $p < 0.05$ using Tukey's HSD test.

3.2. Early Growth and P Uptake of Rice

The shoot biomass at 42 DAT was substantially increased in all P-dipping treatments (9.71 to 11.62 g pot^{-1}) compared to that in the Cont. (0.49 g pot^{-1}) (Table 2). Moreover, excluding the seedlings in the S4 treatments with dipping durations of 4 h and 8 h, the seedlings in other P-dipping treatments had a significantly greater biomass, despite having much lower P application rates than that in the $P_{inco.}$ (9.00 g pot^{-1}). Likewise, the shoot P uptake was significantly increased with P-dipping compared to with $P_{inco.}$ (6.69 mg pot^{-1}).

Different P concentrations in the slurry and different dipping durations significantly affected both the shoot biomass and the shoot P uptake (Table 2). There were no interactions between the two. A significantly higher shoot biomass was observed in the slurries with lower P concentrations (S1, S2, and S3) compared to that in the slurry from S4. There was no significant difference in the shoot biomass between the S1, S2, and S3 treatments. Although the seedlings in S1 had significantly lower shoot P concentrations than the seedlings in the other treatments, shoot P uptake was comparable with that in the seedlings in the other slurry treatments because of the high biomass production. Shoot P uptake was the lowest in the seedlings in S4 because it had the lowest biomass production. In the treatments with the short dipping durations of 0.5 h and 2 h, the seedlings tended to have a higher shoot biomass and higher shoot P uptakes the treatments with longer dipping durations. The plants in the treatment with the dipping duration of 4 h had the lowest shoot biomass and the lowest P uptake.

4. Discussion

Improved P fertilizer management is required for a sustainable increase in rice production while addressing the depletion of future P reserves. The pot experiment clearly demonstrated that initial biomass production can be greatly improved by dipping seedlings into a P-enriched slurry before transplanting, compared to an application with no P, or compared to a $P_{inco.}$ treatment. In the $P_{inco.}$ treatment in this study, the amounts of P applied were 167.4%–242.9% higher than in the P-dipping treatments (Table 2, Figure 1). This result is consistent with previous observations which observed that P-dipping produced greater shoot biomass [17] and root biomass [15] from a very early growth stage after transplanting and eventually resulted in greater rice yields than those in conventional P application via broadcasting. Therefore, P-dipping can be considered as a potential approach to improve both applied P use efficiency and the production of rice in transplanted lowland systems.

More importantly, the experiment detected that both the seedling P concentration/P uptakes and the initial shoot biomass/P uptakes after transplanting were significantly affected by the P-concentrations in the slurry and were also affected by the dipping durations (Table 2). The seedling's P concentration/P uptakes tended to increase with higher P concentrations in the slurry and longer dipping durations (up to 4 h), but the values were slightly reduced at 8 h. This result was consistent with Kalidas-Singh et al. [15], which found that the seedling P concentration/P uptake increased with increased doses of P in the slurry and with longer dipping durations, and reached the maximum at a dose of 125 mg P kg^{-1} soil and at a 12 h dipping, beyond which the values started to decrease. Based on these observations, they proposed the optimum P application dose of 125 mg kg^{-1} soil for slurry and optimum dipping duration of 10 h for the P-dipping technique, in order to maximize the seedling P concentration/P uptake. They argued that the additional P uptake in the seedlings might help develop robust root systems, explore more P in soils, and accelerate initial biomass growth after transplanting.

However, our results reveal that higher P uptake and higher P concentration in the seedlings under the P-dipping treatments did not necessarily lead to optimal biomass production after transplanting. There was rather an occurrence of rolling and drying leaves soon after transplanting, which was attributable to salt stress when seedlings were exposed to the highest P concentration in the slurry (S4) combined with the longer dipping durations (4 h and 8 h). These adverse effects, despite the higher P uptake in the seedlings, slowed the recovery of the seedlings from transplanting shock and made the advantage of P-dipping less significant. None of the previous studies reported chemical injuries of rice seedlings with the application of the P-dipping technique, except that of Lu et al. [11], who stated that it is necessary to avoid any injuries to seedlings when dipping plants into nutrient-rich slurry. Our study is the first to observe that recovery from transplanting shock can be slowed when the seedlings are dipped in a high P concentration slurry and left inside for a long time. In addition, the results of the different dipping duration treatments imply that the key effect of P-dipping is ascribed not to the development of P-enriched seedlings but to concentrated P transfer with seedlings in the rhizosphere at transplanting. It should be noted, however, that the P-dipping with the highest concentration in the slurry and the longer dipping durations still produced equivalent biomasses to those of $P_{inco.}$, with smaller P application rates.

The P-dipping with either lower P concentrations in the slurry or shorter durations were more advantageous to rice biomass. This finding is important as shorter dipping durations would make it more practical for smallholder farmers to apply this technique. Moreover, in order to avoid the potential salt stresses, P-dipping in 4.3%–5.0% P_2O_5 slurry for 0.5 h is the recommended practice to improve both P use efficiency and biomass production of transplanted rice. Our concomitant on-farm trial demonstrated significant increases in initial biomass production and grain yields, obtained by dipping the seedlings in approximately 5.0% P_2O_5 slurry for 0.5 h before transplanting, relative to those in seedlings under P broadcasting in highly P-deficient soils in Madagascar [17]. It should be noted that we used a single soil type with high P retention capacity (99%). Further studies are expected, using various soils to clarify any interaction between the P-dipping technique and soil types to be used for slurry and for rice cultivation.

5. Conclusions

Different P concentrations in the soil slurry and different dipping durations were investigated in order to find the appropriate P-dipping technique for transplanted rice. The results showed that the P-dipping technique promoted early growth of the transplanted rice. However, the slurry with the high P concentrations had a higher chance of seedling damage as a consequence of chemical injuries to rice seedlings during dipping, which is why it took these seedlings a longer time to recover from transplanting shock, affecting early rice growth. As longer dipping duration is not practical for farmers to follow and adopt, this study proved that a short dipping duration of 0.5 h is enough to enhance the early growth of rice. Our results indicated that low P concentrations in the slurry (4.3% P_2O_5) and short dipping durations of the seedling roots (0.5 h) are optimal for the P-dipping technique for transplanted rice.

Author Contributions: Conceived and designed the experiments: A.Z.O., Y.T., and N.M.R. Performed the experiment: A.Z.O. Analyzed the data: A.Z.O. and Y.T. Wrote the paper: A.Z.O. and Y.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors have declared that no competing interests exist.

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P-dipping of rice seedlings increases applied P use efficiency in high P-fixing soils

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Applied phosphorus (P) use efficiency is generally low due to the low mobility of P in soil and its affinity to form insoluble complexes. Localized P application nearby the root zone is a potential approach to overcome this issue in crop production. However, the interaction with soil conditions is little understood, which results in less effective application of this approach. Using root-box experiments and changing P-retention capacity of soils, we revealed that applied P use efficiency of rice can be substantially improved by dipping seedlings in P-enriched slurry at transplanting (P-dipping) even in highly P-fixing soils. Spatial analysis of soluble P in soils indicated that P-dipping creates a P hotspot because the P-enriched slurry is transferred with seedling roots. The P hotspot could have induced vigorous surface root and facilitated further P uptake from the spot. In contrast, the effect of conventional P incorporation depended on P-retention capacity of soils; no increases in soluble P content in soils or plant P uptakes were observed when P-retention capacity was high. Our finding of significant interaction between localized P application and a specific soil property should help improving applied P use efficiency and achieving sustainable rice production against depleting P fertilizer resources.

Availability of phosphorus (P) is generally low in crop production systems relative to other nutrients due to its immobile nature and affinity to form insoluble complexes with other minerals in soil. Fertilizer P added to soils is promptly fixed by active Al and Fe or poor crystalline aluminosilicates, ferrihydrite, and Al- and Fe-humus complexes[1]. Moreover, soil P retention capacity is particularly high in volcanic soils or Andosols with large amounts of active Al and Fe oxides and in highly weathered soils in the tropics, e.g., Oxisols, Alfisols, Ultisols[2]. Such soils with high P retention capacity have low applied P use efficiency, that is, low crop P uptake relative to the amount of P applied. Fixen et al. summarized that the typical range of apparent fertilizer recovery efficiency for cereal crop production (maize, rice, and wheat) is merely 15 to 25% for P, much lower than that for nitrogen (N) at 40 to 65%[3].

To overcome the low applied P use efficiency, large amounts of P have been continuously applied to obtain high grain yields in developed countries where crop and fiber productions largely rely on external mineral fertilizer inputs. For instance, the P application rate for lowland rice production in Japan averages from 52 to 105 kg P ha^{-1} depending on the soil type[4,5], while the P uptake by grain and straw were estimated at merely 18 kg P ha^{-1} (using the average grain yield of 6 t ha^{-1} and a harvest index of 0.5). However, continuous application of excess amounts of P fertilizer in agricultural systems causes environmental problems such as the eutrophication of lakes and marine estuaries[6]. Moreover, given the finite nature of rock phosphate, from which P fertilizers are produced, and its increasing cost, it is vital to investigate availability of P in soil and strategies to improve applied P use efficiency. Such strategies are also critical in low-input systems, such as in rice production on smallholder farms in Sub-Saharan Africa (SSA), where rice yield is primarily restricted by P-deficient soils and inadequate P fertilizer inputs[7–9].

Localized P application—the application of P fertilizer in the root zone, where P is readily accessible to the plants, instead of conventional broadcasting or incorporation—is one of the most studied options for improving applied P use efficiency[10,11]. A number of studies have demonstrated significant increases in grain yield and applied P use efficiency with localized P application for upland crops such as maize, pearl millet, sorghum,

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Parameters	Volcanic soil (VS)	Volcanic + sand (VS + Sand)	Red-yellow soil (YS)	Red-yellow soil + sand (YS + Sand)
pH (H_2O)	5.7	7.0	7.8	8.1
EC (mS m^{-1})	4.4	8.6	14.2	20.4
Total N (g kg^{-1})[a]	1.8	0.9	0.7	0.4
Total C (g kg^{-1})[a]	45.5	23.8	12.8	8.3
C:N ratio	26.0	25.5	19.4	21.6
P retention (%)[b]	99.0	91.0	23.0	7.0
$P_{oxalate}$ (mg kg^{-1})[c]	400.0	242.0	267.0	154.0
$Al_{oxalate}$ (g kg^{-1})[c]	46.1	22.6	1.5	0.9
$Fe_{oxalate}$ (g kg^{-1})[c]	25.7	13.4	3.6	2.2
Sand (%)[d]	83.4	–	41.2	–
Silt (%)[d]	10.5	–	23.7	–
Clay (%)[d]	6.1	–	35.1	–
Texture	Loamy sand	–	Clay loam	–

Table 1. Physicochemical properties of experimental soils. [a]NC analyzer, Sumigraph NC-220F (SCAS, Japan). [b]The proportion of absorbed P after shaking 5 g of soil with 25 ml of 1,000 ppm P solution for 24 h. [c]Inductively coupled plasma mass spectrometer (ICPE-9000, Shimazu, Japan) after oxalate extraction. [d]Sieving and pipetting method.

cowpea, and groundnut[12–16]. Positive effects of localized P application have been observed in direct-seeded upland and lowland rice production systems where small amounts of P are placed along with planting[17–19]. Root architectural responses of rice may also facilitate access to available P hot spots created by localized P application, and thus improve applied P use efficiency. For example, He et al. observed root architectural changes in upland rice, such as the formation of cluster-root-like fine roots and high root allocation to areas with high P concentrations, suggesting preferential root proliferation in P hot spots[20].

In transplanted rice production systems, small amounts of P application to the nursery bed is one conventional approach to increase P use efficiency. A key function of this technique is to develop vigorous seedlings and accelerate initial growth after transplanting which in turn improve grain yields or alleviate post-transplanting stresses such as flooding and salt stresses[21–23]. However, this technique has a risk of P mining from soils even when large yield gains are achieved because additional nutrients transferred to the main fields with "vigorous seedlings" are negligible while the large proportion of applied P is retained in the nursery bed. Alternatively, dipping rice seedlings into P-enriched slurry (P-dipping) is more direct and localized P application method by placing a certain amount of P with slurry attached to seedling roots at transplanting and has little risk of P-mining[24]. While there have been few studies on this P-dipping technique, institutional reports and newsletters have noted that P-dipping results in yield increases of 10–50% or equivalent yields with a 40–60% reduction in P application rates relative to P broadcasting or incorporation[25–27]. Our recent study on P-dipping found that it is an effective technique to improve both applied P use efficiency and rice yield in smallholder farms in Madagascar[24].

However, to date, little is known about how localized P application interacts with field conditions. This information is critical for farmer decision-making when it comes to this laborious technique. In particular, interactions with soil properties should be considered, such as soil available P concentration and P retention capacity.

Results from our recent field study imply that P-dipping might be more effective in soils with high P retention capacity[24]. Balasubramanian et al. also reported consistently higher yields with P-dipping relative to P-broadcasting in high P-fixing soils in the central highlands of Madagascar; however, no soil data were presented[28]. De Bauw et al. observed that P placement in the planting hole is more important when mobility of P is low, for example, in moist field conditions relative to irrigated fields[19]. Based on these preliminary results, we hypothesized that localized P application via P-dipping is more effective in high P-fixing soils or when soil P mobility is limited. This is because most of the broadcasted or incorporated P may become immobile and unavailable to plants in the high P-fixing soils, while a greater fraction of applied P may remain available in the root zone when P-dipping is used.

In the present study, a root-box experiment was conducted to compare biomass production and plant P uptake in rice as a response to three different P application methods—P-dipping (P_{dip}), P incorporation (P_{inco}), and no P (Ct)—with soils ranging in P retention capacity. Volcanic soil (VS) and red-yellow soil (YS) were used as typical high P-fixing soils, and the P retention capacities of both soils were artificially reduced by mixing them with granite sand (VS + Sand and YS + Sand). Then, additional experiments were conducted to identify the mechanisms contributing to the interaction between P application method and soil P retention capacity, that is, root architectural changes and spatial distributions of soluble P in soils.

Results

Interaction between P application method and soil P retention capacity on biomass production and plant P uptake (Experiment 1).

The physical and chemical properties of the experimental soils are summarized in Table 1. Briefly, the volcanic soil (VS) was a sandy loam with a pH of 5.7 and high concentrations of oxalate-extractable Al and Fe. The red-yellow soil (YS) was a clay loam with a pH of 7.8 and low concentrations of oxalate-extractable P (available P). The P retention capacities of VS and YS were 99 and 23%, respectively. By mixing with sand, their P retention capacities were reduced from 99 to 91% for VS and from 23 to 7% for YS.

The P_{dip} treatment substantially increased shoot biomass production relative to Ct from 0.22 to 8.52 g box^{-1} for VS, 0.17 to 5.07 g box^{-1} for VS + Sand, 0.22 to 4.30 g box^{-1} for YS, and 0.27 to 4.34 g box^{-1} for YS + Sand (Fig. 1a,c; Fig. S1). The effect of P_{dip} on shoot biomass was greater without sand incorporation for VS and equivalent between '+ Sand' and '− Sand' treatments for YS. Likewise, the shoot P uptake in P_{dip} was substantially increased by 8.09 mg box^{-1} for VS, 4.46 mg box^{-1} for VS + Sand, 5.87 mg box^{-1} for YS, and 5.78 mg box^{-1} for YS + Sand (Fig. 1e,g). The P_{dip} treatment achieved equivalent or greater increases in P uptakes even in the high P-fixing original soils without sand incorporation. Similar to shoot biomass, P_{dip} increased root biomass relative to Ct (Fig. 1i,k; Fig. S1).

On the other hand, shoot biomass and P uptake were not different between P_{inco} and Ct in the original soils, VS and YS, which is to say, P_{inco} had no effect on biomass production or shoot P uptakes under high P-fixing conditions (Fig. 1b,d,f,h; Fig. S1). However, P_{inco} significantly increased biomass production relative to Ct from 0.17 to 0.32 g box^{-1} for VS + Sand (Fig. 1b) and from 0.27 to 0.51 g box^{-1} for YS + Sand (Fig. 1d). Likewise, P_{inco} significantly increased shoot P uptake in soils with sand incorporation. These increases in shoot biomass and P uptakes in the '+ Sand' treatment was more pronounced for YS than VS, whose P-fixing capacity was less affected by sand incorporation. No significant interaction between P (Ct vs. P_{inco}) and sand treatments were observed for root biomass (Fig. 1j,l). The P_{inco} treatment slightly increased root biomass, even for the original soils of VS and YS; however, the effect was larger for soils mixed with sand.

Effect of P application on the spatial distribution of soluble P (Experiment 2).

Spatial analysis of soluble P in soils clearly showed hot spots of soluble P where P was locally applied to simulate P-dipping (Fig. 2). This spatial pattern was consistently observed for both VS and YS with and without sand incorporation. Conversely, no hot spots of soluble P were observed in either P_{inco} or Ct.

The average soluble P concentration across the entire root box was slightly higher in the original soils than those with sand incorporation. However, for all soils, the average soluble P concentration was higher in the P_{dip} treatment compared to P_{inco} and Ct. On the other hand, the average soluble P concentration did not differ significantly between the P_{inco} and Ct treatments, that is, P_{inco} did not increase soluble P in either VS or YS. The P_{inco} treatment increased average soluble P concentrations compared with Ct, when soil P-retention capacity was lowered by sand incorporation. As a result, the differences in average soluble P concentration between P_{dip} and $P_{inco.}$ were smaller with sand incorporation than in original soils.

Root architectural changes in responses to different P application method (Experiment 3).

Experiment 3 produced equivalent shoot biomass and shoot P uptakes between P_{dip} and P_{inco} by amplifying the P application rates of P_{inco} from 90 mg P_2O_5 box^{-1} to 300 mg P_2O_5 box^{-1} (Table 2). For this experiment, only the VS and VS + Sand soils were used. Because there was no significant interaction between P application treatment and sand incorporation for any measured variables, the "+ Sand" and "− Sand" treatments were combined and means are shown in Table 2. While shoot biomass was the same, P_{dip} had significantly greater root biomass than P_{inco}, and therefore had a higher root to shoot ratio (Table 2, Fig. S2). P_{dip} developed greater and wider nodal root systems than P_{inco}, with nodal root number increasing by 23%, nodal root length by 16%, and root cone angle by 7%. Likewise, secondary branching degree, basal lateral root density, and relative root allocation to the topsoil layer (0–3 cm) were significantly greater in P_{dip} than P_{inco}, by 26%, 37%, and 24%, respectively, indicating vigorous surface root development. The total root length in P_{dip} was greater than P_{inco} by 20%.

Discussion

The present study clearly demonstrated that P-dipping can achieve high applied P use efficiency in transplanted rice, even in high P-fixing soils, compared to conventional incorporation of P. In order to achieve similar plant biomass and P uptake with incorporation, 300 mg P_2O_5 box^{-1} was needed compared with only 90 mg P_2O_5 box^{-1} for P-dipping. These results demonstrate that P-dipping is a potential strategy to overcome low applied P use efficiency in high P-fixing soils, and hence reduce the need for excess P application.

The effect of P incorporation was improved by lowering P retention capacity of soils by sand incorporation. This result also supports there exists significant interaction between P application method and P retention capacity of soils. Previous studies have shown that localized P application is more effective in P-deficient soils and less P-mobile conditions in millet[14], lucerne[29] and rice[18,19,24,28]. However, the present study is the first to show a significant interaction between P application method and soil P retention on plant biomass and P uptake. This finding will help inform farmers about where they should apply this slightly laborious localized P application technique effectively. Nishigaki et al. identified large variations in the P retention capacity and the amounts of oxalate-extractable Al and Fe (active Al and Fe) in soils in the central highlands of Madagascar, even among nearby lowland fields[30]. Their results and our finding imply that returns from P fertilizer inputs can be further improved by selectively using the P-dipping technique in fields with high P retention capacities.

The interaction between P application method and soil P retention capacity on aboveground biomass and P uptake corresponded to the spatial distribution of soluble P in soils (Fig. 2). The hotspot of soluble P as a result of P-dipping is in accordance with the P diffusion model of De Bauw et al. in which they assumed that larger proportions of applied P remain soluble with localized P application because the binding sites around the application points get saturated[19]. In the same mechanism, the P-dipping could have developed the P hotspot near the root zone even under highly P-fixing soils. Previous field experiments also detected soluble P hotspots as a result of localized P fertilizer application compared to uniform P incorporation[31,32]. Akahane et al. reported that high amount of P was remained available up to harvest within a relatively small area of 2 cm (vertical) by 4 cm

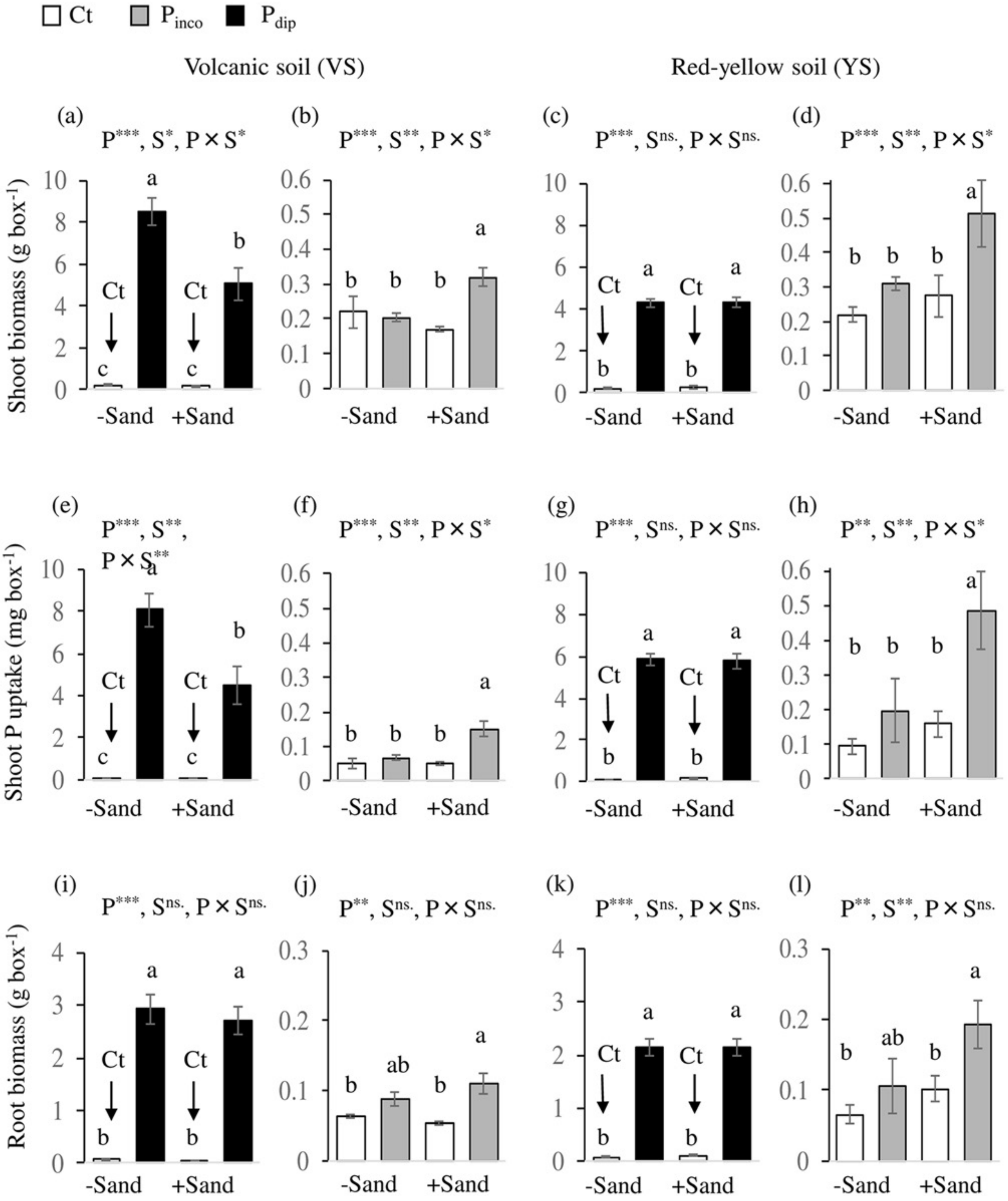

Figure 1. The effect of dipping seedlings in P slurry on shoot mass and shoot P content at 42 days after transplanting under different soil conditions (Experiment 1). Error bars indicate standard deviation. P_{dip}: P-dipping, P_{inco}: P incorporation, Ct: control. VS: Volcanic soil, YS: Red-yellow soil. (**a**), (**e**), (**i**): Ct vs. P_{dip} in VS. (**b**), (**f**), (**j**): Ct vs. P_{inco} in VS. (**c**), (**g**), (**k**): Ct vs. P_{dip} in YS. (**d**), (**h**), (**l**): Ct vs. P_{inco} in RS. *$p < 0.05$, **$p < 0.01$, ns: not significant at 5% level. P, S, and P × S indicate the effect of P treatment, sand incorporation, and their interaction, respectively.

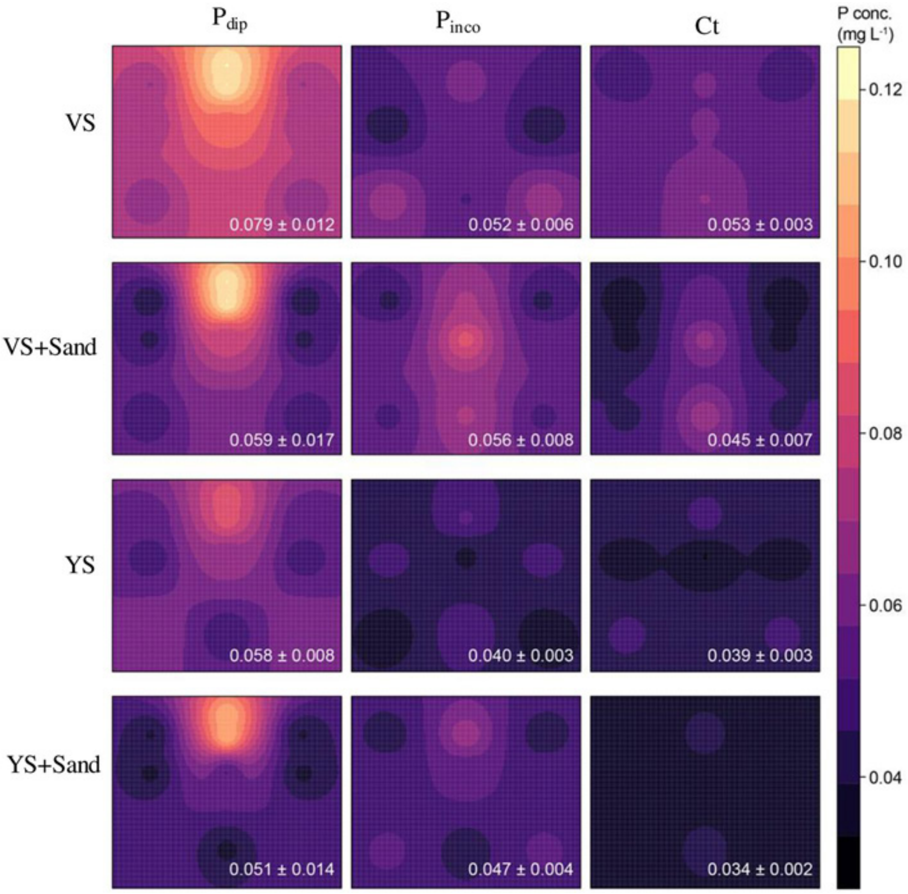

Figure 2. Spatial distribution of soluble P concentration in the soils of root boxes (Experiment 2). P_{dip}: P-dipping, P_{inco}: P incorporation, Ct: control. VS: Volcanic soil, YS: Red-yellow soil. The average (± standard deviation) soluble P concentration across the entire root box is given in white text.

	Shoot biomass (g box^{-1})	Shoot P uptake (mg P box^{-1})	Root biomass (g box^{-1})	Total root length (cm)	Nodal root length (cm)	Nodal root number	Basal lateral root density score	Secondary branching degree score	Root cone angle (°)	Relative root allocation to the topsoil layer
P_{dip}	1.8a	2.69a	0.64a	7208a	2796a	95.9a	7.1a	3.9a	160.8a	0.21a
P_{inco}	1.6a	2.73a	0.43b	6027b	2405b	77.8b	5.2b	3.1b	150.3b	0.17b
P	ns	ns	*	**	**	**	**	**	**	**
Sand (S)	ns	ns	*	**	**	**	**	**	**	ns
P × S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 2. Shoot and root architectural responses of rice to localized and conventional P application (Experiment 3). P_{dip}: P-dipping (90 mg P_2O_5 box^{-1}), P_{inco}: P incorporation (300 mg P_2O_5 box^{-1}). *$p < 0.05$, **$p < 0.01$, ns = not significant at 5% level. Different letters within a column indicate significant differences between treatments at $p < 0.05$ using Tukey's HSD test.

(horizontal) from the application spot as a result of localized P application in continuously flooded lowlands[32]. Therefore, with the P-dipping technique, the P hotspot nearby the root zone consistently supplied P for rice growth, which in turn developed vigorous root systems. Then, the vigorous root systems facilitated further P uptakes from the soils. This positive feedback loop could have caused large differences in biomass and P uptakes between the P dipping and P incorporation treatments.

Contrarily, in the case of uniform P incorporation, all the applied P was apparently fixed in the original soils, which could have severely restricted both initial P uptakes and root development. Increased amounts of soluble P in reduced P-fixing conditions explain the responses of rice to P_{inco} with and without sand incorporation. This is in agreement with the general understanding of why applied P use efficiency is low in high P-fixing soils[33,34].

The lower shoot P uptake and soil soluble P content with P-dipping in soil mixed with sand compared to original soil could be because (1) sand incorporation reduced soil fertility, not only of P but also of other minerals or (2) localized P was fixed of diffused away from the application point. According to De Bauw et al., changes in soil moisture from field capacity to saturated can enhance diffusion of locally applied P, resulting in lower soluble P within the root system[19].

Changes in root architecture in response to P deficiency is well documented in rice and other plant species[6,20,35–37]. Our finding in Experiment 3 are in accordance with previous studies, showing preferential root allocation to soluble P hot spots. P-dipping accelerated root development and, in particular, development of surface root systems relative to P incorporation. P-dipping resulted in wider root cone angles and increased lateral root density and secondary branching degree. The same root architectural responses to P_{dip}, i.e., wider in root cone angle and greater in lateral root density and secondary branching degree (root mass was substantially different between P_{dip} and P_{inco}, though), were also observed for both soils in Experiment 1 (Table S1).

Wider root cone angles are, theoretically, a strategic response of rice when exposed to P deficiency. They result in greater root growth in the top layer of soil where P generally accumulates[38,39]. However, there was previously little empirical evidence for this in regard to localized P application or in submerged soil. The root architectural changes induced by P-dipping might have facilitated plant P uptake from the P hot spots in the soil surface. However, dense rooting "patches" or cluster-root-like fine roots, which have previously been observed in P hot spots[20,40], were not present in our study. It should be noted that our experiment was conducted in small plastic boxes in which root development was spatially constrained. However, our observation of nonuniform distribution of soluble P in soils, preferential root architectural development, and aboveground plant responses are the first of its kind to explain the sequential mechanism of high P use efficiency of localized P application even in high P-fixing soils.

Further, the root morphological changes found in our study provide an opportunity to explore suitable varieties of rice that have ideal root systems for cultivation with localized P application. Specifically, applied P use efficiency may be further improved by combining P-dipping and shallow root varieties of rice. Recently, root architectural traits, such as steep root angle[41], deep rooting[42], and shallow rooting[43], have been genetically identified in rice and the use of such quantitative trait loci in breeding activities has progressed. For instance, using a near isogenic line (DRO1-NIL) with a functional allele of *DRO1* that confers deep rooting, Uga et al. demonstrated that cadmium (Cd) accumulation in rice can be significantly reduced by altering root architecture as bioavailable Cd is present in upper or oxidized soils layers in paddy fields[38]. The potential interaction between genotypic variation in root architecture and localized P application need to be further explored.

Conclusion

While localized P-application is a promising approach to overcome low applied P use efficiency in crop production, few studies have investigated the effect under different soil conditions. We demonstrated a significant interaction between P-dipping and soil P retention capacity, which was manipulated with sand incorporation, on the growth of rice. P-dipping substantially increased both plant biomass and P uptake irrespective of P retention capacity of soils, or even in the volcanic soil, which had very high P retention capacity. On the other hand, conventional incorporation of P into soil had little effect on soil soluble P, plant biomass, and P uptake of rice plants in high P-fixing soils. P incorporation had an effect on these factors only when the P retention capacity of the soil was reduced. Localized P placement indicated that P-dipping can create soluble P hot spots around the root system at transplanting, and plants with vigorous surface root systems, which might have facilitated P uptake from the P hot spots. These results not only provide evidence for a practical approach to overcome low P use efficiency in lowland rice production, but also provide information to help farmers select where to apply this slightly laborious technique depending on soil characteristics in order to maximize returns. Field experiments are required to confirm the interaction between P-dipping and P retention capacity of soils on rice yields.

Materials and methods

Soil and growing conditions.

Experiments 1, 2, and 3 were conducted in a greenhouse with an automatic ventilation system at the Japan International Research Center for Agricultural Science (JIRCAS), Tsukuba, Japan. The daily mean temperature in the greenhouse throughout the experiments ranged from 25.0 to 34.2 °C (Thermo Recorder TR-50U2, T&D Corporation, Nagano, Japan).

Two different soils with contrasting P retention capacities were collected from the forest sub-soil layer (20–40 cm). The soils were a volcanic soil (VS) from a typical Andosol area in the Kanto district, Japan, and a typical red-yellow soil (YS) from Ishigaki Island, a subtropical island in Japan[44]. The soils were air-dried and passed through a 2.0 mm sieve. The soils were partly mixed with decomposed granite (+ Sand) at a ratio of 1:1 (w/w) to artificially reduce their P retention capacities. This resulted in four different soil condition: (1) VS, (2) YS, (3) VS + Sand, and (4) YS + Sand. The soils were thoroughly puddled in a bucket by adding NH_4NO_3 and K_2SO_4 and were filled into root boxes. The dimensions of the boxes were 30 cm height × 30 cm length × 3 cm width. They had a transparent acrylic sheet on one side, and soil was added to the boxes to a depth of 28 cm. The application rates of N and K_2O were both adjusted to 220 mg box^{-1} by measuring the metric weight of each soil type in the boxes (2.52 L) after being puddled. The root boxes were put into 50-L containers with a height of 32 cm to maintain a consistent soil water level (4 cm water level) throughout the growing period and incubation for all the experiments.

Experiment 1.

Three P application methods—P-dipping (P_{dip}), P incorporation (P_{inco}), and no P application (Ct)—were factorially combined with the four soil conditions in a randomized complete block design with five replicates. For the P_{dip} treatment, a slurry with a P_2O_5 concentration of 4.3% (a mixture of 6.25 g triple super phosphate (TSP), 70 g air-dried soil, and 30 ml water) was prepared, in which seedling roots were dipped for 30 min before transplanting. The P concentration of the slurry and dipping duration were determined as optimal

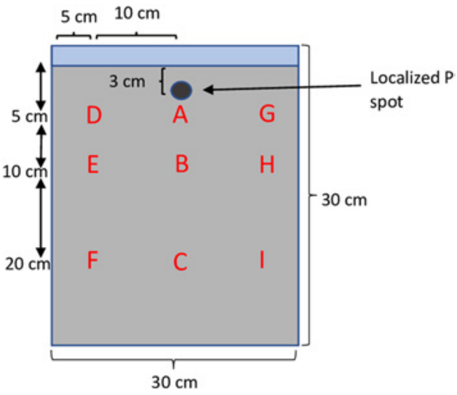

Figure 3. Schematic representation of a root box (30 cm × 30 cm × 3 cm) with soil water solution sampling points A to I. Soil solution samplers were installed in root boxes and soil water solutions were sampled at weekly intervals from the points A–F assuming that the horizontal distribution in the root box was symmetric.

and most efficient based on our previous study[45]. The study identified that the P-dipping in the slurry with a range of P_2O_5 concentrations from 4.3 to 6.0% had an equivalent effect on initial biomass and P uptakes of rice plants while the higher concentration at 7.5% had a risk of seedling damage because of chemical injuries to rice seedlings. With the 4.3% P_2O_5 slurry, the amount of P transferred at transplanting (slurry attached to seedling roots) was estimated at approximately 90 mg P_2O_5 box^{-1}. For the P_{inco} treatment, TSP was added with N and K at puddling at the same application rate of 90 mg P_2O_5 box^{-1}.

Then, 21-day old seedlings of cv. IR 64 (*Oryza sativa* L.) were transplanted with one seedling per box on July 25, 2019 and grown for 42 days after transplanting (DAT). At 42 DAT, plant shoots were removed at ground level and oven-dried at 70 °C for > 48 h to determine shoot dry weight. Shoot P concentration was measured with the molybdate blue method[46] after dry ashing at 550 °C for 2 h and digesting with 0.5 M HCl. Shoot P uptake (mg box^{-1}) was calculated by multiplying the P concentration by the dry weight. Root architectural parameters and root mass were determined in the same manner as detailed in Experiment 3.

Experiment 2. Additional complete sets of root boxes—factorial combinations of the four soil types and three P application methods with four replicates—were established beside Experiment 1 to repeatedly sample and analyze the P content in soil solutions under flooded and uncultivated conditions. Soil solution samplers attached to ceramic tubes were installed in six different positions in each root box; at 5 cm, 10 cm, and 20 cm depths both in the center (Position A, B, and C in Fig. 3) and at 5 cm from one side (Position D, E, and F in Fig. 3). Nutrients were applied in the same way as Experiment 1, except for the P_{dip} treatment in which 90 mg P_2O_5 was dissolved in 20 ml water and injected into the soil at a depth of 3 cm in the center of the root box using a 50-ml syringe to simulate the localized P application in the P-dipping treatment. All boxes were put in a large container and kept under flooded conditions for 42 days as with Experiment 1. Soil water samples were collected at 7, 14, 21, 28, 35, and 42 days after flooding using a 50-ml syringe.

Collected soil water samples were analyzed for soluble P concentration using the Malachite green method[47]. The average of four replicates at 7 and 14 days after flooding were used for the spatial analysis because the data varied considerably at the other sampling dates. The vertical spatial distribution of soluble P concentration was estimated by interpolating on nine positions (A–I in Fig. 3) with the inverse distance weighting (IDW) method using R software (ver. 3.6.2)[48]. The soluble P values for positions D–F were used for the positions G–I, assuming that the horizontal distribution in the root box was symmetric.

Experiment 3. Experiment 3 was conducted to assess the effect of P application method on root architecture under similar levels of shoot biomass and P content. The soil and nutrient preparations and rice cultivation were conducted in the same manner as in Experiment 1, with a few exceptions. The P_2O_5 application rate for P_{inco} was increased to 300 mg box^{-1}. For this experiment, only the VS and VS + Sand soils were used due to the shortage in available amounts of YS soils. The 21-day old seedlings of cv. IR 64 (*Oryza sativa* L.) were transplanted with one seedling per box on Sep 11, 2019. Shoots were sampled at 28 DAT and analyzed in the same manner as Experiment 1.

Root development was photographed using the pin-board method of Kano-Nakata et al.[49] with a slight modification. Briefly, roots were pinned with a 5 mm mesh net and pinboard after which soils were washed off and digital images were taken. Then, root samples were collected to determine various root architectural traits and dry matter. Relative root allocation to the topsoil layer (0 to 3 cm), and root cone angle—the angle between the two most external left and right nodal roots to the vertical axis[50]—were determined using the digital images of root development and ImageJ (Version 1.52a, NIH, USA). The relative root allocation to the topsoil layer was calculated in the following equation;

$$\text{Relative root allocation to the topsoil layer} = \frac{\text{Fractional root coverage in the topsoil layer (\%)} \times \text{Area of topsoil layer}(3\,\text{cm} \times 30\,\text{cm})}{\text{Fractional root coverage of the whole box}(\%) \times \text{Area of whole box}(30\,\text{cm} \times 30\,\text{cm})}$$

Here, the fractional root coverage in the topsoil layer was estimated by the following procedure using ImageJ software; (1) The topsoil layer (3 cm in depth by 30 cm in length) was selected from the digital image of root development; (2) The root pixel in the selected area was extracted by adjusting the brightness of the Color Threshold command; (3) The fractional root coverage was calculated as the number of root pixels divided by the total number of pixels in the selected area using the Analyze Particles command.

The number of nodal roots were manually counted. Nodal root thickness score, basal lateral root density, and secondary branching degree were determined following De Bauw et al.[51]. Basal lateral root density—the spacing of lateral S-type branches[52] at the nodal root base (from stubble up to 15 cm depth)—was scored using the shovelomics scoreboard (scores from 1 to 9 represent very sparse to highly dense lateral roots). The secondary branching degree—the degree of higher order root branching on L-type roots[52] evaluated over the whole root system—was scored visually (scores from 1 to 5 represent very low (almost no branching) to very high branching). Nodal root length (cm box^{-1}) and lateral root length (cm box^{-1}) were determined based on root diameters using WinRhizo Pro (Regent Instrument, Quebec, Canada). Root diameters > 2 mm were discarded, as this is larger than the nodal root size, roots with a diameter < 0.2 mm were considered lateral roots[53], and roots with a diameter between 0.2 and 2 mm were considered nodal roots.

Statistical analysis. The data from Experiment 1 were analyzed using two-way analyses of variance (ANOVAs) to assess the single and interaction effects of P treatment (P_{dip} vs. Ct and $P_{inco.}$ vs. Ct) and sand incorporation treatment (− Sand vs. + Sand) for each soil type on the measured variables using XLSTAT 2019 (Addinsoft SAS). The replicates were treated as a random factor. The treatment means were compared at 5% level of probability using Tukey's HSD test. Likewise, the data from Experiment 3 were analyzed using two-way ANOVAs to assess the single and interaction effects of P treatment (P_{dip} vs. P_{inco}) and sand incorporation treatment (− Sand vs. + Sand).

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Author contributions

Conceived and designed the experiments: A.Z.O., Y.T., T.N. Performed the experiment: A.Z.O., N.M.R. Analyzed the data: A.Z.O., Y.T., K.K. Wrote the paper A.Z.O., Y.T. All authors read and approved the final manuscript.

Competing interests

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Additional information

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Dipping rice seedlings in P-enriched slurry increases grain yield and shortens days to heading on P-deficient lowlands in the central highlands of Madagascar

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ABSTRACT

Phosphorus (P) deficiency is a major yield constraint for lowland rice production on highly weathered soil in Sub-Saharan Africa. To overcome this constraint, we examined the effect of dipping seedling roots into a P-enriched slurry before transplanting (P-dipping) on yield and P use efficiency in the typical P-deficient lowlands in the central highlands of Madagascar. Experiment 1 was conducted at a high-elevation site (Site1) and consisted of three levels of P treatments, *0 P* (no P applied), *60BP* (60 kg ha^{-1} of P_2O_5 broadcasted), and *30DP* (30 kg ha^{-1} of P_2O_5 applied via P dipping), combined with two levels of N treatments, *−N* (no N applied) and *+N* (total of 60 kg ha^{-1} applied). Experiment 2 was conducted continuously at Site1 and additionally at middle-elevation site (Site 2) following the same design but adding the *30BP* treatment (30 kg ha^{-1} of P_2O_5 broadcasted). The *30DP* treatment significantly and consistently accelerated initial biomass production with high crop growth rate (CGR) and shortened days to heading by 14 days compared to *0 P* and by 6 to 9 days compared to *30BP* and *60BP*. The *30DP* treatment increased grain yields by 59–171% relative to *0 P* and, more importantly, by 9–35% relative to *30BP* and *60BP*, with a significant site × P-treatment interaction. The effect of P-dipping was consistent between the N treatments. The effect of P-dipping was particularly significant at a high-elevation and cool climate site (Site 1), which was partly attributable to the improved grain fertility by avoiding cold stresses at the reproductive stage. Furthermore, P-dipping achieved remarkably high agronomic P use efficiency (increase in grain yield per kilogram of P applied): 85–198 kg kg^{-1} across the sites. A set of on-farm trials revealed that P-dipping can increase both grain yields and P use efficiency, even with shorter growth durations, than equivalent or doubled P application rates via broadcasting. Because lowland rice production in Sub-Saharan Africa is widely subjected to environmental stresses and to highly P-deficient soils, P-dipping could be an efficient P fertilization technique for resource-limited farmers in the region. Further participatory farmers' trials are expected to assess the farmers' appreciation and potential constraints for adopting this technique.

1. Introduction

Rice is the most rapidly increasing food commodity in terms of both production and consumption in Sub-Saharan Africa (SSA). However, the average rice yield in SSA is only around 2.1 t ha^{-1} (USDA, 2018), which is far below the potential yield of rice in the region (Global Yield Gap Atlas, available at http://www.yieldgap.org/home) and below the average of major rice-producing areas of the world. P deficiency is one of the main constraints for rice production (Saito et al., 2019; Tanaka et al., 2015; Vandamme et al., 2016). P deficiency in SSA is related to the highly weathered soils in the tropics, which are low in bioavailable P contents and high in P-sorption capacity related to their acidity and richness in Fe and Al oxides (Batjes, 2012; Bekunda et al., 2010; Nishigaki et al., 2019). Inadequate P application due to limited purchasing capacity of smallholder farmers is another key issue associated with P deficiency in SSA. Nziguheba et al. (2016) noted that fertilizer input in general is low in SSA, and P fertilizer application is even lower than in other regions of the developing world. Currently, the use of

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Abbreviations: AE_P, Agronomic P use efficiency; CDD, Cooling-degree days; CGR, Crop growth rate; DAT, days after transplanting; GDD, Growing-degree days; RGW, a rough grain weight; SSA, Sub-Saharan Africa

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mineral P_2O_5, which was estimated by dividing total mineral P_2O_5 consumption by total arable land area, was merely 3.8 kg ha^{-1} in SSA, whereas the value was 36.2 kg ha^{-1} in Southeast Asia (FAOSTAT, accessed at http://www.fao.org/faostat/en/ on 26 Aug 2019).

Under such soil and capital constraints for smallholder farmers in SSA, it is imperative to find effective P fertilizer management practices for crop production that will achieve higher yield increases per unit of P fertilizer applied. As summarized by Vandamme et al. (2016), one practical approach to increase P fertilizer use efficiency for resource-limited smallholder farmers in SSA is micro-dose and localized P application. The most widely studied options in this regard are placing small amounts of P fertilizer with seeds at planting and in a band close to the planting area instead of broadcasting. These approaches facilitate plants accessing P, which is relatively immobile in soil as compared to N, and boost root and shoot development at the initial growth stages (Aune and Bationo, 2008; De Bauw et al., 2019a; Valluru et al., 2010). Previous field experiments demonstrated significant increases in grain yields and/or applied P use efficiencies with these micro-dose and localized P application techniques for upland crops such as maize, millet, sorghum, and pearl millet in typical P-deficient soils in SSA (Aune and Bationo, 2008; Aune and Ousman, 2011; Blessing et al., 2017; Buerkert et al., 2001; van der Eijk et al., 2006). Likewise, recent field experiments have shown that micro-dosing P into planting holes at seed dibbling boosted early vigor and grain yield of direct-seeded rice under both upland and lowland conditions in SSA (De Bauw et al., 2019b; Vandamme et al., 2018).

However, research is limited regarding the micro-dose and localized P application approaches for the transplanted rice cultivation system, the dominant rice establishment method for irrigated lowlands in West Africa (Niang et al., 2017) and both irrigated and rainfed lowlands in Tanzania and Madagascar, which are the two major rice-producing countries in East Africa (Minten et al., 2004; Nakano and Kajisa, 2014). One approach is to apply small amounts of P fertilizer to the nursery beds. This technique is to develop vigorous and P-enriched seedlings which has an advantage in the initial root development after transplanting and subsequent grain yield by expecting a positive feedback loop between root development and more exploration of P in soils under P-deficiency (e.g., Vandamme et al., 2016). However, as Vandamme et al. (2016) argued, the technique has an issue of P-mining from soils because the amount of P transferred to the main field with P-enriched seedlings are negligible relative to the amount of extra P removed with increased grain yields. Instead, a large portion of applied P is not used and remained in the nursery bed. Soaking rice seedling roots into P solution for a certain period is a similar approach to develop P-enriched seedlings (Fukuda et al., 2012; Watanabe et al., 2007) while these studies reported significant effects only at the initial growth stage. This is understandable because the amount of P transferred to the main field with P-enriched seedlings is negligible.

P-dipping or dipping rice seedling roots in a P-enriched soil slurry is an approach to enable direct and localized P application in the main field for transplanted rice cultivation. Our recent study indicated that the key aspect of this P-dipping technique is to place a certain amount of P in the main field with the slurry attached to seedling roots, which in turn assures the P supply after transplanting and avoid the P-mining risk (Oo et al., 2020). This technique has been conventionally examined in lowland rice production systems in India (Raju et al., 1980; Ramanathan and Kothandaraman, 1984; De Datta et al., 1990) and in Madagascar (Balasubramanian et al., 1994). Lu et al. (1982) noted that P-dipping was a traditional method used by rice farmers in China. Although a few conventional studies reported little or negative effects of P-dipping (Saggar et al., 1985; Sahu, 1987), many other studies noted significant yield increases by 10–50% with the same application rates or the same yield levels with 40–60% reductions in P application rates relative to broadcasting or incorporating P at transplanting (Raju et al., 1980; Ramanathan and Kothandaraman, 1984; Balasubramanian et al., 1994; De Datta et al., 1990).

The significant effects of P-dipping should attract further attention as a potential solution for resource-limited and P-deficient lowland rice production systems in SSA. However, most of these studies were reported in institutional documents/newsletters or partially cited in book chapters that provided little information on the treatments (e.g., durations of dipping and P concentrations in enriched slurry), field environments (e.g., soil chemical properties, cropping histories, weather conditions), and methodologies (e.g., statistics, yield measurement procedures). Moreover, lack of a mechanistic understanding of how and under what environments P-dipping is most effective might hinder farmers from adopting this technique.

Therefore, the objectives of our study are (1) to reconfirm the effect of P-dipping in typical P-deficient fields in SSA and (2) to fill the gap between empirical observations and scientific understanding of this technique. Specifically, we examined how P-dipping treatment affected biomass production, phenology development, grain yields, and yield components of rice under different climatic conditions in typical P-deficient fields in the central highlands of Madagascar to clarify the mechanism of P-dipping and its interaction with field environments.

2. Materials and Methods

2.1. Site description

On-farm trials were conducted in the region of Vakinankaratra in the central highlands of Madagascar in the wet seasons of 2017–2018 (Experiment 1) and 2018–2019 (Experiment 2). The region is a major rice-producing area of the country, where smallholder farmers grow rice in lowlands mostly once a year in the warm/wet season (November–May). Rice production in the region is characterized—as is the case of the whole country—by limited yields below 3 t ha^{-1}, on average, with little mineral fertilizer input (Tsujimoto et al., 2019) and low total and available P in soils (Nishigaki et al., 2019). The regional rice production is often exposed to low temperature stresses at late growth stages particularly in high elevation sites and when transplanting is delayed (Dingkuhn et al., 2015; Raboin et al., 2014). The rice cultivation in the region is little mechanized, and relatively small-sized and bunded fields (mostly less than 0.05 ha per field) are managed by hand for ploughing, puddling, transplanting, weeding, and harvesting. Our experiments were conducted at representative fields in the region where farmers continuously cultivated rice once a year without crop rotation and with no mineral fertilizer inputs for at least 10 years prior to the start of the experiments.

2.2. Experimental design

Experiment 1 was conducted at the commune of Ambohibary (19°37′36″S, 47°8′44″E; 1651 m a.s.l.; Site 1) under cool and wet climatic conditions. The field was clay loam and flooded annually. The surface soil (0–15 cm) had a pH of 6.3 and relatively high contents of both total N and C (Table 1). The soil had high P-retention capacity, as associated with large amounts of oxalate-extractable Al and Fe. In the following wet season of 2018–2019, the Experiment 2 was conducted continuously at Site 1 and additionally at the commune of Ankazomiriotra (19°39′14″S, 46°32′58″E; 1119 m a.s.l.; Site 2) to confirm the effect of P-dipping treatment and its interaction with field environments. Within the same field, the plot allocation for Site 1 was slightly shifted from the place used in the previous season to avoid any residual effects. Because the Site 2 was located at a lower elevation than Site 1, it experienced warmer and drier climatic conditions. Soil at Site 2 was sandy clay loam and dried during the off season. The surface soil had a pH of 5.4 and lower contents of both total N and C than Site 1. Site 2 had a relatively low P-fixation capacity with low amounts of oxalate-extractable Al and Fe (Table 1).

The most common rice variety in the region, X265, was consistently used at all the sites. In the Experiment 1, 25-day-old-seedlings were

Table 1
Soil properties (0-15 cm) of the experimental sites.

Parameter	Unit	Site1	Site2
Clay[a]	%	29.2	30.4
Silt[a]	%	32.5	12.9
Sand[a]	%	38.3	56.8
pH (1:2.5 H_2O)	-	6.3	5.4
Total N[b]	g kg^{-1}	6.8	1.2
Total C[b]	g kg^{-1}	89.1	13.0
Oxalate-Al[c]	g kg^{-1}	14.7	0.9
Oxalate-Fe[c]	g kg^{-1}	5.8	3.5
Oxalate-P[c]	mg kg^{-1}	1551.4	201.6
P-retention capacity[d]	%	93.8	3.9
mineralizable N[e]	mg kg^{-1}	154.4	56.2
Exchangeable Ca[f]	c mol kg^{-1}	2.33	1.61
Exchangeable K[f]	c mol kg^{-1}	0.04	0.04
Exchangeable Mg[f]	c mol kg^{-1}	0.70	1.13
Exchangeable Na[f]	c mol kg^{-1}	0.07	0.03

[a] sieving and pipetting method.
[b] NC analyzer, Sumigraph NC-220 F (SCAS, Japan).
[c] Inductively coupled plasma mass spectrometer (ICPE-9000, Shimazu, Japan) after oxalate extraction (Courchesne and Turmel, 2008).
[d] The proportion of absorbed P amounts after shaking 5 g of soil and 25 ml of 1000 ppm P solution for 24 hours (Soil Survey Staff, 2014).
[e] Ammonium-N extracted with 10%KCl after 4-week anaerobic incubation at 30 °C.
[f] Ammonium acetate extract method at pH 7.0.

transplanted with two seedlings per hill at a planting density of 25 hills m^{-2} (0.20 m × 0.20 m) on 6 December 2017. In the Experiment 2, 30-day-old seedlings were transplanted at the same planting density on 13 November 2018 at Site 1 and on 18 December 2018 at Site 2. Weeds were controlled by hand throughout the growing periods. The fields were consistently flooded from transplanting to maturity. No marked damage from pests or disease was observed at any sites.

A split-plot factorial design was applied with three replicates. In the Experiment 1, the main plot consisted of three levels of P treatments: *0 P* (no P applied), *60BP* (60 kg ha^{-1} of P_2O_5 was broadcast at transplanting), and *30DP* (30 kg ha^{-1} of P_2O_5 was applied through dipping of seedling roots at transplanting). In the Experiment 2, the main plot consisted of four levels of P treatments by adding *30BP* treatment (30 kg ha^{-1} of P_2O_5 was broadcast at transplanting) to compare the effect of P-broadcasting and P-dipping at the same P application rate. The subplot consisted of two levels of N treatments: $-N$ (no N applied) and $+N$ (a total of 60 kg ha^{-1} of N was uniformly top-dressed in equal splits at 30 days after transplanting [DAT] and 60 DAT). The sizes of subplot were 12 m^2 (3 m × 4 m) for Experiment 1 and 6 m^2 (3 m × 4 m) for Experiment 2. Commercially available triple superphosphate and ammonium sulphate were used as the sources of P and N fertilizers, respectively. Apart from the treatments, no organic or inorganic fertilizer were applied at any sites.

In the *30DP* treatment, soil–water slurry was prepared by mixing 500 g of saturated soil from the experimental field and 200 ml of irrigation water in a 1.5-L plastic bucket for each replicate. For a 12-m^2 plot in the Experiment 1, 78 g of triple superphosphate (equivalent to 30 kg ha^{-1} of P_2O_5) was added to the slurry and 600 seedlings were dipped in the plastic bucket for 30 min just before transplanting. Then, seedlings with a certain volume of slurry attached to the surface of the roots were transplanted.

At maturity, grain yields (t ha^{-1}) were determined by harvesting plants from an area of 4 m^2 (Experiment 1) or 2.64 m^2 (Experiment 2) in the center of each plot. Grain yield is expressed based on filled grain weight, corrected to 14% moisture content by using a grain moisture sensor (Riceter f, Kett Electric Laboratory, Tokyo, Japan). Then, 12 average-sized hills for Experiment 1 and 8 average-sized hills for Experiment 2 were cut separately at the ground level to determine aboveground biomass and yield components. The aboveground biomass is expressed on a dry matter basis by oven-drying at 70 °C for more than 72 h. The filled grain rate (%) and spikelet sterility (%) were determined by counting the number of submerged spikelets and floating spikelets in distilled water and then in 70% ethanol, respectively, using the procedure described by Kobata et al. (2010). Additionally, changes in aboveground biomass were determined in the Experiment 2 by cutting 8 average-sized hills at 22 DAT, 56 DAT, and heading at Site 1 and at 37 DAT, 63 DAT, and heading at Site 2. The heading dates were estimated by frequent visual observations to determine when 50% of plants had headed within each plot. Crop growth rate (CGR, g m^{-2} day^{-1}) was calculated by dividing the changes in aboveground biomass by the number of days between two adjacent sampling periods.

The agronomic efficiency of P fertilizer (AE_P, kg kg^{-1}), defined as increase in grain yield per kilogram of applied P, was calculated by using the following formula:

$$AE_P = \frac{Y_P - Y_{cont}}{P_{applied}} \tag{1}$$

where Y_p and Y_{cont} indicate the grain yields in the P-applied plots and non-P-applied plots, respectively. $P_{applied}$ refers to the amounts of elemental P applied in the P-applied plots: 13.1 kg ha^{-1} in *30BP* and *30DP* and 26.2 kg ha^{-1} in *60BP*.

2.3. Weather data analysis

The ambient temperature, solar radiation, and precipitation during the experiments were collected from the AfricaRice Weather Data (available at http://www.mlaxmel.com/weatherdata/index.php) whose weather station (WS-GP 1, Delta-T Devices Ltd., Cambridge, UK) was set within 100 m radius of Site 1 and by Watchdog 1525 micro station (Spectrum Technologies Inc., Plainfield, IL, USA) at Site 2.

In Experiment 2, growing degree-day (GDD, °C days) from transplanting to heading was calculated by the following formula to compare the differences in phenology development among treatments and sites:

$$GDD = \sum \left\{ \frac{T_{max} + T_{min}}{2} - 10 \right\} \tag{2}$$

in which T_{max} and T_{min} are daily maximum and minimum temperature (°C), respectively, and 10 is an assumed basal air temperature (°C) for rice development (Dingkuhn and Miezan, 1995). In Experiment 1, we estimated the heading dates by assuming that GDD from transplanting to heading ($GDD_{TP\text{-}H}$) for each treatment were the same as those observed at the same site in Experiment 2. The estimated heading dates corresponded to those recorded in several plots with less frequent observations in Experiment 1.

By using these observed and estimated heading dates, we applied the simple cooling degree days (CDD) model based on the CDD concept (Uchijima, 1976) to assess the duration and magnitude of the cold temperatures experienced by rice plants by the following formulas:

$$CDD = \sum CD \tag{3}$$

$$CD = 22 - T_{mean}\ (T_{mean} < 22\,^{\circ}C) \tag{4}$$

$$CD = 0\ (T_{mean} \geq 22\,^{\circ}C) \tag{5}$$

in which T_{mean} is daily mean temperature and 22 is an assumed critical temperature below which rice plants are exposed to cold-induced stresses (Horie et al., 1995). We calculated CDD by accumulating CD from 15 days before heading to 7 days after heading, which should have covered from the micropore stage to the early ripening stage, the period which is the most sensitive to cold stress and relevant to grain fertility of rice (Horie et al., 1995). The degree of grain fertility was assessed by two parameters: (1) rough grain weight (mg; RGW) as the product of "filled grain weight" and "filled grain rate" or the grain weight averaged across filled and non-filled grains (Yoshida and Hara, 1977) and (2) spikelet sterility (%).

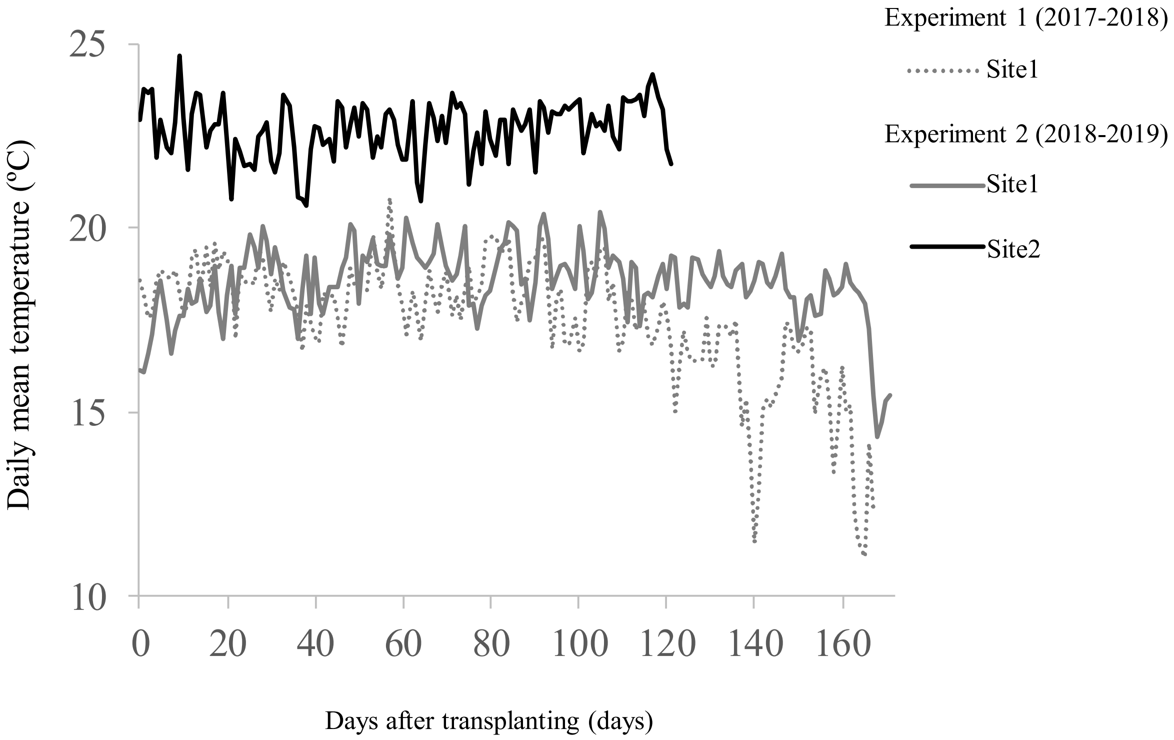

Fig. 1. Changes in daily mean air temperature from transplanting (T) to harvest of the latest matured plot in each experimental site.

2.4. Statistics

Data were subjected to the methods described for the split-plot arrangement. ANOVA was performed to identify the individual and interaction effects of P treatments and N treatments on the measured variables. The replicates were treated as a random factor within each site. Means between treatments were compared with the Tukey's HSD (honestly significant difference) test ($P < 0.05$) using R Studio software (version 1.2.1335).

3. Results

3.1. Weather conditions

The daily mean temperatures from transplanting to harvest of the latest maturing plot are shown in Fig. 1. Site 1 had a decreasing trend in temperature down to < 15 °C at the later growth stages in both seasons. This decreasing trend was particularly sharp in Experiment 1 (2017–2018), which was due to the transplanting date being 23 days later in Experiment 1 than in Experiment 2. Additionally, the season of Experiment 1 had the lowest mean temperature on average from Mar to Apr—the typical period of the reproductive stage at the site—at 17.2 °C relative to 18.4 °C in 2016, 17.6 °C in 2017, and 18.3 °C in 2019. Site 2 had a relatively constant mean temperature between 20 and 25 °C throughout the growing period. The average solar radiation in the same period was 19.7 MJ m^{-2} day^{-1} in 2017–2018 and 20.8 MJ m^{-2} day^{-1} in 2018–2019 at Site 1 and 22.4 MJ m^{-2} day^{-1} at Site 2. The total precipitation in the same period was 1033 mm in 2017–2018 and 1242 mm in 2018–2019 at Site 1 and 852 mm at Site 2.

3.2. Phenology development

Table 2 summarizes the days to heading in the means of P treatments and N treatments for each site in Experiment 2. There was no interaction among P treatment, N treatment, and site (data not shown). P treatment consistently had large effects on the phenology development across sites. The *30DP* treatment had significantly shorter days to heading (by 14 days) than those of *0 P* at both Site1 and Site2. Moreover, the *30DP* treatment had significantly shorter days to heading (by 6–9 days at Site1 and 7–9 days at Site2) even when compared to the *30BP* and *60BP* treatments. The effect of N treatment on phenology development was not significant at Site 1, whereas N application significantly shortened days to heading (by 6 days) at Site 2. On average, plants at Site 2 reached heading 20 days earlier than those at Site 1 in response to its warmer temperature.

Table 2
Growth duration (days) from transplanting (T) to heading (H) as affected by P and N fertilizer treatments in Experiment 2 (2018–2019).

	Duration from T to H (days)	
	Site1	Site2
0 P	112^{a}	92^{a}
30BP	107^{ab}	85^{ab}
60BP	104^{b}	87^{b}
30DP	98^{c}	78^{c}
−N	105^{a}	89^{a}
+N	105^{a}	83^{b}

Within each column, values with different alphabets indicate significant differences among the treatments at 5% of Tukey's HST test.

3.3. Grain yields and AE_P

Grain yields in Experiment 1 were relatively low across the treatments, ranging from 0.53 t ha^{-1} in the *0 P + N* treatment to 1.81 t ha^{-1} in the *30DP-N* treatment, which was attributable to severe cold-induced sterility and cold stresses at the ripening stage. The effect of P treatment was significant, but there was no effect of N treatment or interaction between P and N treatments (Table 3). The *30DP* treatment significantly increased grain yield by 167% (1.11 t ha^{-1}) relative to the *0 P* treatment and by 17% (0.25 t ha^{-1}) relative to the *60BP* treatment (Table 4). There was no significant difference in mean grain yield

Table 3
Levels of significance in F statistics for the effect and interaction of P treatment, N treatment, and Site on measured variables.

Exp	Source	Grain yield (t ha^{-1})	AE_P (kg kg^{-1})	RGW (mg)	Spikelet sterility (%)	CDD (ºC days)
Experiment1	P	***	*	***	***	-
	N	ns.	ns.	*	*	-
	P × N	ns.	ns.	ns.	ns.	-
Experiment2	Site	***	ns.	ns.	ns.	***
	P	***	***	*	ns.	***
	N	***	ns.	ns.	ns.	ns.
	Site × P	***	**	ns.	ns.	***
	Site × N	**	***	ns.	ns.	ns.
	P × N	ns.	ns.	ns.	ns.	ns.
	Site × P × N	ns.	ns.	ns.	ns.	ns.

ns. not significant, *$P < 5\%$, **$P < 1\%$, ***$P < 0.1\%$.

between +*N* and –*N* treatments.

In Experiment 2, grain yields among different P and N treatments ranged from 1.94 to 5.02 t ha^{-1} at Site 1 and from 1.28 to 3.64 t ha^{-1} at Site 2. At both sites, the *30DP + N* treatment had the highest grain yield. There was no interaction between N treatment and P treatment at any site, whereas the N treatment × site and P treatment × site interactions both had significant effects on grain yield (Table 3). At Site 1, the *30DP* treatment had significantly higher yield by 81% (2.60 t ha^{-1}) compared to that of the *0 P* treatment and by 26–36% (0.97–1.20 t ha^{-1}) than those of the two BP treatments (Table 4). At Site 2, P application (i.e., *30DP*, *30BP*, and *60BP*) significantly increased the grain yield by 45–59% (0.88–1.16 t ha^{-1}) relative to *0 P*. The *30DP* treatment had slightly higher yield by 9% than the average of two BP treatments at the level of $P = 0.07$ while the yield difference among the P application methods were much smaller in Site2 than in Site1. No significant differences were detected in grain yields between the *30BP* and *60BP* treatments at either site. N application slightly increased the yields by 13% (0.43 t ha^{-1}) on average at Site 1 and greatly increased the yields by 45% (1.00 t ha^{-1}) on average at Site 2.

Corresponding to the yield responses, AE_P was greatly improved with the *30DP* treatment. The AE_P in the *30DP* treatment was 84.7 kg kg^{-1} in Experiment 1 and 198.1 kg kg^{-1} at Site 1 and 88.3 kg kg^{-1} and Site 2 in Experiment 2 (Table 4). The *30DP* treatment showed significantly higher AE_P than that of the *60BP* treatment in Experiment 1 and the *30BP* treatment at Site 1 in Experiment 2.

3.4. Effect of P-dipping on changes in aboveground biomass and crop growth rate

Changes in aboveground biomass as affected by P treatments were shown in the means of N treatments because there was no interaction between two. The *30DP* treatment had substantially greater biomass production relative to the two BP treatments and to the *0 P* treatment from the very early growth stage across the sites (Fig. 2). The aboveground biomass in the *30DP* treatment was significantly greater than that of the BP treatments by 91–102% at 22 DAT and 106–147% at 55 DAT at Site 1 and by 66–67% at 37 DAT and 36–39% at 63 DAT at Site 2. The rapid initial growth with the *30DP* treatment resulted in the plants' high CGR (Table 5).

The CGR with the *30DP* treatment tended to be continuously greater than those of the two BP and *0 P* treatments from transplanting to heading. However, the differences in aboveground biomass between the *30DP* and two BP treatments became less pronounced or not significant at heading. This was largely because of the prolonged days to heading in the BP treatments (6–9 days at Site 1 and 7–9 days at Site 2), as described in section 3.2. These extra days to heading provided additional biomass growth to plants in the BP treatments, particularly at Site 2 due to its higher CGR than at Site 1. Maximum biomass production was estimated at 115.4 g m^{-2} in the *60BP* treatment at Site 2, by multiplying the gain in days to heading (9 days) by the CGR during the period (12.82 g m^{-2} day^{-1}). The CGR did not differ between the *30DP* and two BP treatments during the maturity period, whereas the CGR at maturity was greatly reduced in the *0 P* treatment at both sites. The effect of N treatment on CGR was particularly large and significant at the pre-heading stage at both sites: the + N treatment increased the CGR by 37% at Site 1 and by 96% at Site 2.

3.5. Degree of cold stress and grain fertility

Corresponding to the changes in days to heading and weather conditions at each site, P treatment significantly affected CDD during the period from 15 days before heading to 7 days after heading (Table 3). The CDD values were lowest in the order of the *30DP* treatment, two BP treatments, and *0 P* treatment: 71.8, 73.9, and 77.1 °C days, respectively, in 2018–2019 and 93.1, 97.3, and 103.0 °C days in 2017–2018 at Site 1 (data not shown). Under the relatively warm climatic condition of Site 2, CDD values were < 1 °C days irrespective of the treatment.

These site × treatment differences in CDD had a strong correlation with RGW. The RGW values were relatively high across the treatments at Site 2. The values decreased from 22.6 mg in the *30DP + N* treatment in 2018–2019 to merely 3.3 mg in the *0 P + N* treatment in 2017–2018 at Site 1 as the CDD increased from 69.7 to 104.3 °C days (Fig. 3A). Likewise, spikelet sterility tended to increase as the CDD increased (Fig. 3B). However, the effect of P treatment was significant on RGW in both Experiment 1 and Experiment 2 and on spikelet sterility only in Experiment 1 (Table 3).

The replicate errors for RGW were large, particularly at the threshold of CDD, where the values started to decrease (see the error bars in Fig. 3A). This is likely because grain fertility can be sensitively

Table 4
Grain yield and agronomic P use efficiency (AE_P) as affected by P and N treatments at each experimental site.

	Grain yield (t ha^{-1})			AE_P (kg kg^{-1})		
	Site1 (2017–2018)	Site1 (2018–2019)	Site2	Site1 (2017–2018)	Site1 (2018–2019)	Site2
0 P	0.65^c	2.02^c	1.97^b	-	-	-
30BP	-	3.41^b	2.88^a	-	106.2^{b}*	69.4^a
60BP	1.51^b	3.64^b	2.86^a	32.8^b	61.8^{b}*	33.9^b
30DP	1.76^a	4.61^a	3.13^a	84.7^a	198.1^a	88.3^a
−N	1.36^a	3.21^b	2.21^b	53.3^a	148.1^a	80.3^a
+N	1.26^a	3.63^a	3.21^a	64.3^a	95.9^b	47.5^b

*The AE_P difference between 30BP and 60BP in Site1 was significant at the level of $P = 0.06$.
Within each column, values with different alphabets indicate significant differences among the treatments at 5% of Tukey's HST test.

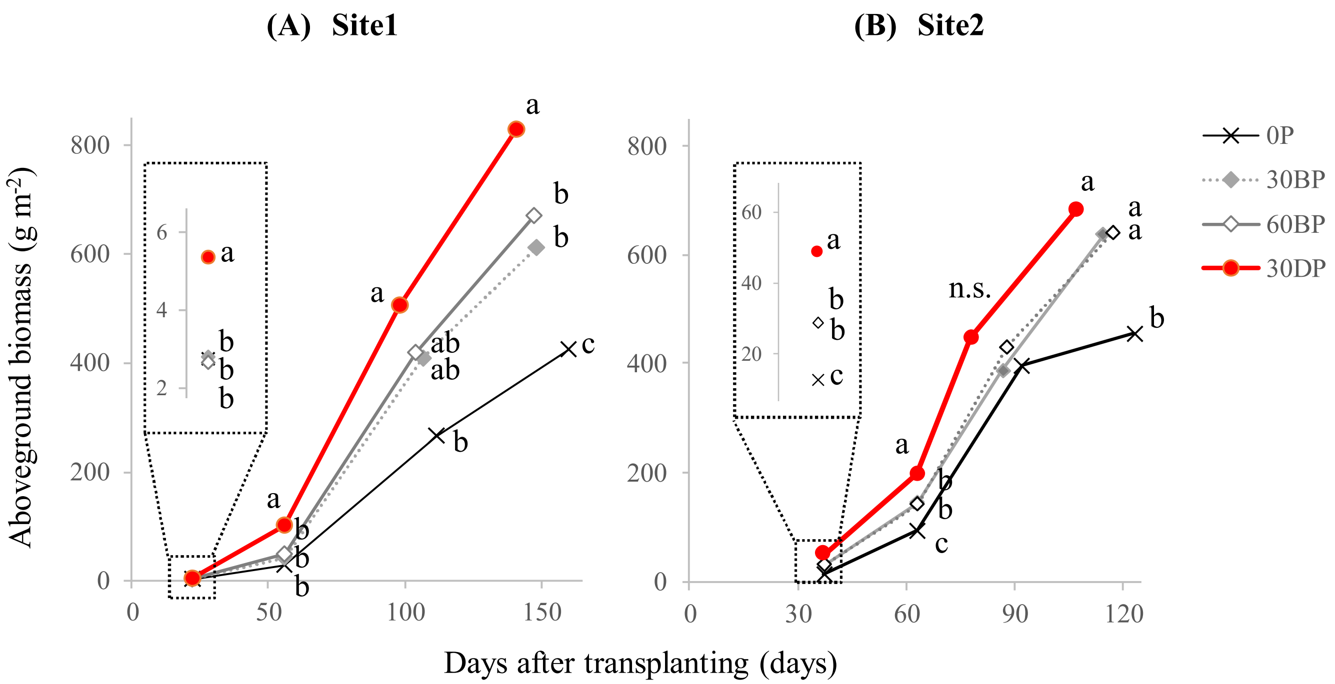

Fig. 2. Changes in aboveground biomass from days after transplanting to maturity in (A) Site1 and (B) Site2 in the Experiment 2 (2018–2019). Different letters indicate significant differences at the same sampling period at 5% of Tukey's HST test. The data points are the means of −N and +N treatments.

Table 5

Changes in crop growth rate (CGR) in different growing periods from transplanting to maturity (M) as affected by P and N fertilizer treatments at each experimental site in Experiment 2.

	CGR (g m^{-2} day^{-1})							
	Site1				Site2			
	0-22 days	22-55 days	55 days to H	H to M	0-37 days	37-63 days	63 days to H	H to M
0 P	0.13^{b}	0.74^{b}	5.88^{b}	1.44^{b}	0.36^{c}	3.09^{b}	10.39^{b}	1.92^{b}
30BP	0.13^{b}	1.15^{b}	7.16^{ab}	4.86^{ab}	0.80^{b}	4.42^{ab}	10.85^{b}	8.81^{a}
60BP	0.12^{b}	1.39^{b}	6.87^{ab}	6.64^{a}	0.81^{b}	4.29^{ab}	12.82^{ab}	7.09^{a}
30DP	0.24^{a}	2.86^{a}	9.63^{a}	7.52^{a}	1.33^{a}	5.64^{a}	17.22^{a}	8.07^{a}
−N	0.15^{a}	1.34^{a}	6.24^{b}	5.36^{a}	0.54^{b}	3.57^{b}	8.65^{b}	5.95^{a}
+N	0.16^{a}	1.73^{a}	8.53^{a}	4.83^{a}	1.11^{a}	5.15^{a}	16.99^{a}	7.00^{a}
Levels of significance								
P	***	***	**	***	***	*	**	**
N	ns.	ns.	**	ns.	***	**	***	ns.
P × N	ns.	ns.	ns.	ns.	ns.	ns.	ns.	ns.

Within each column, values with different alphabets indicate significant differences among the treatments at 5% of Tukey's HST test.
ns. not significant, *$P < 5\%$, **$P < 1\%$, ***$P < 0.1\%$.

affected by various factors such as microclimates, the number of spikelets, and nutrient status of individual plants, and thus the treatment effects were statistically less pronounced than those of the other measured parameters. Yet, the *30DP* treatment had greater RGW by 27% relative to the *60BP* treatment ($P = 0.08$) and by 104% relative to the *0 P* treatment at Site 1 in Experiment 1 (Table 6). Although there were no significant differences, the *30DP* treatment had higher mean RGW by 5–8% relative to the BP treatments and by 21% relative to the *0 P* treatment at Site 1 in Experiment 2. When averaged across the three sites, RGW was greatest in the *30DP* treatment (18.2 mg), followed by the two BP treatments (17.0 mg), and the *0 P* treatment (14.5 mg). N application consistently reduced both RGW and spikelet sterility (Table 6).

4. Discussion

4.1. Effect of P-dipping on grain yield and agronomic P use efficiency

Dipping rice seedling roots in P-enriched slurry for 30 min before transplanting (P-dipping) demonstrated yield increases of 9–35% relative to the same or higher P application rates via broadcasting, and the effect was particularly large in high-elevation and low temperature condition (Tables 3,4). The magnitude of yield increases were similar to or slightly lower than those of previous reports of yield increases with the P-dipping relative to the same P application rate via broadcasting: 13% at one site with a red sandy clay loam soil (Typic Haplustalf) in Tamil Nadu, India (Ramanathan and Kothandaraman, 1984), 15–49% in four-season trials at one site with high P-fixing soils (no specific soil data are available) in the central highlands of Madagascar (Balasubramanian et al., 1994), and 43% at one site in India (no specific

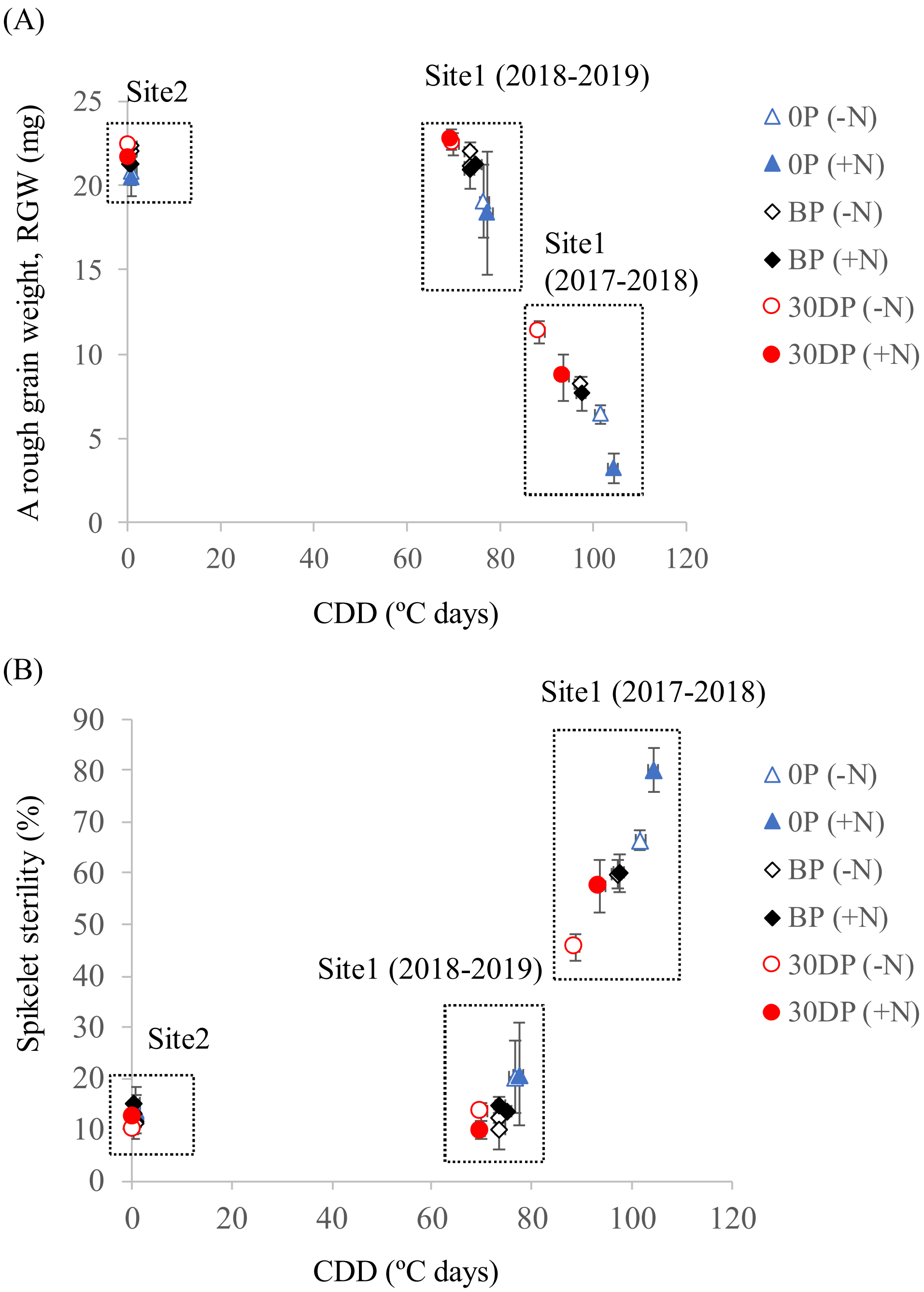

Fig. 3. Relationship between cooling-degree days (CDD) from 15 days before heading to 7 days after heading and (A) a rough grain weight (RGW), i.e., the product of filled grain rate by filled grain weight and (B) spikelet sterility. The error bars indicate standard error among replicates (n = 3).

site or soil information are available; De Datta et al., 1990).

The AE_P values achieved by P-dipping in the present study (85–198 kg kg^{-1}) at the P application rate of 13.1 kg ha^{-1} were similar to or higher than the ranges of 85–135 kg kg^{-1} reported in previous P-dipping trials with the similar P application rates (Balasubramanian et al., 1994; Raju et al., 1980; Ramanathan and Kothandaraman, 1984; Sahu, 1987). Moreover, these AE_P values with P-dipping were substantially higher than those achieved by conventional P application methods: 49 ± 38 kg kg^{-1} (mean ± SD of 10 sites) in irrigated lowlands in Asia (Dobermann et al., 1998) and 29 ± 22 kg kg^{-1} (mean ± SD of 27 sites) in rainfed and irrigated lowlands across SSA (Saito et al., 2019). It should be noted that the P application rates were slightly higher in the conventional P application trials in Asia (17–25 kg ha^{-1}) and in SSA (20–30 kg ha^{-1}) than the P-dipping treatment in the current and other studies. The AE_P and other nutrient use efficiencies generally tend to decrease when the application rates increase (e.g., Nziguheba et al., 2016).

Additionally, the P-dipping has little risk of P-mining by applying a certain amount of P in the main fields. Vandamme et al. (2016) estimated that of 3 kg P ha^{-1} applied in the nursery bed, merely 0.07–0.24 kg P ha^{-1} was transferred to the main fields with P-enriched seedlings while that an additional 2 kg P ha^{-1} was mined due to increased grain production in response to nursery P application. In this regard, a combination of micro-dose nursery application and P-dipping may offer a highly efficient and sustainable P fertilizer management for transplanted rice production system. Field experiments on the combined effects of these two localized P application techniques are yet to be conducted.

Table 6

A rough grain weight (RGW) and sterility rate as affected by different P and N treatments in Experiment 1 and Experiment 2.

	A rough grain weight, RGW (mg)				Sterility rate (%)			
	Experiment 1	Experiment 2		Site mean**	Experiment 1	Experiment 2		Site mean**
	Site1	Site1	Site2		Site1	Site1	Site2	
0 P	4.9^{b}	18.7^{a}	20.6^{a}	14.5^{c}	73.3^{b}	20.5^{a}	13.7^{a}	35.8^{b}
30BP	-	21.6^{a}	21.6^{a}	17.0^{b}	-	12.9^{a}	13.2^{a}	28.4^{a}
60BP	7.9^{a}*	21.0^{a}	21.7^{a}		59.9^{b}*	12.4^{a}	12.2^{a}	
30DP	10.0^{a}*	22.6^{a}	21.9^{a}	18.2^{a}	51.5^{b}*	11.6^{a}	11.2^{a}	24.8^{a}
−N	8.4^{a}	21.1^{a}	21.9^{a}	17.0^{a}	57.3^{b}	14.0^{a}	11.5^{b}	27.9^{b}
+N	6.8^{b}	20.8^{a}	21.1^{a}	16.1^{b}	65.9^{a}	14.7^{a}	13.6^{a}	31.4^{a}

*The difference between 60BP and 30DP in Experiment 1 was significant at P = 0.08 for 'A rough grain weight' and at P = 0.09 for 'Sterility rate'.

**In the Site mean comparison, *30BP* and *60BP* in Experiment 2 and *60BP* in Experiment 1 were treated as the BP treatment.

Within each column, values with different alphabets indicate significant differences among the treatments at 5% of Tukey's HST test.

4.2. The effect of P-dipping differs among field environments

Another important finding in this study was that, across sites, the P-dipping treatment significantly shortened days to heading relative to conventional P-broadcasting. P is an important element that promotes early flowering and ripening of rice (Dobermann and Fairhurst, 2000; Fageria, 1980) and other annual plants (Nord and Lynch, 2008), although few quantitative field observations are available regarding the effect of P application on phenology development.

Vandamme et al. (2016) reported a heading delay of 2 days when omitting P in micro-dose nutrient applications (NPK vs. NK) to nursery beds in P-deficient lowlands of Benin. Furthermore, in severely P-deficient and historically non-P-applied fields in Tanzania, Vandamme et al. (2018) observed that days to heading was shortened by around 20 days relative to the control by placing small amounts of P into the planting hole for upland rice. Our study detected significant differences in days to heading not only by P application, that is, between non-P-applied and P-applied treatments, but also by P application methods. Days to heading was 7–9 days shorter in P-dipping than in P-broadcasting even at Site 2 where these two treatments increased grain yields equally.

This finding is noteworthy because shortening days to heading by P application and further by P application methods should have important agronomic impacts in both positive and negative ways. A positive impact is likely particularly in field environments where rice is exposed to risks of cold stress at the later growth stage such as the case of Site1 in the present study (Fig. 3). The threshold where RGW started to decrease or spikelet sterility started to increase was more or less in accordance with the spikelet sterility model as an exponential function of CDD (Horie et al., 1995)—the basis of the Oryza2000 model (e.g., Bouman et al., 2001). In the current study, RGW—the product of filled grain rate and filled grain weight—better explained the P treatment effect on the degree of cold stress, likely because prolonged days to heading leads to plants experiencing low temperatures not only at the micropore stage but until the early ripening stage. Spikelet sterility (or filled grain rate) is most sensitive to the former stage but shows little sensitivity to the latter stage (Shimono et al., 2002), whereas grain weight can be reduced by low temperature at the ripening stage (Yoshida and Hara, 1977).

As reviewed in various papers (e.g., Cooper et al., 1999), the shortened growth duration can be also favorable in areas where the risk of late-season drought is high. In addition, shorter growth duration should reduce the risk of biotic stresses and allow wider "safe sowing windows" to avoid such biotic and abiotic stresses (Dingkuhn, 1995), which provides benefits to farmers, who can reduce their labor intensity, and for fields with limited water availability at the start of the rainy season. Because of these positive aspects, the traits of short growth duration with high productivity have been continuously targeted in breeding, particularly for rice cultivation under unfavorable field environments (Dingkuhn, 1995; Dramé et al., 2013; Fukai and Cooper, 1995). Our study provides empirical evidence that P-dipping is another practical approach that farmers working P-deficient lowlands can readily apply to their respective varieties to achieve shorter growth duration and higher CGR to an even greater extent than achieved by P-broadcasting. Because lowland rice production in SSA is widely subjected to both drought and cold stresses (van Oort, 2018) and to P-deficient conditions, the P-dipping technique may improve rice production by alleviating both P deficiency and environmental stresses.

The benefit of shortened growth duration was less pronounced under the relatively favorable climatic conditions at Site 2. This is because prolonged growing duration should allow plants to further accumulate biomass if not subjected to biotic and abiotic stresses (Fig. 2B). In addition, the advantage of extra growing days for biomass production must have been greater at Site 2 than at Site 1 due to its higher daily mean temperature and higher daily solar radiation. However, it should be noted that the P-dipping treatment still achieved equivalent or slightly higher grain yields with significantly shorter growth duration than the same application rate of P-broadcasting at Site 2.

N application had less significant impacts than P application on phenology development. But the N application had consistently negative impact on grain fertility (Table 6), which may be attributable to increased susceptibility to low temperature with higher N status at the microspore stage in rice (Hayashi et al., 2000). Across a three-season field experiment in the highlands of Kenya, with daily minimum temperatures consistently below 18 °C in the middle to late growth stages, Njinju et al. (2018) observed that greater N application rates above 75 kg N ha^{-1} linearly reduced grain fertility and significantly reduced yield. The impacts of climate change or suboptimal nutrient management on rice production in SSA have been studied intensively but separately (e.g., Saito et al., 2019; van Oort 2018; van Oort and Zwart, 2018). Our empirical observations suggest that the interactions between the climate-induced stresses and nutrient management (both P and N) deserve further attention in future research.

4.3. Considerable interaction between P-dipping and soil properties

As discussed above, the interaction with climatic conditions is a factor that influences the effect of P-dipping treatment. However, the reduced RGW by 5–8% was not large enough to explain substantial yield increases by 26–36% with the P-dipping treatment relative to the same and doubled P application rates via broadcasting at Site 1. One important factor to consider is the difference in the P-retention capacity of soils. As shown in Table 1, the P-retention capacity was much higher at Site 1 than at Site 2. Although no soil data were presented, Balasubramanian et al. (1994) reported consistently superior yield increases with P-dipping relative to P-broadcasting in highly P-fixing soils in the central highlands of Madagascar. De Bauw et al. (2019a, b) argued that a smaller fraction of P will be fixed with more localized P application because the binding sites get saturated in that applied area. The same mechanism can be assumed for the greater effect of P-dipping in highly P-fixing soils. Most of the broadcast P might have become immobile in the highly P-fixing soils at Site 1, whereas more remained available to roots by the localized P-dipping treatment. Thus, P-dipping may overcome the soil P-fixation problems widely found in the tropics. Further field studies in soils with different degrees of P-fixation could help to clarify this interaction effect.

4.4. Scope for farmers' adoption of P-dipping technique

As discussed by Vandamme et al. (2018), factors such as additional labor requirements, access to P fertilizer, and appropriate technical trainings to enable consistent returns need to be addressed for smallholder rice farmers to implement localized P application techniques. The accessibility to mineral fertilizer has been increasing in Madagascar and elsewhere in SSA (Tsujimoto et al., 2019). For instance, the ratio of TSP fertilizer price in market to farmgate price of paddy was estimated at approximately 7.9 in the late 1980s when the P-dipping technique was initially tested while the ratio went down to 2.7 at present (Breg, 1989; OdR (L'Observation du Riz de Madagascar), 2019; FAOSTAT accessed at http://www.fao.org/faostat/en/ on Mar26, 2020). Yanggen et al. (1998) indicates that the ratio of the extra output value over the cost of fertilizer should be higher than 2 and preferably 3–4 for farmers to consider financial incentives using mineral fertilizer in the SSA. To achieve the value/cost ratio of 3–4, the AE_P should be 120–160 kg kg^{-1} and 41–55 kg kg^{-1} for the price ratio of TSP fertilizer to paddy rice in the late 1980s and at present, respectively. The former values are hardly achieved agronomically, while the latter values are feasible if effective P fertilization techniques are provided. The socioeconomic change in access to mineral fertilizer might be reflected by an increasing number of farmers apply small amounts of NPK fertilizer to the planting hole for upland rice production in the central highlands of Madagascar. In this regard, the scope for farmers' adoption of localized fertilizer application techniques is increasing and the P-dipping can be one practical option for smallholder farmers start P fertilizer management for lowland rice production under P deficiency. One technical concern of P-dipping is a potential negative effect related to a chemical damage to seedlings from high salt concentrations, as is the case of direct P application to the planting hole for upland rice. Our recent study identified that the P-dipping duration can be flexibly set and avoid the chemical damage if not exceed 4 hours and the effect on initial growth is equivalent in a range of P concentrations from 4.3% to 7.5% in the slurry (Oo et al., 2020). The accumulation of these sets of information and flexibility of the technique should be also important to facilitate farmers' adoption.

5. Conclusion

We demonstrated the superior effect of P-dipping compared to P broadcasting for improving initial growth, grain yields, and applied P use efficiencies on P-deficient lowlands in the central highlands of Madagascar. P-dipping is particularly effective in fields with risks of late-season low-temperature stress because of its significant impact to shorten the growth durations and is possibly so in fields with high P-fixing soils. These new insights should help farmers to selectively apply the technique for maximizing the return. Further studies are needed to assess their interest in using the technique and potential constraints for adoption such as acceptable costs of labors and materials relative to the benefits and how to prepare the P-enriched slurry in a greater scale.

CRediT authorship contribution statement

Njato Mickaël Rakotoarisoa: Conceptualization, Methodology, Investigation, Writing - original draft. **Yasuhiro Tsujimoto:** Methodology, Data curation, Writing - original draft, Writing - review & editing, Supervision. **Aung Zaw Oo:** Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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scientific reports

Synergy between a shallow root system with a *DRO1* homologue and localized P application improves P uptake of lowland rice

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Improved phosphorus (P) use efficiency for crop production is needed, given the depletion of phosphorus ore deposits, and increasing ecological concerns about its excessive use. Root system architecture (RSA) is important in efficiently capturing immobile P in soils, while agronomically, localized P application near the roots is a potential approach to address this issue. However, the interaction between genetic traits of RSA and localized P application has been little understood. Near-isogenic lines (NILs) and their parent of rice (*qsor1*-NIL, *Dro1*-NIL, and IR64, with shallow, deep, and intermediate root growth angles (RGA), respectively) were grown in flooded pots after placing P near the roots at transplanting (P-dipping). The experiment identified that the P-dipping created an available P hotspot at the plant base of the soil surface layer where the *qsor1*-NIL had the greatest root biomass and root surface area despite no genotyipic differences in total values, whereby the *qsor1*-NIL had significantly greater biomass and P uptake than the other genotypes in the P-dipping. The superior surface root development of *qsor1*-NIL could have facilitated P uptakes from the P hotspot, implying that P-use efficiency in crop production can be further increased by combining genetic traits of RSA and localized P application.

Phosphorous deficiency restricts crop growth, particularly in the tropics, due to the inherently low P content of soils and the high P-fixing capacity of other minerals such as active Al- and Fe- oxides[1]. Large amounts of mineral P fertilizer have been continuously applied to overcome low P-use efficiency and achieve high grain yields. Given the finite nature of the P fertilizer resource and increasing ecological concerns about the excess use of P in agricultural systems[2–4], it is vital to investigate sustainable crop production strategies that facilitate the efficient utilization of applied and available P in soils. Such strategies are also critical for the food security of resource-poor farmers with low fertilizer inputs in developing countries[5].

Roots play a pivotal role in exploring immobile P in the soil. An increased root surface area with minimal carbon costs is one strategy, through the formation of finer roots, aerenchyma, and root hairs[6–8]. Changes in root system architecture (RSA) such as the development of surface roots is another root function to adapt to P deficiency, that is called 'topsoil foraging', because P is most available in surface soil layers[9]. This topsoil foraging can be enhanced by a shallower growth angle of axial roots[9], adventitious root abundance[10], and many/short lateral root branching[11]. Field-based studies have demonstrated the yield advantages of genotypes with these architectural traits for several crops under P-deficiency[8]. Therefore, identification of key root traits and their genetic mechanisms and conferring genes or quantitative trait loci (QTL) should offer avenues for improving P acquisition efficiency in crop breeding[12].

The agronomic approach for improving P-use efficiency includes localized fertilization, which refers to the placement of small amounts of fertilizers nearby the root zone. Several field experiments have demonstrated the positive impacts of localized P fertilization on grain yields and/or fertilizer use efficiencies for crop production (e.g., Vandamme et al.[13]). Our recent study identified that applied P-use efficiency can be substantially improved by dipping seedling roots in P-enriched slurry at transplanting (P-dipping) in severely P-deficient rice fields in Madagascar[14]. The P-dipping transfers P with the slurry attached to seedling roots, creating a soluble P hotspot

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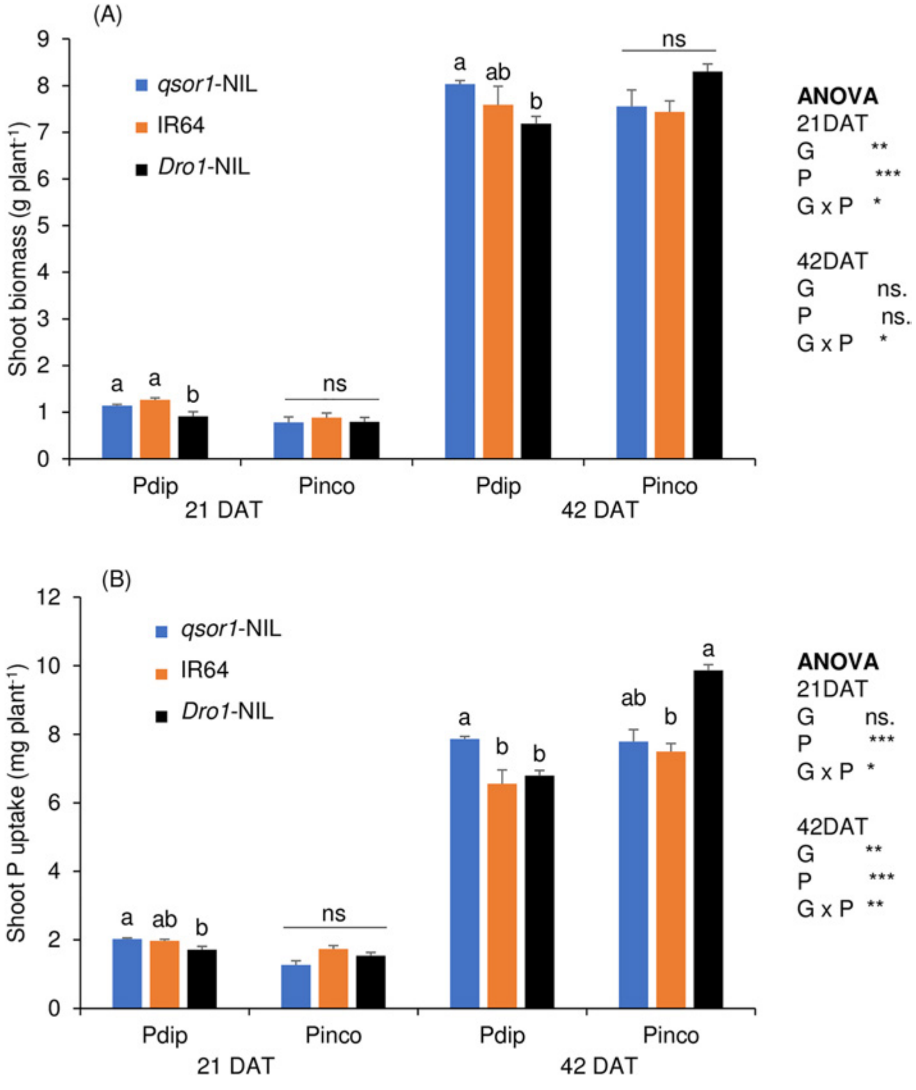


Figure 1. Shoot biomass (**A**) and shoot P uptake (**B**) of rice genotypes as affected by different P application methods (P incorporation (P_{inco}) of 500 mg P_2O_5 box^{-1} vs. P-dipping (P_{dip}) of 90 mg P_2O_5 box^{-1}) at 21 days after transplanting (DAT), and 42 DAT. Different letters and ns within each treatment indicate significant and non-significant differences, respectively, among genotypes at 5% using Tukey's HSD test. Error bars represent the standard error of replications. The *, **, and *** indicate that the individual effects of and interaction between genotype (G) and P application method (P) are significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

nearby the transplanted roots and facilitating plant P uptake, even under the high P-fixing soils of the tropics[15]. The use of P-dipping is currently being tested by hundreds of smallholder farmers in Madagascar.

Despite a range of studies in both genetic and agronomic approaches, none have examined how the combination of RSA traits and localized fertilization would affect plant P-use and acquisition efficiencies. In the present study, we aimed to identify the combination effect by using near-isogenic lines (NILs) of *DRO1*, and its homologue (*qSOR1*), the major QTLs of rice controlling root growth angle (RGA). The parent variety, 'IR64', is a high-yielding, modern variety with a relatively shallow RGA with the combination of the nonfunctional allele of *DRO1*, and the functional allele of *qSOR1*. The *Dro1*-NIL, developed by Uga et al.[16], has a relatively deep RGA with the combination of functional alleles of both *DRO1* and *qSOR1*. The *qsor1*-NIL, developed by Kitomi et al.[17], has a shallower RGA than IR64, with the combination of nonfunctional alleles of both *DRO1* and *qSOR1*. We hypothesize that P-dipping, creating a P hotspot at the soil surface, will have a positive interaction with the shallow root system in rice. By understanding the interaction, further research can be expected to improve applied P-use efficiencies by designing RSA traits for localized fertilizer application techniques.

Results

Shoot growth and P uptake. Localized P application via P-dipping (P_{dip}) achieved equivalent biomass and P uptakes at one fifth of the application rate of uniform P incorporation (P_{inco}) (Fig. 1). The ANOVA detected consistent and significant interactions between genotype and P treatment for shoot biomass and P uptakes at both 21 days after transplanting (DAT) and 42 DAT. In the P_{dip} treatment, *qsor1*-NIL consistently had greater shoot biomass and P uptake than *Dro1*-NIL. In contrast, in P_{inco}, *Dro1*-NIL tended to have greater shoot biomass and significantly greater P uptakes than the other genotypes at 42 DAT. Applied P-use efficiency (calculated as the ratio of shoot P uptake at 42 DAT to the amount of P applied) increased from 3.4 to 16.2% for IR64 by changing the P application methods from P incorporation to P-dipping and further increased to 20.0% by using *qsor1*-NIL (data not shown).

Genetic root traits. The RSA traits among genotypes were consistent under P_{dip}: the RGA was the shallowest in the order of *qsor1*-NIL > IR64 > *Dro1*-NIL at both 21 DAT and 42 DAT (Fig. 2). As a result of the RGA differences, *qsor1*-NIL developed a large proportion of root biomass and root surface area in the 0–3 cm layer and little in the 14–28 cm layer. In contrast, *Dro1*-NIL distributed a relatively large proportion of root mass in the 14–28 cm layer. For instance, at 21 DAT, *qsor1*-NIL developed 50.3% of the root mass in the 0–3 cm layer and only 2.0% in the 14–28 cm layer while these proportions were 32.7% and 10.3%, respectively, for *Dro1*-NIL. The root distribution pattern of IR64 was intermediate between *qsor1*-NIL and *Dro1*-NIL. The trend in RSA among genotypes was the same in P_{inco} while IR64 and *Dro1*-NIL tended to have deeper RGAs than those in P_{dip} (Fig. 3). The RGAs of *qsor1*-NIL, IR64, and *Dro1*-NIL at 21 DAT were 7.1°, 23.6°, and 33.3° in P_{dip} and 5.0°, 39.8°, and 52.2° in P_{inco}, respectively.

By reflecting on the differences in RGA, *qsor1*-NIL had a greater root biomass, greater root surface area, and longer lateral root length than *Dro1*-NIL at both the center position (0 to 3 cm from the plant base on both sides), and side position (3 cm from the plant base to the edges of the box) in the 0–3 cm soil depth layer at 21 DAT (Figs. 4; 5). On the other hand, *Dro1*-NIL had greater root surface area and longer lateral and nodal root length than *qsor1*-NIL at the side position in the 14–28 cm layer despite its significantly lower values in total for these parameters at 21 DAT (the mean values were also higher in the center position, but the differences were not statistically significant) (Fig. 4). IR64 was intermediate for these parameters in both the 0–3 cm and 14–28 cm layers. At 42 DAT, genotypic differences in root distribution patterns vertically and horizontally became less significant as root development and root growth angle were increasingly constrained by the size of the root box (Fig. S1). Yet, *qsor1*-NIL had consistently greater root mass and greater root surface area than *Dro1*-NIL at the side position in the 0–3 cm layer and vice versa in both center and side positions in the 14–28 cm layer.

Spatio-temporal dynamics in soluble P concentrations. Soluble P concentrations in soils were averaged across genotypes because there were no significant genotype differences in any sampling times or sampling layers. The P_{dip}, in which high P solution was applied by spot at a depth of 1.5 cm from the soil surface, had a substantially large soluble P concentration at a depth of 3 cm (Fig. 6). The maximum P concentration at a depth of 3 cm for P_{dip} was > 100 times greater than the other depths for both P treatments throughout the growing period. In P_{dip}, soluble P concentrations were greater at a depth of 7 cm than at 21 cm in the latter growth stages, but apparently the vertical P diffusion from the 3 cm hotspot was relatively small. In contrast, the soluble P concentrations were significantly higher at a depth of 21 cm than at 7 cm in P_{inco} after 28 DAT.

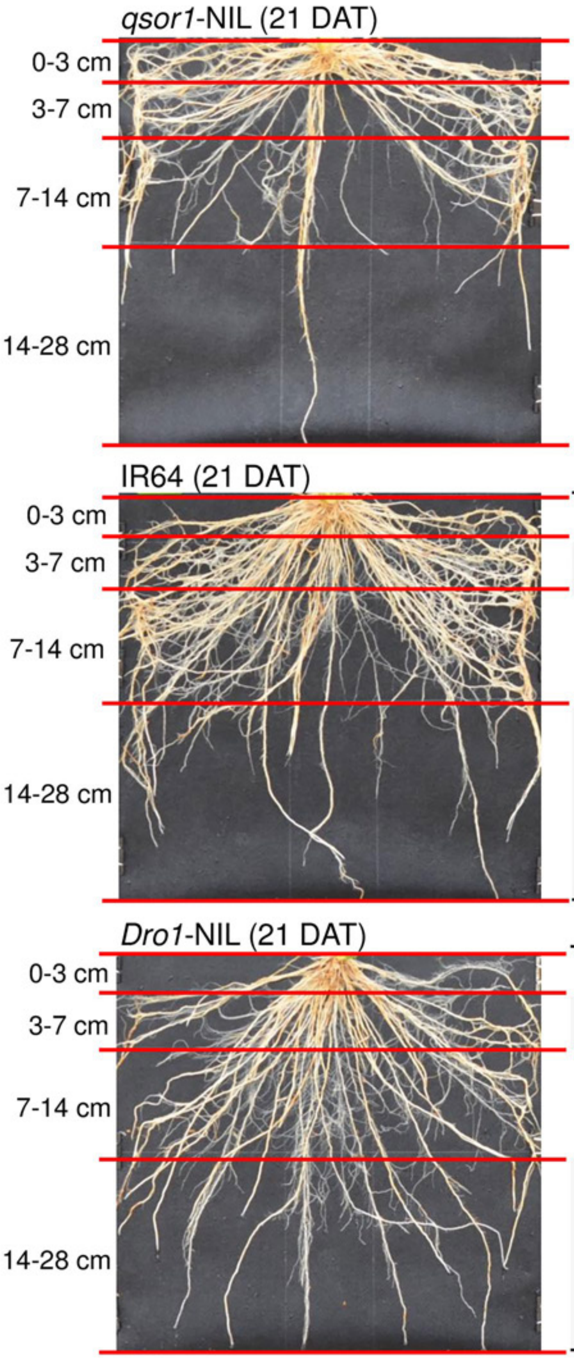
Discussion

The results support the hypothesis that the shallow root system of *qsor1*-NIL has a positive interaction with localized P application via P-dipping and that the combination additively improves applied P-use efficiency for initial rice growth. The other genotypes also reduced the RGA by 16–19° in response to the P hotspot (Figs. 2, 3), yet the synergy with P-dipping was greater in *qsor1*-NIL. This implies that breeding efforts to design the RGA in localized P spots can be more beneficial than relying on the intrinsic root plasticity of each genotype. It is also considered that root phenotypic adaptations to growing environments (as found in RGA changes of the other genotypes) may have a certain metabolic cost[18].

Superior P uptake of *qsor1*-NIL with P-dipping is attributable to the greater root biomass, greater root surface area, and longer lateral root length, especially at the center position in the 0–3 cm soil layer where high soluble P is available throughout the growing period. This is most likely the same mechanism as topsoil foraging, prioritizing the root development in the P-rich domains to efficiently capture immobile P in soils. Spatio-temporal P variations in the P-dipping indicate that applied P mobility is highly restricted despite a general understanding that P becomes less immobile under flooded conditions[19], emphasizing the importance of RSA for the localized P acquisition, even under flooded soil culture. The relative immobility of applied P even in irrigated lowlands was also reported by Akahane et al.[20], in which they detected high amounts of P retained up to harvest within a small area of 2–3 cm (vertical) by 4–5 cm (horizontal) centered on the application spot. This area of P distribution surrounding the application spot under the flooded soil culture corresponds to the center position of the 0–3 cm soil layer surrounding the P-applied spot of the P_{dip} treatment in the present study.

The effect of topsoil foraging itself has been reported in several upland crops[11,21–23], but not in rice. Previous studies detected no significant effects of root distribution patterns or RGA for rice P acquisition under P deficiency (e.g., Mori et al.[24]), which may be due to the materials differing not only in root system architecture but in other traits or in more complex screening environments. The present study had an advantage in using NILs that differed in RGAs (but were otherwise equivalent phenotypes[17]), under non-water-stressed, and greatly uneven P availability because of P-dipping.

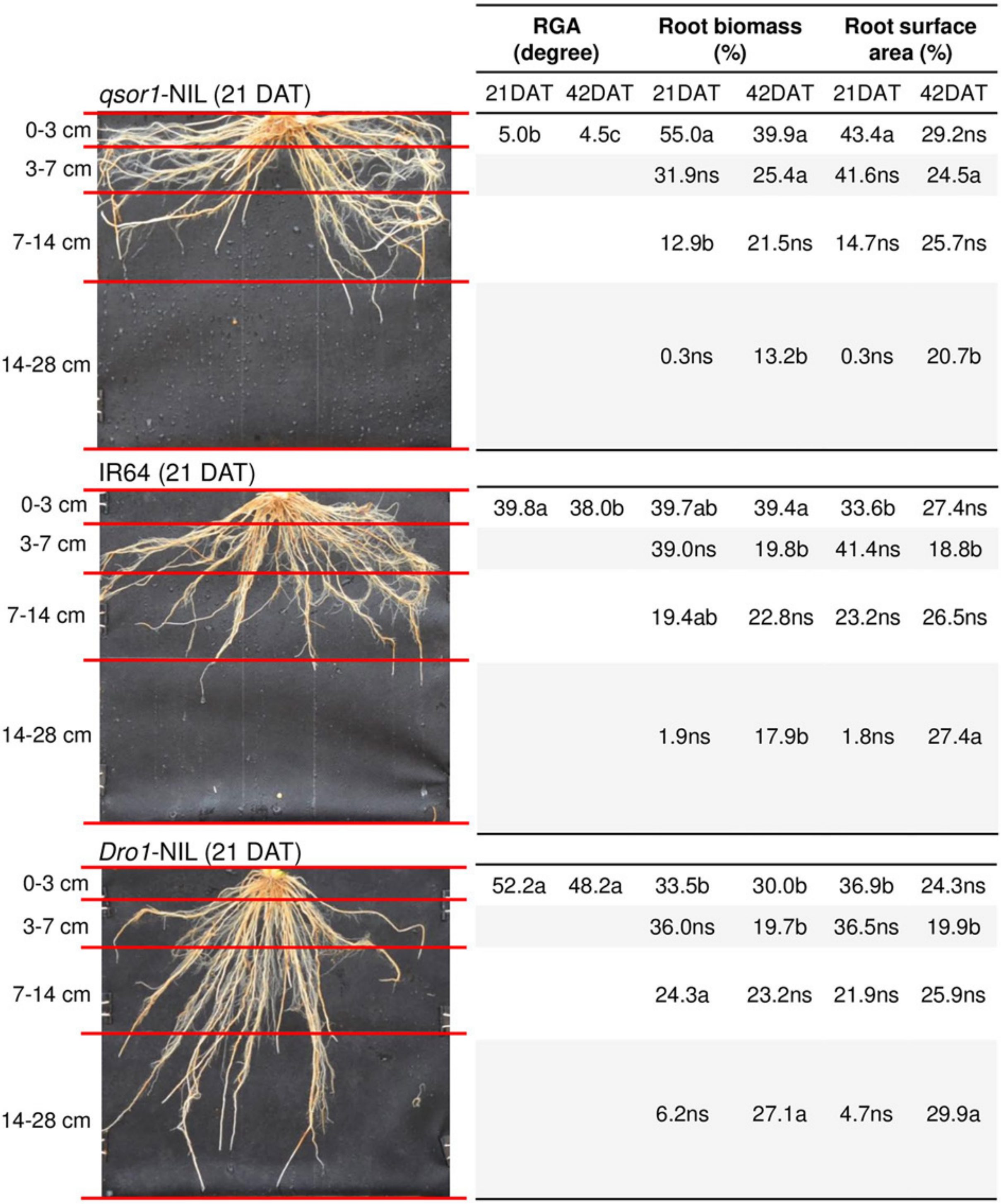
In addition, the present study detected a positive effect of *Dro1*-NIL on P uptake under uniform, P-sufficient conditions. The reason for this positive interaction should be further explored but can be related to consistent P acquisition from the P-rich subsoil layers after the depletion of available P in topsoil layers (Fig. 6). Another potential reason is the more efficient acquisition of other nutrients, such as N, which are vertically more mobile than P. Deep rooting has been reported as a positive trait for N acquisition in upland crops[8] and also in rice in



		RGA (degree)		Root biomass (%)		Root surface area (%)	
		21DAT	42DAT	21DAT	42DAT	21DAT	42DAT
qsor1-NIL (21 DAT)	0-3 cm	7.1b	6.8c	50.3a	43.0a	41.9a	29.1a
	3-7 cm			30.1ns	21.3ns	33.9ns	22.4a
	7-14 cm			17.7b	21.4c	22.0b	26.2ns
	14-28 cm			2.0b	14.4c	2.2b	22.3c
IR64 (21 DAT)	0-3 cm	23.6a	20.8b	36.9b	30.1b	28.6b	23.1b
	3-7 cm			31.6ns	19.4ns	33.3ns	20.9ab
	7-14 cm			26.1a	25.6a	31.2a	27.0ns
	14-28 cm			5.4b	24.9b	6.9b	29.0b
Dro1-NIL (21 DAT)	0-3 cm	33.3a	30.8a	32.7b	26.9b	26.7b	21.6b
	3-7 cm			31.4ns	19.1ns	30.5ns	18.6b
	7-14 cm			25.6a	23.6b	30.3a	25.7ns
	14-28 cm			10.3a	30.4a	12.5a	34.1a

Figure 2. Root growth angle (RGA) and proportions of root biomass and root surface area in different soil layers of *qsor1*-NIL, IR64, and *Dro1*-NIL at 21 days after transplanting (DAT), and 42 DAT under the P-dipping (P_{dip}) treatment. Different letters in the same soil layer indicate significant differences among genotypes at 5% of Tukey's HSD test. *ns* not significant at 5% level.

flooded paddy fields in the latter growth stages[25]. In the common bean, Rangarajan et al. postulated that the greater vertical range of roots with deeper RGA, and a greater number of basal root whorls is advantageous for biomass production when both N and P are deficient[26]. Likewise, dispersed root distribution of *Dro1*-NIL might have benefited from the relatively uniform nutrient conditions of the P_{inco} treatment. *Dro1*-NIL had significantly smaller coefficients of variation across soil layers in root biomass than *qSOR1* (58% vs. 98% at 21 DAT, and 23% vs. 47% at 42 DAT, respectively), indicating more uniform and dispersed root development.



		RGA (degree)		Root biomass (%)		Root surface area (%)	
		21DAT	42DAT	21DAT	42DAT	21DAT	42DAT
qsor1-NIL (21 DAT)	0-3 cm	5.0b	4.5c	55.0a	39.9a	43.4a	29.2ns
	3-7 cm			31.9ns	25.4a	41.6ns	24.5a
	7-14 cm			12.9b	21.5ns	14.7ns	25.7ns
	14-28 cm			0.3ns	13.2b	0.3ns	20.7b
IR64 (21 DAT)	0-3 cm	39.8a	38.0b	39.7ab	39.4a	33.6b	27.4ns
	3-7 cm			39.0ns	19.8b	41.4ns	18.8b
	7-14 cm			19.4ab	22.8ns	23.2ns	26.5ns
	14-28 cm			1.9ns	17.9b	1.8ns	27.4a
Dro1-NIL (21 DAT)	0-3 cm	52.2a	48.2a	33.5b	30.0b	36.9b	24.3ns
	3-7 cm			36.0ns	19.7b	36.5ns	19.9b
	7-14 cm			24.3a	23.2ns	21.9ns	25.9ns
	14-28 cm			6.2ns	27.1a	4.7ns	29.9a

Figure 3. Root growth angle (RGA) and proportions of root biomass and root surface area in different soil layers of *qsor1*-NIL, IR64, and *Dro1*-NIL at 21 days after transplanting (DAT), and 42 DAT under the P incorporation (P_{inco}) treatment. Different letters in the same soil layer indicate significant differences among genotypes at 5% of Tukey's HSD test. *ns* not significant at 5% level.

It should be noted that crop production environments are complex with multiple abiotic stresses, particularly on smallholder farms in developing countries where stress-resilient and nutrient-efficient technologies are most needed. In this respect, field-based experiments to maturity are further required to confirm the effect of the combination of genetic RSA traits and P fertilizer management practices. The combination of shallow roots and localized P application can never be a silver bullet. A careful selection of field environments where P deficiency is the primary limiting factor is needed to effectively apply this combination, ideally together with the development of bimodal root phenotypes (shallow and deep), or high RSA plasticity[27] against complex growing environments.

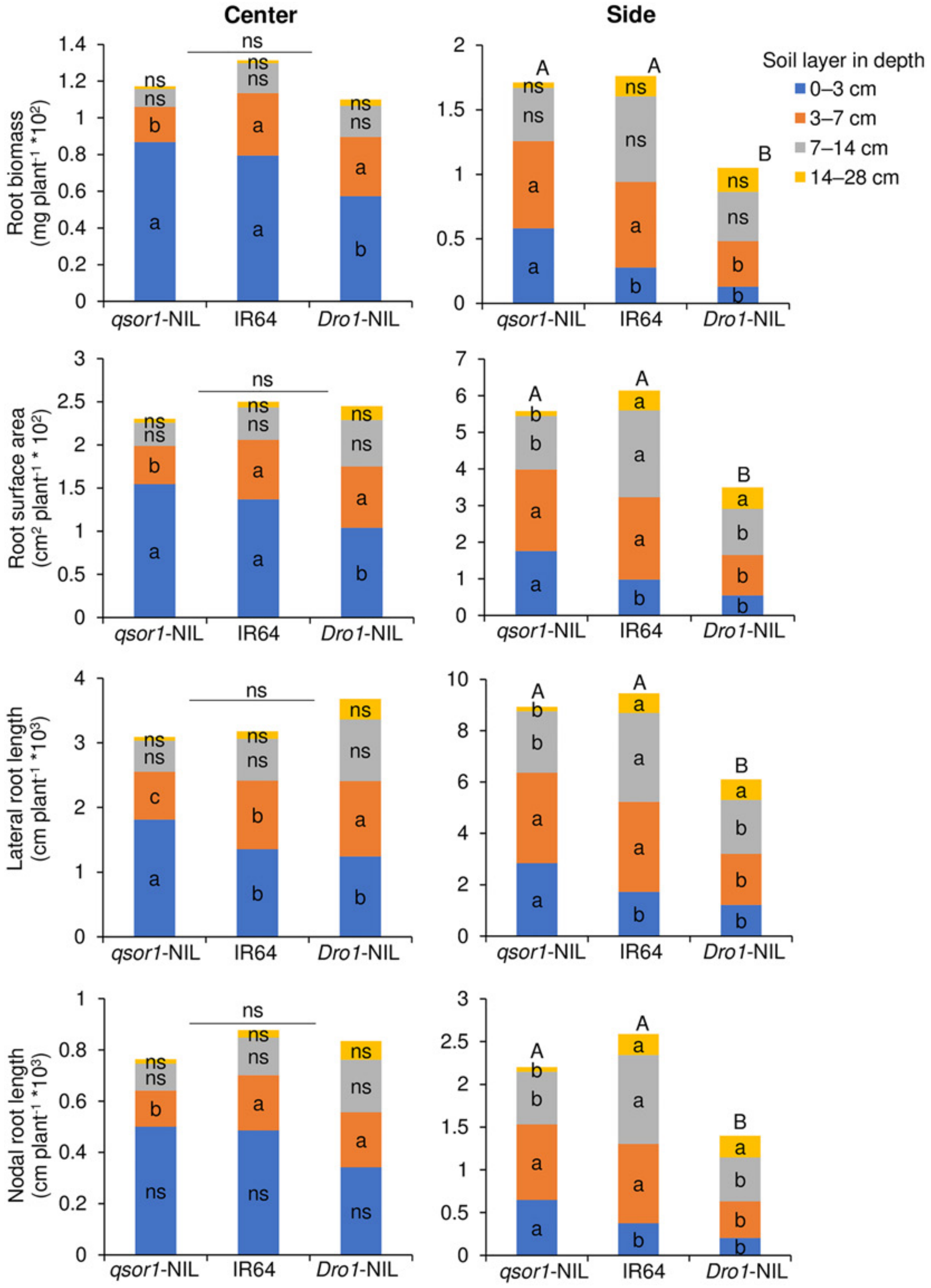


Figure 4. Horizontal and vertical root distribution patterns of three rice genotypes at 21 days after transplanting under the P-dipping (P_{dip}) treatment. Root parameters were shown in the center and side positions of four different soil layers (0–3 cm, 3–7 cm, 7–14 cm, and 14–28 cm). The center position indicates 3 cm from the plant base in both horizontal directions. The side position is apart from the center position. Different small letters and capital letters indicate significant differences among genotypes in these parameters within each soil layer and in total of all layers, respectively, at 5% of Turkey's HSD test. *ns* not significant at 5% level.

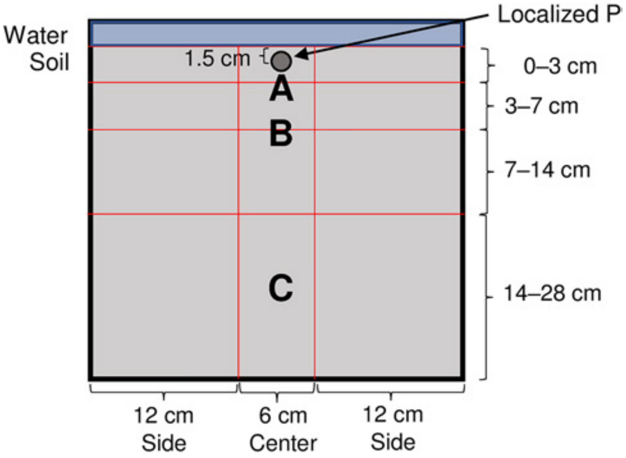


Figure 5. Schematic representation of the root box (30 cm × 30 cm × 3 cm) with the sampling points of soil water solution. Ceramic Rhizon samplers were installed in the middle of the box at (**A**) 3 cm, (**B**) 7 cm, and (**C**) 21 cm depths. The observation at 7 cm (**B**), and 21 cm (**C**) depth was conducted in both treatments while the observation at 3 cm depth (**A**) was only conducted in the P-dipping (P_{dip}) treatment.

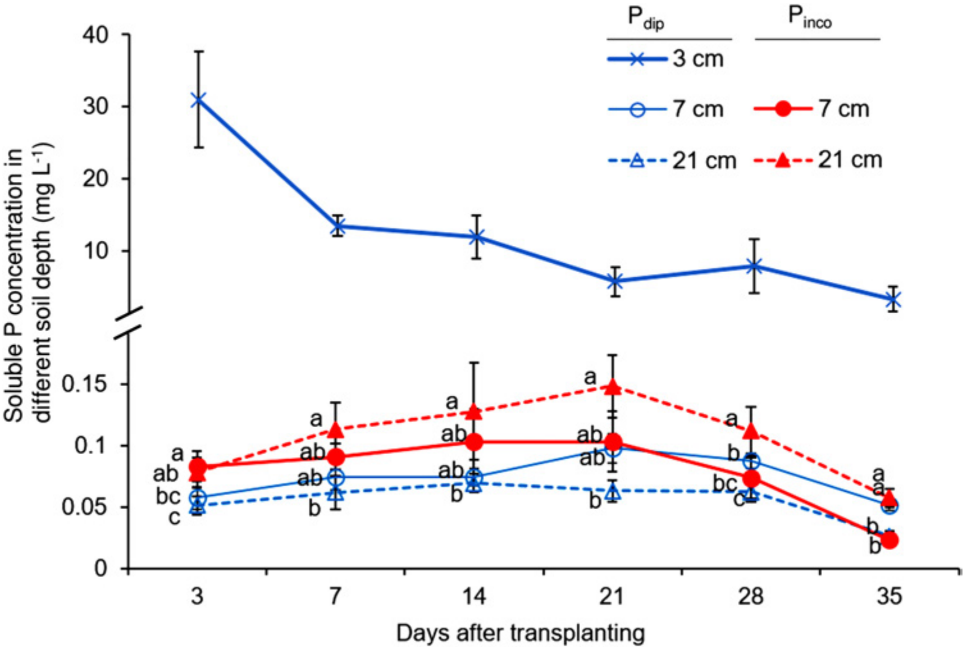


Figure 6. Spatio-temporal variations in soluble P concentration as affected by different P application methods. The cross symbols indicate the value at the 3 cm depth of the P-dipping (P_{dip}) treatment. The open and closed circles indicate the value at the 7 cm depth of the P_{dip} treatment, and P incoropration (P_{inco}) treatment, respectively. The open and closed triangles indicate the value at the 21 cm depth of the P_{dip} treatment and P_{inco} treatment, respectively. Data values are an average of three rice genotypes because no significant genotype difference in soluble P concentration was observed at each sampling time. Error bars indicate standard error of replications. Different letters indicate significant differences at 5% using Tukey's HSD test among different soil depths (7 cm and 21 cm) by P application methods. The observation at 3 cm depth was only conducted in the P_{dip} treatment.

In rice, *qSOR1* and *DRO1* can be promising genetic resources for the development of such bimodal root phenotypes, without increasing costs of root elongation but by controlling the root growth angles[28,29]. A combination of shallow root system and RSA plasticity may be another possible trait ensuring both efficient P uptake from localized spots, and flexible responses to unpredictable changes in growing environments.

Parameters	Red-yellow soil
pH (H_2O)	4.86
EC (mSm^{-1})	4.63
Total N ($g\ kg^{-1}$)[a]	0.91
Total C ($g\ kg^{-1}$)[a]	4.82
P retention (%)[b]	57.5
Available P (Bray II) ($mg\ kg^{-1}$)[c]	17.5
$P_{oxalate}$ ($mg\ kg^{-1}$)[d]	207.5
$Al_{oxalate}$ ($g\ kg^{-1}$)[d]	2.70
$Fe_{oxalate}$ ($g\ kg^{-1}$)[d]	2.58
Sand (%)[e]	44.3
Silt (%)[e]	12.0
Clay (%)[e]	43.7
Texture	Silty clay

Table 1. Physicochemical properties of soil. [a]NC analyzer, Sumigraph NC-220F (SCAS, Japan); [b]The proportion of absorbed P after shaking 5 g of soil with 25 ml of 1000 ppm P solution for 24 h; [c]UV spectrophotometer (UV-1800, Shimadzu); [d]Inductively coupled plasma mass spectrometer (ICPE-9000, Shimazu, Japan) after oxalate extraction. [e]Sieving and pipetting method.

Conclusion

The study provides significant evidence that a shallow root system has a positive interaction with localized P application nearby the root at transplanting by using NILs differing in their RGA. The combination substantially improves applied-P use efficiency for initial rice growth. This finding should encourage relevant research focusing not only on physiological root traits or agronomic management approaches, but on their combination to address to the global issue of increasing crop production while minimizing the environmental impacts.

Materials and methods

Experimental design and treatments.

The experiment was conducted in a greenhouse with an automatic ventilation system at the Japan International Research Center for Agricultural Science (JIRCAS), Tsukuba, Japan. The average daytime and nighttime temperatures during the experiment ranged from 26.2 to 35.8 °C and 24.7 to 28.7 °C, respectively (Thermo Recorder TR-50U2, T&D Corporation, Japan).

The soil for the experiment was collected from a subsoil layer (40–50 cm in depth) at the JIRCAS Tropical Agricultural Research Front, Okinawa, Japan. Physicochemical properties of experimental soil are summarized in Table 1. The soil was silty clay with a pH (H_2O) of 4.86 and low available P content, and high P retention capacity with abundant active Al and Fe oxides. The soil was air-dried and passed through an 8 mm sieve prior to the experiment.

Two different P treatments, sufficient P incorporation (P_{inco}) and localized P application via P-dipping (P_{dip}), were factorially combined with three rice genotypes in a randomized complete block design with seven replications. For both treatments, NH_4NO_3 and K_2SO_4 were mixed with soils and puddled in a bucket at a rate of 220 mg N box^{-1}, and 220 mg K_2O box^{-1} to develop uniform and N- and K-sufficient conditions. For the P_{inco}, triple super phosphate (TSP) was added at puddling. The mixed soils were filled into a root box at a rate of 500 mg P_2O_5 box^{-1} to develop a uniform and P-sufficient condition. The P application rate of the P_{inco} treatment was determined based on Oo et al.[15] to expect similar levels of plant P uptakes and biomass production with the P_{dip} treatment for the comparison of root development. The root box was made of transparent acrylic sheets with a size of 30 cm height × 30 cm length × 3 cm width. The soil was added to the box to a depth of 28 cm.

For the P_{dip} treatment, a P solution was placed in a spot nearby the transplanted root zone to apply the exact amount of P in all boxes. We estimated the amount of P-enriched slurry transferred or attached to seedling roots at transplanting as 90 mg P_2O_5 box^{-1} based on our previous study[30]. After the N- and K- added soil was filled in the root box, 90 mg P_2O_5 as TSP dissolved in 20 ml water was injected into the soil at a depth of 1.5 cm in the center of the root box (Fig. 5). On the same day of these P treatments, one 10-day old seedling was transplanted in the middle of each root box and grown under continuously flooded conditions.

Measurement.

Soil solution samplers (DIK-8393, Daiki Rika Kogyo Co. Ltd., Japan) were installed in one side of the acrylic board in the middle of the 3 cm, 7 cm, and 21 cm depths for the P_{dip} treatment and at 7 cm and 21 cm for the P_{inco} treatment for four out of the seven replicates (Fig. 5). Based on our previous observation[15], we assumed that the spatial variation in soluble P concentration were relatively small in the box because we thoroughly mixed P with soil at the time of puddling and thus omitted the measurement at 3 cm in the P_{inco} treatment.

Soil water samples were collected at 3, 7, 14, 21, 28, and 35 DAT. The samples were analyzed for soluble P concentration as an index of P available to plants using a microplate reader spectrophotometer at an absorbance of 630 nm by following the Malachite Green method[31].

Three and four replicates were harvested at 21 DAT and 42 DAT, respectively. At each harvest time, shoots were cut at ground level and oven-dried at 70 °C for > 48 h to determine shoot biomass. Shoot P concentration was measured with the molybdate blue method[32] after dry-ashing at 550 °C for 2 h and digestion with 0.5 M HCl. Shoot P uptake was calculated by multiplying the P concentration and shoot biomass.

After shoots were removed, root samples were collected using pin-board method as per Kano-Nakata et al[33]. In brief, roots were pinned with a 5 mm mesh net and pinboard after which soils were washed off and digital images were taken. The RGA was determined from the digital image taken by a commercial camera (D7000, Nikon Corp., Japan) as the angle from the soil surface to the shallowest nodal root using ImageJ software (Version 1.52a, NIH, USA). The root system was then divided into 12 compartments or into the center (0 to 3 cm from the plant base) and both sides of the 0–3 cm, 3–7 cm, 7–14 cm, and 14–28 cm soil layers to assess spatial root distributions (Fig. 5). The values of both sides (left and right) were summed as there must be no physiological meaning in the difference between these two. Root length and surface area of each compartment were measured using Epson Pro-selection X980 Scanner and WinRhizo Pro software (Regent Instruments, Quebec, Canada). Roots were classified as lateral roots (< 0.2 mm) as per Sandhu et al.[27] and nodal roots (0.2 to 2 mm) as per Kano-Nakata et al.[34]. Roots of > 2 mm were excluded from the analysis, as they were too large for a single root diameter and most likely occurred as a result of a measurement error. After the morphological analysis, root biomass of each compartment was determined by oven-drying at 70 °C for > 48 h.

Statistical analysis. JMP software (v14.0.0, SAS Institute Inc., Japan) was used to perform the statistical analyses. The treatment means were compared at 5% level of probability using Tukey's honestly significant difference (HSD) test after the single and/or interaction effects of genotypes and P treatment were confirmed by a generalized linear model.

The use of plant materials. Near-isogenic lines (NILs) and their parent of rice (*qsor1*-NIL, *Dro1*-NIL, and IR64) that we used in the present experiment was transferred from National Agricultural Research Organization (NARO) to Japan International Research Center for Agricultural Sciences (JIRCAS) by the Joint Research Contract, and the experiment was conducted by compiling with the guideline and regulation of this contract.

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Author contributions

A.Z.O., and Y.T. designed research and analyzed data; A.Z.O., Y.T., M.M., and T.N. performed research; A.Z.O., and Y.T. wrote the article with contribution of all authors; Y.U. and T.T. developed and provided plant materials; All authors reviewed, revised, and approved the articles; Y.T. agrees to serve as the author responsible for contact and ensures communication.

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Sequential micro-dose fertilization strategies for rice production: Improved fertilizer use efficiencies and yields on P-deficient lowlands in the tropical highlands

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ABSTRACT

Localized micro-dose fertilization near the seed or root zone can maximize returns from minimal fertilizer inputs. In transplanted rice production systems, two opportunities exist for implementing localized micro-dose fertilization: Micro-dosing the nursery bed at sowing and dipping seedling roots at transplanting. Previous studies have focused on the individual effects of these management options, whereas none have identified how a combination of these techniques affect rice yields and fertilizer use efficiencies. Herein, we examined the effects of nursery bed micro-dosing combined with dipping seedling roots in an N-enriched solution (N-dipping) and P-enriched slurry (P-dipping) at transplanting. On-farm experiments were conducted at three sites with nutrient-poor soils in the central highlands of Madagascar. The results demonstrated that phosphorus is a key element for localized micro-dose fertilization, while single and sequential N applications could hinder initial growth and grain yields in severely and moderately P-deficient fields. Grain yields were significantly improved by nursery bed N and P micro-dosing (16 %–23 %) and by P-dipping at transplanting (33 %–46 %), except for nursery bed micro-dosing in a relatively high-yielding and less P-deficient site. The effect of these treatments were independent, and thus the yield additively increased by 55 %–67 % in the severely and moderately P-deficient sites. Moreover, the nursery bed micro-dosing and P-dipping additively shortened the number of days to heading by 17–21 days in these sites, which reduced the risk of cold-induced stress at the reproductive stage. We conclude that the combination of N and P nursery bed micro-dosing and P-dipping at transplanting can be recommended for improving yields while reducing the risk of climate-induced stress for lowland rice production under low-input and P-deficient soils.

1. Introduction

Inadequate fertilizer input and poor soil fertility are the major constraints to crop production in Sub-Saharan Africa (SSA) (Haefele et al., 2013; Tittonell and Giller, 2013; Tsujimoto et al., 2019). Application rates of the major nutrients—nitrogen (N), phosphorus (P), and potassium (K)—have remained at 9.7, 3.9, and 2.3 kg ha^{-1}, respectively, in SSA, which is far below the values of that in the rest of the world (89.5, 36.7, and 29.6 kg ha^{-1}, respectively, estimated from the total nutrient inputs per total arable land area averaged from 2013 to 2017, accessed at http://www.fao.org/faostat/en/ on March 26, 2020). Consequently, on-farm yields are low even in irrigated rice production systems in SSA (Paresys et al., 2018). Recent studies on yield gaps demonstrated that opportunities for significant yield increases can be created with improved fertilizer management practices for rice production in SSA (Saito et al., 2017, 2019).

Increasing fertilizer input is only possible if it is readily available to local farmers, affordable, and profitable for crop production. Therefore, it is important to implement agronomic interventions that increase the profits from fertilizer inputs, that is, interventions that maximize the yield gain per unit of fertilizer applied. For example, site-specific nutrient management using decision support tools (Haefele and Wopereis, 2005; Haefele et al., 2013; Saito et al., 2015), integrated soil fertility management (Vanlauwe et al., 2011), and localized micro-dose

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fertilization (Vandamme et al., 2016, 2018; Rakotoarisoa et al., 2020) could improve fertilizer use efficiencies in SSA.

The use of localized micro-dose fertilization could be an entry technique for resource-poor and little-mechanized farmers to start using mineral fertilizer. This application method refers to the placement of small amounts of fertilizer with seeds at planting and in a band close to the planting area instead of broadcasting fertilizers in upland cropping systems (Aune and Bationo, 2008; Aune and Ousman, 2011). In the lowland rice production systems, one conventional technique is to apply a micro-dose of fertilizer to the nursery bed. This technique leads to the development of vigorous seedlings and accelerates initial growth after transplanting, which in turn improves grain yields or alleviates post-transplanting stresses, such as flooding and salt stress (Ros et al., 2015; Sarangi et al., 2015; Vandamme et al., 2016; Rakotoarisoa et al., 2020). Soaking seedling roots in N and P solutions prior to transplanting can similarly lead to the development of vigorous seedlings and accelerate initial plant growth in low fertility soils (Ehara, 1993; Fukuda et al., 2012). However, these techniques can also lead to nutrient mining even when large yield gains are achieved because the amount of nutrients transferred to the main fields with vigorous seedlings is negligible. For instance, Vandamme et al. (2016) estimated that out of 3 kg P ha^{-1} applied in the nursery bed, merely 0.07–0.24 kg P ha^{-1} was transferred to the main fields with P-enriched seedlings while an additional 2 kg P ha^{-1} was mined due to the increased grain production in response to nursery P application.

Alternatively, dipping rice seedlings into a P-enriched slurry (P-dipping) is a more direct and localized P application method, which allows ample P addition to the main field in the form of slurry attached to seedling roots at transplanting. The technique has been conventionally examined for lowland rice production in India (De Datta et al., 1990) and in Madagascar (Balasubramanian et al., 1994). Rakotoarisoa et al. (2020) reported that P-dipping resulted in a positive balance of P applied compared to that removed, and achieved significantly greater yields and agronomic P use efficiency than conventional P application via broadcasting in P-deficient lowlands in the central highlands of Madagascar. Our recent study demonstrated that P-dipping can effectively create soluble P hotspots near the root zone and facilitate P uptake of rice plants even under highly P-fixing soils in SSA (Oo et al., 2020).

Therefore, two types of localized micro-dose fertilization strategies for lowland rice production —nursery bed micro-dosing and P-dipping at transplanting—are applicable to efficiently increase returns from minimum fertilizer inputs. Their combination may avoid a negative nutrient balance in the main field, that is a concern in the single application of micro-dose nursery fertilization. However, previous studies have focused on the effects of these management strategies individually. To the best of our knowledge, there have been no studies conducted to identify how combinations of these strategies affect rice yields. Transplanted rice production systems are uniquely suited to combine localized micro-dose fertilization to the nursery at the time of sowing and to the seedling roots at the time of transplanting. We hypothesized that vigorous seedlings developed by nursery bed micro-dosing should have a additive or synergetic effect with fertilizer treatments applied to the seedlings, and thus initial plant growth and grain yield can be further improved by combining these application techniques without the risk of nutrient mining. The objective of this study was to evaluate the aforementioned interactions of these fertilizer management options on rice growth under poor soil nutrient conditions in SSA.

2. Materials and methods

2.1. Experimental site

On-farm trials were conducted at three sites: One in the commune of Behenjy (Site 1) and two in the commune of Mandriankeniheny (Site 2 and Site 3) located in the Vakinankaratra region in the central highlands of Madagascar during the wet season of 2017–2018. The region is a major rice producing area where smallholder farmers generally grow rice in the lowlands once a year in the warm and wet season from November to May. Rice production in the region is characterized—as is the case in the whole country—by limited yields below 3 t ha^{-1} on average under minimal mineral fertilizer inputs (Tsujimoto et al., 2019) and soils with low total and available P concentrations (Nishigaki et al., 2018). The regional rice production is often exposed to low temperature stress during the late growth stages, particularly at high elevations and when transplanting is delayed (Raboin et al., 2014; Dingkuhn et al., 2015; Rakotoarisoa et al., 2020).

The experimental sites were selected based on preliminary surveys using the following criteria: 1) low rice yields; 2) no apparent biotic or drought stresses; 3) no input of manure or inorganic fertilizer in previous seasons; and 4) no off-season crops. The geographical locations and soil chemical properties of each site are summarized in Table 1. Briefly, the amount of oxalate-extractable P—a suitable indicator of P availability for lowland rice production in the region (Rabeharisoa et al., 2012)—followed the order Site 1 < Site 2 < Site 3. The concentration in Site 1 was only 41 mg kg^{-1}, which is the lowest level among lowland rice fields in Madagascar (Kawamura et al., 2019). Based on the extensive oxalate-P analysis for lowland rice fields by Kawamura et al. (2019) that shows the range of 30.7–826.6 mg kg^{-1} and median of 245.8 mg kg^{-1} for oxalate-P, respectively, we categorized the soil P deficiency status of Site 1, Site 2, and Site 3 as" severe"," moderate", and" mild", respectively. The ambient temperature, solar radiation, and precipitation during the experiments were collected by establishing a Watchdog 1525 micro station (Spectrum Technologies Inc., Plainfield, IL, USA) at each commune (Fig. 1).

2.2. Nursery bed trial

A nursery bed and main field trial were conducted at each site. Firstly, nursery beds with a size of 1 m × 1 m were established within each field with three treatments: *n0* (no fertilizer); *nN* (5 g N m^{-2} applied); and *nNP* (5 g N m^{-2} and 3 g P m^{-2} applied), with four replicates of each treatment. Commercially available urea (46 % N) and triple superphosphate (TSP, 45 % P_2O_5) were used as the sources of N and P, respectively. The fertilizer was mixed with approximately 1 kg of surface soil from each nursery bed in a bucket and the mixture was applied to the nursery bed to assure the uniform distribution of this small quantity of fertilizer. Then, 60 g m^{-2} seeds (approximately 2,250 seeds) of X265 were sown and covered with a fine layer of hand-crushed soil. X265 is a common high-yielding variety of rice in the region. Ten seedlings from each nursery treatment were randomly selected at 22 days after sowing in Site 1 and Site 3, and at 24 days after sowing in Site 2. Plant height (cm) and leaf age were determined. The leaf age was determined by counting the incomplete leaf as the first leaf. If the top leaf was not fully expanded, the leaf age was estimated by determining the ratio of the length of the elongating top leaf to that of the preceding leaf. Then, seedlings were cut at the soil surface and dried at 70 °C for >48 h to determine the dry weight (mg). The seedling vigor index (mg cm^{-1}) was calculated by dividing the dry weight by plant height (Matsushima, 1974).

2.3. Main field trial

2.3.1. Experimental design

On the same day that the seedlings were sampled, the remaining seedlings from each nursery treatment were uprooted, seedlings from the four replicates were combined, and then the seedlings were subjected to one of three dipping treatments: *dp0* (no dipping); *dpN* (soaked in 2,300 mg L^{-1} N solution for 12 h); and *dpNP* (dipped in P-enriched slurry for 30 min after the *dpN* treatment). The methodologies of *dpN* and P-dipping treatments were adopted from Ehara (1993) and Rakotoarisoa et al. (2020), respectively. For the P-dipping treatment, P-enriched slurry was developed by mixing 500 g of TSP with 4,500 g of

Table 1
Geographical locations, soil properties, and P deficiency status of three experimental sites.

	Geography			Soil properties				
	Long.	Lat.	Elev. m	pH ($CaCl_2$)[a]	Oxalate P[b] mg kg^{-1}	Total N[c] g kg^{-1}	Total C[c] g kg^{-1}	P deficiency status[d]
Site1	S 19°10’	E 47°29’	1381	4.0	41	1.0	13.0	severe
Site2	S 19°55’	E 47°01’	1467	4.6	197	4.1	71.8	moderate
Site3	S 19°56’	E 47°00’	1453	5.1	350	1.9	27.5	mild

[a] Measured in a 1:5 (w/w) soil suspension of 0.01 M $CaCl_2$.
[b] Extracted by ammonium oxalate (Courchesne and Turmel, 2008).
[c] Dry combustion by NC analyzer (Sumigraph NC-220 F, SCAS, Japan).
[d] P deficiency status was categorized based on the extensive soil survey on lowland rice fields in the central highlands of Madagascar (Kawamura et al., 2019).

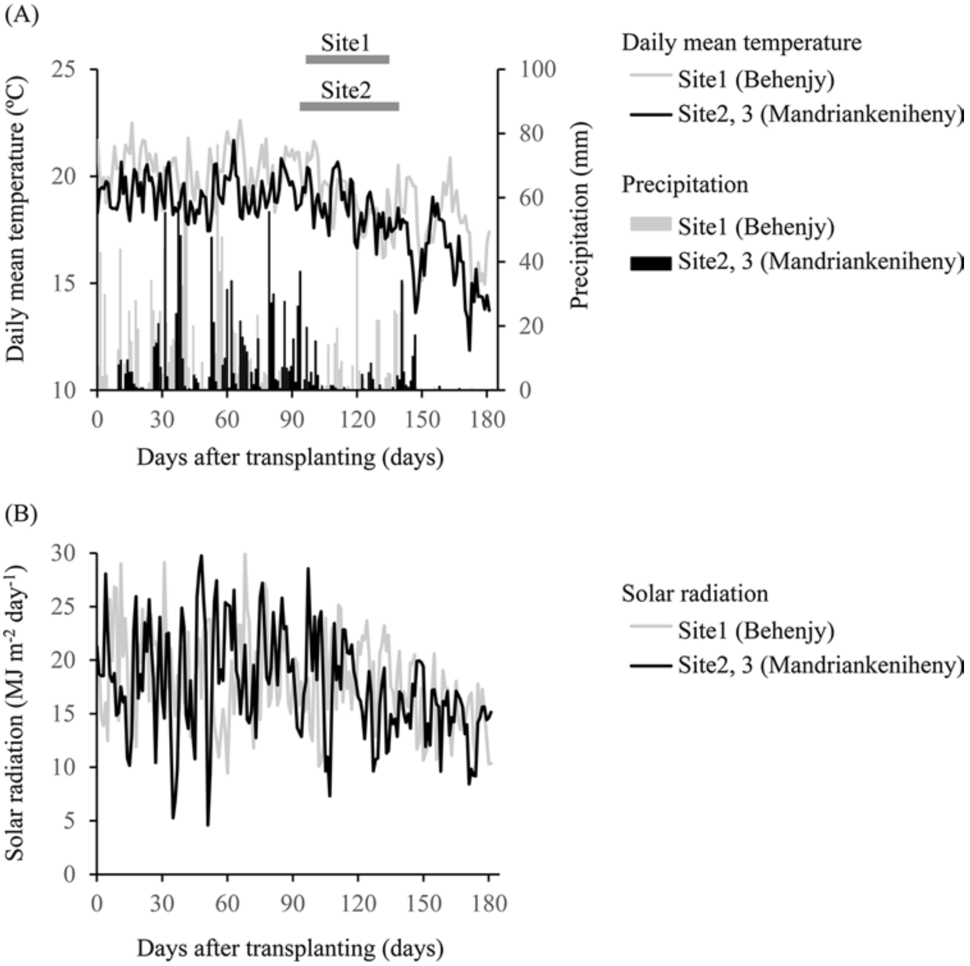

Fig. 1. Changes in (A) daily mean temperature and precipitation and (B) solar radiation from transplanting to harvest of the latest matured plot in each commune. Gray bars in the graph indicate the periods of heading between the earliest headed plot to latest headed plot at each site.

air-dried soil and 1.5 L of water in a plastic bucket for the 2,000 seedlings from each nursery treatment at each site. After being soaked in the N solution, seedlings were dipped in the slurry for 30 min and transplanted with the slurry attached to seedling roots. For each nursery × dipping treatment, two seedlings were transplanted per hill at a rate of 25 hills m^{-2} (20 cm × 20 cm) in the main field. Transplanting occurred on Nov 26, 2017 in Site 1, Dec 3, 2017 in Site 2, and Dec 2, 2017 in Site 3. A different N top-dressing treatment was arranged in the whole plot: *top0* (no top-dressing) or *topN* (30 kg N ha^{-1} applied). The N top-dressing was split across two application times, with the first half applied 18–20 days after transplanting (DAT) and the second half at 74–75 DAT.

In summary, a split-split plot design was sequentially established with three replicates at each site. The design consists of three levels of nursery treatments in the sub-subplot, three levels of dipping treatments in the subplot, and two levels of top-dressing treatments in the whole plot. The treatments were randomly allocated within each plot level. The size of each sub-subplot was 2.8 m × 1.8 m. The total amounts of N and P applied for each treatment are described in Table 2. Equivalent application rates to the main field were estimated from the ratio of seedling density to the transplanting density for the nursery treatment. Amounts of N and P transferred to the main fields with seedlings were estimated for the *dpN* and *dpNP* treatments, respectively. Potassium in the form of KCl was uniformly broadcast at transplanting at a rate of 40 kg ha^{-1} to exclude any potential effects of K deficiency. The fields were consistently flooded at a range of appropriate depths throughout the

Table 2
N and P application rates of each treatment.

Treatment	Application rate (kg ha^{-1})	
	N	P
Nursery fertilization (*n*)		
n0	0	0
nN	1.1	0
nNP	1.1	0.7
Dipping at transplanting (*dp*)		
dp0	0	0
dpN	0.9	0
dpNP	0.9	7.2
Topdressing (*top*)		
top0	0	0
topN	30.0	0

Equivalent application rates to the main field were estimated from the ratio of seedling density to the transplanting density for the nursery treatment. Amounts of N and P transferred to the main fields with seedlings were estimated for *dpN* and *dpNP* treatments, respectively.

growing period except at Site 3, which was exposed to an excessive water height above the bunds due to cyclone Ava on Jan 7 and Jan 8, 2018, in between the 1st and 2nd top dressing periods. All the sites were kept weed-free by regular manual weeding. No apparent biotic stresses were observed at any site.

2.3.2. Measurements and analysis

Aboveground biomass was determined by sampling 8 hills per plot at the time of the 1st topdressing and 10 hills per plot at the 2nd topdressing. The difference in the sampling number of hills between the 1st and 2nd topdressing was introduced to avoid border effects as much as possible within the limited plot size. The sampling at the 2nd topdressing was not carried out in Site 3 because of the aforementioned effect from the cyclone. Dry weights of sampled plants were determined after oven-drying them at 70 °C to constant weights. The heading dates were estimated when >50 % of panicles were exerted by counting the number of exerted and non-exerted panicles of 8 hills every 4–7 days within each plot in Site 1 and Site 2.

At maturity, 32 hills (1.6 m × 0.8 m) were harvested to determine grain yields. Plant growth at maturity was relatively uniform with adequate management of water, weeds, and pests within each plot. Grain yields were expressed in t ha^{-1}, corrected to a 14 % moisture content using a grain moisture sensor (Riceter f, Kett Electric Laboratory, Japan) after being threshed, winnowed, and air-dried. The agronomic P use efficiency (AE_P, kg grain yield increase per kg P applied) was calculated as the yield increase that resulted from P application in comparison with no P application divided by the amount of P applied. Apart from the yield samples, 8 hills were separately sampled to determine the yield components in Site 1 and Site 2. The filled grain rate (%) was determined as the ratio of the number of submerged spikelets to that of all spikelets by separating submerged spikelets and floating spikelets in tap water. Neither the heading date nor yield components were recorded in Site 3 due to a shortage of manpower.

Further, we assessed the magnitude of cold temperature stress experienced by rice plants by adopting the methodology as per Rakotoarisoa et al. (2020). The cooling degree days (CDD) was calculated for each plot using the following formulas:

$$\mathrm{CDD} = \sum \mathrm{CD} \tag{1}$$

$$\mathrm{CD} = 20 - T_{\mathrm{mean}}\ (T_{\mathrm{mean}} < 20\ ^{\circ}\mathrm{C}) \tag{2}$$

and

$$\mathrm{CD} = 0\ (T_{\mathrm{mean}} \geq 20\ ^{\circ}\mathrm{C}) \tag{3}$$

in which T_{mean} is the daily mean temperature and 20 is an assumed critical temperature below which rice plants are exposed to cold-induced stress (Horie et al., 1995). We calculated the CDD by accumulating CD from 15 days before heading to 7 days after heading, which would be the micropore stage to the early ripening stage, the period which is the most sensitive to cold stress and relevant to the grain fertility of rice (Horie et al., 1995). The degree of grain fertility was assessed by the rough grain weight (RGW, mg) as the product of the filled grain weight and the filled grain rate (Yoshida and Hara, 1977).

2.4. Statistics

All statistical analyses were conducted using the JMP 14 software (JMP 14.0.0, SAS Institute Inc.). After checking the normality and homogeneity of variance using the Shapiro-Wilk and the Levene test, respectively, some data, i.e., grain yield and biomass, were transformed using a box-cox transformation for the normality. Then, a multiple linear regression model was developed to determine the effects and interaction of the treatments on the measured variables within each experimental site. The site effect was included in the model for the observations of the seedling growth. The replicate was treated as a random factor. A post-hoc mean comparison was performed using Student's *t*-test for two groups or the Tukey's HSD (Honestly Significant Difference) test for more than two groups at $P < 0.05$. We implemented additional ANOVA and subsequent mean comparisons for the combination of nursery and dipping treatments when these effects were significant but not interactive. This manipulation was to present how each of these factors were quantitively additive to the other because the main objective of this study is to understand the combined effects of localized micro-dose fertilization. The RGW was regressed on CDD using a logistic function as a typical response of grain fertility to temperature stress (Horie et al., 1995).

3. Results

3.1. Grain yield and agronomic N use efficiency

The grain yields varied widely among different combinations of fertilizer treatments and sites (Table 3). The effect of nursery bed micro-dosing was significant at Site 1 and Site 2, but not at Site 3. The ***nNP*** treatment significantly increased grain yields, by 16 % at Site 1 and 23 % at Site 2, relative to the ***n0*** treatment. The ***nN*** treatment had no positive effect on grain yield at any of the sites. The *dp* treatment consistently had the greatest effect among the fertilizer treatments across all sites. The *dpNP* treatment significantly increased grain yields relative to the *dp0* treatment by 33 % irrespective of *n* or *top* treatments at Site 3. A significant interaction between the *dp* and *top* treatments was detected at Site 1 and Site 2 where the *topN* treatment significantly increased grain yields under the *dp0* treatment. The *dpNP* treatment significantly increased grain yields by 32 %–36 % at Site 1 and by 41 %–58 % at Site 2 irrespective of the top-dressing treatments. In contrast, the effect of the *dpN* treatment tended to be negative when combined with the *topN* treatment. As a result, the combination of *dpNtopN* had significantly lower yields than *dp0topN* which was 20 % lower at Site 1 and 40 % lower at Site 2.

There were no significant interactions between the *n* and *dp* treatments, *n* and *top* treatments or among the *n*, *dp*, and *top* treatments at any site, indicating the individual and additive effects of these factors where they were significant. In the regression model, the coefficients of ***nNP*** and *dpNP* treatments were both positive and significant. As the result, the mean yields from the ***nNPdpNP*** combination were 2.6 t ha^{-1} at Site 1 and 3.4 t ha^{-1} at Site 2 while those values from the ***nNPdp0*** and ***n0dpNP*** were 2.1 t ha^{-1} and 2.3 t ha^{-1}, respectively, at Site 1 and were 2.6 t ha^{-1} and 3.1 t ha^{-1}, respectively, at Site 2 (Table 3).

Table 3
Effect of nursery treatment, dipping treatment, and top dressing on grain yield.

		Grain yield (t ha^{-1})		
		Site1	Site2	Site3
Nursery treatment mean (*n*)				
	n0	1.9b	2.3b	3.4a
	nN	2.0b	2.2b	3.5a
	nNP	2.2a	2.8a	3.8a
Dipping treatment mean (*dp*)				
	dp0	1.8b	2.2b	3.3b
	dpN	1.7b	1.8b	3.0b
	dpNP	2.4a	3.2a	4.4a
Top dressing mean (*top*)				
	top0	1.7b	2.5a	3.4b
	topN	2.3a	2.4a	3.8a
dp x top mean				
dp0	*top0*	1.5d	2.1cd	2.9bc
	topN	2.2b	2.3bc	3.7ab
dpN	*top0*	1.8bc	2.2bcd	2.8c
	topN	1.7cd	1.4d	3.2bc
dpNP	*top0*	1.9bc	3.0ab	4.5a
	topN	2.9a	3.4a	4.4a
n x dp mean				
n0	*dp0*	1.7bc	2.0bcd	3.1bc
	dpN	1.6bc	1.8cd	2.6c
	dpNP	2.3a	3.1ab	4.5a
nN	*dp0*	1.6c	2.1bcd	3.1bc
	dpN	1.7bc	1.2d	2.8bc
	dpNP	2.4a	3.3ab	4.7a
nNP	*dp0*	2.1ab	2.6abc	3.7ab
	dpN	1.9abc	2.5abc	3.6abc
	dpNP	2.6a	3.4a	4.1ab
Levels of significance in F statistics				
	n	**	**	ns.
	dp	***	***	***
	top	***	ns.	*
	n × dp	ns.	ns.	ns.
	n × top	ns.	ns.	ns.
	dp × top	***	**	ns.
n × dp × top		ns.	ns.	ns.

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HST test.
ns. not significant, *$P < 5$ %, **$P < 1$ %, ***$P < 0.1$ %.

Table 4
Effect of nursery treatment, dipping treatment, and top dressing on days to 50 % heading.

		Days to 50 % heading	
		Site1	Site2
Nursery treatment mean (*n*)			
	n0	117a	119a
	nN	117a	117a
	nNP	107b	113b
Dipping treatment mean (*dp*)			
	dp0	116a	118a
	dpN	117a	121a
	dpNP	107b	110b
Top dressing mean (*top*)			
	top0	113a	116a
	topN	114a	117a
dp × top mean			
dp0	*top0*	117a	119a
	topN	115a	118a
dpN	*top0*	114a	119a
	topN	121a	124a
dpNP	*top0*	107b	110b
	topN	107b	109b
n x *dp* mean			
n0	*dp0*	120a	121abc
	dpN	120a	123ab
	dpNP	112b	112cde
nN	*dp0*	121a	118abc
	dpN	122a	123a
	dpNP	108bc	110de
nNP	*dp0*	107bc	114bcde
	dpN	111b	117abcd
	dpNP	101c	107e
Levels of significance in F statistics			
	n	***	**
	dp	***	***
	top	ns.	ns.
	n × dp	ns.	ns.
	n × top	ns.	ns.
	dp × top	*	P = 0.06
n × dp × top		ns.	ns.

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HSD test.
ns. not significant, *$P < 5$ %, **$P < 1$ %, ***$P < 0.1$ %.

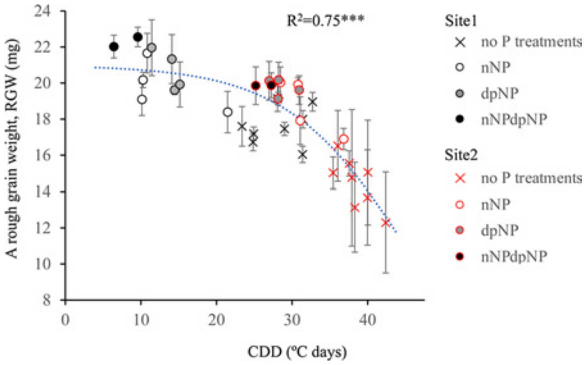

Fig. 2. Relationship between cooling-degree days (CDD) from 15 days before heading to 7 days after heading and a rough grain weight (RGW), i.e., the product of filled grain rate by filled grain weight.

3.2. Phenology development and the magnitude of low temperature stress

The fertilizer treatments significantly affected the number of days to heading and, consequently, growth durations (Table 4). The *nNP* treatment shortened the number of days to heading relative to the *n0* treatment by 10 days in Site 1 and 6 days in Site 2. There were no significant differences in the number of days to heading between the *n0* and *nN* treatments. The effect of the dipping treatment on phenology development was consistent at both Site 1 and Site 2. The *dpNP* treatment shortened the number of days to heading by 8–10 days compared with the *dp0* treatment under the *top0* and *topN* treatments. The interaction between *n* and *dp* was not significant, and thus the individual effects were statistically additive. In the regression model, coefficients of *nNP* and *dpNP* treatments were both significant to shorten the growth durations to the other levels within each treatment. As a result, the number of days to heading was additively shortened by 17–21 days in Site 1 and by 11–16 days in Site 2 by combining the *nNP* and *dpNP* treatments relative to the non-P applied treatments, i.e., *n0dp0*, *n0dpN*, *nNdp0*, and *nNdpN* (Table 4). There was a significant interaction between the *dp* and *top* treatments at Site 1 ($P < 0.05$) and at Site 2 ($P = 0.06$) on phenology development. The *topN* treatment tended to delay the heading dates by 5–7 days when combined with the *dpN* treatment.

These changes in phenology development affected CDD, that is the magnitude of cold temperature stress (Fig. 2). Site 2 tended to have a higher CDD than Site 1 because of its higher elevation and lower temperature (Fig. 1). The accumulation of CDD was accelerated as the heading dates were delayed because temperature gradually declined at later growth stages for both Site 1 and Site 2. More importantly, CDD was closely and negatively correlated with the RGW. The effect of CDD change on RGW was stronger at Site 2 than at Site 1, following a logistic decay curve. Within each site, the RGW increased as CDD decreased due to the *nNP* and *dpNP* treatments. The *nNP* had significantly greater RGW than the *n0* and *nN* on average by 7–13 % at Site 1 and by 15–21 % at Site 2. The *dpNP* had significantly greater RGW than the *dp0* and *dpN* on average by 14–18 % at Site 1 and by 21–27 % at Site 2 (Table S1). When both *nNP* and *dpNP* were applied, the RGW was increased by 33 % at Site 1 and by 52 % at Site 2 (*nNPdpNP* vs. *n0dp0*). Likewise, in response to the delayed heading, the combination of *dpN* and *topN* treatment significantly reduced RGW by 13 % relative to that of *dpNtop0* at Site 1 (Table S1).

3.3. *Initial to mid-stage plant growth*

Nursery bed micro-dosing had consistent effects on seedling growth across all the three sites. There were no interactions between the site and treatments for any measured variables; therefore, the treatment means and site means were compared (Table 5). The *nNP* treatment resulted in the highest mean values for all variables. The *nN* treatment also significantly increased plant height and leaf age relative to the *0 N* treatment; however, the effect of the *nN* treatment was less pronounced than that of the *nNP* treatment.

The effect of nursery bed micro-dosing was observed at 18–20 DAT; the *nNP* treatment continuously produced the highest mean biomass at all sites (Table 6). In contrast, there was no significant effect of the *nN* treatment at any site at 18–20 DAT. The effects of the dipping treatments were consistent across the sites. The *dpNP* treatment significantly increased aboveground biomass by 34 %–68 % relative to the *dp0* and *dpN* treatments, while there were no significant differences between the *dp0* and *dpN* treatments at any site. The interaction between *n* and *dp* treatments was not significant at any sites, and thus the positive effects of *nNP* and *dpNP* were additive. As the result, the *nNPdpNP* treatment had significantly greater biomass, by 69 % at Site 1, 27 % at Site 2, and 41 % at Site 3, than that from the single application of nursery NP treatment (*nNPdp0*), and by 108 % at Site 1 and 35 % at Site 3, than that from the single application of NP dipping treatments (*n0dpNP*) (Table 6).

At 74–75 DAT, the effect of nursery bed micro-dosing was still significant at both Site 1 and Site 2; the observation in this growth stage was not conducted at Site 3 (Table 7). The *nNP* treatment produced significantly greater biomass, by 86–89 % in Site 1 and by 29–31 % in Site 2, than that of the *n0* and *nN* treatments. There was no significant effect of *nN* at this growth stage. The interaction between *n* and *dp* treatments was not significant, and thus the positive effects of *nNP* and *dpNP* were consistently additive at this growth stage at both Site 1 and Site 2. The *nNPdpNP* treatment resulted in significantly greater biomass, by 100 % at Site 1 and 68 % at Site 2, than that of the single application of the nursery NP treatment (*nNPdp0*), and by 53 % at Site 1, than that of the single application of NP-dipping treatments (*n0dpNP*) (Table 7). Similar to the responses of yield and number of days to heading, there was a significant interaction between the dipping and top-dressing treatments at Site 1 and Site 2 (Table 7). The *dpNP* treatment had a positive effect on aboveground biomass irrespective of the top N treatments at both Site 1 and Site 2. In contrast, the *topN* treatment had a negative effect on biomass when combined with the *dpN* treatment.

Table 5
Effect of nursery treatment on seedling growth at transplanting.

	Plant height cm	Leaf age leaf	Aboveground biomass mg plant^{-1}	Seedling vigor index mg cm^{-1}
Nursery treatment mean (*n*)				
n0	13.7 c	3.4 c	34.4 b[†]	2.8 b[†]
nN	15.0 b	3.8 b	48.3 b[†]	3.2 ab[†]
nNP	17.3 a	4.2 a	64.6 a	3.6 a[†]
Site mean				
Site1	16.8 a	3.6 b	57.9 a	3.4 a
Site2	12.9 b	3.5 b	37.0 b	2.8 b
Site3	16.3 a	4.2 a	56.4 a	3.4 a
Levels of significance in F statistics				
n	***	***	**	*
site	***	***	***	***
site × *n*	ns.	ns.	ns.	ns.

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HST test.
Equivalent application rates to the main field were estimated from the ratio of seedling density to the transplanting density for the nursery treatment. Amounts of N and P transferred to the main fields with seedlings were estimated for *dpN* and *dpNP* treatments, respectively.
ns. not significant, *P < 5 %, **P < 1 %, ***P < 0.1 %.
[†] The difference in aboveground biomass between *n0* and *nN* was significant at the level of P = 0.09, and that in seedling vigor index between *n0* and *nN* and between *nN* and *nNP* were both significant at the level of P = 0.07.

Table 6
Effect of nursery treatment and dipping treatment on biomass production at 18–20 days after transplanting.

	Aboveground biomass at 1 st topdressing (g m^{-2})		
	Site1	Site2	Site3
Nursery treatment mean (*n*)			
n0	3.1b	2.9b	5.6b
nN	3.4b	3.5b	6.2b
nNP	6.6a	4.3a	8.1a
Dipping treatment mean (*dp*)			
dp0	3.6b	2.8b	6.2b
dpN	4.2b	3.1b	5.5b
dpNP	5.4a	4.8a	8.3a
n x *dp* mean			
n0dp0	2.8c	2.0d	5.6cde
n0dpN	2.6c	2.4d	4.0e
n0dpNP	3.9bc	4.4ab	7.2bc
nNdp0	3.1bc	2.5d	6.1bcd
nNdpN	3.0c	3.3bcd	4.8de
nNdpNP	4.1bc	4.8ab	7.9b
nNPdp0	4.8b	4.1bc	6.9bc
nNPdpN	6.9a	3.6bc	7.7b
nNPdpNP	8.1a	5.2a	9.7a
Levels of significance in F statistics			
n	***	***	***
dp	***	***	***
n × *dp*	ns.	ns.	ns.

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HST test.
ns. not significant, *P < 5 %, **P < 1 %, ***P < 0.1 %.

4. Discussion

4.1. *Phosphorus is a key element for accelerated initial growth and phenology development under localized micro-dose fertilization*

Nursery bed N and P micro-dosing followed by P-dipping at transplanting did not present a synergetic effect but an additive effect on biomass production from the initial to mid-growth stage. This result is in accordance with our hypothesis. It is noteworthy that the small increase in biomass observed at transplanting due to the nursery bed micro-dosing (a difference of only 1.5 g m^{-2} between the *n0* and *nNP* treatment) was retained even when high amounts of P were added via the dipping treatment. In other words, seedling vigor is an important factor and enhanced the effect of the subsequent P-dipping treatment. More importantly, the combination of these localized P micro-dosing techniques additively shortened the number of days to heading substantially by a maximum of 21 days at the severely and moderately P-deficient fields of Site 1 and Site 2, respectively. Previous studies have demonstrated that the individual effects of small-dose P application to the nursery and P-dipping shorten growth duration under P-deficient lowland soils (Vandamme et al., 2016; Rakotoarisoa et al., 2020). Our study revealed that the number of days to heading can be cumulatively shortened by combining P-dipping and nursery bed P micro-dosing with consistently using farmers' preferable and available varieties. These results corroborate the claim of Ros et al. (2015) that the effect of small-dose nursery fertilization is not reversed by applying higher rates

Table 7
Effect of nursery treatment, dipping treatment, and top dressing on biomass production at 74–75 days after transplanting.

		Aboveground biomass at 2nd topdressing (g m^{-2})	
		Site1	Site2
Nursery treatment mean (*n*)			
	n0	54.6b	78.6b
	nN	51.0b	79.8b
	nNP	101.5a	102.9a
Dipping treatment mean (*dp*)			
	dp0	51.7b	62.7b
	dpN	50.8b	63.9b
	dpNP	104.6a	134.7a
Top dressing mean (*top*)			
	top0	68.0a	78.3b
	topN	70.0a	95.9a
dp x top mean			
dp0	*top0*	45.0b	62.6c
	topN	58.5b	62.8c
dpN	*top0*	59.9b	67.9c
	topN	41.7b	59.9c
dpNP	*top0*	99.2a	104.4b
	topN	109.9a	165a
n x *dp* mean			
n0	*dp0*	35.3c	56.9c
	dpN	37.9c	52.8c
	dpNP	90.7b	126.2a
nN	*dp0*	34.3c	54.4c
	dpN	34.2c	60.7c
	dpNP	84.3b	124.3ab
nNP	*dp0*	82.8b	76.9bc
	dpN	83.2b	78.3bc
	dpNP	138.8a	153.5a
Levels of significance in F statistics			
	n	***	*
	dp	***	***
	top	ns.	**
	n × *dp*	ns.	ns.
	n × *top*	ns.	ns.
	dp × *top*	**	**
n × *dp* × *top*		ns.	ns.

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HST test.
ns. not significant, *P < 5 %, **P < 1 %, ***P < 0.1 %.

of fertilizer after transplanting. As argued in our previous studies (Rakotoarisoa et al., 2020; Tsujimoto et al., 2019), a shorter growth duration due to improved P management practices should have various impacts for rice cultivation. The results of the present study clearly showed that the risk of cold stress (CDD) can be mitigated by shortening growth durations, particularly in high-elevation sites. Our results are in accordance with the result of Rakotoarisoa et al. (2020), who reported reduced CDD and improved RGW with shortened growth durations by following application of the P-dipping technique in the central highlands of Madagascar. Shorter growth durations can also reduce the risk of drought stress at late growth stages (Fukai et al., 1999). Moreover, a shorter growth duration can reduce the risk of any biological stress during rice cultivation and increase the opportunity to intensify land use by enabling double- and triple-cropping of rice or rotations with vegetable crops (van Oort et al., 2016). Lowland rice production in SSA is widely subjected to both drought and cold stresses (van Oort, 2018) and P-deficiency (Haefele et al., 2013; Saito et al., 2019). Our finding that the growth durations can be shortened by nursery bed P micro-dosing and P-dipping, either separately or together, provides a practical approach for resource-limited farmers to address these issues.

In contrast, a single N application, either to the nursery bed or to the seedling roots via 12-h soaking, had little effect or interaction with other fertilizer management practices. These results are consistent with previous findings that P is more important than N for developing vigorous seedlings and improving plant growth after transplanting (Ros et al., 2015; Sarangi et al., 2015; Vandamme et al., 2016). Ella and Ismail (2006) found that excess N content in transplanted seedlings can even delay the recovery from transplanting shock under submergence-stressed conditions while N and P combinations improve. This may explain the negative effect of the *dpN* and *topN* or *dpN* and *nN* combinations on grain yields and phenology development in the present study. In addition, it is considered that excess plant N status increases susceptibility to low temperature stresses in rice (Hayashi et al., 2000; Njinju et al., 2018). Single and sequential N applications should be avoided when initial plant growth is limited under low-temperature and low-P-supply conditions.

4.2. Individual and combined effects of localized micro-dose fertilization techniques on grain yield and agronomic P use efficiency

Our results confirmed that both nursery bed NP micro-dosing and P-dipping at transplanting, in most cases, improve grain yields. Individually, the effect of nursery bed micro-dosing was not significant at the mild P-deficient field of Site 3, where both rice yields and the P-supplying capacity of soils were the highest among all the three sites. Therefore, nursery bed N and P micro-dosing could be adopted on farms with extremely low grain yields, around 2 t ha^{-1} as an entry-level technique for smallholder farmers to begin using fertilizers, as observed in Site 1 and Site 2. Under these conditions, the initial advantage at transplanting is retained and gradually amplified in later growth stages although the amount of nutrients taken up by seedlings should be negligible. Our results are consistent with previous field experiments showing that the effect of nursery bed fertilization is particularly increased under nutrient-poor conditions (Vandamme et al., 2016). However, it should be noted that this efficient approach can lead to nutrient mining from soils as a result of the significant yield gains with negligible nutrient inputs in the main field. Vandamme et al. (2016) argued that P-mining is justifiable to increase production and income in the short-term, whereas the approach should be combined with some form of P application to the main field in the long-term.

The present study suggests that P-dipping can be used as an additional localized P management technique, resulting in a high fertilizer use efficiency and replenishing the negative P balance that may occur by a continuous and single application of micro-dose nursery bed fertilization. The agronomic P use efficiency of P-dipping ranged from 87 to 151 kg kg^{-1} on average across all the three sites. This is a high efficiency compared with those achieved by conventional P application methods: 49 ± 38 kg kg^{-1} (mean ± SD of 10 sites) in adequately-managed irrigated lowlands in Asia (Dobermann et al., 1998) and 29 ± 22 kg kg^{-1} (mean ± SD of 27 sites) in rainfed and irrigated lowlands across SSA (Saito et al., 2019). In addition, the results imply that grain yields could be further increased by combining the nursery bed micro-dosing and P-dipping at transplanting in P-deficient and low-yielding fields of Site 1 and Site 2.

Further studies are needed to assess the economic gains and interests of farmers in using the combined micro-dosing fertilization techniques and potential constraints for adoption. As discussed by Vandamme et al. (2018), localized fertilizer management techniques can be more applicable to the areas where farmers grow rice in relatively small farm sizes and where laborers are available at the time of planting or transplanting. A simple cost-benefit analysis using the fertilizer and paddy price as per Rakotoson et al. (2021) provides a rough estimate of the return from the yield gains with the *nNP*, *dpNP*, and their combination, at 240 USD ha^{-1}, 305 USD ha^{-1}, and 467 USD ha^{-1}, respectively, at Site 1, at 290 USD ha^{-1}, 535 USD ha^{-1}, and 739 USD ha^{-1}, respectively, at Site 2, and at 302 USD ha^{-1}, 700 USD ha^{-1}, and 508 USD ha^{-1}, respectively, at Site 3, implying a benefit of the combined application. Although additional labor costs are needed to apply these techniques, the combination of localized micro-dose fertilization techniques can be beneficial for smallholder farmers to grow lowland rice under P-deficient fields in the region. Repeated trials are also important to confirm the individual and interactive effects observed in the present study.

5. Conclusion

This study confirmed a positive effect of nursery bed N and P micro-dosing on seedling vigor, initial biomass production, and grain yields of rice under P-deficient and low-yielding conditions. P-dipping at transplanting, in combination with nursery bed micro-dosing, can be recommended as it replenished the negative P balance and consistently improved grain yields. The positive effects of nursery bed micro-dosing and P-dipping at transplanting were additive, and cumulatively shortened growth durations reduced the risk of cold stress at the reproductive stage on P-deficient and low-yielding farms. These techniques provide a nutrient-efficient management strategy for climate resilience in transplanted rice production systems in SSA.

CRediT authorship contribution statement

Yasuhiro Tsujimoto and Atsuko Tanaka conceived and designed the experiments, analyzed data, and wrote the original manuscript. Atsuko Tanaka and Tovohery Rakotoson performed the experiments. All authors have read and approved the final manuscript

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Declaration of Competing Interest

The authors have declared that no competing interests exist.

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Appendix A. Supplementary data

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Effects of fertilizer micro-dosing in nursery on rice productivity in Madagascar

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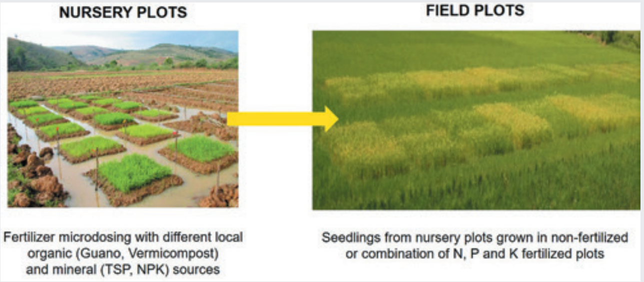
ABSTRACT

Currently, most rice farmers in the central highlands of Madagascar do not apply mineral fertilizer in their fields and we investigated whether a fertilizer micro-dose applied to the seedling nursery could serve as an entry point for intensification. Effects of nursery applications of a micro-dose of mineral (P and NPK) or locally produced sources of fertilizers (Guanomad, Vermicompost) on seedling vigour were evaluated, as was final grain yield after transplanting to main fields that were either not fertilized (farmers' practice) or received combinations of mineral N, P and K fertilizer. Applying only P to the nursery had minor effects and we conclude that early seedling vigor is more limited by N than P, while grain yield in the main field was more limited by P than N. Carry-over effects of the nursery application of NPK and of guano on final grain yield were observed under farmers' practice and when only urea was applied. The nursery NPK application significantly increased agronomic nitrogen use efficiency of urea application. We conclude that the low cost of micro-dosing NPK in the nursery makes this a profitable option for small-scale farmers cultivating rice on poor-fertility soils. Sole urea application in the main field is not a profitable option but would at least need additional nursery NPK application as an insurance against losing investments in N fertilization. Longer-term sustainability would require direct nutrient inputs into the main plot and additional low-cost nutrient management options should therefore be considered.



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Introduction

Rice yields in sub-Saharan Africa (SSA) are currently low and limited fertilizer inputs combined with the poor nutrient supplying capacity of soils are key factors limiting rice productivity. P deficiency is one major stress (Dogbe et al., 2015; Saito et al., 2019) caused by its poor mobility in soils as P is rapidly bound as a result of fixation/adsorption reactions with Fe and Al oxyhydroxide minerals in soils (Nishigaki et al., 2019). Farmers in SSA are generally smallholders and lack financial means to purchase adequate quantities of mineral fertilizers that could alleviate P deficiency and improve grain yields. Although a strong relationship between agriculture production and the availability of credit to farmers has been established for SSA (Akinkunmi, 2017), the lack of appropriate credit facilities and high interest rates still remain a constraint (Africa Rice, 2011). As a result, fertilizer application rates remain low and for Madagascar, the 3rd largest rice producer in Africa, annual fertilizer application rates on cropland were estimated to be as low as 8.7 kg N ha^{-1}, 1.1 kg P_2O_5 ha^{-1} and 1 kg K_2O ha^{-1} in 2017 (FAOSTAT, 2019).

Recommended fertilizer application rates are often high and pose a rather large cost for smallholder farmers in SSA. Micro-dosing fertilizers may represent an alternative and for rice, options exist to do so in the seedling

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Supplemental data for this article can be accessed here.

nursery, where seedlings are raised before transplanting, as well as in the main field. The application of a micro-dose of P in the nursery bed can improve seedling growth was shown to have a carry-over effect on grain yield of transplanted rice under P deficient conditions (Vandamme et al., 2016). This strategy consists of concentrating small rates of P fertilizer in the densely planted nursery. The high density of seedlings assures applied fertilizer is in close proximity to roots and therefore nutrient uptake is optimized, unlike in the main plot where larger spacing between rows reduces contact between roots and broadcast fertilizer. This method had been developed to increase crop productivity at low fertilizer rates (Valluru et al., 2010), and increased rice grain yields are an effect of vigorous seedling growth and an accumulation of nutrients in these seedlings (Ros et al., 2003; Vandamme et al., 2016). Since P uptake of rice can start as early as 2 days after germination (Julia et al., 2018), P is expected to rapidly accumulate in seedlings and excess stored P may give seedlings a boost in growth after they were transplanted into a low-P main field.

A second reason to consider micro-dosing of P stems from the fact that P fertilizer prices are predicted to increase in the coming years because of the decrease in world reserves of high-quality rock phosphates, which are the non-renewable resource from which P fertilizers are made (Cordell et al., 2009). It is clear that such a situation calls for alternatives to blanket recommendations of mineral P fertilizers at high doses, especially in the context of smallholder farmers in SSA. However, as far as we are aware, studies related to P micro-dosing in the nursery bed have all focussed on the effect of P when combined with NK application, without considering sole effects of P or combined effects with fertilizer management in the main field. Phosphorus deficiency is often associated with other macronutrient deficiencies both at nursery and field scales in SSA (Saito et al., 2019; Tsujimoto et al., 2019) and these potential effects should be considered when evaluating the efficacy of micro-dosing P in the seedling nursery.

Consequently, we follow two main objectives in this field study conducted in the lowland rice system in central Madagascar: i) we investigate the effect of micro-dose P applications of different mineral and local P sources to the nursery on seedling vigor and subsequent crop performance in an unfertilized main plot (not applying fertilizers to fields is current farmers' practice on about 80% of the lowland rice area in Madagascar (Tsujimoto et al., 2019)); and ii) to extend this analysis to include different blanket fertilizer applications to the main plot.

Materials and methods

Field sites

The experiments were conducted in three different paddy fields located in Behenjy 1 (19°10′46.5312 S, 47°29′49.3872″ E, 1361 m elevation), in Behenjy 2 (19°10′47.71″S, 47°29′37.46″E, 1376 m elevation) and Antohobe (19°46′41.016″S, 46°41′59.99″E, 1238 m elevation) in the Vakinankaratra Region in Madagascar. Temperature conditions for each experiments are as follows (average/average minimum/average maximum): 21°C/16°C/28°C for Behenjy 1; 23°C/19°C/30°C for Behenjy 2 and 22°C/18°C/29°C for Antohobe. Selected soil physical and chemical characteristics of composite samples (0–20 cm depth) from the three fields are shown in Table 1. All three fields can be considered P-deficient based on soil extractable resin-P values below 19 mg P kg^{-1}, which is considered the threshold necessary to produce 80% of the biomass achievable under P-sufficient conditions (Six et al., 2013).

Experiments

Experiments were conducted over two seasons under irrigated lowland conditions. In year 1 rice was grown between October 2016 and May 2017 at the Behenjy 1 site, and in year two at the Behenjy 2 and Antohobe sites, again between October 2017 to May 2018. In the nursery, rice was grown for 30 days without any fertilization applied (control or nCt), application of sole 6 g P m^{-2} soil as Triple Superphosphate (nTSP), Guanomad (nGN), Vermicompost (nVC) or NPK fertilizer (nNPK) in two replications (Table 2).

Nursery plots were ridges of 1 m^{2} area per treatment elevated 20 cm above irrigation/drainage furrows. Watering was done with a watering can during the initial

Table 1. Selected soil characteristics of fields Behenjy 1, Behenjy 2 and Antohobe. Values are mean of 4 replicates and standard deviations are between brackets.

	Behenjy 1	Behenjy 2	Antohobe
pH^{a}	4.59 (0.07)	4.13 (0.06)	4.15 (0.06)
Organic C^{b} (g kg^{-1})	17.17 (1.07)	22.08 (0.97)	26.25 (1.97)
Resin P^{c} (mg kg^{-1})	5.33 (2.26)	1.75 (0.22)	2.84 (0.42)
Oxalate P^{d} (mg kg^{-1})	80.80 (13.21)	59.32 (17.93)	57.84 (15.78)
Total N^{e} (g kg^{-1})	1.25	1.60	1.11
Exchangeable K^{f} (cmol kg^{-1})	0.04	0.04	0.08
Clay^{g} (%)	29.92 (0.45)	30.65 (3.04)	36.10 (1.30)
Silt^{g} (%)	47.10 (1.26)	33.26 (6.14)	21.04 (1.33)
Sand^{g} (%)	22.98 (0.80)	36.09 (3.85)	42.86 (1.93)

[a]Measured in a 1:5 (weight/weight) soil suspension of 0.01 M $CaCl_2$. [b]Measured with Walkley and Black method (Walkley & Black, 1934). [c]Extracted with anion exchange membrane. [d]Extracted by ammonium oxalate (Schwertmann, 1964). [e]Method adapted from Rabeharisoa et al. (2012). [f] Extracted with cobaltihexamine chloride (Aran et al., 2008). [g]Pipette method.

Table 2. Nutrients (N, P and K) application rates with different fertilizer treatments in nursery for the three different sites.

	Nutrient application rates (g m^{-2})								
	Behenjy 1			Behenjy 2			Antohobe		
Nursery Treatments	N	P	K	N	P	K	N	P	K
nCt	0	0	0	0	0	0	0	0	0
nTSP	0	6	0	0	6	0	0	6	0
nVC[$]	30.5	6	8.2	25.8	6	14.5	25.8	6	14.5
nGN[$]	2.6	6	1.9	0.7	6	0.3	0.7	6	0.3
nNPK	6.9	6	8.3	8.6	6	8.6	8.6	6	8.6

[$] C:N ratio of VC is 12.6 (±2.7) and GN is 2.37 (±1.48) (internal database)

2 weeks of seedling establishment, and by furrow irrigation (not submerging the plots) until transplanting. The amendments and fertilizers were crushed to powder, mixed well with about 1 kg of the hand-crushed surface soil from each nursery plot in a plastic cuvette and then uniformly applied. After that, nursery beds were wetted and 60 g (2200 seeds m^{-2}) of pregerminated (for nRB, nGN, nVC) and non-germinated (for nTSP and nNPK) seeds of X265 variety were sown and covered with a fine layer of hand-crushed soil and dry grass. Using pre-germinated seeds was supposed to compensate for the delayed nutrient release because inorganic fertilizers nTSP and nNPK release their nutrients fast while the release is expected to be slower for the three organic amendments. At 30 days after sowing (DAS), seedlings were transplanted to the main field. On the same day, seedlings (shoot and root) were sampled from three different 10 cm x 10 cm squares of each nursery plot. First, a small shovel was used to excavate the roots by inserting from the top of the ridge to its bottom following the edges of each 10 cm x 10 cm square. Roots were gently pulled together with any sticking soil and shaken gently in the irrigation water to rinse, shoots and roots were separated afterwards. Shoots and roots were further washed with tap water and oven dried at 75°C for 48 hours, and weight recorded. Shoots were ground and analyzed for N concentrations after an overnight extraction with sulfosalicylic reagent and digestion in concentrated H_2SO_4 at 200°C followed by colorimetric analyses in a flow injection analyzer (Skalar) (adapted from Rabeharisoa and al (Rabeharisoa et al., 2012)). Phosphorus concentrations in shoots were analyzed after hot HNO_3 digestion with the molybdenum blue colorimetric method in a spectrophotometer at 882 nm (Murphy & Riley, 1962). Nitrogen and P contents in shoots were calculated from tissue concentration and dry weight.

In the main field, four treatments were applied for Behenjy 1 in year 2017 and that increased to five for Behenjy 2 and Antohobe in year 2018. For Behenjy 1, treatments were control (no fertilizer), P only as TSP at 25 kg P ha^{-1} (57.3 kg P_2O_5 ha^{-1}), NK as urea at 100 kg N ha^{-1} and KCl at 50 kg K ha^{-1} (60 kg K_2O ha^{-1}), and NPK as NPK fertilizer completed with urea and KCl to have 25 kg P ha^{-1}, 100 kg N ha^{-1} and 50 kg K ha^{-1}. This experiment in year 2017 was to assess the effect of nursery fertilization on final rice yields in the absence/presence of P with or without NK fertilizer addition. For experiments in year 2018, the no fertilizer control, sole P and NPK additions were as in 2017.Instead of the NK fertilization we applied sole N as urea at 100 kg N ha^{-1} and combined NP as urea at 100 kg N ha^{-1} and TSP at 25 kg P ha^{-1}. Here, nursery treatment effects on final yields under sole N, sole P, combined N and P, and K omission can be evaluated. Treatments were arranged in a split-plot design with field treatments as main plots with 4 replications and nursery treatments as sub-plots randomized within each main plot. Main plots (field treatments) were separated to each other by 50 cm-wide bunds. Main plot size was 6 m x 3 m and contained 6 sub-plots of 3 m x 1 m. Nitrogen and K were split applied at transplanting (basal) and maximum tillering (top-dressed). Irrigation and drainage were done by avoiding inter-exchange of water from plots. Soil was ploughed, submerged with water and subsequently puddled prior to transplanting which was manually done with two seedlings per hill with spacing of 20 × 20 cm between hills. The water level was maintained at 10 cm above the soil surface after transplanting to the harvest. Two weedings were done at 4 and 7 weeks after transplanting with a hand-pushed weeder. At harvest, the maturity date was recorded and panicle and straw of plants excluding borders (one row) were collected with 2.24 m^2 of harvest area per treatment. Panicle and straw weight was recorded after air-drying (~ 14% of samples humidity).

Agronomic efficiency of N application (AEN) in the main field

Agronomic N use efficiency (AEN, g g^{-1}) as the increase in grain yield per kg of fertilizer N input in the main field was compared under different nursery fertilizer treatments in the following equation:

$$\mathrm{AEN} = (Y_{nX-N} - - Y_{nX-Ct})/N_{\mathrm{applied}}$$

where Y_{nX-N} indicates the grain yield when N was applied in the main field – NK and NPK treatments in Behenjy 1 and N, NP and NPK treatments in Behenjy 2 and Antohobe – at a given nursery fertilizer treatment, nCt, nTSP, nVC, nGN or nNPK. Y_{nX-Ct} indicates the grain yield without fertilizer application in the main field under the given nursery fertilizer treatment. N_{applied} refers to the amounts of N rates in the main field that were all 10 g m^{-2} in both NK and NPK treatments in Behenjy 1 and N, NP and NPK treatments in Behenjy 2 and Antohobe.

Economic analyses

Benefits related to the use of different micro-dose P nursery fertilizations were calculated based on fertilizer, labor and seed costs incurred from each nursery and main field treatments for year 2018 in Behenjy 2 and Antohobe. Fertilizer costs, seed cost and paddy price were of 2018. Labor costs included for the nursery: field preparation, fertilizer application, sowing, watering and transplanting. For the main field, labor costs are field preparation, fertilizer application, weeding, harvest, transport and post-harvest tasks.

Statistical analyses

Nursery treatment effects were analyzed across all three sites using a mixed model ANOVA with nursery treatment as a fixed effect and sites and nursery treatment x site interactions as random effects. This was then followed by Tukey HSD post-hoc analyses for nursery treatment means. To analyze carry-over effects of nursery treatments on grain yields in the main plot, two separate analyses were conducted. Since one of our main objectives was to test nursery treatment effects on grain yield under farmer practice (Ct in main field), one separate ANOVA was conducted for just this sub-set of data. This was followed by a split-plot ANOVA with field treatment as main plot and nursery treatment as sub-plot for the entire data set. Tukey HSD post-hoc analyses were afterwards run for group means for both field and nursery treatments. Nursery treatment effect on AEN was analyzed by one-way ANOVA also followed by Tukey HSD post-hoc tests. 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

Seedlings characteristics affected by nursery treatments

Using a mixed model to analyze nursery treatment effects on seedling characteristics showed highly significant nursery treatment effects for all measured parameters at the time of transplanting (P values ranging from $P < 0.001$ for shoot biomass, plant height, leaf number, root number, root:shoot ratio, P uptake and N uptake; to $P < 0.05$ for root biomass, data not shown). Site effects were only significant for traits root number ($P < 0.01$) and leaf number and root: shoot ratio ($P < 0.05$) and the interaction effect of nursery treatment x site was generally not significant. Given that interaction effects were negligible and that seedling characteristics were most strongly affected by nursery treatments, mean nursery effects across sites shall be further investigated.

Nursery application of mineral NPK fertilizer (nNPK) and of compost (nVC) increased seedling shoot biomass relative to the control (nCt) (Figure 1(a)) with NPK application

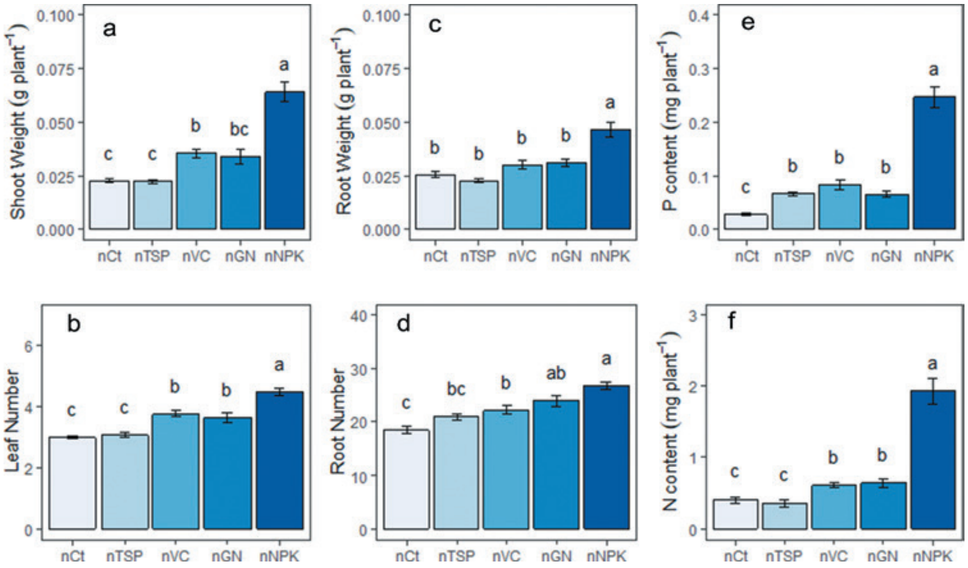

Figure 1. Data from seedlings sampled on the day of transplanting (30 days after sowing): shoot weights (a) and leaf number (b) root weights (c) and number (d), P (e) and N (f) contents of seedlings from nursery plots affected by different types of fertilizers. Values are mean of all three fields (n = 6), error bars are standard errors and letters represent significant differences between nursery treatments within each field treatment. For shoot weight was log-transformed and square-root transformed for P content and N content and the statistical analysis performed on the transformed data. Nursery mean data shown is non-transformed data.

having the most pronounced effect (2.8 times increase over nCt). Application of phosphate fertilizer only (nTSP) and of guano (nGN) had no effect on shoot biomass. Very similar effects were observed for leaf number (Figure 1(b)), indicating nursery fertilization increased seedling biomass partly through speeding up plant development. For root biomass (Figure 1(c)), only seedlings with nNPK had significantly bigger roots compared to the control treatment with nNPK increasing root biomass by 69%. In terms of seedling root number (Figure 1(d)), nTSP had no effect compared to the control with other treatments increasing root number by 20, 29, or 45% for nVC, nGN and nNPK, respectively. The strong nursery treatment effects on biomass are reflected by similar effects on seedling shoot P and N content (Figure 1(e,f)). The increases in P and N content were most pronounced in the nNPK treatment (> 400%), while compost and guano also significantly increase P and N content over control but to a lesser extent. Supplying TSP to the nursery had a positive effect on P content only but the soluble P was apparently not better in supplying P compared to the organic P sources.

Grain yields affected by nursery and field treatments

Figure 2 shows combined effects of nursery treatments and main field fertilization on grain yield for the Behenjy experiment in 2017. Relative to the main plot control without any fertilizer application (Ct), significant yield increases were observed for the NK and NPK treatments. While applying only P had no significant effect, the application of P when N and K were present had a significant and large effect (+50% for NPK compared to NK). Average effects of nursery treatments (across main plots) were detected and showed that all nursery treatments resulted in significantly improved grain yield compared to nCt, with advantages ranging from 10% for nTSP to 22% for nNPK (Table 3). A further breakdown of nursery effects within main plots only detected significant effects for the NK main plot treatment, where the nNPK and guano additions had lasting effects relative to no additions in the nursery (Figure 2).

Main plot fertilization and nursery treatments furthermore affected crop maturity that ranged between 154 days (NPK) and 166 days after sowing in the control without fertilizer application (suppl Fig. S1). Thus, the lack of fertilizer application delayed maturity by up to 12 days and this was mostly attributable to the lack of P, as the NK treatment showed a delay of 11 days compared to only 5 days in the P treatment. Average nursery effects were smaller and not detectable when P was applied in the main plot (P or NPK). However, in the absence of main plot P application (Ct, NK) a nursery application of NPK was able to reduce the delay in maturity by 11–13 days.

The effect of nursery treatment and field treatment on grain yield is shown in Figure 3 for the two sites used in 2018. Main plot and sub-plot (nursery treatments) were highly significant at both sites, while the interaction term was only significant in Antohobe. In both sites, highest yields were achieved with NPK fertilizer followed by NP and P treatments. In these three higher yielding treatments nursery effects were not significant. This changed for the lower yielding N treatment where the nursey application of NPK significantly increased yields

Table 3. Year 1 (2017) grain yield affected by nursery treatments across field treatments. Values are mean of nursery treatments (n = 16) with standard deviations between brackets.

Nursery Treatments	Grain yield (g m^{-2})
nCt	353^{c} (139)
nTSP	391^{b} (147)
nVC	405^{ab} (158)
nGN	423^{ab} (149)
nNPK	437^{a} (152)

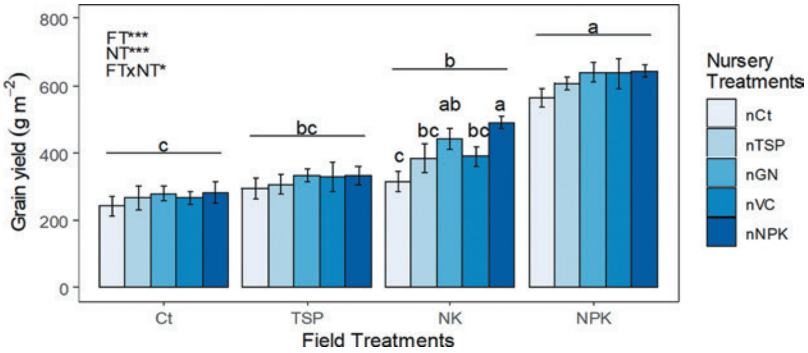

Figure 2. Year 1 (2017) grain yield affected by nursery and field treatments in Behenjy 1 site. Values are mean of 4 replicates and error bars represent standard error of mean. Different letters above lines represent significant difference between field treatments. Significant differences between nursery treatments within field treatment are indicated by different letters. NT: nursery treatment, FT: field treatment, NTxFT: interaction nursery and field treatments. *: p-value < 0.05, **: p-value < 0.01 and ***: p-value < 0.001.

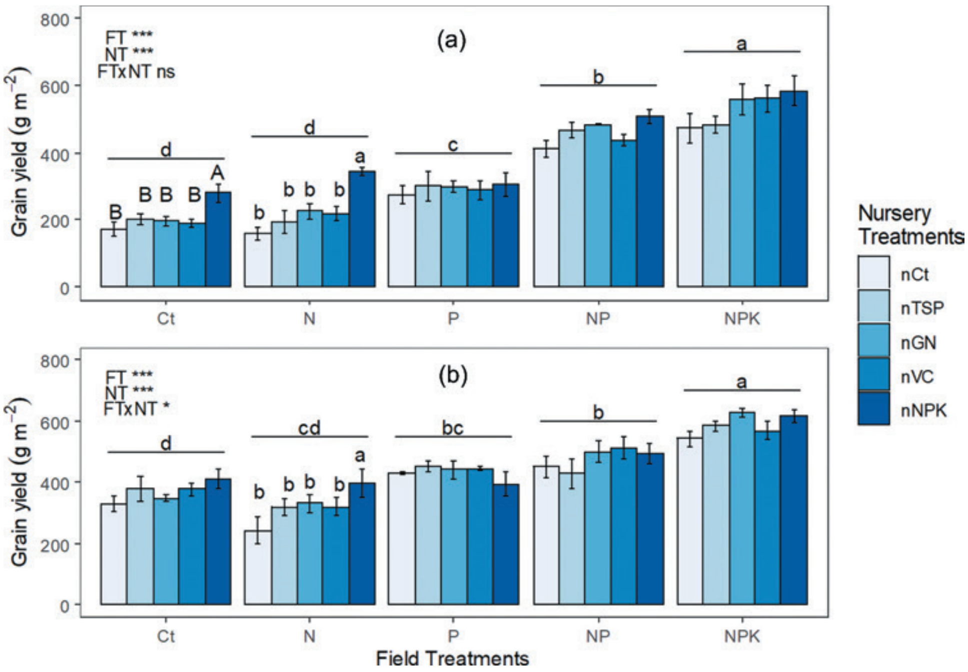

Figure 3. Year 2 (2018) grain yield affected by nursery and field treatments in Behenjy 2 (a) and Antohobe (b) sites. Values are mean of 4 replicates and error bars represent standard error of mean. Different letters above lines represent significant difference between field treatments. Significant differences between nursery treatments within field treatment are indicated by different letters. Significant differences between nursery treatments within Ct treatment only are indicated by different capital letters. N T: nursery treatment, FT: field treatment, NTxFT: interaction nursery and field treatments. ns: not significant, *: p-value < 0.05, **: p-value < 0.01 and ***: p-value < 0.001.

compared to the nCt control (no application in nursery). When no fertilizer was applied to the main plots, the nursery NPK application improved yield in Behenjy (Figure 3A). However, this effect only became significant in an ANOVA testing nursery effects within the Ct main plot in Behenjy 2 but not in Antohobe (Figure 3B). This may be related to the higher general soil fertility in Antohobe where yields in Ct plots were 50% higher compared to Behenjy. As in year one, a delay in maturity of 15 to 17 days relative to the NPK treatment was observed in main plots not having received any P fertilizer (Ct and N treatments) (Figure S2). Nursery effects on reducing the delayed maturity were not detected in year 2.

Agronomic efficiency of N application (AEN) in the main field affected by nursery treatment

Because nursery treatment effects on grain yields were only significant in NK (Behenjy 1) or N (Behenjy 2 and Antohobe) applications in the main field (Figures 2 and 3), AEN values as affected by nursery treatments were compared for the NK plots in Behenjy 1 and N plots in Behenjy 2 and Antohobe (Table 4). In Behenjy1, the small amount of NPK application to the nursery (nNPK) significantly increased AEN in the main field from 7.3 to 20.8 kg kg^{-1}. For the other sites, nNPK tended to produce higher AEN values than nCt while differences were not statistically significant.

Table 4. Agronomic efficiency of N field application (NK for Behenjy 1 in year 2017, N for year 2018 in Behenjy 2 and Antohobe) affected by nursery treatments. Values are mean of 4 replicates, standard deviations are between brackets and letters represent significant differences between nursery treatments for each site. AEN of a given nursery treatment is difference between grain yield of that nursery treatment in the N or NK main field minus that of main field control.

	AEN (g gN^{-1})		
Nursery Treatments	Behenjy 1	Behenjy 2	Antohobe
nCt	7.3^{b} (2.6)	−1.4^{a} (3.6)	−8.7^{a} (5.8)
nTSP	11.7^{b} (2.4)	−0.9^{a} (2.3)	−6.1^{a} (6.1)
nVC	12.3^{b} (1.5)	2.9^{a} (2.8)	−5.8^{a} (4.7)
nGN	16.4^{ab} (1.9)	3.0^{a} (2.3)	−1.7^{a} (2.8)
nNPK	20.8^{a} (2.5)	6.4^{a} (3.8)	−1.5^{a} (2.9)

Economic benefits

In order to calculate benefits of nursery and main plot fertilizer options, we have calculated the general costs of rice production that occur irrespective of fertilizer application such as costs for seed or labour for nursery and main plot activities, and we calculated the specific costs of fertilizer application in the nursery or main plot. General costs amount to an equivalent of 397 US$ ha^{-1} (Table 5, nCt/Ct treatment combination). These include 14 US$ ha^{-1} for seeds, from labour costs of 41 US$ ha^{-1} (28.5 man days ha^{-1} at 1.45 US$ day^{-1}) for the nursery preparation and maintenance plus 342 US$ ha^{-1} (236 man days ha^{-1} at 1.45 US$ day^{-1}) for the main field operations from land preparation to transplanting, weeding and harvesting. Specific additional costs of nursery and main plot fertilizer applications were added to these general costs for each treatment combination (Table 5). Nursery fertilizer additions generally incur a negligible labour cost of 2 US$ plus rather small fertilizer costs of between 12 and 27 US$, with the exception of compost application (VC: 344 US$). Main plot costs are due to 14 US$ for labour in applying fertilizers and fertilizer costs of between 98 US$ (TSP only) to 310 US$ ha^{-1} for NPK. When nursery and main plot costs are combined, treatments with nursery application of VC across main plot treatments cost on average 1.6-times more compared to other nursery treatments.

For the calculation of economic benefits of different treatment combinations, we estimated the market value of the harvested rice (0.54 US$ kg^{-1}) and subtracted the cost listed in Table 5. Benefits from the farmers practice of not applying any fertilizer to nursery nor main plot (nCt/Ct) amount to 499 US$ ha^{-1} at Behenjy 2 and that increases to around 2000 US$ ha^{-1} for the NPK application in the main plot, with the NP treatment being a close second (Figure 4). In the more fertile Antohobe site, farmers' practice incurs a benefit of 1320 US$ ha^{-1} and that almost doubles to about 2200 US$ ha^{-1} when

Table 5. Year 2 (2018) total costs for each nursery/field treatments combination for Behenjy 1 and Antohobe fields. NT: nursery treatment, FT: field treatment.

			Labor costs		Fertilization costs		Total costs
NT	FT	Seed costs	Nursery	Field	Nursery	Field	(US$ ha^{-1})
nCt	Ct	14	41	342	0	0	397
	N	14	41	356	0	116	527
	P	14	41	356	0	98	509
	NP	14	41	356	0	214	625
	NPK	14	41	356	0	310	721
nTSP	Ct	14	43	342	12	0	410
	N	14	43	356	12	116	541
	P	14	43	356	12	98	523
	NP	14	43	356	12	214	639
	NPK	14	43	356	12	310	735
nVC	Ct	14	43	342	344	0	742
	N	14	43	356	344	116	873
	P	14	43	356	344	98	855
	NP	14	43	356	344	214	971
	NPK	14	43	356	344	310	1067
nGN	Ct	14	43	342	21	0	419
	N	14	43	356	21	116	550
	P	14	43	356	21	98	532
	NP	14	43	356	21	214	648
	NPK	14	43	356	21	310	744
nNPK	Ct	14	43	342	27	0	425
	N	14	43	356	27	116	556
	P	14	43	356	27	98	538
	NP	14	43	356	27	214	654
	NPK	14	43	356	27	310	750

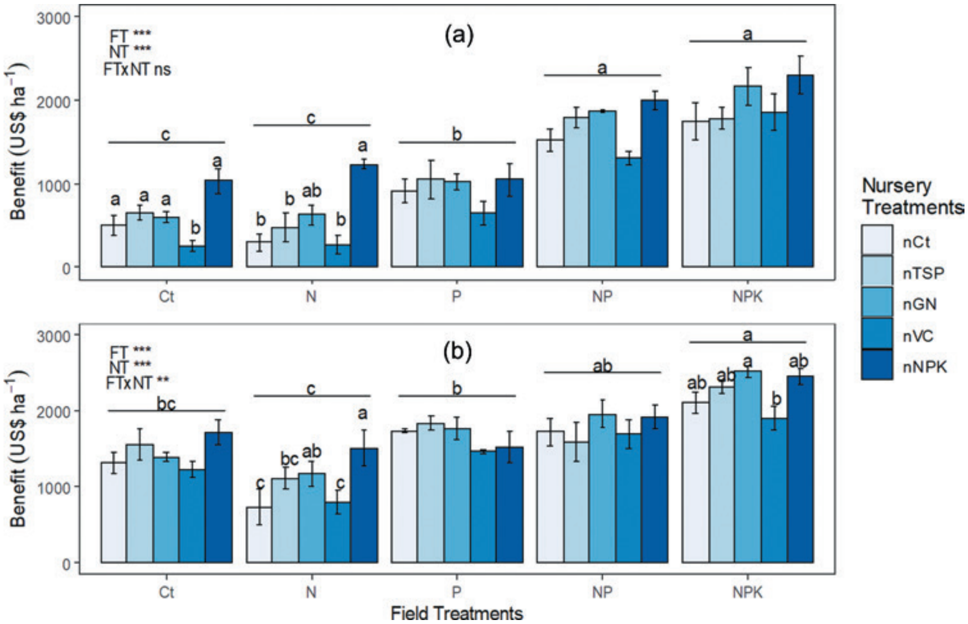

Figure 4. Year 2 (2018) benefits (US$ per hectare) affected by nursery and field treatments in Behenjy 2 (a) and Antohobe (b) sites. Values are mean of 4 replicates and error bars represent standard error of mean. Different letters above lines represent significant difference between field treatments. Significant differences between nursery treatments within field treatment are indicated by different letters. NT: nursery treatment, FT: field treatment, NTxFT: interaction nursery and field treatments. ns: not significant, *: p-value < 0.05, **: p-value < 0.01 and ***: p-value < 0.001.

NPK is applied in the main plot. Nursery applications of fertilizers had minor effects, but application of the expensive compost tended to suppress economic benefits. Surprisingly, sole N application in the main field resulted in overall low economic benefits and that could only be reversed when NPK was applied in the nursery. When nursery treatment effects were analyzed for the main plot farmers' practice (Ct) alone, nursery NPK treatment increased benefits in the low-fertility site (Figure 4(a)), but not in the more fertile site.

Discussion

Most rice in Central Highlands of Madagascar is produced without addition of inorganic fertilizers (> 80%, (Tsujimoto et al., 2019)) and average national rice yields are below 3 t ha^{-1} (USDA, 2020). Some intensification is therefore desirable and a main objective of this study was to evaluate fertilizer micro-dosing options in the nursery since this has been reported as effective in studies from Benin and Tanzania (Vandamme et al., 2018, 2016).

Effects of micro-dosing in the nursery on seedling vigor and final grain yield

Across all three sites the NPK treatment produced by far the most vigorous seedlings. Applying only TSP did not improve seedling growth markedly in contrast to the NPK treatments, suggesting that seedling growth was more limited by N than P. This is likely due to seed reserves of N being exhausted earlier compared to P reserves, coupled with the inability of the soils in the nursery to supply either N or P in sufficient quantities. As a result, the application of P alone (as TSP) had no positive effect on seedling vigour and, surprisingly, only marginal effects on P uptake. Thus, the objective to load seedlings with P as a reservoir to be used for boosting crop growth following transplanting was not achieved by the TSP application. NPK application fulfilled above objective well while locally available sources GM and VC having effects comparable to TSP. NPK supplied seedlings had 90% higher root growth compared to TSP supplied seedlings yet P and N uptake increased by 300% (compared to nTSP; Figure 1). Thus, better root growth can only partly explain the high nutrient uptake in NPK supplied seedlings and it is possible that this uptake was also driven by higher demands of more rapidly growing seedlings, at least compared to the equally soluble TSP. In case of organic sources, solubilization rates may have been an additional factor, especially for VC with more than 3-fold higher total N content compared to NPK.

Farmers' practice in the study area of the central highlands of Madagascar is to not apply any mineral fertilizer to rice (Tsujimoto et al., 2019) and one objective of the present study was to evaluate whether a micro-dose of fertilizer to the nursery may offer an entry point to intensification in this system. Considering the consistently positive effect of NPK application on seedling vigour in the nursery and the importance of this trait in transplanted rice (Ros et al., 2003; Sarwar et al., 2014), we expected carry-over effects on grain yield in the unfertilized main field. However, these were not consistent across sites being low and not significant in Behenjy 1 (+16.4% over the farmer's practice) (Figure 2) and Antohobe (+25.1% over the farmer's practice) but rather pronounced in Behenjy 2 (+62.8% over the farmer's practice) (Figure 3). Studies conducted elsewhere in Africa (Ros et al., 2003; Vandamme et al., 2016) reported micro-dosing P to the nursery increased grain yield by 30–40%, which is in the range of the nNPK effects but would contradict the insignificant effect of sole P application seen here. Yet above studies estimated P effects in the comparison on nursery NK vs. NPK application, not the effects of sole P application. It is therefore likely that benefits arose from combined P and N effects similar to the NPK effect reported here.

Application of NPK to the seedling nursery incurs very low costs (27 US$ ha^{-1}, Table 5) yet leads to increased economic benefits compared to current farmers practice by up to 500 US$ (Behenjy 2, Figure 4). Even where yield increases were small and not significant, benefits remained positive. The risk associated with nursery NPK applications, therefore, seems negligible while benefits can be substantial and we conclude that nursery application of NPK, but not TSP, is economically recommendable. It is likely that a similar positive effect could be achieved by the nursery addition of Diammonium phosphate (DAP), however NPK offers advantages over DAP in terms of lower cost with 0.6 US$ kg^{-1} for the first against 0.8 US$ kg^{-1} for the second one. Locally produced fertilizers were either too costly as in case of VC, or did not show benefits under current farmers practice (GN). Given the low cost of GN, an increase in nursery application rates is feasible and whether these would produce positive grain yield effects should be studied further.

Effects of micro-dosing in the nursery versus fertilization in main field

Our second main objective was to compare micro-dosing in the nursery to macro-dosing fertilizers in the main field. It was obvious that the application of NPK in the main field was the best option across sites in terms of increasing grain yield, as well as in terms of maximizing economic benefits. This is certainly not a novel result as similar fertilizer recommendations have been around for decades. They have more recently been reconfirmed for the Madagascar highlands (PAPRiz, 2015). Despite the strong evidence in support of NPK fertilization, farmers have not adopted this technology and in absence of major policy changes making the adoption of fertilizer application a national priority, it is likely that current practices will continue. Relatively high costs and poor availability of sufficient quantities of NPK fertilizers at the local level represent persistent bottlenecks.

For sub-Saharan Africa (SSA), Vandamme et al. (2018) suggested P micro-dosing as an entry point to sustainable intensification for rice. They also reported urea application being common practice for lowland rice in Tanzania. Whether this would be an additional intensification option for Malagasy farmers shall be discussed. The relatively low cost of 116 US\$ ha^{-1} for urea compared to 310 US\$ ha^{-1} for NPK would explain why urea application is often the first intensification option adopted by farmers. However, our results clearly indicate that the application of only N in the main field is neither agronomically nor economically viable because the agronomic efficiency of N application (AEN) was either very low (7.3 kg kg^{-1}, Behenjy 1, Table 4) or even negative. This likely indicates that grain yields were more limited by P than by N and that the delay in heading brought about by N application in the absence of P can even have negative effects on grain yield in the highlands of Madagascar. The low AEN of the urea-only treatment could be improved through nursery NPK application at all three sub-experiments but only in Behenjy 1 did they reach acceptable levels of 20.8 kg kg^{-1}. We therefore conclude that sole urea application is not a sustainable option on highly P deficiency soils in Madagascar, and that if urea is applied, the additional nursery NPK application would be needed as an insurance against the loss from investing in N fertilization. It should be also noted that maximum returns with minimal inputs with micro-dosing to the nursery have a risk of nutrient mining. Thus, while the nursery NPK application with its very low costs can be recommended as an entry point to intensification for rice in the central highlands of Madagascar, longer-term sustainability would require direct nutrient inputs into the main plot and additional low-cost nutrient management options should therefore be considered.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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REGULAR PAPER, AGRONOMY & CROP ECOLOGY

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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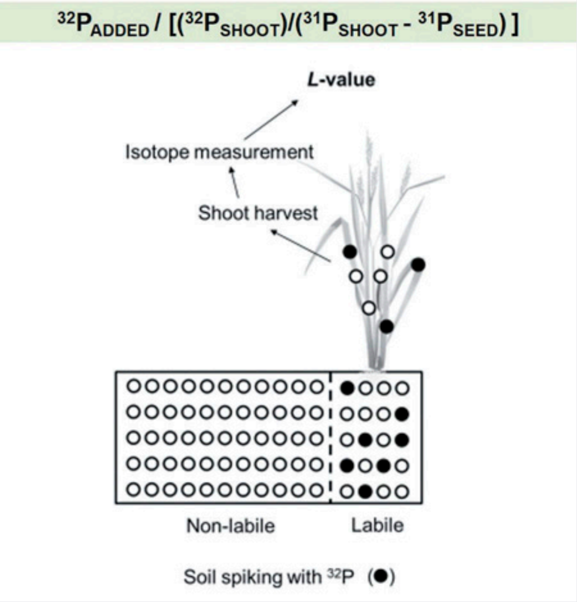
ABSTRACT

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_{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_{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.



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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.,

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2019) and little 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 (P_{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 P_{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 P_{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 P_{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, P_{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, P_{Ox}, and pH (Table 1). The soils were also characterized by high contents of oxalate extractable iron (Fe_{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[a]	TotC (g kg^{-1})[b]	P_{Ox} (mg kg^{-1})[c]	pH[d]	Fe_{Ox} (g kg^{-1})[c]	Estimated P deficiency level[e]
1	Antanetikely (−19°41′11″, 46°35′34″, 1110 m)	Rice-upland crop rotation	Gleysol	11.0	38	4.54	9.7	High
2	Sahalombo (−19°51′06″, 47°00′37″, 1492 m)	Rice monoculture	Fluvisol	10.1	704	6.05	14.2	Low
3	Mandriankiheniheny (−19°56′03″, 47°01′09″, 1469 m)	Rice monoculture	Gleysol	28.1	56	4.31	5.9	High
4	Mandriankiheniheny (−19°56′08″, 47°02′35″, 1469 m)	Rice-upland crop rotation	Gleysol	27.2	644	4.84	16.9	Medium
5	Mandriankiheniheny (−19°55′59″, 47°00′59″, 1467 m)	Rice-upland crop rotation	Gleysol	36.4	81	4.84	10.6	Medium
6	Mandriankiheniheny (−19°56′02″, 47°01′50″, 1471 m)	Rice monoculture	Gleysol	39.3	654	5.35	26.7	Low

[a]IUSS Working Group WRB. [b]Dry combustion by NC analyzer (Sumigraph NC-220F, SCAS, Japan). [c]Extracted by ammonium oxalate (Courchesne & Turmel, 2008). [d]Measured in a 1:5 (w/w) soil suspension of 0.01 M $CaCl_2$. [e]Estimated from P_{Ox} and pH (Rabeharisoa 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 NH_4-N and 51.0 mg kg^{-1} of NO_x-N as determined by a flow injection analyzer (AutoAnalyzer3, BL-Tech, Tokyo, Japan) after extracting by 2M KCl solution (Mulvaney, 1996). The C:N ratio and C:P 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 KH_2PO_4, 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 KH_2PO_4. Nitrogen as NH_4NO_3 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 KH_2PO_4 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% HNO_3 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 $^{32}PO_4$ ions (^{32}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}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}P was sprayed onto the soils at a final rate of 11.1 MBq ^{32}P kg^{-1} soil. Then, the soils were thoroughly mixed again. An aliquot from the ^{32}P spike solution was stored and analyzed for total activity to know the exact activity added to each soil. After ^{32}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. Three 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}P and ^{31}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}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}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}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 $^{32}P/^{31}P$ ratio) in aboveground biomass is equal to the *SA* in the labile-P pools in soils (Larsen, 1952):

$$SA_{Plant} = SA_{Soil} \text{ or } \frac{^{32}P_{Plant}}{^{31}P_{Plant}} = \frac{^{32}P_{Soil}}{^{31}P_{Soil}} \qquad (1)$$

$$L = \frac{D}{SA} = \frac{D}{^{32}P_{Plant}/\left(^{31}P_{Plant} - {}^{31}P_{Seed}\right)} \qquad (2)$$

where *D* is the concentration of radioactivity added to the soil (MBq ^{32}P kg^{-1} soil); *SA* is the specific activity in the aboveground biomass (MBq ^{32}P mg P^{-1}); $^{32}P_{Plant}$ is the activity in the aboveground biomass (MBq ^{32}P kg^{-1} soil); $^{31}P_{Plant}$ is the non-radioactive P in the aboveground biomass (mg P kg^{-1} soil); and $^{31}P_{SEED}$ is the ^{31}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.

	Exp.1		Exp.2
Factor	Biomass yield	P uptake	*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.

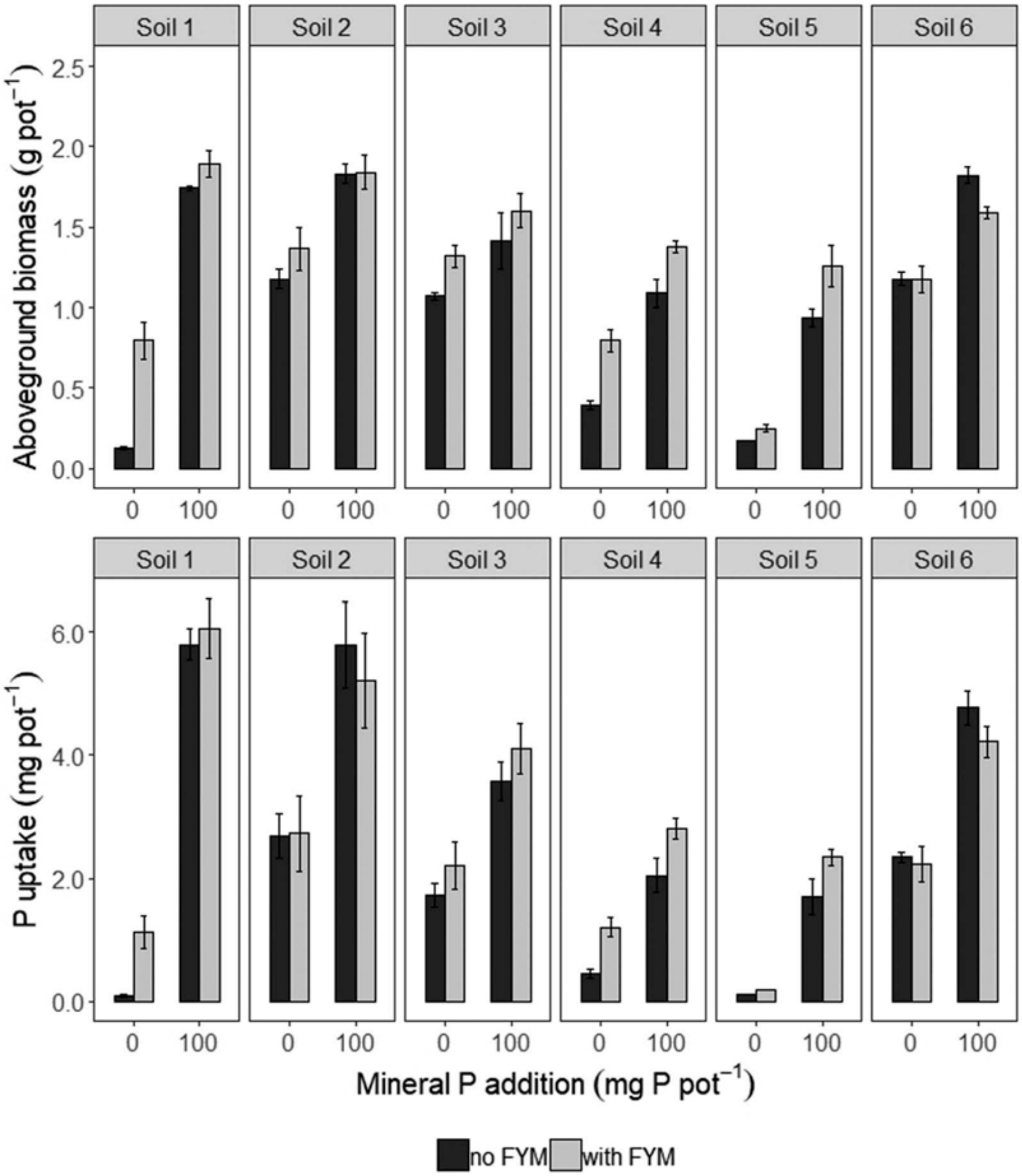

Figure 1. Aboveground biomass and P uptake of rice plants as affected by mineral P and FYM applications for the six soils in Exp.1. Black-colored bars indicate treatment without FYM, and grey-colored bars indicate treatment with FYM. Data are shown as the mean ± standard error.

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 P_{Ox} for the variations in ΔBiomass and ΔPup (Table 3). The

Table 3. Stepwise regression retained parameters related to increases in aboveground biomass (ΔBiomas) and P uptake (ΔPup) of rice plants as affected by FYM and mineral P applications in Exp.1.

	Intercept	P_{Ox}	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^{-1} and 0.65–2.03 mg pot^{-1}, respectively. These increases were more or less equivalent to the values observed with mineral P applications that were 0.37–1.37 g pot^{-1} for Δbiomass and 0.93–3.77 mg pot^{-1} for ΔPup. The increase in P uptake tended to be slightly higher with TSP than FYM, but there were no significant differences.

Table 4. Aboveground biomass, total P uptake without seed P, and *L*-values in Exp.2.

	Biomass (g pot^{-1})	P uptake (mg kg^{-1})	*L*-value (mg kg^{-1})
Soil 1			
Control	1.64^{B} (0.39)	1.76^{C} (0.48)	49.0^{D} (2.3)
FYM	2.81^{A} (0.40)	3.79^{BC} (0.47)	61.6^{C} (2.8)
Mineral P	3.01^{A} (0.39)	5.53^{AB} (0.98)	139.1^{B} (3.5)
Mineral P + FYM	3.27^{A} (0.25)	6.98^{A} (1.53)	234.1^{A} (6.6)
Soil 2			
Control	2.97^{A} (0.19)	6.48^{A} (0.36)	146.8^{C} (4.9)
FYM	3.55^{A} (0.11)	7.60^{A} (0.15)	167.3^{C} (9.1)
Mineral P	2.65^{A} (0.89)	5.20^{A} (2.12)	215.7^{B} (9.4)
Mineral P + FYM	3.59^{A} (0.21)	7.75^{A} (0.90)	315.5^{A} (12.7)
Soil 5			
Control	0.50 C (0.04)	0.34 C (0.03)	67.2^{C} (13.8)
FYM	1.10^{AB} (0.10)	0.99^{B} (0.04)	97.9^{BC} (7.5)
Mineral P	0.81^{BC} (0.04)	1.27^{AB} (0.11)	192.3^{B} (2.8)
Mineral P + FYM	1.43^{A} (0.26)	1.57^{A} (0.18)	346.0^{A} (46.0)

L-value: isotopically exchangeable P which indicates labile P pool in soils. Seed P content was 0.064 mg kg^{-1}. Data are shown as the mean (standard deviation); n = 3. Values with different capital letters indicate significant differences between treatments within each soil sample (Scheffe, $P < 0.05$).

The *L*-values in the control treatment were 49.0, 146.8, and 67.2 mg kg^{-1} 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^{-1}, 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^{-1} – 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^{-1}.

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_{Ox}, 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_{AEM} 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.

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Disclosure statement

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

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RESEARCH ARTICLE

Organic materials with high P and low C:P ratio improve P availability for lowland rice in highly weathered soils: Pot and incubation experiments#

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Abstract

Background: Phosphorus (P) deficiency remains a serious problem for lowland rice cultivation in Sub-Saharan Africa. Locally available organic materials (OM) are potential amendment resources, but they vary widely in nutrient composition. How different OM affect P availability and rice production under different soil types remains poorly understood.

Aims: We aimed to determine soil responses to OM application varying in carbon (C) and P contents on P uptake, rice production, and P availability.

Methods: A pot experiment with eight different soils from lowland rice fields amended with four different farmer-produced OM at an equal dose of 7.5 g kg^{-1} soil; and an incubation experiment with six soils amended with cellulose and two OM applied at the same C dose were conducted.

Results: An OM associated with high P and low C:P ratio increased shoot biomass and P uptake of rice in all soils by two- and threefold, respectively, compared to the control treatment. Low P saturation in soils (low P:Fe in oxalate extract) produced greater OM effects. Shoot biomass and P uptake decreased significantly in one soil with a high P saturation following application of the other three OM. Although increased soil P solubilization was observed with the addition of fresh C, OM effects on P availability were mostly attributed to their direct P supply.

Conclusion: OM with high P and low C:P ratio is effective in improving P availability for rice in P-deficient lowland rice soils.

KEYWORDS
low P saturation, P deficiency, P fertilizer, P solubilization

1 | INTRODUCTION

Phosphorus (P) deficiency remains one of the major limiting factors for lowland rice production in Sub-Saharan Africa (SSA), of which Madagascar is a typical example. Phosphorus deficiency is mainly caused by low plant-accessible P content in soils (Rakotoson et al., 2015) when P is strongly immobilized by high amounts of iron (Fe) and aluminum (Al) oxyhydroxides (Bado et al., 2018; Nishigaki et al., 2021; Nziguheba et al., 2016). Due to poor financial and physical access to mineral fertilizers, smallholder farmers, in most cases, grow rice either without

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fertilizer application or with the application of any available organic resources such as farmyard manure (FYM) or compost (Tsujimoto et al., 2019).

To date, a few of studies have focused on strategies to overcome the problem of P deficiency for lowland rice production, in particular by exploring the potential benefits of locally available organic resources. Although FYM application reportedly increases P availability in irrigated rice (Andriamananjara et al., 2016), Rakotoson and Tsujimoto (2020) found that the extent to which an increase in P availability led to an increase in biomass and yield was highly dependent on the soil characteristics. Farmers in SSA, including Madagascar, utilize extensive organic resources for fertilization, which affect crop production differently depending on various soil factors. In Madagascar, Rakotoarisoa et al. (2016) reported that farmers do not buy manure, instead use the organic manure from their cattle, pigs, poultry, or rabbit. To our knowledge, no studies have investigated the potential effects of the characteristics of these organic resources, such as their content of P or other elements such as carbon (C); the effect of organic material (OM) application would naturally depend on such characteristics (Vanden Nest et al., 2014).

OM applied to submerged soils can have two distinct actions on P availability: (1) C effect, C affecting microbial activity and consequently the redox reactions that lead to solubilization of fixed-P, and release of organic anions that prevent P sorption (Fink et al., 2016; Khan et al., 2019; Rakotoson et al., 2014); and (2) P effect, P addition through mineralization of organic P and also from inorganic P (Almeida et al., 2019; George et al., 2018). These findings confirm the importance of C and P from OM, which would be as important as other soil factors that govern the redox mechanisms and consequently affect soil P dynamics in submerged soils (Gross et al., 2020). In soils with limited P availability, P released into the soil solution under anoxic conditions can be used by soil microbes and plants (Bonneville et al., 2004). Nevertheless, Asai et al. (2021) recently observed some reduction in P uptake following the application of FYM to soils with high oxalate extractable-P (Pox); however, they did not determine the underlying mechanisms.

Regarding soil factors that may modify the effects of OM, Nishigaki et al. (2019) established that P deficiency of lowland soils in the central highlands of Madagascar varies largely among different fields; thus, there is a need for field-specific fertilization management. Rakotoson and Tsujimoto (2020) attempted to identify the relationships between soil characteristics and OM effects; and reported that soils with low C and low pH soils are more responsive to OM application, in terms of biomass production and P uptake of rice compared to soils with higher C and pH. In their study, Pox, total carbon content (TotC), and pH were useful parameters for predicting the OM effect. In addition, some other soil characteristics could separately or in combination be more important. Tropical soils are characterized by a high concentration of P-bearing (fixing) Fe and Al oxyhydroxides, either in an amorphous or a crystalline form (Zhang et al., 2003). As stated earlier, OM decomposition and dissolution favor P solubilization (Fink et al., 2016; Guppy et al., 2005). The amount of P associated with amorphous Fe oxides or Pox determines the amount of dissolved P (Scalenghe et al., 2010). The molar ratio of oxalate-extractable P and oxalate-extractable Fe (Pox:Feox) in soils, which describes the P saturation of the surface sorption site for amorphous Fe (Wuenscher et al., 2015), is an important factor controlling the dissolved P concentration in the soil solution. However, Amery and Smolders (2012) suggested that the soil cation exchange capacity (CEC) is a factor influencing P release in submerged soils. Lastly, soil clay has been shown to have a positive relationship with P fixing capacity but to a lesser extent than did the other soil factors mentioned earlier (Gérard, 2016; Nishigaki et al., 2021). However, it remains unknown how the different characteristics of OM applied to the system would affect the abovementioned mechanisms.

Within the context of OM management and practice by smallholder farmers, the objectives of this study were (1) to determine the soil responses to the application of OM, with various C and P contents, in terms of P uptake and rice production; (2) to confirm what are the most influential soil factors related to the OM effects; and (3) to assess the magnitude of P solubilization and P availability in waterlogged soil as a result of single C versus combined C and P applications. A pot experiment with a factorial design of different soils and OM was carried out to achieve the first two objectives, where P availability and rice production were assessed as P uptake and aboveground biomass, respectively. The third objective was assessed in a soil incubation experiment using selected soils and OM from the pot experiment plus cellulose as a single C source for the evaluation of the soil-level mechanism.

2 | MATERIALS AND METHODS

2.1 | Soils and OM characteristics

Eight surface soils (0–15 cm) were collected from different rice paddy fields in the Central Highlands of Madagascar from the region of Vakinankaratra (Tables 1 and Table S1). The total C content and CEC of soils had a large variation ranging from 1.02% to 7.45% and from 3.42 to 14.24 $\text{cmol}_c\ \text{kg}^{-1}$, respectively. The soil pH was strongly acidic to slightly acidic. The textures of soils were sandy clay loam, clay, silty clay, and mostly clay loam. The soils had different P saturation ranging from 0.023 to 0.214 of Pox:Feox, the least saturated to the most saturated. The soils were also characterized by the most P-deficient soils (70 mg kg^{-1} of Pox) to soils with high available P (1134 mg kg^{-1} of Pox), and with varied Feox contents from 5.65 to 20.81 g kg^{-1}. Four different OM were used (Table 2). All are produced by and widely used among the local smallholder farmers. OM were classified in terms of C and P contents: low and low for OM1, high and low for OM2, medium and medium for OM3, and high/high for OM4.

2.2 | Pot experiment

A pot experiment was conducted in a greenhouse at the Laboratoire des Radioisotopes in Madagascar; with a full factorial combination of four OM applications and eight soil types, with three replications for each combination. A mineral P treatment (as triple superphosphate) with a dose equal to the highest P dose from the OM (i.e., 61.26 mg

TABLE 1 Physical and chemical characteristics of soils used in the two experiments

Soils characteristics	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 6	Soil 7	Soil 8
Organic C (%)[a]	5.45	7.35	3.69	1.20	3.96	4.88	6.25	7.45
Total N (%)[b]	0.44	0.61	0.41	0.22	0.40	0.49	0.53	0.45
pH ($CaCl_2$)[c]	4.35	4.84	5.01	5.21	4.65	5.21	5.14	4.83
pH (H_2O)[c]	5.55	5.58	6.14	6.45	5.59	6.26	5.99	5.81
Sand %[d]	64.83	23.13	9.85	37.01	38.13	20.69	22.05	32.84
Silt %[d]	12.37	30.09	51.96	32.14	24.43	50.38	43.07	30.25
Clay %[d]	22.80	46.78	38.19	30.85	37.44	28.93	34.88	36.91
CEC ($cmol_c$ kg^{-1})[e]	5.22	4.04	14.24	4.86	3.42	9.68	8.20	5.26
Oxalate-P (mg kg^{-1})[f]	1134	360	399	115	70	428	292	232
Olsen-P (mg kg^{-1})[g]	33.16	5.37	15.19	4.33	4.86	9.31	6.31	6.84
Oxalate-Fe (g kg^{-1})[f]	9.59	8.88	20.81	7.24	5.65	6.56	11.14	7.05
Pox:Feox[h]	0.214	0.073	0.035	0.029	0.023	0.118	0.048	0.060

[a] Walkley and Black method (Walkley and Black, 1934).

[b] Mineralization by sulfuric acid and continuous flow autoanalyzer dosing.

[c] Measured in a 1:5 (weight/weight) soil suspension of distilled water and 0.01 M $CaCl_2$.

[d] Centrifugal liquid sedimentation methods.

[e] Cobalt hexammine (0.1 M) extraction.

[f] Extracted by ammonium oxalate (Schwertmann and Jackson, 1964).

[g] Extracted by 0.5 M sodium bicarbonate (pH 8.5) (Olsen and Khasawneh, 1980).

[h] Molar ratio of oxalate-extractable P to oxalate-extractable Fe.

TABLE 2 Carbon (C) and phosphorus (P) contents of the organic materials used in the pot experiment (OM1, OM2, OM3, and OM4) and incubation experiment (OM2, OM4, and cellulose)

Organic materials	OM1	OM2	OM3	OM4	Cellulose
Compositions	Ashes and garbage[a], plant residues	Dung of zebu[a], straw	Dung of zebu and pig[a], straw	Dung of pig[a], grass	Cellulose
C (g kg^{-1})[b]	41.19	275.30	126.98	281.17	444.44
P (g kg^{-1})[c]	1.42	1.84	4.76	9.29	–
C:P[d]	74.9	386.5	68.9	78.2	–
$C_{applied}$ (mg kg^{-1} soil)	277.74	1792.38	848.07	1853.41	1800
$P_{applied}$ (mg kg^{-1} soil)	9.59	11.98	31.80	61.26	–

[a] More than 80% of dry weight.

[b] Walkley and Black method (Walkley and Black, 1934).

[c] Mineralization by sulfuric acid and continuous flow autoanalyzer dosing.

[d] Molar ratio C:P.

P kg^{-1} soil for OM4; Table 2) was included to assess the P responses of each soil. The soils were air dried, passed through a 5-mm sieve, and placed in 1-L plastic pots (diameter 13 cm and height 15 cm) to 1 kg dry weight per pot. The applied OM dose of 7.5 g air dry weight per kg soil for all four OM was based on the quantity that farmers in the Vakinankaratra region can use on rice, which was similar to what was used by Rakotoson et al. (2015). OM for each pot was ground to a powder, mixed with the soil in a pot, and then tap water was added. Nitrogen (N) and potassium (K) effects were excluded by adding 180 mg N kg^{-1} and 180 mg K kg^{-1} as urea and KCl, respectively, for all treatments

Two 15-day-old seedlings of the X265 variety were grown in sand without fertilizer and were transplanted to each pot under submerged conditions. The water level was maintained at 4 cm by regular addition of tap water. The experiment was performed under the following conditions: a daily temperature of 17–38°C and up to 1628 $\mu M\ m^{-2}\ s^{-1}$ of light. On day 37 after the transplantation, plants were cut at the plant collar and oven-dried at 70°C for 48 h before weighing to evaluate their aboveground biomass. Phosphorus concentration in the shoot was determined by hot nitric acid 69% (HNO_3) digestion (180°C for 4 h), and the total P concentration was measured using the molybdenum blue colorimetric method (Murphy and Riley, 1962) with a spectrophotometer (SP-8001, Metertech Inc.) at 882 nm. Total P uptake (mg pot^{-1}) was calculated by aboveground biomass and P concentration per plot.

2.3 | Incubation trial

The soil incubation experiment was conducted at the Japan International Research Center for Agricultural Sciences, using selected soils and OM from the previous pot experiment but plus an additional treatment: cellulose (C6288 Cellulose fiber, medium) as a single C source. Six representative soils were used (soil 5 and soil 7 were dropped because they had similar characteristics to soils 2, 4, and 8) and two OM with the same C concentrations but different P concentrations were selected (namely, OM2 and OM4). The cellulose and OM were applied at the same doses as in the pot experiment: 7.5 g air dry weight per kg soil. Sieved soil (35 g) was weighed in 50-mL centrifuge tubes. OM and cellulose were added and thoroughly mixed while dry. The mixture was homogenized by adding distilled water and removing the air bubbles. Thereafter, each tube was filled up to the lid level and kept at room temperature (25°C). The incubation was set up in three replications and five sampling times for 45 days.

Total Fe (Tot-Fe) and phosphate (malachite green-P [MG-P]) in pore water, pH in water [pH(H_2O)], and the available P of the soil as Olsen-P were measured at days 1, 8, 21, 33, and 45 after incubation. At each sampling time, the standing water was discarded before the sample was taken. The tube was centrifuged for 15 min at 3080 × g, and the extracted solutions were filtered at 0.45 μm; then 10 μL of 5 M HNO_3 per 5 mL were added. Tot-Fe was measured with an inductively coupled plasma mass spectrometer (ICPE-9000, Shimadzu, Japan). Phosphate in pore water was analyzed by a spectrophotometer (UV-1800, Shimadzu, Japan) using the malachite green colorimetric method (Van Veldhoven et al., 1987). To adjust for possible interference with other anions in the pore water (Novozamsky et al., 1993), phosphate content was expressed relative to the maximum MG-P concentration in all treatments and all sampling points. The remaining wet soil in the tube was used for the measurement of pH(H_2O), which was measured in a 1:5 (w/w) soil suspension of distillate water, and for the concentration of available P by the Olsen extraction method (Olsen and Khasawneh, 1980).

2.4 | Statistical analysis

To evaluate the effect of OM addition for each soil in the pot experiment, the shoot biomass (Δshoot) and P uptake (ΔPuptake) changes were calculated as the difference between control (no OM applied) and OM treatments. The effects of soil and OM were analyzed using two-way ANOVA. Tukey's post hoc test was used for mean comparisons. Ridge regression was used to identify the characteristics of the soil that had significant roles as explanatory variables in Δshoot and ΔPuptake for the applied OM. A linear regression model (1) was used to evaluate the overall OM effect, as either a P source ($P_{applied}$) or C source ($C_{applied}$), on the increases in P uptake and shoot biomass of different soils and different OM:

$$Y = (\beta 0 + \beta 0, Soil) + (\beta 1 + \beta 1, Soil) \times (P_{applied}) + (\beta 2 + \beta 2, Soil) \times (C_{applied}) \tag{1}$$

Soil is a categorical variable with $i = 8$ levels and assigned as soil-specific corrector value (βi, *Soil*), to evaluate the overall effect of the soil and its interaction with the applied P and C. The significance of the intercept for each soil shows whether it differs from the average response of all soils ($\beta 0$, *Soil*), as well as its sensitivity to P application ($\beta 1$, *Soil*) and C application ($\beta 2$, *Soil*). Simple linear regression was used to identify the OM characteristics that were important as explanatory variables for Δshoot and ΔPuptake in each soil.

For the incubation trial, three-way repeated-measures ANOVA was tested to check the influence of treatments, incubation time (days), and different soils on the changes in MG-P and Tot-Fe in pore water, pH(H_2O), and Olsen-P of soil. The mean comparison was evaluated with Tukey's post hoc test.

Statistical analyses were performed using R Software, 4.0.0 version. Ridge regression was done with the package "*ridge*."

3 | RESULTS

3.1 | Pot experiment

3.1.1 | Shoot biomass and P uptake responses to different sources of OM

In the control treatment, the highest shoot biomass was observed in soils S1, S3, and S6 (>2 g) compared to soils S2, S4, S5, S7, and S8 (<1 g). Tissue P concentration indicated that soils S1 (1.9 g kg^{-1}), S3 (2.4 g kg^{-1}), and S6 (1.4 g kg^{-1}) were less deficient in P than were the other soils where plant tissue P concentrations were below 1 g kg^{-1}. Regarding mineral P application, all soils responded positively in terms of shoot biomass, P uptake, and tissue P concentration (Figures S1 and S2), suggesting that they were all P deficient.

Overall, two-way ANOVA showed that the differences in shoot biomass and P uptake by rice plants were greatly influenced by soil characteristics, which explained 81% and 83% of the variance, respectively, against only 9% explained by OM (Table 3; Figure S1). Comparison of soils showed that the highest biomass (two- to sixfold greater) and P uptake (two- to 24-fold greater) were observed in soils S1, S3, and S6, confirming that these soils were more fertile or less P deficient. However, the rice response values (i.e., Δshoot and ΔPuptake) were more influenced by OM types (40% of explained variance) than by soil characteristics (19%; Table 4). Across different soils, mean comparisons revealed that the highest Δshoot and ΔPuptake (with differences of approximately 10- and sevenfold, respectively) were achieved with OM4 or pig dung mixed with grass (having the highest P content but low C:P ratio among the four OM). No significant difference was detected between the other three OM across the different soils.

TABLE 3 Average shoot biomass (g) and P uptake (mg) across OM for each soil of the pot experiment, for each soil combination. Values are means of treatments per soil ($n = 15$) with standard deviations in brackets. Values in the same column followed by the same character are not significantly different (Tukey's test, $p < 0.05$)

	Shoot biomass	P uptake
Soil 1	2.31^{B} (0.57)	5.22^{B} (2.09)
Soil 2	0.38^{E} (0.21)	0.28^{G} (0.20)
Soil 3	2.51^{A} (0.37)	6.86^{A} (1.28)
Soil 4	1.05^{C} (0.32)	1.68^{D} (0.93)
Soil 5	0.53^{DE} (0.30)	0.55^{FG} (0.44)
Soil 6	2.17^{B} (0.61)	3.40^{C} (1.24)
Soil 7	0.97^{C} (0.27)	1.04^{E} (0.42)
Soil 8	0.67^{D} (0.31)	0.75^{EF} (0.56)
	Variance explained (%)	
Soils	81^{***}	83^{***}
Organic materials (OM)	9^{***}	9^{***}
Soils × OM	4^{***}	5^{***}
R-adj	0.94	0.96
p-value	<0.001	<0.001

$^{***}p < 0.001$; $^{**}p < 0.01$ $^{*}p < 0.05$.

TABLE 4 Average shoot biomass increase (Δshoot) (g) and P uptake increase (ΔPuptake) (mg) across soils for each organic material (OM) of pot experiment. Values are means of soils per OM ($n = 24$) with standard deviation between brackets. Values in same column followed by the same character are not significantly different (Tukey's test, $p < 0.05$)

Treatments	Δshoot[a]	ΔPuptake[a]
OM1	0.06^{B} (0.36)	0.26^{B} (0.84)
OM2	0.03^{B} (0.24)	0.23^{B} (0.48)
OM3	0.06^{B} (0.49)	0.28^{B} (0.94)
OM4	0.70^{A} (0.26)	2.02^{A} (1.39)
	Variance explained (%)	
Soil	19^{***}	23^{***}
Organic materials (OM)	40^{***}	39^{***}
Soil × OM	19^{***}	20^{***}
R-adj	0.77	0.82
p-value	<0.001	<0.001

$^{***}p < 0.001$; $^{**}p < 0.01$ $^{*}p < 0.05$.

[a] Excluding the control treatment; ΔShoot or shoot biomass increase = Shoot (OM) − Shoot (control); ΔPuptake or P uptake increase = P uptake (OM) − P uptake (control).

However, for both Δshoot and ΔPuptake, significant interactions were detected between soil and OM.

A further breakdown of OM effects between soils confirmed that OM4 application increased both shoot biomass and P uptake (i.e., positive Δshoot [0.5–1 g pot^{-1}] and ΔPuptake [0.5–4 mg P pot^{-1}]), in all eight soils (Figure 1). The soil S3 was the most responsive soil to all OM applications, with OM1 and OM3 treatments equaling the effect of OM4 in Δshoot. OM1, OM2, and OM3 increased Δshoot and ΔPuptake, while OM3 showed better performance than the other two OM except in soil S3. Regarding mineral P application, OM effects on shoot biomass and P uptake were lower except in soils S3 and S1 (Figure S2). There was a statistically significant reduction in shoot biomass with the application of OM3 relative to the control treatment in soil S1 (Figure S1).

3.1.2 | OM and soil characteristics in relation to shoot biomass and P uptake increases in rice plants

For the overall OM characteristics affecting biomass production and P uptake, the mixed regression model (1) that evaluated the OM effect as either a P source ($P_{applied}$) or C source ($C_{applied}$) showed that the effects on both Δshoot and ΔPuptake are largely caused by P than by C (Table S3). This was confirmed by the simple linear regression performed on the data using P and C contents of OM as regressors, where P content mostly explained both Δshoot and ΔPuptake, except in the most fertile soil S1 (Table 5). In soil 2, both P and C contents explained Δshoot and ΔPuptake, although with a higher coefficient associated with the P content.

For the combination of all four OM, Δshoot was negatively correlated with the Pox:Feox ratio and Pox, while it was positively correlated with Feox (Table 6). ΔPuptake was in turn only correlated with Feox but with very low *R*-squared as for Δshoot (0.21 and 0.17, respectively). Since the effects of OM1, OM2, and OM3 on Δshoot and ΔPuptake are consistent over all eight soils (Figure 1), the ridge regression was split into two where OM1/OM2/OM3 together and OM4 were analyzed separately. For the combination of OM1, OM2, and OM3, the Pox:Feox ratio and Feox were confirmed as the main explanatory variables of Δshoot (−0.9129 and 1.2823 at $p < 0.001$, respectively) and ΔPuptake (−1.499 and 3.4701 at $p < 0.001$, respectively). For OM4, none of the different soil parameters were retained by the ridge regression for Δshoot, while all parameters except pH(H_2O) were retained for ΔPuptake with clay (−1.0298, $p < 0.001$) and Pox (1.0174, $p < 0.001$) associated with the highest coefficients.

3.2 | Incubation experiment

3.2.1 | Changes in Fe concentration in pore water and soil pH in different soils affected by cellulose and OM applications

The results of the three-way ANOVA with repeated measures showed that the soil factor had the greatest effect on the changes over time in MG-P and Fe concentrations in pore water, Olsen-P, and soil pH, compared to the treatments and their combinations (Table 7). Compared to the treatments, the effect of incubation time was higher on MG-P in pore water and Olsen-P compared to the effect on Fe in pore water and

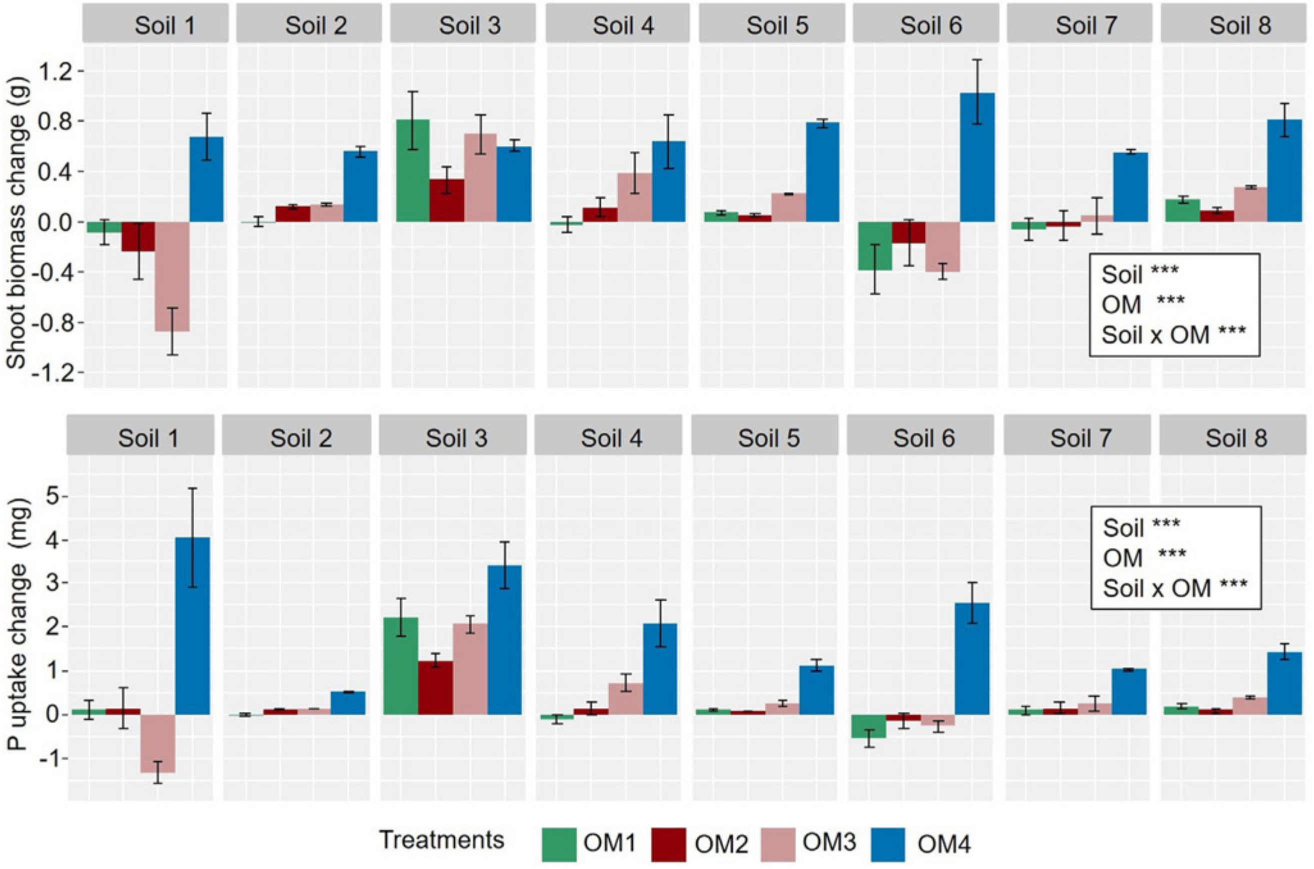

FIGURE 1 Change in shoot biomass (g pot^{-1}) and P uptake (mg pot^{-1}) of each organic material (OM1, OM2, OM3, and OM4) for all soils (S1 to S8). Error bars are standard errors of the mean (*n* = 3). Shoot biomass change = shoot (OM) – shoot (control); P uptake change = P uptake (OM) – P uptake (control)

TABLE 5 Parameter estimates and probability significance of the simple linear regression coefficients on shoot biomass (ΔShoot) and P uptake increase (ΔPuptake) for all soils combined and for each soil, affected by C content and P content of the organic materials. Variable parameters are scaled

	ΔShoot[a]			ΔPuptake[a]		
	C content	P content	R^2	C content	P content	R^2
All soils	0.0594	0.548***	0.32	0.0747	0.5387***	0.32
Soil 1	0.2305	0.3842	0.13	0.2548	0.5550	0.41
Soil 2	0.2821*	0.7920***	0.91	0.2775**	0.8101***	0.95
Soil 3	−0.7242*	0.4002	0.25	−0.3704	0.8894**	0.51
Soil 4	0.0613	0.7382*	0.51	0.0795	0.8458**	0.74
Soil 5	0.0137	0.9666***	0.94	0.0312	0.9165***	0.81
Soil 6	0.0137	0.9666***	0.94	0.2436	0.7573**	0.78
Soil 7	0.0950	0.7838**	0.63	0.1317	0.8054**	0.72
Soil 8	−0.0775	0.9543**	0.80	−0.0044	0.9347***	0.84

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

[a] ΔShoot or shoot biomass increase = Shoot (OM) – Shoot (control); ΔPuptake or P uptake increase = P uptake (OM) – P uptake (control).

soil pH. Interactions among treatments, soils, and incubation time were also higher for MG-P and Olsen-P.

Concentrations of Fe in pore water sharply increased or even peaked between 1 and 21 days after incubation in all soils in general (Figure 2). Thereafter, the concentrations decreased for S2 and S3, while it fluctuated or showed a second peak for the other soils until the end. In S1 and S3, Fe concentrations in pore water topped and seconded in the control treatment, respectively. Cellulose treatment reduced more Fe in soils compared to the other treatments for the remaining soils. Comparison of the two OM showed that OM4 tended to produce more Fe in pore water than OM2 except for soils S1 and S6 (OM4 had much higher P than OM2). The highest Fe concentrations in pore water were observed in S1 and S2 (175 mg Fe L^{-1} by OM2 and 225 mg Fe L^{-1} by OM4, respectively) against <150 mg Fe L^{-1} in the other soils.

Overall, soil pH decreased after 8 days of incubation to stabilize in the end except in S3 where it showed a steep increase after 8 days of incubation and decreasing afterward but remained above the initial level. Per treatment, cellulose had a strong effect in decreasing soil pH except in S3. The largest pH decreases due to cellulose application were from 5.84 to 4.95 and from 5.71 to 4.70 in S1 and S2, respectively,

TABLE 6 Parameter scaled estimates and probability significance of the ridge regression coefficients for the effect of soil characteristics on shoot biomass increase (Δshoot) and P uptake (ΔPuptake) for the control treatment; shoot and P uptake increase for each organic material (OM) treatment and mineral P fertilizer

	TotC	pH (H_2O)	Clay	CEC	Pox	Feox	Pox:Feox	*R*-squared
Control								
Shoot	−0.3367*	0.3264*	−0.8204***	0.8841***	0.8389***	0.4713**	0.8098***	0.82
Puptake	−0.6196*	0.2640	−0.9137**	1.3032***	1.2731***	1.2283***	0.9640***	0.61
All organic materials (OM)[a]								
Δshoot	−0.2558	−0.0486	0.4454.	0.2272	−0.3723*	0.6022*	−0.5895**	0.17
ΔPuptake	−1.5712.	−0.2639	−0.0188	1.5211.	0.5823	2.8800***	−0.4375	0.21
OM1/OM2/OM3[a]								
Δshoot	−0.3723	−0.1483	0.5703.	−0.1048	−0.3755*	1.2823***	−0.9129***	0.54
ΔPuptake	−1.1085	−0.6341	0.6691	0.8766	−0.3334	3.4701***	−1.499**	0.66
OM4[a]								
Δshoot	0.0002	0.0070	−0.0142	0.0018	−0.0023	−0.0194	0.0081	0.02
ΔPuptake	−0.7081*	0.2075	−1.0298***	0.6868*	1.0174***	0.6920*	0.8256**	0.52

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

[a] Δshoot or shoot biomass increase = shoot (OM) – shoot (control); ΔPuptake or P uptake increase = P uptake (OM) – P uptake (control).

TABLE 7 Effects of treatments, soils, and incubation time, analyzed by three-way repeated-measures ANOVA on relative malachite green-P (MG-P) concentration (%) in pore water, Fe concentration in pore water (mg L^{-1}), Olsen-P (mg kg^{-1}), and pH(H_2O) and their combination

Factors	Relative MG -P	Fe concentration	Olsen-P	pH(H_2O)
Treatment	39***	18***	57***	43***
Incubation time	56***	02*	93***	38***
Soil	88***	20***	96***	81***
Incubation time × Soil	43***	01**	40***	06***
Treatment × Incubation time	11***	04^{ns}	08***	01^{ns}
Treatment × Soil	46***	02^{ns}	16***	09***
Treatment × Incubation time × Soil	07***	01^{ns}	04***	03^{ns}

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.5$; ns. not significant.

after 33 days of incubation. In soil 3, soil pH increased by 0.1 units on average at the end of the incubation where cellulose treatment had the lowest effect. In general, peaks of pH decrease or increase overlapped with those of Fe concentrations in pore water. OM2 and OM4 did not change the soil pH in all soils compared to the control but a slight decrease was observed in soils 4 and 6 at the end of the incubation.

3.2.2 | Effects of cellulose and OM applications on the MG-P concentration in pore water and Olsen-P

The MG-P concentration in pore water was expressed relative to the maximum value of MG-P in all treatments and sampling points. The relative MG-P concentration in pore water increased over time in all soils and treatments, and was highest in S3 and S4 under OM4 application at the end of the incubation (13-fold higher compared to the lowest MG-P concentration in pore water, observed in S2 on the first day of the incubation). In general, compared to the other treatments, values were higher under the OM4 application. However, cellulose application sometimes yielded a higher MG-P concentration in pore water than in the other treatments, and MG-P concentration was always above or equal to OM2 application at certain points of the incubation in most of the soils (S1, S2, S4, and S6). In all soils, the observed values in the control treatment were equal to or below those of the cellulose treatment.

In contrast to the general trend of MG-P concentration in pore water, unchanged or an overall decrease in Olsen-P was observed over time in S1, S2, S3, and S4 (Figure 2). In the other soils, increases with fluctuations were observed with the clearest increases in S6 and S8 (8–12 and 1.8–4 mg kg^{-1}). Between treatments, OM4 topped Olsen-P in all soils and almost all sampling points (5–57 mg P kg^{-1}). The increases due to OM4 in S2 and S8 compared to the control treatment did not exceed 5 mg kg^{-1}, whereas these were 5–10 mg kg^{-1} for soils S1 and S6. No significant difference was observed between the other treatments in all soils.

4 | DISCUSSION

4.1 | Optimal OM for improving P availability for rice

This study aimed to assess the effect of P supply, and the indirect effect of C in OM on improving P availability and rice production, and to confirm the underlying mechanisms in planted and incubated soils. Results

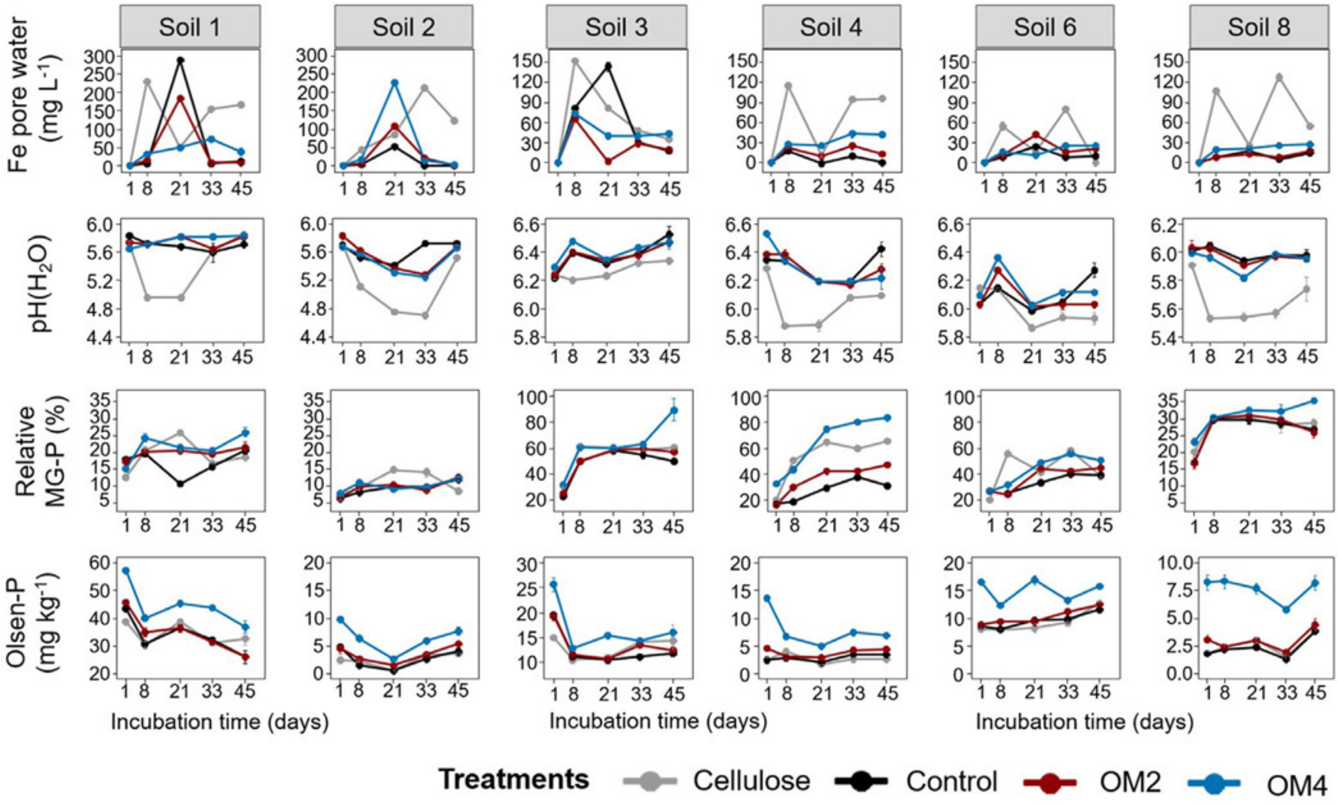

FIGURE 2 Means of Fe concentration (mg L^{-1}) in pore water, pH(H_2O) of soil, relative malachite green-P (MG-P) (%) in pore water, and Olsen-P (mg kg^{-1}) of all incubated soils affected by cellulose, OM2, and OM4 application or control, at each samplings time (1, 8, 21, 33, and 45 days of incubation). Error bars represent standard error ($n = 3$)

of the pot experiment showed that the OM with high P (0.93%) and a low C:P ratio (78.2), (i.e., OM4, referred to here as pig dung mixed with grass) was the most effective and increased shoot biomass and P uptake of rice among four different OM applied at equal dry weight basis in all the eight soils studied. It was also confirmed that the OM effect on the increase in biomass and P uptake of young rice plants was mainly attributed to its P supply.

The incubation experiment underpinned the result of the pot experiment where the OM associated with high P and low C:P ratio produced the largest amounts of soil available P (Olsen P) in almost all of the six soils studied and over all the incubation periods (Figure 2). In terms of P solubilization, OM4 also had the highest relative MG-P concentration in pore water in five out of the six soils particularly at the end of the incubation. Thus, the idea of providing extra C through OM application to release or solubilize more native soil P under reduced conditions is by far outweighed by the application of OM rich in P but with a low C:P ratio. The C:P ratio of OM4 (78.2) is comparable to the low ratio of *Setaria sphacelata* as a plant residue observed by Umrit and Friesen (1994), which resulted in the highest P uptake and biomass yield of *Panicum maximum* compared to the residue with high C:P ratio (704 and 227). The reason could be attributed to a slight microbial immobilization of P because of C limitation (Zhang et al., 2018). The high P content of the OM4 reduced the effects of P immobilization that most occurs under application of organic matter with P content below 0.3% (Singh et al., 2005).

The highest P uptake by rice plants in the pot experiment and the highest Olsen-P concentration measured in the incubation experiment were achieved by OM application with high P content and low C:P ratio. However, based on the shoot biomass responses observed in the pot experiment, one can suggest that OM with high P and low C:P (such as OM4) can be an effective P amendment (i.e., as P source) regardless of soil characteristics. In addition to its known high concentrations of P and C compared to cattle manure (Peters et al., 2011), pig manure provides a high proportion of labile P and P available to rice plants (Li et al., 2014; Pagliari and Laboski, 2012).

4.2 | Soil characteristics affecting OM effectiveness

In relation to soils characteristics affecting rice response to OM application, our results for the OM with high P and low C:P ratio showed that P uptake depended on a set of soil parameters apart from soil pH(H_2O), while shoot biomass did not significantly change in the different soils (Table 6). Regarding the other OM used in the pot experiment, which differed in terms of C and P contents (i.e., low and low for OM1, high and low for OM2, and medium/medium for OM3), it was clear that their effects largely depended on soil characteristics and were consistent throughout the eight soils. Specifically, the OM3 treatment led to a decrease in shoot biomass in soil S1, and the ridge regression confirmed that the high soil Pox:Feox ratio (i.e., higher P solubility condition) explained such decreases, as illustrated in Figure 1. Since the increases in tissue P concentration were all positive in these three soils (Figure S2), the adverse effects on shoot biomass and P uptake must have originated from an additional or a different factor that was not investigated in this study such as Zn deficiency (Abid et al., 2002; Rehman et al., 2012) or Fe toxicity (Dobermann and Fairhurst, 2000). Thus, further studies are needed to unravel the underlying mechanisms of OM applications in relations to soil characteristics, but also to clarify whether OM nutrient content besides P and C:P ratio would be an additional important factor for consideration, for the effective use of OM in water-submerged rice fields.

4.3 | Magnitude of P solubilization and P availability in waterlogged soils as a result of single C versus combined C and P applications

In the incubation experiment data, the increase in MG-P concentration in pore water is consistent with previous observations on P solubilization dynamics under waterlogged conditions (Maranguit et al., 2017; Ponnamperuma, 1972). The dynamics of solubilized P (MG-P in pore water) and the soil available P (Olsen-P) (Singh et al., 1988) were in most cases dominated by higher P application such as that from OM4. However, the strategy of adding extra C to the waterlogged soils was effective at some points during the incubation time and for the four soils in which the cellulose treatment surpassed the other treatments in solubilizing P. Similarly, the observation with the values in the control treatment were equal to or below those of the cellulose treatment in all soils, illustrating P solubilization due to amplified Fe reduction (Figure 2). This was most pronounced in S4, which could be attributed to its low C content (Mohammadi et al., 2009; Rakotoson and Tsujimoto, 2020; Vanden Nest et al., 2014). The rate of P solubilization due to OM2 addition was similar to that of cellulose addition, suggesting possible P immobilization due to a high C:P ratio, of around 386.5, and it is a low P content (1.84 g kg^{-1}).

In a striking contrast to MG-P concentration in pore water, Olsen-P concentration remained unchanged or even decreased over time in most of the soils, thereby indicating (1) an increase in P adsorption due to waterlogging (Zhang et al., 2003) and (2) a possible inappropriateness of Olsen-P test to detect P availability changes under such circumstances and with the type of soils used in this study. Zhang et al. (2003) attributed the increase in P adsorption capacity to increased Feox or amorphous Fe upon waterlogging. In different soil types [$pH(H_2O) = 8.5$, Olsen-P = 44 mg kg^{-1}], Singh et al. (1988) obtained clear and overtime increases in Olsen-P at least for the first 4 weeks of anaerobic incubation, which decreased thereafter because of Ca-P formation. In the present study, P must have changed to the Pox form, as described in Zhang et al. (2003).

5 | CONCLUSIONS

Our results showed that rice responses to OM application are greatly influenced by certain characteristics of OM and soils under anaerobic submerged conditions. Although soil P solubilization can occur through the addition of extra fresh C, OM effects on P availability were far more a P effect than a C effect in the soils used in the present study. A low molar ratio of Pox:Feox in soils had more pronounced effects of OM application, whereas adverse effects were observed when this ratio was extremely high. Consequently, OM with high P and low C:P ratio are potentially effective and available resources for smallholder farmers to improve P availability in lowland rice of weathered tropical P-deficient soils.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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OPEN ACCESS

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

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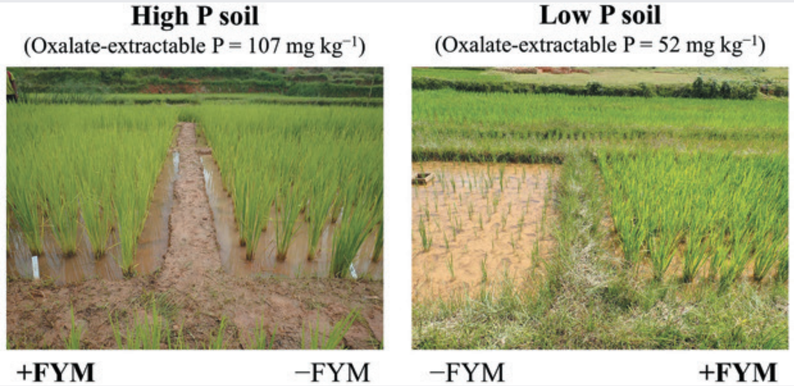
ABSTRACT
Phosphorus (P) deficiency is a major yield constraint for lowland rice production in the tropics. As P-fertilizer resources are finite, alternative fertilizer management is needed for sustainable rice production. We examined whether farmyard manure (FYM), a major nutrient source for smallholder 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.



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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

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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 (Dobermann & Fairhurst, 2000). Tsujimoto et al. (2019) found that phenology 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 (Rakotoson et al., 2014; Rakotoson & 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. Linquist 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		Antohobe				Behenjy		
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).

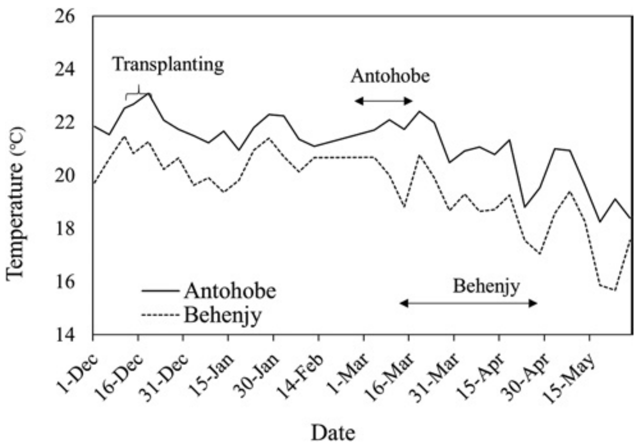

Figure 1. Mean temperature (5-day averages) during the rice cropping season in Antohobe and Behenjy (December 2017 to May 2018).

2.8% and total N ranging from 0.10% to 0.19% (c. v. = 36% and 28%, respectively).

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 P_2O_5, 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 HNO_3 /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

Table 2. F ratios from ANOVAs showing the effect of Site, P source, and their interactions on rice grain yield and yield components at eight sites in in Antohobe and Behenjy, Madagascar.

	Grain Yield		Panicle number		Grain number per panicle		Grain filling ratio		Grain weight	
Site	16.0	***	3.5	*	11.5	***	20.0	***	1.7	ns
P source	15.8	***	1.0	ns	0.6	ns	19.7	***	3.2	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.

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

	Grain yields (t ha^{-1})						Probability
	Control		FYM		P fertilizer		
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	a	1.75	b	2.43	c	**
S7	1.46	a	2.1	b	2.38	b	*
S8	1.52	a	2.23	b	2.61	b	**
Average	2.48	a	2.88	b	2.91	b	-

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 $p = 0.05$.

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

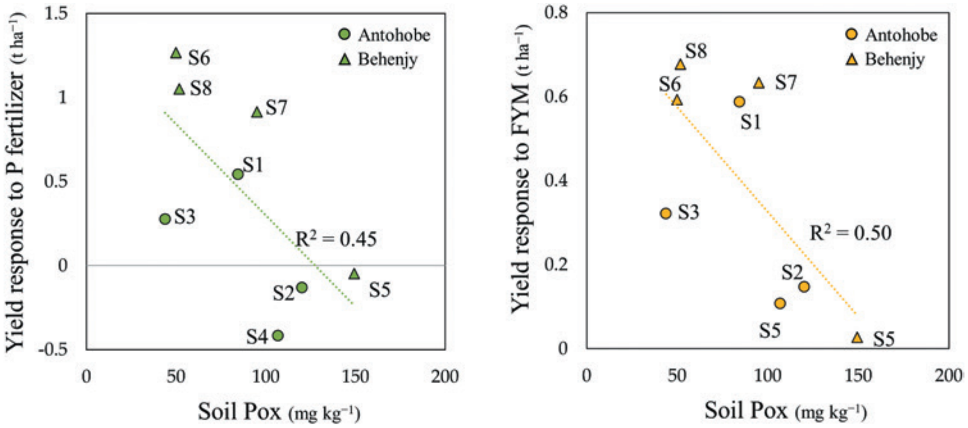

Figure 2. The relationship between Pox and rice yield response to P fertilizer (left) or to FYM (right) across eight sites in Antohobe and Behenjy, Madagascar.

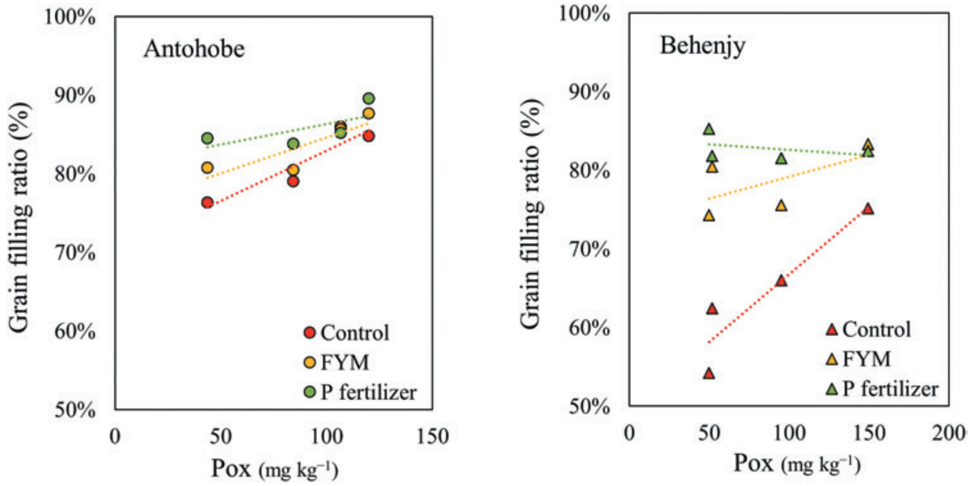

Figure 3. The relationship between grain filling ratio and Pox across eight sites at Antohobe (left) and at Behenjy (right) for each P source treatment.

P fertilizer, was effective for enhancement of plant P uptake under low Pox conditions.

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 ($mg\ g^{-1}$) Grain		Shoot		Total P uptake ($kg\ ha^{-1}$)	
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
(F ratio)						
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, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

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.

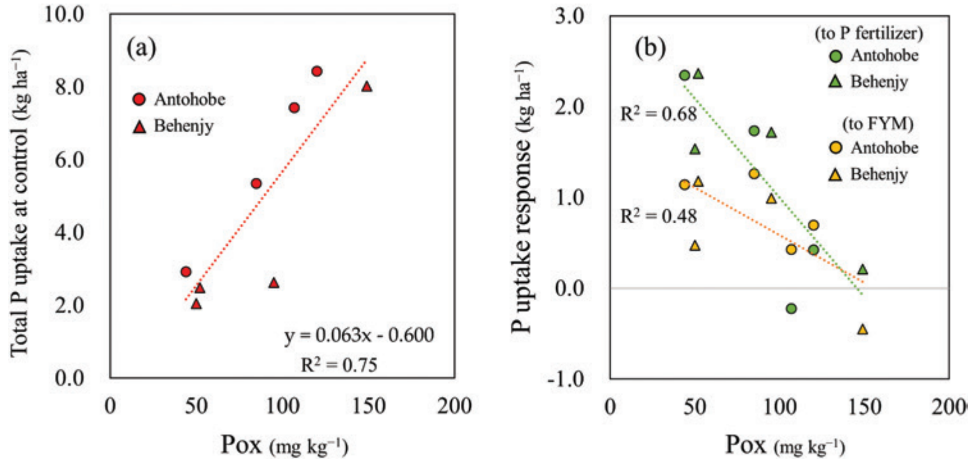

Figure 4. Relationship of oxalate-extractable P (Pox) with total P uptake in the control (a), with P uptake response to P fertilizer and to farmyard manure (FYM) (b) across the eight sites.

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 effected 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	Ambatondrazaka	Ambohinaorina		Ambohibary	Ankazo-miriotra
Grain yield (t ha^{-1})					
Control	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}))					
P from TSP	20	20	20	25.8	25.8
P from FYM	12	6	6	-	-
Probability TSP*	n.s.	s.	n.s.	s.	s.
Probability FYM*	n.s.	n.s.	n.s.	-	-
References	Andriamananjara et al. (2016)			Rakotoarisoa et al. (2020)	

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

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 resulted 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, highliting 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

The authors declare no conflict of interest.

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Phosphorus application affects lowland rice yields by changing phenological development and cold stress degrees in the central highlands of Madagascar

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ABSTRACT

Despite a general perception that phosphorus (P) deficiency delays phenological development in annual crops, the impacts of interaction between this phenological delay and climatic conditions on crop productivity remain poorly understood. On-farm experiments were conducted in the central highlands of Madagascar, where P deficiency and late-season low temperature stress frequently restrict rice yields. Rice X265 was grown under four different fertilizer treatments with different combinations of N and P during early, intermediate, and late transplanting dates (ETP, ITP, and LTP, respectively). Plants subject to no fertilizer or single N treatments showed delayed heading by 6–24 days. This notable delay in the phenological development favored biomass accumulation and resulted in greater yield in ETP when low temperature stress was negligible. In contrast, delay in phenological development without P application increased cooling degree days and spikelet sterility in ITP. Consequently, the effect of a single N application had a positive effect only in ETP. The effect of P was much greater in ITP than in ETP because P application alleviated not only P deficiency but low temperature stress as well by shortening day to heading. In LTP plots, yield was severely suppressed to less than 1 t ha^{-1}, with sterility rate above 75 %, irrespective of fertilizer treatment. This study provides field evidence that phenological delay under P deficiency has dual effects on grain yield and that optimal N and P management practice differs with climatic growing conditions. Changes in phenological development due to plant nutrient status and its interaction with climate-induced stress needs further attention for improving fertilizer management practice.

1. Introduction

Improved nutrient management practices are needed to achieve sustainable crop production given the depletion of fertilizer resources and the increase in environmental concerns regarding the excessive use of nitrogen (N) and phosphorus (P) in agricultural systems (Campbell et al., 2017, Steffen et al., 2015). Management practices that aim to maximize returns from minimal use of fertilizers are also crucial for food security in sub-Saharan Africa (SSA), where smallholder farmers have physically and economically little access to commercial fertilizers (Chianu et al., 2011; Druilhe and Barreiro-Hurlé, 2012). Consistently, Zhang et al. (2015) highlighted that retaining a low nutrient surplus in SSA while increasing input and production is a critical challenge for simultaneously addressing the issues of food security and environmental degradation. Currently, agricultural production in SSA is low in both input and surplus N (Zhang et al., 2015) and P (MacDonald et al., 2011).

One major strategy to approach this challenge in SSA, or elsewhere, is to develop site-specific nutrient management practices. This approach is considered beneficial in heterogeneous SSA fields, where large variations prevail among fields with respect to soil nutrient and hydrologic

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Abbreviations: ETP, early transplanting date; ITP, intermediate transplanting date; LTP, late transplanting date; SSA, sub-Saharan Africa; DAT, days after transplanting; CDD, cooling degree days.

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characteristics, and consequently, in plant responses to fertilizer input (Kihara et al., 2016, Tsujimoto et al., 2019). Thus, for example, Arouna et al. (2020) emphasized that specific advice on optimal input as determined based on the differences in soil quality is a requirement to increase farmers' profit in SSA. Numerous studies have been conducted to evaluate site-specific nutrient management practices based on the interactions between field characteristics and crop responses to fertilizer input (Dossou-Yovo et al., 2020; Haefele and Wopereis, 2005; Vanlauwe et al., 2011; Zingore et al., 2007). The knowledge gathered from these studies has been integrated into decision-support tools partly using tablets or smartphones (MacCarthy et al., 2017; Saito and Sharma, 2018) and allowing a significant enhancement of nutrient use efficiency or farmer profits or both (Arouna et al., 2020; Rurinda et al., 2020; Saito et al., 2015a).

However, there is another important but rarely studied aspect for optimizing fertilizer management practices, namely, a significant change in phenological development caused by plant nutrient status. It is well known that P deficiency or the balance of P and N contents in plants delays flowering and maturity of annual crops (Dobermann and Fairhurst, 2000; Kant et al., 2011; Rossiter, 1978; Ye et al., 2019). Thus, for example, our recent survey evidenced a one-month difference (maximum) in rice maturation with and without P application in the typical P-deficient lowlands of Madagascar (Rakotoson and Tsujimoto, unpublished). Similarly, in severely P-deficient fields in Tanzania, Vandamme et al. (2018) observed that the number of days to heading of upland rice was shortened by approximately 20 days relative to the control, by placing a small amount of P into the planting holes.

The abovementioned changes in plant phenological development alter the duration of each development stage, thereby causing plants to be exposed to different climatic growing conditions and affecting crop growth. For instance, the effects of P application on the growth of *Arabidopsis thaliana* (Nord and Lynch, 2008) and rice (Rakotoarisoa et al., 2020) were less pronounced under favorable growing conditions because the initial advantage in biomass production was offset by a shortened days to maturity. In contrast, prolonged growth duration under P deficiency may increase the risk of biotic and abiotic stress. Therefore, the relationship between nutrient input and crop yield can be largely affected by changes in phenological development caused by inputs per se. However, the changes in plant phenological development have received little attention in the context of improved fertilizer management practices. Therefore, in this study, we aimed to demonstrate that the effect of nutrient input on plant growth and productivity can be significantly affected by its impact on plant phenological development. We focused on lowland rice in the highlands of Madagascar, where both P deficiency and low-temperature stress restrict the rice yield. Our hypothesis is that the effect of P application is more pronounced, even under the same soil nutrient conditions, when transplanting of rice is delayed, because, in addition to supplying the plant P demand, shorter days to heading will favor the avoidance of low-temperature stress at the reproductive to ripening stages toward the end of the rainy season. For this purpose, we established on-farm trials in which N and P were combined for application under a range of transplanting dates (i.e., climatic conditions) on the same fields (i.e., the same soil nutrient conditions) in the central highlands of Madagascar.

2. Materials and methods

2.1. Site description

On-farm trials were conducted in Behenjy (19°10'48''S, 47°29'44''E; 1379 m) in the central highlands of Madagascar during the rainy seasons of 2018–2019 and 2019–2020. Our preliminary survey indicated that transplanting dates largely varied from the beginning of October to the end of January even within the same river valleys. Rice production in the region—as in the whole country—is characterized by low available P in soils (Nishigaki et al., 2018), little mineral fertilizer input (Tsujimoto et al., 2019), and poor average yields below 3 t ha^{-1}. Further, regional rice production is often exposed to low temperature stress at the reproductive and ripening stages toward the end of the rainy season (Dingkuhn et al., 2015).

2.2. Experimental design

The experiments were conducted at four different sites located within the same river valley (F1 and F2 in the 2018–2019 season and F3 and F4 in the 2019–2020 season). The soils in these fields are classified as clay-loams (F1, F2), clay (F3) and silty-clay loam (F4) with pH ($CaCl_2$) at 4.2–4.8 (Table 1). The amount of oxalate-extractable P—a suitable indicator of P availability for lowland rice production in the region (Rabeharisoa et al., 2012)—ranges from 31.9 mg kg^{-1} to 79.9 mg kg^{-1}, which is the lowest level among the lowland and upland rice fields in Madagascar (Kawamura et al., 2019). The F4 field had slightly higher oxalate-extractable P content than the other three fields. A split plot design with three replicates was established at each field. The design consisted of different transplanting dates as main plots (TP_{date}) and different fertilizer treatments as subplots (*Fert*), i.e., Ct: no fertilizer; N: 80 kg of N ha^{-1}; P: 50 kg of P_2O_5 ha^{-1}; NP: 80 kg of N and 50 kg of P_2O_5 ha^{-1}. The size of each subplot was 6 m × 3 m. The most common rice variety in the region, X265, was consistently used in all plots. X265 is a high-yielding *indica* cultivar, which was released in 1986 in Madagascar (Diagne et al., 2015), with shorter maturity duration and weaker photoperiod sensitivity than traditional varieties.

In the 2018–2019 season, X265 seeds were sown in a nursery bed on October 30, and 30- to 31-day-old seedlings were manually transplanted to F1 and F2 on November 29–30 (ETP: early transplanting). Similarly, seeds were sown in the same nursery bed on November 28 and transplanted to F1 and F2 on December 27–28 (ITP: intermediate transplanting). In the 2019–2020 season, X265 seeds were sown in a nursery bed on October 30, November 29, and December 28. Then, 30- to 31-day-old seedlings after each sowing incidence were manually transplanted to F4 on November 29 (ETP), to F3 and F4 on December 30 (ITP), and to F3 on January 27 (LTP: later transplanting). Due to the shortage of irrigation water at the ETP establishment, F3 had only ITP and LTP (F3 was in the higher topographical position than F4 in the same valley). On the contrary, F4 had only ETP because many plants were damaged by flooding after the ITP establishment and the LTP was not implemented due to the high-water level of the field

In this way, the seedlings with an equivalent age were transplanted in three different periods across four fields: ETP in fields F1, F2, and F4; ITP in fields F1, F2, and F3; and LTP in field F3. The seedlings were assumingly in similar phenological development stages as the mean temperatures from sowing to transplanting were consistent in the range 20.2–21.2 °C for any transplanting dates in both seasons. The aboveground biomass of seedlings was also equivalent with the range of 35.7 mg and 42.5 mg across transplanting dates and fields.

As for the N and NP plots, N fertilizer as urea was top-dressed at two application times, with 50 kg ha^{-1} at 7 days after transplanting (DAT) and the remaining 30 kg ha^{-1}, at 60 DAT. In the P and NP plots, P

Table 1
Physical and chemical properties of soils (0–15 cm) of the experimental fields.

Parameters	Unit	F1	F2	F3	F4
Clay[a]	%	30.1	31.5	46.9	28.5
Silt[a]	%	33.0	29.8	28.1	57.2
Sand[a]	%	36.9	38.7	25.0	14.3
pH ($CaCl_2$)	–	4.2	4.2	4.3	4.8
Total C[b]	g kg^{-1}	27.7	28.2	31.1	21.1
Total N[b]	g kg^{-1}	2.0	2.0	2.5	1.5
Oxalate-P[c]	mg kg^{-1}	36.6	31.9	39.1	79.9

[a] sieving and pipetting method.
[b] NC Analyzer, Sumigraph NC-220 F (SCAS, Japan).
[c] oxalate extraction (Courchesne and Turmel, 2008).

fertilizer as triple super phosphate was top-dressed in a single application at 7 DAT. Weeds were controlled by hand throughout the growing periods. The fields were consistently flooded from transplanting to maturity. No remarkable damage from pests or disease was observed at any site.

2.3. Measurements and analysis

Grain yield (t ha^{-1}) was determined by harvesting plants from an area of 2.56 m^2 (1.6 m × 1.6 m) in the center of each plot, and correcting to 14 % grain moisture content by using a grain moisture sensor (Riceter f, Kett Electric Laboratory, Tokyo, Japan). Within the harvested area, 10–12 average-sized hills were selected to determine the spikelet sterility (%) by counting the number of submerged and floating spikelets in 70 % ethanol, as per Kobata et al. (2010). Heading date in each plot (i.e., date when 50 % of the plants had headed in each plot) was estimated by frequent visual observations and from canopy photographs taken at one-week intervals. In the 2018–2019 season (fields F1 and F2), the changes in aboveground biomass (g m^{-2}) were determined from 100 seedlings at transplanting and by cutting 8–12 average-sized hills at 28, 56, 75, and 96 days after transplant (DAT), and at harvest. Samples were oven-dried to a constant weight at 70 °C for more than 72 h. Biomass samplings were not conducted in the 2019–2020 season (fields F3 and F4) except at the time of transplanting due to the "lockdown" safety measure decreed by the Malagasy government to prevent the spread of COVID-19 at that time.

Ambient temperature was recorded at 30 min intervals throughout both rice growing periods by a Watchdog 1525 micro station (Spectrum Technologies Inc., Plainfield, IL, USA) set up at the experimental site. To assess the magnitude of low temperature stress experienced by rice plants, the cooling degree days (CDD) model (Uchijima, 1976) was applied using the following formulas:

$$CDD = \Sigma CD$$

$$CD = 22 - T_{mean} \ (\text{if } T_{mean} < 22\ ^\circ C)$$

$$CD = 0 \ (\text{if } T_{mean} \geq 22\ ^\circ C)$$

where CD is the daily cooling degree and T_{mean} is the daily mean temperature. The constant with value 22 is an assumed critical temperature for the *indica* cultivars below which rice plants are exposed to cold-induced stresses (Horie et al., 1995). CDD was calculated by accumulating CD from 15 days before heading to 7 days after heading, which is the most cold-sensitive period of rice grain fertility (Horie et al., 1995).

2.4. Statistical analysis

Statistical analyses were performed using the JMP 14 software (JMP 14.0.0, SAS Institute Inc.). A generalized linear model was applied to determine the individual effects and interactions between TP_{date} and *Fert* on the experimental variables within each experimental field. Replicates were treated as a random factor. Tukey's honestly significant difference test was conducted to compare the mean values at the 5 % probability level. An exponential curve was fitted to correlate spikelet sterility rate against CDD, as per Horie et al. (1995).

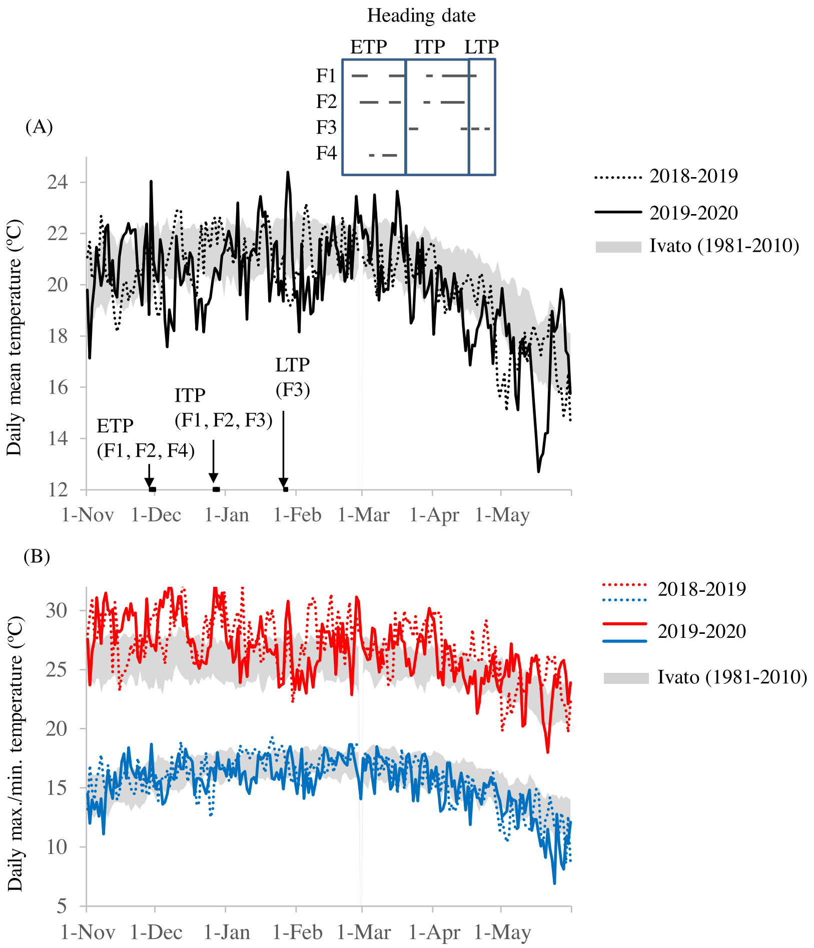

Fig. 1. Changes in (A) daily mean temperature and (B) daily max. and min. temperatures from November to May in 2018-2019 and 2019-2020 at the experimental site and the normal value of 1981-2010 at Ivato (18°48′ S, 47°29′ E, 1,276 m above sea level), the nearest long-term weather records in the central highlands of Madagascar.

3. Results

3.1. Weather conditions and grain yield

Ambient temperature changes during the course of the experiments corresponded to the normal values at the nearby weather station (Fig. 1). In both years, the daily mean temperature slightly increased from the beginning of rainy season in November, plateaued from January to February, and then gradually declined to < 18 °C toward the end of the rainy season. The amount of solar radiation showed a similar declining trend from March to the end of the rainy season (Supplementary Fig. S1).

Grain yields varied from 0.1 t ha^{-1} to 3.9 t ha^{-1} with significant individual and interactive effects of TP_{date} and *Fert* within each experimental field (Table 2). The yield in Ct plots decreased slightly as transplanting was delayed from ETP to ITP in both F1 and F2 fields. More importantly, the effect of N and P application differed with transplanting date even within the same fields. The single N application treatment significantly increased yield in ETP at F1 but not in ITP plots. Single N application had a rather negative impact in ITP plots at F2. In contrast, the effect of P, as the yield differences between N and NP treatments were much greater in ITP than in ETP plots. The yield increase rate under NP relative to N treatment was 48 %–49 % in the ETP and 86 %–138 % in the ITP plots at F1 and F2. Similarly, the yield difference between NP and N was substantial (2.6 vs. 0.3 t ha^{-1}) in ITP plots at F3, although there was no comparison with ETP. Yield was greatly suppressed when transplanting was further delayed (F3, LTP), irrespective of fertilizer treatment.

3.2. Phenological development and spikelet sterility

Fertilizer treatment significantly affected the number of days to heading across the experimental fields (Table 3). Phosphorus application significantly shortened the number of days to heading compared to no P applied (Ct vs. P and N vs. NP) by 8–19 days in fields F1 and F2 and by 23–24 days in ITP in field F3. The shortening effect of P application on the number of days to heading was relatively small (6–7 days) for LTP in field F3 and in field F4, where the amount of oxalate-extractable P in soil was high (Table 1). In contrast, N application had no effect on rice phenological development in any field or transplanting date.

Phenological changes with and without P application affected CDD depending on transplanting date and the change in CDD was closely related to spikelet sterility (Fig. 2). Spikelet sterility increased exponentially with increasing CDD in the range between 15 and 85 °C days. In ETP, phenological delay in Ct and N plots had little effect on CDD or spikelet sterility, as the mean temperature near heading stage in these plots was still high and equivalent to that during the heading periods in P and NP plots. In addition, the observed CDD range in ETP (18–28 °C days) was still low enough to avoid cold-induced sterility or was at the plateau phase of the exponential curve. As the result, there were no significant differences in spikelet sterility among fertilizer treatments for ETP in any experimental field (Table 4).

Table 2
Grain yields as affected by different transplanting dates and fertilizer applications.

		Grain yield (t ha^{-1})			
TP_{date}	*Fert*	F1	F2	F3	F4
ETP	Ct	1.9 cd	2.2 cd	–	2.4 b
	N	2.5 b	2.7 bc		3.7 a
	P	2.4 bc	2.5 c		2.6 b
	NP	3.8 a	3.9 a		3.9 a
ITP	Ct	1.7 d	2.0 cd	0.3 bc	–
	N	2.0 cd	1.5 d	0.3 bc	
	P	2.5 b	2.5 c	2.3 a	
	NP	3.6 a	3.6 ab	2.6 a	
LTP	Ct	–	–	0.2 bc	–
	N			0.1 c	
	P			0.4 bc	
	NP			0.7 b	
Levels of significance in F statistics					
TP_{date}		**	**	***	–
Fert		***	***	***	***
TP_{date} x *Fert*		*	*	***	–

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HST test.
ns. not significant, *P < 5 %, **P < 1 %, ***P < 0.1 %.

Table 3
Days from transplanting to heading as affected by different transplanting dates and fertilizer applications.

		Days from transplanting to heading (days)			
TP_{date}	*Fert*	F1	F2	F3	F4
ETP	Ct	111 a	110 a	–	108 a
	N	111 a	109 a		110 a
	P	97 b	102 b		102 b
	NP	92 b	95 c		102 b
ITP	Ct	107 a	106 b	113a	–
	N	111 a	107 ab	115a	
	P	97 b	96 c	90cd	
	NP	96 b	95 c	91bcd	
LTP	Ct	–	–	92bc	–
	N			94b	
	P			86e	
	NP			88d	
Levels of significance in F statistics					
TP_{date}		ns.	ns.	***	–
Fert		***	***	***	***
TP_{date} x *Fert*		ns.	*	***	–

The differences in CDD and spikelet sterility with and without P application was most significant in ITP plots (Fig. 2). Delayed heading in ITP corresponded to the period of when the mean temperature sharply declined which enlarged the CDD accumulation per day (Fig. 1). In addition, the CDD range in ITP plots was at the exponential phase to sharply increase the spikelet sterility. Consequently, P application in ITP plots significantly reduced spikelet sterility by shortening the number of days to heading and by reducing CDD across experimental fields (Table 4). The difference in spikelet sterility with and without P application was particularly large at F3, resulting in large differences in grain yield (Tables 3 and 4). When transplanting date was further delayed, the differences in CDD and spikelet sterility became again insignificant among fertilizer treatments. In LTP, the phenological differences among fertilizer treatments were small; furthermore, mean temperature was already very low irrespective of heading dates, and thus, spikelet

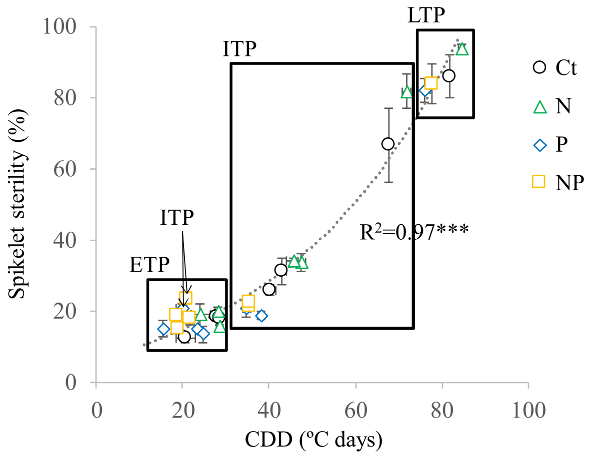

Fig. 2. Relationship between cooling-degree days (CDD) from 15 days before heading to 7 days after heading and spikelet sterility.

Table 4
Spikelet sterility as affected by different transplanting dates and fertilizer applications.

		Spikelet sterility (%)			
TP_{date}	*Fert*	F1	F2	F3	F4
ETP	Ct	18.2 b	17.6 cd	–	12.3 a
	N	19.9 b	15.9 d		18.9 a
	P	14.7 b	13.4 d		15.0 a
	NP	14.8 b	17.6 cd		18.5 a
ITP	Ct	31.0 a	25.8 b	66.5 a	–
	N	32.4 a	33.9 a	81.7 a	
	P	18.7 b	18.7 cd	20.7 b	
	NP	21.3 b	23.7 bc	23.3 b	
LTP	Ct	–	–	85.9 a	–
	N			93.5 a	
	P			81.8 a	
	NP			79.8 a	
Levels of significance in F statistics					
TP_{date}		***	**	**	–
Fert		***	***	***	P = 0.054
TP_{date} x Fert		*	***	***	–

Within each column, values with different alphabets indicate significant differences among the treatments at 5 % of Tukey's HST test.
ns. not significant, *P < 5 %, **P < 1 %, ***P < 0.1 %.

sterility increased significantly across fertilizer treatments (Table 4). Correspondingly, a significant interaction between TP_{date} and *Fert* on spikelet sterility was detected across F1, F2, and F3 sites (Table 4). Single N application treatment (Ct vs. N) tended to increase spikelet sterility in ITP plots, whereby significant differences were observed in F2, and at P = 0.11 in F3.

3.3. Biomass growth is affected by fertilizer treatments and transplanting dates

Changes in aboveground biomass were compared among fertilizer treatments within each transplanting date at F1 and F2 (Fig. 3). Irrespective of transplanting date, NP and P treatments consistently showed superior biomass production than N and Ct treatments from the initial growth stages up to the pre-heading period at 90 DAT (Fig. 3). However, in ETP, N treatment gradually reduced this biomass difference and surpassed the mean of the P treatment at maturity, because the plants with N treatment had longer days to maturity for biomass production at both F1 and F2 (Fig. 3A, C). On the other hand, in ITP plots, the advantage of prolonged growth duration was relatively small, as crop growth rate or the inclination of biomass from 90 DAT to maturity was low (Fig. 3B, D). Therefore, plants with Ct and N treatments tended to have lower biomass production at maturity, when transplanting was delayed from ETP to ITP, while P and NP treatments had equivalent biomass production at maturity, irrespective of transplanting date. As noted above, biomass sampling could not be performed in the 2019–2020 season due to COVID-19 safety protocols.

4. Discussion

The results summarized herein demonstrate that the effects of N and P application on rice yield are greatly influenced by transplanting date in the central highlands of Madagascar. Specifically, the effect of P is much greater when transplanting is delayed but is vice versa for N. This interaction is mainly attributed to a strong change in phenological development with P application, thereby exposing plants to different climatic conditions during the reproductive to ripening stages. A range of delay in heading date by 6–24 days due to P deficiency (N vs. NP plots) is comparable to previous observations for both lowland and

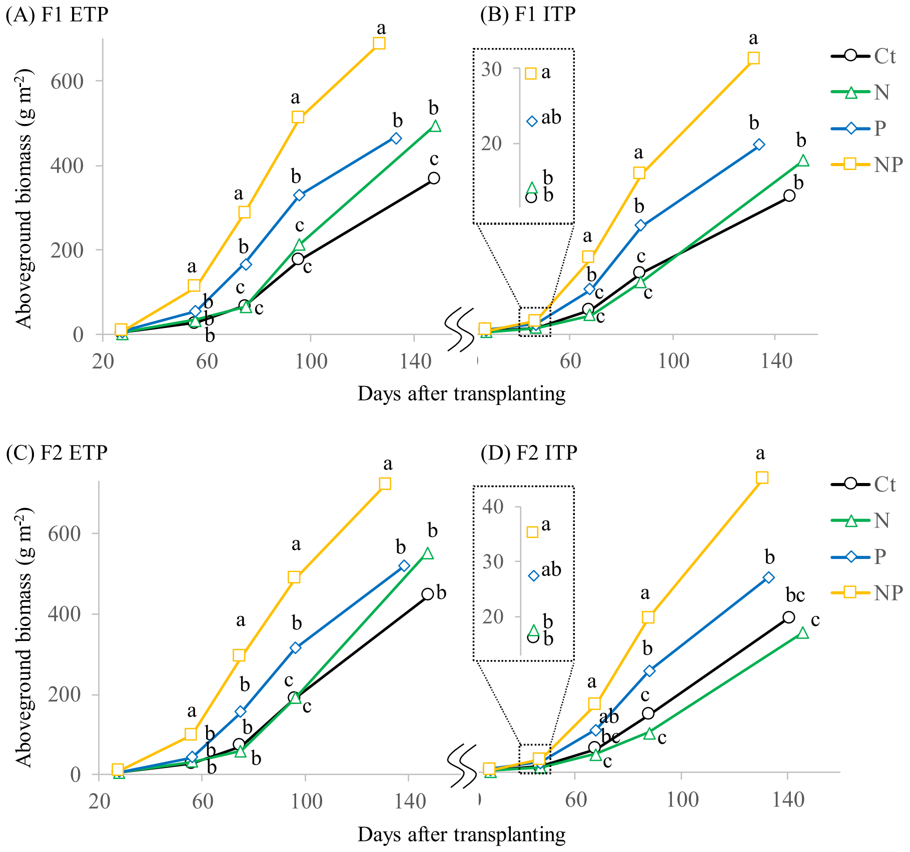

Fig. 3. Changes in aboveground biomass from days after transplanting to maturity, as affected by transplanting date and fertilizer treatment.

upland rice under P-deficient conditions (Rakotoarisoa et al., 2020, Rakotoson et al., 2021; Sahrawat et al., 1995, Vandamme et al., 2018). The effect of this phenological change on climatic growing conditions is clearly illustrated by the exponential relationship between CDD and spikelet sterility under different transplanting dates. The threshold where spikelet sterility started to increase (Fig. 2) coincided with a model in which spikelet sterility was an exponential function of CDD (Horie et al., 1995)—the basis of rice growth models, such as Oryza2000 (e.g., Bouman et al., 2001).

Our empirical evidence supports our hypothesis and previous arguments proposed by Tsujimoto et al. (2019): crop responses to fertilizer inputs can be changed by their impacts on phenological development, even under the same soil nutrient status. As demonstrated herein, the extent of change in phenological development was significant enough to affect crop production in both positive and negative ways. The extended days from transplanting to maturity due to P deficiency favored biomass accumulation under a non-stress environment, as represented by the N plots under ETP. This advantage underlines the general perception that late-maturity types tend to have higher yield than early maturity types under non-stress conditions (Fukai et al., 1998; Vergara et al., 1966). In N plots under ETP, longer days to maturity accounted for 16 %–27 % of the total aboveground biomass at maturity (roughly estimated as the product of crop growth rate (g m^{-2} day^{-1}) at the pre-heading stage between 75 DAT and 96 DAT and prolonged days to heading). This gain contributed to a significant yield increase with a single N application even under highly P-deficient soils; this reveals a plant adaptation strategy to slowly increase the P uptake from a deficient soil, as reported in *Arabidopsis thaliana* grown under climate-controlled greenhouse conditions (Nord and Lynch, 2008). This adaptation strategy of rice under P deficiency may partly explain why yield gain upon P fertilization is sometimes marginal (Haefele and Wopereis, 2005; Saito et al., 2019) despite the general perception of prevailing P-deficient soils in SSA (Haefele et al., 2013; Nziguheba et al., 2015) or a distinct response to P fertilization during vegetative growth or in pot experiments (Nishigaki et al., 2018; Saito et al., 2015b). It should be noted that this adaptation occurs at the expense of longer periods of field occupation by rice and extra use of resources, such as irrigation water.

On the contrary, a negative impact of phenology delay under P deficiency occurred because a prolonged days to heading and to maturity increases the risk of biotic and abiotic stress factors, as observed in the case of Ct and single-N application plots under ITP. In addition, the low benefit of extended growth duration in ITP could be due to lower temperature and lower solar radiation toward the end of the rainy season. Then, the effect of P application, accelerating the phenological development, was more pronounced in ITP than in ETP due to coping with both P-deficiency and low temperature stress. The combined benefits of P application allowed for its greater agronomic efficiency (kg of grain yield increase per kg P applied in NP vs. N plots) at 77–108 kg kg^{-1} in ITP plots across the three fields than the values of 57–58 kg kg^{-1} in ETP plots across two fields. The typical ranges in the agronomic P use efficiency were observed at 49 ± 38 kg kg^{-1} (mean ± SD of 10 sites) in adequately managed lowlands under irrigation in Asia (Dobermann et al., 1998) and at 29 ± 22 kg kg^{-1} (mean ± SD of 27 sites) in rainfed and irrigated lowlands across SSA (Saito et al., 2019). This calculation emphasizes the importance of considering the effect on phenological development for the improvement of P management practice.

In addition, consistent yield and spikelet sterility in P-treated plots between ETP and ITP indicate that the P application widens the safe-sowing windows to avoid any environmental risks. This also benefits the farmers to reduce the labor intensity at the time of transplanting (Dingkuhn, 1995). Decreasing temperature and water shortage at the start and end of the rice growing season commonly occur in the highlands of East and Southern Africa and elsewhere in SSA (Cotter et al., 2020; Samejima et al., 2020; van Oort, 2018; van Oort et al., 2016). Therefore, under certain climatic conditions, the impact of improved P management can be much greater than expected from merely the soil factor. Shortened days to maturity may also increase the opportunity to intensify land use by enabling double- and triple-cropping of rice or rotation with vegetable crops as simulated in the cropping calendar construction model (van Oort et al., 2016). The benefit of avoiding low-temperature stress with P management is not expected in LTP because the temperature at heading stage is too low even after the P application accelerated the phonological development.

Another observation to be noted with respect to the interaction between nutrient management and transplanting date, is that spikelet sterility tended to increase with N application despite its little impact on phenological development (See ITP plots in F2 and in F3). This was consistent with similar observations in the highlands of Kenya (Njinju et al., 2018) and Madagascar (Rakotoarisoa et al., 2020) where increasing rice sterility in N-treated plots upon exposure to low temperature stress was observed. These findings are consistent with the general understanding that high N status of rice plants increases susceptibility to low temperature stress at the microspore formation stage (Hayashi et al., 2000). This observation implies that N and P fertilizer management practices need to be optimized based on the interaction between plant nutrient status and climate-induced stress.

To expand the implications of this study, we first need to integrate the relationship between crop nutrient status and phenological development (and sensitivity to climate-induced stress for plant N status) into crop growth models and decision support tools. This integration should attract extensive attention, as a thorough understanding of phenological development is a critical factor to optimize cropping management practice and to improve the accuracy in predicting environmental and technical impacts on grain yield under present and future climatic conditions (Cotter et al., 2020; van Oort et al., 2015; van Oort, 2018; van Oort and Zwart, 2018). As reviewed by van Oort and Dingkuhn (2021), thermal spikelet sterility and its possible avoidance by combining planting date and varietal choice are one of the earliest areas in which crop models were applied for rice production in SSA (e.g., Dingkuhn and Miezan, 1995). However, none of these crop modeling approaches have focused on nutrient deficiency or management practice as factors to influence phenological development. To do so, further research needs to identify whether there is any quantitative relationship between soil P status and P deficiency-induced delay in phenological development. For instance, a small difference in days to heading between P-treated and P-untreated plots at F4 (the field with the highest amount of oxalate-extractable soil P) implies a potential quantitative effect in degrees of phenology changes depending on the specific P deficiency status. Further, our field experiments repeated in the same study areas corroborated a negative relationship between the degree of extension in number of days to heading and the amount of oxalate-extractable soil P (Asai et al., 2021). Geo-spatial data and rapid prediction methods for soil nutrient status are increasingly available for wider areas and at higher resolutions in SSA (Hengl et al., 2017; Johnson et al., 2019; Kawamura et al., 2019; Leenaars et al., 2018). These technological advances help us to incorporate the relationship between phenology and nutrient status into crop models and decision support tools that might aid in improving nutrient management practices by smallholder farmers.

5. Conclusions

The effects of N and P application on rice yield were greatly dependent on transplanting date via their impact on phenological development under P-deficiency in climate stress-prone environments. Prolonged days to heading due to P deficiency favored extra biomass production but increased the risk of cold stress at the reproductive and ripening stages. The benefit of P application to crop productivity by accelerating phenological development was enhanced by delayed transplanting owing to a combined effect which alleviated both P deficiency and low temperature stress. These findings indicate that impacts of P deficiency and application on crop phenological development and growing climatic conditions need to be further studied. The studies are important for improving the nutrient management practice and crop modeling for rice production in SSA.

Author contributions

B.H.A. and Y.T. conceived and designed the experiments. B.H.A and H.R performed the experiments. B.H.A and Y.T. analyzed the data. B.H.A, Y.T., A.Z.O., wrote the paper. N.R., M.R., A.A., H.R. review & edited the paper. All authors have read and approved the final manuscript.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108256.

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Output4 Introduction

A policy recommendation is compiled to promote the extension of developed techniques for rice production in the target area

Output 4 aimed to elucidate the determinant factors related to the dissemination of improved techniques and to evaluate the impact of rice production on household income and human nutrition. For this, we set three targets:

1. Identify the socioeconomic factors to disseminate fertilizer management techniques and varieties in the target area.
2. Quantify the effect of improved rice cultivation techniques on household income and human nutrition based on ≥ 500 household surveys in the target area.
3. Initiate an implementation plan based on the policy recommendations to extend the developed techniques and information to the target area.

Output 4 provided the knowledge and policy recommendation to better disseminate the technology and understand the impact of rice production on farmers' income and nutrition status based on qualitative and quantitative interviews in rural areas.

Six waves of semi-structured interviews and group discussions at the JICA technical cooperation Papriz selected sites found two complemental types of farmers important for farmer-to-farmer technology dissemination: the informal leader who is influential in a small community and the outgoing transmitter to outside communities. On the other hand, inefficient farmer trainers were characterized as having 1) poor understanding of the training program and techniques and 2) weak relationships with and lack of support from the government agents. Therefore, quality assurance of farmer training and follow-up support of the agent ensures the efficacy of the cascade model.

In the quantitative approach, we constructed an interview-based survey panel data of randomly selected 600 lowland rice-growing households in the region of Vakinankaratra from 2018 to 2022, covering seasonal changes in rice production. In terms of human nutrition, for which we closely collaborate with ONN, we found that higher lowland rice yield and market-oriented vegetable production contributed to the household income and the amount and balance of nutrient intake of rice farmers. Our findings also include the contribution of agricultural production diversity to dietary diversity, leading to nutritional improvement, and the seasonality of nutritional intake due to the harvest season. These findings have been shared with JICA technical cooperation project "PASAN" so that they incorporate these findings into their activities, such as enhancing the variety of crops or improving farmers' nutritional intake by selecting appropriate crops for the farmers to grow.

The panel data and randomized control trials also identified that upland rice cultivation plays a significant role in food security in the region, and a plot-specific prescription for fertilizer use based on soil information can improve the efficiency of farmers' fertilizer application for lowland rice productions.

The data were compiled as policy recommendations that should improve the technology dissemination for efficient rice production and alleviate poverty and malnutrition.

A memory of Output4 activities

Policy recommendation

Plot-specific prescription for the use of fertilizer based on soil information facilitates farmers apply more chemical fertilizer and increase yields for lowland rice production

Findings

- Currently, farmers' rice production in plots with nitrogen (N) application does not have a significantly higher yield on average than the plots without N application (Ozaki et al., 2021).
- Farmers who received the information that their target lowland plots were N fertilizer (urea) responsive (Figure 1) increased N application rate by 53.4 kg/ha ($P<0.1$) and yield by 0.95 t/ha ($p<0.05$) at the target plots relative to non-target plots where farmers do not have information about the responsiveness.(Table 1) (Ozaki et al., 2022).

Data Sources

Finding 1: Two-year panel data of 600 households in the 2017/18 and 2018/19 cropping seasons. The sample households are randomly selected from 60 villages (fokontany) in 13 communes across 3 districts in the Vakinankaratra region.

Finding 2: Results of a randomized controlled trial conducted in 2019/20 season. Seventy households were randomly selected from 5 villages in three districts in the Vakinankaratra region, of which 35 farmers were provided with plot information about N fertilizer responsiveness based on the soil oxalate-P data of one of their lowlands and the rest were not. All the households received 5 kg of urea for free prior to the season.

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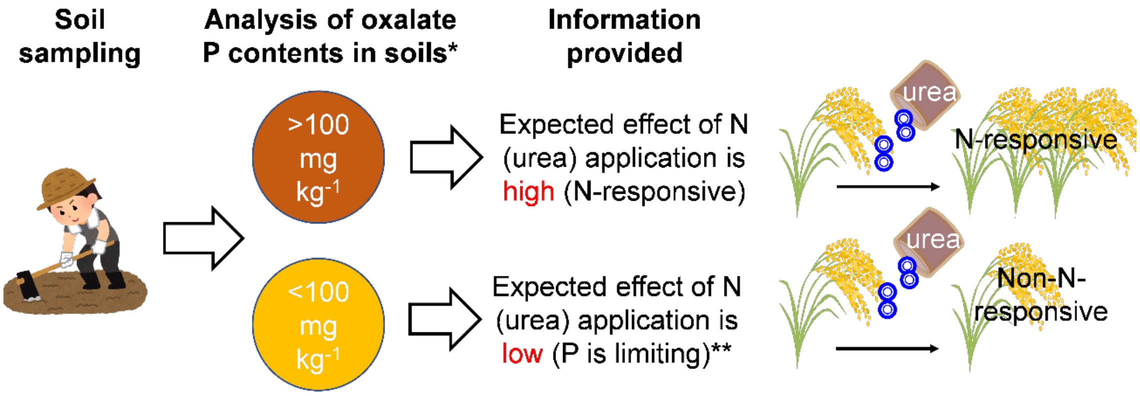
Supporting Data



*The tentative judgement was based on nutrient-omission trials in the region. For the Andosol (volcanic soil) area, a threshold of 300 mg kg^{-1} was used.
**For these soils, the application of P-contained fertilizer (e.g., NPK, DAP), P-dipping, or farmyard manure may be recommended (refer to the Output3).

Figure 1. A flow chart to provide the plot information about the expected effect of nitrogen (urea) application on rice yield.

Table 1. Plot level impact of provision of plot information about nitrogen responsiveness

	Nitrogen Application Rate (kg/ha)	Rice Yield (t/ha)
Plots about which farmers received the information that the lowland plots are N fertilizer (urea) responsive	53.42*	0.95**

The numbers are the difference from plots about which farmers received the information that the plot is N fertilizer responsive and plots without such information. The significant difference implies that the information provision optimized the fertilizer allocation and achieved higher yields at the plots with information than the plots without information.
* $p<0.1$, ** $p<0.05$.

Policy recommendation

Higher lowland rice yield and agricultural production diversity, including market-oriented vegetables or pulses, could contribute to the household income and to the amount and balance of nutrient intakes of rice farmers.

Findings

- Lowland rice farmers are highly dependent on rice for the nutrient intakes, and micronutrient deficiencies (calcium, vitamin A, riboflavin, zinc etc) prevail (Fig. 1).
- Households with higher rice yields increases the cash revenue from rice sales and purchase of nutritious food items such as vegetables, fruits, and meat/fish (Table 1).
- Higher lowland rice yield is associated with an increased intake of energy, zinc, iron and vitamin A (Table 2).
- Agricultural production diversity leads to dietary diversity, and dietary diversity improves children's nutritional status. Especially, pulses production has significant effects on energy and micronutrient intakes (Table 3).
- Market-oriented vegetable production increases household income and dietary diversity. The relationship between vegetable production and nutrition status is weaker for less market-oriented households (Table 4).
- Market seems to be the channel through which increased rice yield and vegetable production translates into improved nutritional outcomes.

Data source

A panel data of randomly selected 600 lowland rice-growing households from 60 villages (fokontany) in 13 communes across 3 districts in the Vakinankaratra region. The interview-based household survey has been conducted since June 2018 for 3 times a year.

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Supporting data

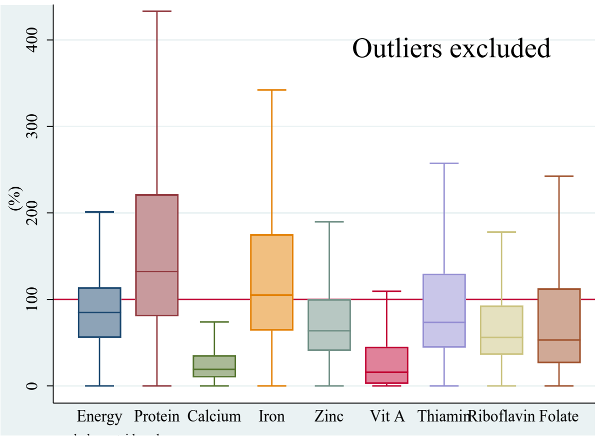

Fig 1. Distribution of nutrient intake to requirement ratio

Nutrient requirement was set based on the recommendation by the Institute of Medicine, and their nutrient adequacy from 1-5 round's survey was calculated individually. For instance, standard requirement of vitamin A is 800 mcgRAE/day/AE. RAE is retinol activity equivalent.

Table 1. Elasticity of cash revenue from lowland rice sales and purchase by food groups with respect to lowland rice yield

Cash revenue	Staple food	Pulse	Tuber	Vegetables	Fruits	Meat & fish
4.753***	-0.024	0.374	0.288	0.456***	0.575**	0.658***

*** p<0.01, ** p<0.05. *Note*: Elasticity shows the percentage change at mean. For instance, an increase of rice yield by 30% (~1t/ha) is associated with 143% (65,000MGA/AE) larger cash revenue from lowland rice sales and 14% (300MGA/month/AE) more purchase of vegetable. AE is adult equivalent (3.6±1.4 AE/household for the samples).

Table 2. Elasticity of calorie and micronutrient intakes with respect to lowland rice yield

Energy	Zinc	Iron	Vitamin A
0.183***	0.115***	0.750***	0.190***

Note: For instance, Rice yield increase by 30% (~1t/ha) increase the households' vitamin A intake by 5.7% (12.5 mcg RAE/day/AE).

Table 3. Association of pulse production with nutrient intake (adult male equivalent)

Energy (kcal/day)	Iron (mg/day)	Zinc (mg/day)
616.3***	8.03***	2.15**

Table 4. Association of vegetable production with income and dietary diversification

	Subsistence veg. growers (n=43)	Market-oriented veg. growers (n=158)
Total household income (1000 MGA/capita)	0.12	0.31**
Household Dietary Diversity Score (HDDS)	-0.016	0.47**

Note: The coefficients are the difference from non-vegetable growers (n=369). HDDS, ranges from 0 to 12, is defined as a number of food groups consumed by the household over one week.

Policy recommendation

Quality assurance of training of trainers and follow up support of the agent ensures efficacy of the cascade extension model. Two complemental types of farmers who are influential to inside and outside communities play pivotal roles for the dissemination beyond the initial farmer-trainer.

Findings

- Two complemental types of farmers—informal leaders who are influential in a small neighbor group and outgoing transmitters to outside communities—play pivotal roles for the dissemination beyond the initial farmer-trainer (Figure 1; Yokoyama 2020).
- The characteristics of inefficient farmer-trainers are summarized as 1) poor understanding of the training program and techniques, and 2) weak relationships and supports of the government agents (Table 1; Sayanagi 2019; Sayanagi et al. in prep.).

Data source

Six waves of interviews were conducted in 2017-2019 in the project sites, applying a cascade model where a selected farmers are trained/certified as a farmer-trainer by the project, then train community members. In the 1st- 2nd waves, a successful case (n=4 farmer-trainers, 76 trainees) in Vakinankaratra. In the 3rd- 4th in Itasy and Analamanga, exploring different local conditions (n=15 trainers, 146 farmers). In the 5 - 6th inefficient cases in Vakinankaratra, Itasy, and Analamanga (n=39 trainers, 46 trainees).

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Supporting data

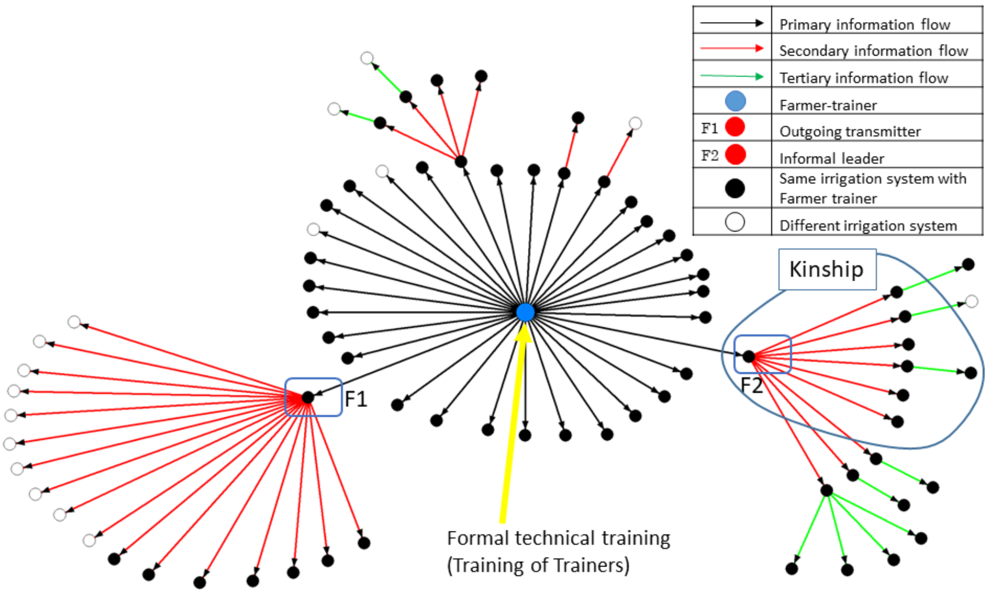

Figure 1 Information flow of an efficient farmer-trainer

An irrigation group leader transferred technologies directly to 33 farmers, 35 via two influential fellow farmers (F1, F2) and 8 via other 3 fellow farmers, 76 in total in 2012-2017.
F1 (Age 21, Male, High school graduate): Vocational trained, conduct a group lecture using PC, work experience in town, same knowledge quality as farmer trainer.
F2 (Age 50, Male, Junior high graduate): Long farming experience, plot demo only, frequent visits of neighbors and relatives, feedbacking to a farmer trainer.

Table 1: Case summaries of farmer-trainers and communes with few trainees

Case	Number of trainees/session	Poor understanding of technique[1]	Poor understanding of program aims[2]	Poor contact with local agent[3]
A	4.2	✓	—	✓
B	Unknown	✓	—	—
C	< 6	✓	—	—
D	< 5	—	✓	✓
E	2.3	—	—	✓
F	7.7	✓	—	—
G[4]	10 <	—	—	—

1. Examples of poor understanding include cases where the farmer-trainer did not use fields with sufficient irrigation for lowland rice, did not include critical techniques in training, or misperceived that training could not be conducted without material inputs.
2. 3 out of 4 farmer-trainers in Commune D did not widely publicize the demonstrations and training on their fields as requested by PAPRIZ.
3. The frequency that the farmers met and/or phoned the agent was low, and additionally, in some cases the formal training was clearly not sufficient.
4. Reference as a successful case. The agent overseeing the commune was in close touch with all farmer-trainers and was very thorough in his training and communication.

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The Adoption of Upland Rice by Lowland Rice Farmers and Its Impacts on Their Food Security and Welfare in Madagascar

Ryosuke Ozaki[1]* and Takeshi Sakurai[1]

The objective of this paper is to examine the impacts of newly adopted upland rice cultivation on lowland rice farmers' food security and welfare. Using cross-sectional data collected from randomly selected 600 farm households in Vakinankaratra region of Madagascar, this study reveals that the adoption of upland rice cultivation has a positive impact on their food security by substantially increasing total rice production per capita. It also increases households' food consumption and total consumption per capita. These results imply that upland rice cultivation should receive more attention from policy makers as a feasible instrument for farmers to increase rice production.

Key words: upland rice, technology adoption, impact assessment

1. Introduction

Rice is the most fundamental staple food for people in Madagascar and the main income source for rural households as well. Sharma and Razafimanantsoa (2016) introduces statistics showing that rice provides 41.9% of the total generated agricultural income of farm households and rice consists of more than half of the total calorie intake for rural households. Hence, the improvement of rice production should be closely related to the welfare of rural households.

Generally, crop production is improved through either yield improvement or land expansion. In the context of Madagascar, the expansion of lowland rice fields is almost impossible due to lowland scarcity and population increase. In addition, the adoption of yield enhancing technologies has remained at low level due to liquidity constraints, high labor requirement, and unstable weather condition (for example, Harvey *et al.*, (2014), Minten, Randrianarisoa, and Barrett (2007), and Moser and Barrett. (2003)).

However, a noteworthy change in rice production is currently taking place in the central highland zone of the island. An increasing number of farmers are adopting upland rice cultivation which is conducted on naturally well-drained fields without water retention on the surface. In Madagascar, except for a few regions in eastern part of the island, upland rice cultivation used to be almost negligible in terms of production volume and planted area. In the early 2000s, new varieties developed by a series of collaborated research program of CIRAD [1] and FOFIFA [2] enabled upland rice cultivation in the central highland zone where no suitable upland rice variety had existed due to the cold temperature (a review is available in Raboin *et al.* (2014)). In addition, NERICA [3] varieties which are more tolerant against drought and more competitive against striga, a parasitic, seriously harmful weed, than conventional varieties began to be promoted. NERICA varieties provided farmers in drier part of the central highland zone with a chance to have better and stable harvest.[4] As of 2019, 17 improved varieties of upland rice have been officially introduced to the central highland zone.[5]

It is true that the newly introduced upland rice varieties have caused the expansion of upland cultivation in the central highland of Madagascar.

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1) The French Agricultural Research Centre for International Development

2) The National Center for Applied Research and Rural Development of Madagascar

3) NERICA stands for New Rice for Africa.

4) Roughly speaking, in central part of the central highland zone lying at a high altitude cold temperature is the constraint and FOFIFA/CIRAD varieties are exclusively dominate, while in western part of the central highland zone lying at a relatively lower altitude dryness is the constraint and NERICA varieties are more suitable.

5) The catalogue is available at https://www.dp-spad.org/content/download/4375/32703/version/1/file/POCHVAR.pdf (accessed on October 10, 2019). However, identifying a variety to its scientific names in the farmers' fields is not realistic because many different local names have been generated and used by farmers.

However, considering that few farmers had grown upland rice before the introduction of the new varieties, this study focuses on the impact of the adoption of "upland rice cultivation" rather than the adoption of any particular rice variety or varieties. In this sense, this study differs from existing studies, which analyze the impact of the adoption of particular upland rice varieties, such as NEIRCA (e.g. Kijima, Sserunkuuma, and Otsuka (2006), Kijima, Otsuka, and Sserunkuuma (2008) and Sakurai *et al.* (2014)).[6]

More importantly, unlike in many sites in Sub-Saharan Africa where upland rice has been introduced, most Malagasy farmers grow lowland rice as traditional staple food and adopt upland rice cultivation as supplemental rice production. In particular, we observe an interesting contrast between the rapid expansion of upland rice practice and the slow progress of lowland rice intensification. However, empirical studies about upland rice are still few. The motivation of this paper is to contribute to filling this gap.

2. Research Question and Hypotheses

The main goal of this study is to examine the impacts of the adoption of upland rice cultivation on farmers who grow lowland rice. This study firstly investigates the determinants of upland rice cultivation. Then, it estimates the impacts of upland rice cultivation on households' food security and welfare.

Regarding the food security, three indicators are used. Total rice production per capita is the main indicator. It is expected that upland rice has a positive impact on it since upland rice is supposed to be supplementary to lowland rice, but it may not be the case if it substitutes for lowland rice production. The quantity of rice purchased in each month from January to March is another indicator. In Madagascar, these three months are generally recognized as lean months before the main harvest from lowland starts in April. Rice price is the highest in these three months in a year. If upland rice harvested a few weeks earlier than lowland rice is for home consumption, it will reduce the quantity of rice purchased in the lean period. Furthermore, the quantity of rice consumed in a week is also used as an indicator of food security.

As the welfare indicators, the value of consumption in the last one month is used. Intuitively, upland rice cultivation should have a positive impact on welfare since it provided supplemental income. However, it may not be true in the following two cases. First, income from upland rice is negative if the paid-out costs for upland rice cultivation such as hired labor and fertilizer are higher than its value. Second, total income does not increase or even decrease if farmers reduce the production of other crops and/or reduce labor supply to off-farm/non-agricultural employment.

3. Analytical Framework

In this study, with cross-sectional data collected in non-experimental setting, a probit model is used to identify the determinants of upland rice cultivation. Then, the impact of upland rice cultivation is analyzed using propensity score matching to address endogeneity. This study employs Kernel matching methods in order to maximize the sample size as well as precision of the analysis. Bootstrapping method is applied to estimate the standard error.

4. Data and Descriptive Statistics

Data for this study was collected through 2 steps. Firstly, a census survey was conducted in 60 villages in 13 communes across 3 districts in Vakinankaratra region from December 2017 to January 2018. The 60 villages are about 50% of the total villages in the 13 communes, and were selected intentionally to have an even geographical distribution within each commune. Then, based on the household list created from the census data, 10 households that grow lowland rice were randomly selected from each of 60 villages as sample households for main survey. The main survey was conducted to the total of 600 households from June to August 2018 and collected detailed household level information via interview: it includes demography, agricultural input and output, monthly transaction (sales and purchases) of rice, monthly expenditure of food and non-food items, weekly food consumption, and non-agricultural/off-farm activities. Out of the 600 households, 34 households are dropped

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[6] In many countries in Sub-Saharan Africa, NERICA has been introduced as a new upland crop where few farmers had experience in upland rice cultivation. Thus, what was really adopted is not a new upland "rice variety" but a new upland "crop." In this sense, the situation is the same as our study site in Madagascar.

Table 1. Descriptive statistics

Variables	Mean of all samples	Mean of non-upland rice growers	Mean of upland rice growers	Difference of the means[1]	
Household characteristics					
Number of household members	4.99	4.78	5.11	-0.33	*
Household with male head (%)	89.75	86.87	91.30	-4.44	*
Age of household head	46.23	47.33	45.64	1.69	
Household head's literacy in French (%)	62.72	65.66	61.14	4.51	
Number of adult members (15 years old or above) in household	3.05	2.97	3.10	-0.12	
Land Endowment					
Number of parcels	3.64	3.32	3.81	-0.48	***
Total area of parcels (ha)	0.75	0.45	0.92	-0.47	***
Total area of lowland parcels (ha)	0.31	0.22	0.36	-0.13	***
Total area of upland parcels (ha)	0.45	0.23	0.56	-0.34	***
Total area of lowland parcels per capita (ha)	0.067	0.055	0.075	-0.019	**
Total area of upland parcels per capita (ha)	0.098	0.057	0.120	-0.064	***
Irrigation condition of lowland (%)	69.58	79.86	64.04	15.82	***
Subjective evaluation of lowland plot soil fertility weighted by plot size (1-3)[2]	2.15	2.12	2.17	-0.045	
Subjective evaluation of upland plot soil fertility weighted by plot size (1-3)[2]	1.92	1.89	1.92	-0.029	
Farming Characteristics					
HH[3] experienced weather-related production shocks in lowland rice (%)[4]	64.84	58.08	68.48	-10.40	**
HH[3] experienced weather-non-related production shocks in lowland rice (%)[4]	20.67	9.09	26.90	-17.81	***
Other characteristics					
Any HH[3] member is engaged in off farm employment (%)	61.84	67.68	58.70	8.98	**
Any HH[3] member is engaged in non-agricultural employment (%)	35.51	43.43	31.25	12.18	***
Livestock (Log of total value per capita)	2.91	3.08	2.82	0.26	*
Asset (Log of total value per capita)	2.94	3.19	2.80	0.38	***
Distance from the national road (10km)	0.58	0.56	0.59	-0.03	
Food security and welfare indicators					
Total rice production per capita (kg)	264.04	208.93	293.69	-84.76	***
Rice consumption in last 7 days (kg/capita)	2.28	2.35	2.24	0.12	
Total value of food items consumed in the last one month (10^3MDA/capita)[5]	51.48	50.45	52.04	-1.60	
Total value of non-food items consumed in the last one month (10^3MDA/capita)[5]	15.13	12.34	16.63	-4.29	**
Aggregated value of items consumed in the last one month (10^3MDA/capita)[5]	66.62	62.79	68.68	-5.89	
Number of Observations	566	198	368	-	-

Note: 1) *, **, and *** indicate that the means are different at the significance level of 10%, 5%, and 1%, respectively.
2) Evaluation is based on three-scale category: low=3, average=2, and high=1.
3) HH stands for household.
4) "Experienced" is defined as having at least one shock in the last 10 years.
5) MDA stands for Malagasy Ariary. 1 USD = about 3275 MDA on July 18, 2018.

from the analyses: 4 households are due to incomplete data and 30 households have no upland plot to adopt upland rice cultivation.

Table 1 presents the descriptive statistics of the remaining 566 sample households. The mean size of households is around 5 people. The mean of household heads' age is 46 years old. On average, a household has 3 to 4 parcels whose total area is less than 1 ha. By agroecology, mean landholding of a household is 0.31 ha in lowland and 0.45 ha in upland.

Among the sample households, 65% of them have experienced production shocks in lowland rice due to weather related events such as cyclones and low temperature at least once in the last 10 years, and 20% of them have experienced weather-non-related production shocks in lowland rice such as crop disease and insect attack.

Among 566 households, 65% of them grew upland rice in the main cropping season of 2017/2018, which is the same percentage as found in the census survey. The mean comparison between upland rice growers and non-growers shows significant differences in many variables. With respect to household's characteristics, upland rice growers have significantly larger household size. In terms of land endowment, total area of lowland parcels, that of upland parcels, and the sum of them are significantly larger among the upland rice growers. In the meantime, upland rice growers are less likely to have irrigated lowland.

As for income source, upland rice growers are less

Table 2. Determinants of upland rice cultivation[1]

Variables	(1)		(2)	
Household characteristics				
Number of household members	-0.01		-0.01	
Sex of household's head (=1 if male)	0.02		-0.00	
Age of household head	-0.00		-0.00	
Household head's literacy in French (=1 if the head can read French)	-0.01		0.09	***
Number of adult members (15 years old or above) in household	0.00		0.01	
Land Characteristics				
Size of lowland parcels per capita (ha)	0.02		-0.01	
Size of upland parcels per capita (ha)	1.22	**	0.61	
Irrigation condition of lowland (=1 if irrigated)	-0.15	***	0.03	
Subjective evaluation of lowland plot soil fertility weighted by plot size (1-3)[2]	0.03		-0.01	
Subjective evaluation of upland plot soil fertility weighted by plot size (1-3)[2]	0.07		0.07	
Farming Characteristics				
HH[3] experienced weather-related production shock in lowland rice (=1 if yes)[4]	0.10	**	0.06	
HH[3] experienced weather-non-related production shocks in lowland rice (=1 if yes)[4]	0.19	***	0.17	***
Other Characteristics				
Any of household member has non-agricultural income source (=1 if yes)	-0.07	*	-0.02	
Log of total value of livestock per capita	0.03		0.03	*
Log of total value of asset per capita	-0.09	***	-0.07	***
Distance from paved road (10km)	0.04		0.13	**
Commune dummy variables				
Belazao	NA		0.34	**
Antanimandry	NA		0.36	**
Betafo	NA		Reference	
Soavina	NA		0.40	***
Antohobe	NA		0.52	***
Mahaiza	NA		-0.01	
Ambohimasina	NA		0.13	
Ambohimanambola	NA		0.39	***
Inanantonana	NA		0.37	***
Ankazomiriotra	NA		0.49	***
Mandoto	NA		0.38	***
Antambao Ambary	NA		0.11	
Vinany	NA		0.78	***
Number of observations	566		566	

Note:1) Coefficients show marginal effects. *, **, and *** indicate significance level at 10%, 5%, and 1%, respectively.
2) Evaluation is based on three-scale category: low=3, average=2, and high=1.
3) HH stands for household.
4) "Experienced" is defined as having at least one shock in the last 10 years.

likely to have family members engaged in off-farm and/or non-agricultural employment. In addition, values of livestock and assets are significantly smaller for upland rice growers. With respect to food security and welfare indicators, rice production per capita and total value of non-food items consumed in the last one month are significantly larger for upland rice growers.

5. Results

1) The determinants of upland rice cultivation

Table 2 shows the results of probit regression. Unobservable factors at the commune level are captured as commune fixed effects by commune dummy variables in the second column.

The most salient is that the upland rice adoption is significantly affected by the commune effects. By comparing the first column and the second column, it is interpreted that the availability of upland, the lack of irrigation in lowland, weather-related risk in lowland, and the opportunities of non-agricultural earning are commune level factors affecting upland rice cultivation rather than household level ones. Moreover, unobservable commune level effects such as the presence of NGOs, farmers' formal associations, and farmers' informal network that promote upland rice cultivation may also be working.

As for household-level variables, French literacy of household head and weather-non-related shock experiences have significant influence on the adoption. While the former is common finding in the literature of technology adoption, for example Kijima, Otsuka, and Sserunkuuma (2011) and Olufunmilola, Bamire, and

Ogunleye (2017) in the case of NERICA adoption, the latter has not been identified in existing literature and is considered to be our contribution.

2)Impact of upland rice cultivation

Common support conditions for propensity score matching estimation are shown in Figure 1 and Figure 2 for the cases of without and with commune dummies respectively. Kolmogorov-Smirnov distance measure of distributions of propensity score is 0.4063 for the former and 0.5620 for the latter. Thus, because the commune dummies worsen the common support condition, the model without commune dummies is used in propensity calculation and consequent analysis imposing common support. We also confirm that there is no statistically significant difference in the mean of each variable after matching (results are not shown).

The result of impact assessment is given in Table 3, which indicates upland rice cultivation improves households' food security through the increase in the total rice production. This result is consistent with the typical explanation that upland rice is a supplemental production to lowland rice, rather than a substitute for lowland rice. Moreover, this analysis provides quantitative evidence that the upland rice plays an important role through the increase of 75.75kg of rice production per capita, which is not negligible as both income source and food. As for household's consumption, the result shows that upland rice cultivation significantly increases household's consumption level, particularly consumption of food items as hypothesized.

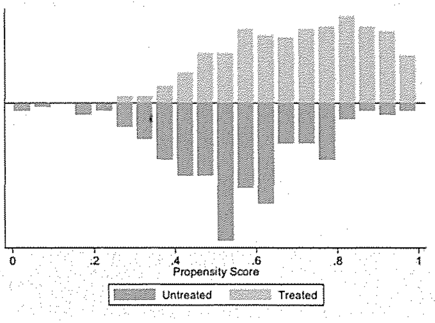

Figure 1. Common support without commune dummy

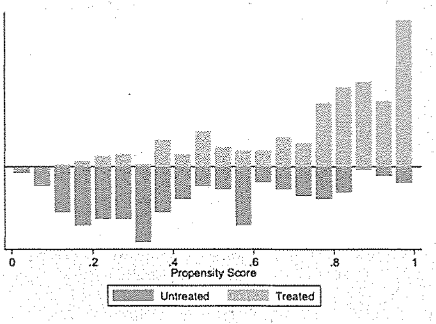

Figure 2. Common support with commune dummy

However, none of the other variables related to rice purchasing behavior in lean months are significantly affected. It implies that households do not use the additional rice production to cope with the food shortage in the lean months.

Moreover, upland rice cultivation does not affect the amount of rice consumption at the time of interview (i.e. after harvest of main rice production), although it significantly increases the value of monthly food consumption in the same period as already shown. We do not have direct evidence, but the contrasting results may imply that additional rice production from upland contributes to the consumption of other food than rice, probably via purchasing.

Robustness check was conducted by using another matching method, nearest-neighbor matching, and similar results were obtained.

6. Conclusion

Upland rice cultivation has rapidly become popular in the central highland zone of Madagascar. Regarding the upland rice cultivation as a new technology that is successfully adopted by rural farm households, this paper provides empirical evidence of the impact of the upland rice cultivation. The results imply that the upland rice cultivation enhances food security and improving households' welfare.

This study suggests that the upland rice is worth receiving more attention from policy makers because it is a realistic instrument for small-scale farmers to increase rice production. Promoting upland rice cultivation to low adoption areas is recommended.

The major limitations of this study are as follows. First, the endogenous factors may not be perfectly controlled in the presented framework. Thus, the construction of a panel dataset is expected to redirect the analysis of this study.

Second, variables for households' consumption and rice purchasing behaviors are constructed based on data only from January to June. Thus, data covering all months may provide a new insight.

Table 3. Impact of upland rice cultivation[1]

Dependent Variables	Unit	Coefficients[1]	
Food Security			
Total rice production per capita	Kg/capita	75.75	*
Quantity of rice consumed in the last 7 days	Kg/capita	0.00	
Quantity of rice purchased in January	Kg/capita	1.30	
Quantity of rice purchased in February	Kg/capita	-0.15	
Quantity of rice purchased in March	Kg/capita	-0.56	
Total quantity of rice purchased during January and March	Kg/capita	0.59	
Welfare			
Total value of food items consumed in the last one month[2]	10^3MDA/capita	5.08	**
Total value of non-food items consumed in the last one month[2]	10^3MDA/capita	2.86	
The aggregated value of items consumed in the last one month[2]	10^3MDA/capita	7.95	**
Number of observations		566	

Note: 1) * and ** indicate significance level at 10% and 5%, respectively.
2) MDA stands for Malagasy Ariary. 1 USD = about 3275 MDA on July 18, 2018.

In addition, future study will be expected to explore profitability and risk of upland rice cultivation in comparison with those of lowland rice cultivation and those of other crops like maize and cassava. Such studies will provide answers to questions such as "Which is better for farmers, intensifying lowland rice production or further expanding upland rice fields?" and "What is the optimal mixture of those crops?"

Acknowledgement

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Profitability of Chemical Fertilizer Application: Comparison of Lowland and Upland Rice Cultivation in Madagascar

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This paper examines whether chemical fertilizer application in rice fields is profitable in the central highland of Madagascar where both lowland rice and upland rice are cultivated. The analyses reveal: (i) upland rice plots are more likely to receive chemical fertilizer; (ii) the impact of nitrogen application on yield is larger on upland rice plots than on lowland rice plots; and (iii) nitrogen application is profitable only when nitrogen is in the form of urea and applied to upland rice plots. We conclude that technological development to improve yield response to chemical fertilizer in lowland rice plots should be promoted.

Key words: chemical fertilizer, profitability, upland rice

1. Introduction

In developing countries, chemical fertilizer use is recommended to boost agricultural productivity that is widely recognized as the key to rural poverty reduction. However, the adoption rate and the extent of its application are limited in sub-Saharan Africa (SSA) compared to other parts of the world. Morris et al. (2007) describe that profitability is the first and most obvious factor that explains the low adoption rate of chemical fertilizer in SSA. However, except for a few empirical studies such as Liverpool-Tasie *et al.* (2017) and Sheahan *et al.* (2013) that examine the profitability of chemical fertilizer application to maize cultivation in Nigeria and Kenya respectively, there is scant evidence that farmers rationally adjust their practice depending on the low and heterogeneous profitability of chemical fertilizer application.

We choose our study site in Madagascar, where the application of chemical fertilizer remains at the lowest level in the world (Sharma and Razafimanantsoa, 2016). Because rice is the single dominant food crop as well as the main income source for rural farm households in Madagascar, our study focuses on rice.

Rice is traditionally grown in lowland plots[1)]. Since the early 2000s, upland rice cultivation[2)] has been introduced with new varieties and rapidly diffused in some part of the country like Vakinankaratra region - one of the major rice producing regions. This is a unique situation because farmers with long experience in lowland rice cultivation have adopted upland rice cultivation[3)]. Upland rice is supplemental since lowland rice growers who simultaneously grow upland rice have larger rice production per capita and higher consumption level than those who do not (Ozaki and Sakurai, 2020)[4)].

Taking advantage of the unique situation, we explore whether rice farmers apply chemical fertilizer based on the expected returns to rice cultivation. This paper assesses the profitability of the two types of rice cultivation to understand the current practice. Then, it attempts to derive policy implications towards the promotion of chemical fertilizer in rice production.

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1) Madagascar is a hilly island, and lowland is the lower portion of landscape like valley bottoms, where lowland rice is grown with water accumulated on the surface of soil by bunds either under irrigated or rainfed conditions.

2) Upland is the upper portion of the hilly landscape, usually sloping, and rice is grown in non-bunded, no-terraced fields with naturally well-drained soils without water accumulation on the surface like maize and cassava. Note that upland and lowland are not related to the altitude of homestead location.

3) Upland rice has been promoted in other SSA countries, but in most cases, it is in areas where lowland rice cultivation is not common or difficult to practice.

4) Most farmers in study area distinguish upland rice varieties from lowland rice varieties. But no major difference is found in the usage of paddy although the data is not presented in this paper.

2. Research Questions and Hypotheses

This study first presents fertilizer use in each type of plots and see whether there is difference in adoption rate and application dose. Then, whether the difference of chemical fertilizer use, if it exists, has something to do with profitability is investigated. The hypothesis is that farmers use chemical fertilizer in the plot with the higher profitability.

3. Analytical Framework

We assume that households decide to apply chemical fertilizer, pursing for optimizing activities at each plot as well as overall farm activities. Following the procedure of Sheahan *et al.* (2013) and Liverpool-Tasie *et al.* (2017), we first estimate the production function to capture how much extent the chemical fertilizer application increases rice yield. The production function is expressed as follows:

$$Yield_{ijt} = f(X_{ijt}, Z_{ijt}, u_{ijt}) \qquad (1)$$

$$u_{ijt} = \varepsilon_{ijt} + c_i \qquad (2)$$

where $Yield_{ijt}$ is defined as rice production in kg per hectare (ha) of plot *i* of household *j* in time *t*. X_{ijt} is plot and time specific variables such as quantity of seeds, plot size, fertilizer use, animal traction use, and labor inputs. Z_{ijt} is a vector of controls that affect the yield, including plot characteristics, distance to the nearest town, and whether the household has rights to sell the plot[5]. Some household characteristics variables such as age, gender, and education of household's head are also included. The u_{ijt} is a composite error term consisting of time invariant and time varying unobserved characteristics. By nature, the use of production inputs is an endogenous decision of plot manager. The error term may include some unobservable characteristics of plot and plot manager that affect both the input use and crop yield, resulting in loss of consistency of estimation results. Therefore, fixed effect model (FE model) that can cancel out the effects of time invariant factors at plot level is employed in addition to a simple pooled OLS.

Next, the marginal physical products (MPP) and the average physical products (APP) of nitrogen application are calculated for each plot in order to estimate the expected average value cost ratio (AVCR) and the expected marginal value cost ratio (MVCR). MPP is derived for each plot by taking the first derivative of the production function with respect to quantity of nitrogen applied. APP is calculated as difference between the estimated yield with nitrogen application ($Yield^{W}$) and the estimated yield without it ($Yield^{WO}$) over the amount of nitrogen applied[6].

$$MPP_{ijt} = \frac{\partial Yield_{ijt}}{\partial Quantity\ of\ nitrogen} \qquad (3)$$

$$APP_{ijt} = \frac{Yield^{W} - Yield^{WO}}{Quantity\ of\ nitrogen\ applied} \qquad (4)$$

$$M(A)VCR_{ijt} = \frac{(Price\ of\ rice_{ct} * M(A)PP_{ijt})}{Price\ of\ nitrogen_{dt}} \qquad (5)$$

where the mean of the selling price of 1 kg of rice of each commune ($Price\ of\ rice_{ct}$) and the mean of the price of nitrogen of each district ($Price\ of\ nitrogen_{dt}$) are used for the calculation of MVCR and AVCR.

Assuming that farmers are risk-neutral and maximizing profit at plot level as well as farm level, farmers have an incentive to use chemical fertilizer when AVCR is greater than 1, which implies that the value of additional product by the use of the chemical fertilizer is greater than the cost of the chemical fertilizer. MVCR of 2 is suggested as a benchmark for chemical fertilizer to be adopted, considering the production risks and transportation costs (Sheahan *et al.*, 2013).

4. Data and Descriptive Statistics

Data was collected in the following procedure. In 2017, a census survey was carried out in 60 villages in 13 communes across 3 districts of Vakinankaratra region. The number of households identified was 5253[7]. The 60 villages are almost the half of the total villages in the 13 communes. They were selected intentionally to have an even geographical distribution within each commune. Based on the census survey data, 10 households that grew lowland rice in the season of 2017-2018 were randomly selected from each village. Trained enumerators interviewed the selected households three

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[5] Bellemare (2013) showed in his analysis of the relationship between land rights and agricultural productivity that household's rights to lease out a plot negatively affect productivity. Since our dataset does not have information about rights to lease out a plot, we include rights to sell it to control similar effects.

[6] This definition follows Liverpool-Tasie *et al.* (2017).

[7] This census survey targeted all the households residing in the main hamlet of each of 60 villages.

times a year to collect detailed information about their farm activities with a focus on rice cultivation. This study constructs a 2-year panel dataset using the plot-level information about 2017-2018 and 2018-2019 rainy season activities. The following analysis uses data of those plots appearing in both seasons.

Table 1. Fertilizer use by plot type

	Lowland rice plots	Upland rice plots	Total
No fertilizer	1,301 (74.94%)	78 (14.80%)	1,379 (60.94%)
Organic fertilizer only	348 (20.05%)	254 (48.20%)	602 (26.60%)
Chemical fertilizer only	19 (1.09%)	102 (19.35%)	121 (5.35%)
Both organic and chemical fertilizer	68 (3.92%)	93 (17.65%)	161 (7.11%)
Total	1,736	527	2,263

Among the total of 2,263 rice plots, 1,736 are lowland rice plots and 527 are upland rice plots. Due to the nature of sampling, all the farmers have lowland rice plots, but not all of them have upland rice plots. Table 1 shows that fertilizer application is not common in general: More than 60% of the rice plots did not receive any fertilizer. The percentage of plots that received chemical fertilizer is only 12.5%, including plots receiving chemical fertilizer only and plots receiving both organic and chemical fertilizer. However, differences are observed. While 75% of the lowland rice plots received no fertilizer, it is only 15% for upland rice plots. Only 5 % of the lowland rice plots received chemical fertilizer, while 37% of the upland rice plots did it.

5. Results

Table 2 presents descriptive statistics at plot level[8]. Comparing lowland rice plots with upland rice plots, the yield without chemical fertilizer is higher by more than 1 ton per ha in the former than in the latter, and the gap becomes bigger if chemical fertilizer is applied. Although chemical fertilizer is less frequently used in lowland rice plots, when it is used the dose is higher in lowland rice plots than in upland rice plots; the average amount is 36.67 kg per ha and 12.55 kg per ha, respectively[9]. Then, we compare plots receiving chemical fertilizer with those not receiving it. First, regardless of the plot location, the probability of hired labor use, the amount of organic fertilizer application, the proximity (the invers of distance) of homestead to the nearest town, and the years in education of household's head are higher in plots with chemical fertilizer. On the one hand, the use of commercial seeds[10], the number of adult members, and the altitude of homestead location are significantly different only for lowland rice plots. On the other hand, seed amount applied, experience of weather-related shock, and the rights to sell the plot are significantly different only for upland rice plots.

Table 3 shows the result of production function estimates. The dependent variable is the yield in kg per ha. Neither the pooled OLS model nor the FE model shows statistically significant impact of nitrogen use on the yield. However, in the FE model, the interaction term of upland rice plots and nitrogen application has a significantly positive coefficient, implying that the yield response to nitrogen is relatively higher in upland rice plots than in lowland rice plots. This underpins the situation that the probability of receiving chemical fertilizer is higher in upland rice plots than in lowland rice plots. Additionally, plot size has a negative association with yield and its quadratic term shows that there is U-shape relationship between yield and plot size.

Column 3 shows the result of OLS regression using only 2018-2019 season data to see the marginal impact of 1 kg of nitrogen on yield[11]. Using the quantity of nitrogen and organic fertilizer applied to plots, the results show the same signs and similar significance levels with previously tested models. 1 kg of nitrogen produces more in upland rice plots than in lowland rice plots by an additional 25.79 kg per ha.

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8) Sixty plots are excluded because of two reasons. First, plots resulted in no harvest or produced less than 100 kg per hectare. These plots are dropped because there should be a serious crop failure. Second, plots whose size are less than 1 Are (0.1 ha) are dropped because these plots seem too small to be important plots for households in terms of crop production.

9) According to our field observations, the major composition of nutrient is 11-22-16 for NPK and 46-0-0 for urea. We used this composition to calculate the quantity of nitrogen applied and the price of nitrogen in this study.

10) "Commercial seeds" mean that the farmer used seeds purchased from seed companies, input suppliers, and general stores in the seasons surveyed (i.e., not recycled).

11) For this part, we used observations of only from 2018-2019 season because the quantity of chemical fertilizer in upland rice plots in 2017-2018 season is not available in our dataset.

Table 2. Descriptive statistics

		Lowland (N=1,698)			Upland (N=505)			TOTAL (N=2203)
Chemical fertilizer application		Yes	No		Yes	No		
	Unit	(1)	(2)		(3)	(4)		(5)
Production	Kg/Ha	5,162.67	3,869.56	***	2,760.89	1,876.28	***	3,494.62
		(3,005.13)	(2,702.75)		(2,815.10)	(1,968.09)		(2,729.50)
Nitrogen applied	Kg/Ha	36.67	0	***	12.55	0	***	23.46
		(45.49)	(0)		(26.95)	(0)		(38.24)
Organic fertilizer applied	Kg/Ha	10,305.23	1,649.04	***	7,992.25	3,932.00	***	7,934.62
		(13,772.38)	(5,069.47)		(9,686.92)	(8,768.55)		(10,083.21)
Seed amount	Kg/Ha	151.07	135.41		121.47	100.00	*	128.76
		(109.83)	(96.75)		(110.11)	(99.01)		(99.22)
Commercial seeds (0/1)	Yes = 1	0.14	0.04	***	0.05	0.09		0.05
		(0.34)	(0.20)		(0.29)	(0.22)		(0.23)
The number of adults in HH	Number	2.92	3.20	*	3.30	3.18		3.20
		(1.11)	(1.40)		(1.23)	(1.35)		(1.38)
Hired labor use (0/1)	Yes = 1	0.99	0.93	*	0.91	0.81	**	0.91
		(0.12)	(0.25)		(0.28)	(0.40)		(0.28)
Plot size	Ares	10.69	18.02	***	22.06	22.52		18.79
		(9.12)	(17.43)		(20.35)	(19.02)		(17.81)
Distance from homestead	Minutes	24.43	30.68		26.52	26.99		29.61
		(24.17)	(34.16)		(29.77)	(27.95)		(32.65)
Weather-related shock (0/1)	Yes = 1	0.34	0.34		0.22	0.33	**	0.34
		(0.48)	(0.47)		(0.42)	(0.47)		(0.47)
Non weather-related shock (0/1)	Yes = 1	0.26	0.18		0.32	0.34		0.23
		(0.40)	(0.44)		(0.47)	(0.47)		(0.42)
Animal traction use (0/1)	Yes = 1	0.32	0.65	***	0.70	0.73		0.66
		(0.47)	(0.48)		(0.46)	(0.44)		(0.47)
HH has a right to sell this land	Yes = 1	0.30	0.32		0.18	0.30	**	0.31
		(0.46)	(0.47)		(0.38)	(0.46)		(0.46)
Asset value per person	10^3MGA	451.95	461.79		488.24	396.38		407.93
		(569.97)	(618.00)		(632.04)	(499.03)		(419.43)
Sex of HH's head (0/1)	Male = 1	0.92	0.91		0.90	0.92		0.91
		(0.27)	(0.28)		(0.29)	(0.28)		(0.28)
Age of HH's head	Years old	47.34	47.32		45.82	46.56		47.13
		(12.04)	(13.41)		(11.96)	(13.65)		(13.35)
Education of HH's head	Years	7.73	5.56	***	6.23	5.13	***	5.59
		(4.35)	(3.70)		(3.84)	(3.54)		(3.73)
Size of HH	Number	4.61	5.04	*	5.45	5.04	*	5.04
		(1.53)	(2.01)		(1.86)	(1.85)		(1.97)
Altitude of homestead	Meters	1477.51	1250.86	***	1234.61	1209.54		1250.13
		(147.12)	(244.66)		(281.15)	(212.69)		(242.26)
Distance to the nearest town	Km	6.08	13.47	***	10.27	15.67	***	13.49
		(5.09)	(9.71)		(7.74)	(10.29)		(9.79)
Observations		74	1,624		96	409		2203

Source: Authors' calculation from our survey data.

Note: Standard deviations are in the parentheses. *, **, and *** indicate that the means are different at the significance level of 10%, 5%, and 1%, respectively. HH stands for household. MGA is local currency, standing for Madagascar Ariary.

Table 3. Production function estimates

		Pooled OLS		Fixed effect		OLS	
	Unit	(1)		(2)		(3)	
Nitrogen use (0/1)	Yes = 1	-123.13		-266.57			
2018-2019 Season	Yes = 1	-459.22	***	-200.18			
Quantity of nitrogen applied	Kg/Ha					-0.37	
Upland rice plot	Yes = 1	-1494.68	***			-1843.12	***
Upland rice plot x Season				212.66			
Upland rice plot x Nitrogen use		407.23		599.92	*		
Upland rice plot x Nitrogen quantity						25.79	***
Other inputs and time-varying factors							
Organic fertilizer use (0/1)	Yes = 1	-110.18		80.36			
Quantity of organic fertilizer applied	Kg/Ha					0.04	***
Upland rice plot x Organic fertilizer use		397.27	**	-79.93			
Upland rice plot x Organic fertilizer quantity						0.02	
Seed amount	Kg/Ha	8.18	***	3.43	*	5.27	**
Seed amount squared		0.01		0.003		0.01	
Commercial seed (0/1)	Yes = 1	242.74		-99.73		396.73	
The number of adults in HH	Number	121.44	**	107.82		94.48	
Hired labor use (0/1)	Yes = 1	682.70	***	420.38	***	752.79	***
Animal traction use (0/1)	Yes = 1	-47.97		227.73	*	0.00	
Plot size	Ares	-88.01	***	-287.77	***	-97.41	***
Plot size squared		0.59	***	0.65	***	0.61	***
Upland rice x Plot size		7.08		204.32	***	17.41	*
Weather related shock (0/1)	Yes = 1	-669.50	***	-542.79	***	-749.62	***
Non-weather-related damage (0/1)	Yes = 1	-764.91	***	-496.19	***	-845.14	
Plot level covariates		YES		YES		YES	
Household covariates		YES		YES		YES	
Commune dummy		YES		YES		YES	
Plot fixed effect		NO		YES		NO	
Constant		5771.71	***	4671.59	***	2983.05	***
Observations		2203		2203		1098	
R-squared		0.551		0.117		0.554	

Source: Authors' estimates from our survey data.

Note: *, **, and *** indicate that the means are different at the significance level of 10%, 5%, and 1%, respectively. Standard errors are clustered at village level in all specifications although they are not shown in the table due to page limitation. HH stands for household. MGA is local currency, standing for Madagascar Ariary. Household level covariates include sex of HH's head, age of HH's head, years of education of HH's head, household size, distance to the nearest town, and dummy variables for high altitude area (>1600m) and medium altitude area (1600m> the altitude > 1200m).

Table 4. Profitability analysis

	MPP	APP	MVCR_NPK	MVCR_UREA	AVCR_NPK	AVCR_UREA
Overall	5.52	16.44	0.182	0.875	0.563	2.810
Upland rice	25.417	25.411	0.844	4.049	0.871	4.348

Source: Authors' estimates from the production function.

Table 4 presents the mean of MPP, APP, MVCR, and AVCR, calculated based on the production function estimated for 2018-2019 season. Two kinds of AVCR and MVCR with different nitrogen sources are presented: one is from NPK, the other is from urea because the nitrogen content is much lower in NPK than urea (or in other words, urea is a cheaper nitrogen source). On average, 1 kg of nitrogen produced 16.44 kg in all samples and 25.41kg if it is used in upland rice plots. From AVCR, it is profitable to apply urea but not so for NPK. The MVCR exceeds 2 only when nitrogen is in the form of urea and applied to upland rice plots.

It is important to note that these results might be still optimistic because of two reasons: the assumption of risk-neutrality and no transportation cost in calculation. The profitable case in this study may become unprofitable due to transportation costs, especially in remote areas, as suggested by Liverpool-Tasie *et al.* (2017).

6. Conclusion

Using the data from Vakinankaratra region of Madagascar, this study explores the profitability of fertilizer application in two different types of rice plot. The first finding of this paper is that the adoption rate of chemical fertilizer is higher in upland rice plots than lowland rice plots.

Using a FE model, this study finds that although yield response to nitrogen is not clear as a whole, the response varies across the two types of plot: it is higher in upland rice plots than in lowland rice plots. In this sense, observed farmers' practice is consistent with the difference in expected returns.

The profitability analysis based on MVCR and AVCR suggests that whether the nitrogen application becomes profitable depends on plot type and chemical fertilizer products. In the context of the study area, MVCR of nitrogen application reaches the recommended level only when it is in the form of urea and applied to upland rice plots.

Policy implications derived from this study are as follows. First, when farmers obtain chemical fertilizer products, information about nutrient composition will help the farmers profitably use them. Second, although this study shows the advantage of upland rice plots in terms of profitability of chemical fertilizer use, it does not necessarily suggest that farmers should increase investment in upland rice. Upland rice still accounts for only a small part of the total rice production in the study area. More importantly, upland rice production is less stable due to its vulnerability to adverse climatic events, and its yield is substantially lower than lowland rice production. Therefore, in the long run, policies to promote technological development[12] to agronomically improve yield response to chemical fertilizer in lowland rice plots, and thereby make its application profitable would have higher potential to enhance welfare than policies to encourage further investment in upland rice cultivation.

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12) For example, development of new rice varieties with higher response and innovative practical methods enhancing efficiency of nutrient uptake by plants.

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Optimization of Farmers' Fertilizer Use by the Provision of Soil Quality Information: Experimental Evidence from Madagascar

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Optimization of Farmers' Fertilizer Use by the Provision of Soil Quality Information: Experimental Evidence from Madagascar

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Abstract

Increasing the use of chemical fertilizer is required to realize a sustained growth of agricultural productivity in sub-Saharan Africa. In addition to various constraints related to input markets and socio-economic characteristics of farmers, previous studies have shown that uncertainty about crop yield response discourages farmers to use fertilizer. This study examines how site-specific information about soil characteristics optimizes farmers' decisions as to fertilizer allocation by reducing the yield response uncertainty. Unlike existing similar works, our unique approach is the use of simple binary information on expected effectiveness (EE) of fertilizer application based on soil chemical analysis. We tested its effect in a randomized controlled trial (RCT) conducted in Madagascar. The results revealed that the binary information regarding EE at plot level induced more optimal allocation of fertilizer among plots as information of high EE significantly increased the rates of nitrogen fertilizer application and as a result achieved higher rice yield. In addition, high EE information led to increased use of nitrogen fertilizer at household level. One important implication of this study is even simple information about plot-level soil characteristics can influence farmers and induce intensification of input use

Keywords: Rice, Chemical fertilizer, Soil property, RCT, Madagascar

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I. Introduction

It is widely recognized that sustained growth of agricultural productivity in sub-Saharan Africa (SSA) requires a substantial increase in chemical fertilizer application (Morris *et al.* 2007; Xu *et al.* 2009; Holden 2018). The pace of increase in nitrogen fertilizer use in agriculture has been substantially slower in SSA than in other parts of the world (Tsujimoto *et al.* 2019). A large body of literature has identified various factors that explain the low use of fertilizer in SSA, mainly focusing on demographic as well as market-related factors. For example, education level of the heads and other household members (Asfaw and Admassie 2004), accessibility to input and credit markets (Croppenstedt *et al.* 2003), and quality of inputs sold in the market (Bold *et al.* 2015).

In addition, recently increasing publications show that site-specific recommendations about soil characteristics can influence farmers' fertilizer application. Harou *et al.* (2022) found that plot-specific information provision together with inputs voucher significantly increased farmers' investment in mineral fertilizer and consequently productivity. Van Campenhout (2021) pointed out that farmers face two types of information deficiencies: technical information for correct implementation of modern inputs and information about the returns on technology adoption. Based on the experiment in which impacts of releasing these two types of information were compared, his study concluded that information about the expected returns had a more prominent role on farmers' productivity improvement. Regarding the former type of information deficiency, the experiment of Abey *et al.* (2022) provided evidence that there were mismatches between farmers' perceptions about types of nutrients insufficient in soils and nutrients actually in need. They concluded that site-specific information provision contributed to productivity improvement because the mismatches were even yield-reducing. Their findings are particularly relevant for smallholder farmers in SSA as their fields are known to be highly heterogeneous in soil fertility or in responses to nutrient inputs even within small distances due to the influence of topography and past management practices (Kihara *et al.* 2016; Zingore *et al.* 2011; Nishigaki *et al.* 2018). Thus, there should be no doubt that site-specific information will improve productivity. But what kind of information should be provided remains to be further investigated. The present study aims to answer this question.

Prior studies on the effect of soil information typically tried to figure out which nutrient is deficient in soils at which extent and examined whether information could close the gap between required rates and actual rates of application (for instance, Harou *et al*. (2022), Ayalew *et al*. (2022), and Abey *et al.* (2022)). However, the relationship between soil analysis information and crop response to fertilizer in field is not straightforward, which is to say that the provision of comprehensive soil characteristics do not necessarily realize effective fertilizer management (Tsujimoto *et al.* 2019). Therefore, our novelty relative to the prior studies is that we adopted much simplified information of soil characteristics and showed even such an intervention could improve farmers' fertilizer use. More specifically, we provided farmers with binary information related to the effectiveness of nitrogen fertilizer in one main plot for rice production. The plot-level effectiveness was judged by a single soil property of oxalate-extractable phosphorus (Pox, hereafter), a suitable indicator to assess phosphorus-deficiency for lowland rice fields in tropics (Rakotoson *et al.* 2022). It is well known from agronomic studies that the lack of nitrogen limits rice yield in SSA most severely (Saito *et al.* 2019; Rurinda *et al.* 2020; Tanaka *et al.* 2017). However, instead of dealing with nitrogen deficiency directly, we adopted an indicator of nitrogen fertilizer effectiveness based on Pox. This single indicator is based on the following agronomic findings in the region where our study sites are located: first, phosphorus-deficiency status greatly varied from fields to fields in the region (Kawamura *et al*. 2019; Rakotoarisoa *et al*. 2020); second, rice little responded to nitrogen fertilizer when Pox value was low because phosphorus-deficiency became a primary limiting factor for rice growth (Asai *et al*. 2020).

As for the optimization of fertilizer use, we assumed that the observed sub-optimal allocation of fertilizer among the plots occurred because farmers did not know the heterogenous distribution of phosphorus in the soil. Therefore, we considered that information about expected effectiveness (EE) of nitrogen fertilizer would reduce the uncertainty in fertilizer responses and help farmers to decide in which plot and how much they should use fertilizer, or in other word to optimize fertilizer allocation. In this regard, we hypothesize that farmers will increase the probability of adoption of nitrogen fertilizer as well as its application rates in the plots with high EE, while they will decrease such probability in the plots with low EE. Thus, our optimization about the allocation of fertilizer is different from the existing studies that consider the adjustment of fertilizer application rate to the recommended level from too high rate (for example, Islam and Beg 2021) or too low rate (for example, Ayalew *et al*. 2022). Since most of small-scale farmers in SSA cannot afford sufficient amount of fertilizer, how to allocate limited amount of fertilizer is a more practical and relevant question. To our best knowledge, this viewpoint has rarely been presented in the existing literature. We further expected that the optimized fertilizer allocation would increase rice yield in plots with high EE because farmers would use nitrogen fertilizer intensively in such plots compared to plots where EE status is low or unknown. Thus, our second hypothesis is that the provision of EE information will lead to higher rice yield and as a result better household welfare than otherwise.

The rest of this paper is organized as follows. In section 2, the experimental design is explained. Analytical framework is proposed in section 3. Section 4 presents results of analysis followed by additional analysis for robustness check in Section 5. Section 6 is conclusion.

II. Experimental design

A. Study Context

The improvement of rice productivity has long been one of the central issues in

Madagascar's national policies for poverty reduction and food security as rice is historically the main staple food crop as well as the major income source for the rural population (World Bank 2020). The study site is located in the Vakinankaratra region, which is in the central highland zone, the major rice-producing area of the country. Although rice is the most important crop in this region, majority of farmers do not use chemical fertilizer for rice production in lowland (Ozaki and Sakurai 2021).

B. Soil nutrition information

We designed an experiment to provide simple binary information about expected effectiveness (EE) of nitrogen fertilizer application. Based on the Asai *et al.* (2020)'s finding, we use the Pox value as the indicator of the effectiveness of nitrogen fertilizer. More specifically, the Pox value of 100 mg/kg was used as the base threshold (θ). However, in the villages where soil is affected by the volcano, although soil is rich in phosphorus most phosphorus exists in a form which plants have difficulty in absorbing and utilizing. In such a case, the Pox value of 300 mg/kg was employed according to a publicly available guideline for fertilizer application in Japan (MAFF 2008). If the Pox value in a plot is more than the threshold, the plot is considered to have high EE regarding nitrogen fertilizer use, and if the value is less than the threshold, the plot is considered to have low EE.

C. Sampling procedure

Five villages were selected across two districts in the region of Vakinankaratra. Purposively, two villages from the eastern part, another two villages from western part, and the other one in between the two groups of villages were selected to evenly represent the agroecological diversity[1]. All the five villages are located along the national road that runs east and west in the middle of the region (Figure 1).

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[1] The Vakinankaratra region has an asymmetric landscape: The altitude of its eastern part reaches nearly 1,800 meters above sea level and there is a long mild slope descending towards the western end of the region. This asymmetry affects agroecological environment and thus agricultural practices although rice production in lowland is a common practice.

Each village has several smaller administrative units. Based on these units, two enumeration areas (EAs) were chosen in each village. The two EAs in a village have similar characteristics in terms of distance from the national road, population, and rice cultivation practices based on information collected in a preliminary field survey[2]. Then, we randomly selected farmers who had grown rice in lowland plots in the 2018-19 rainy season. Before intervention, all the sample farmers were asked to list all the agricultural plots used in that season and then to choose one most important lowland rice plot (we call this plot "target plot"). We visited each of these target plots and measured its location and its size by GPS. In addition, soil was taken from three points in each plot to obtain composites of soil samples. All the soil samples were sent to a national laboratory to examine phosphorus amounts. Based on the result of this soil analysis, all the target plots selected were classified as either high EE or low EE.

D. Randomization

Figure 2 shows the assignment structure. The total number of participants was 70. Randomization at EA level was more suitable than at household level to avoid information spillover between households within an EA. Since two EAs in a village are geographically apart and farmers in control EAs had no information about the selection of the treated EAs, information spillover across EAs could be prevented.

After randomization, both the treatment and the control groups had 35 households. Regardless of the assignment status, we provided all participants with common inputs that consisted of free fertilizer (5 kg of urea), the size of the target plot that was obtained by GPS, and general advice regarding timings and rates of urea application[3]. Because we would like to test if farmers allocate nitrogen fertilizer based on the information about EE, we provided

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[2] When the national road passes through the target village, we selected one EA from the northern side of the national road, the other EA was selected from the southern side of the road.

[3] We recommended the rate of 1kg of urea for 1 Are of land. Recommended timings were 14 to 20 days after transplanting as basal fertilizer application and 40 to 50 days after transplanting as top-dressing application. The actual paper distributed to all participants is presented in appendix.

nitrogen fertilizer free to alleviate financial constraints to buy fertilizer. As for physical access to the fertilizer market, we do not think it is a problem since all the villages are located along the national road. When distributing the common inputs, participants were explicitly informed that there is no restriction on the usage of urea from us and so they might apply it to any crop in any plot, keep it, sell it, or even give it to others. The distribution was implemented in October of 2019.

Then, when the common inputs were distributed, only farmers in the treatment group received the (additional) information that consisted of the EE status, the Pox value in the soil sample of the target plot (mg/kg), and relative ranking of the Pox value among the participants in the same EA[4]. As a result, only the treated farmers could know whether urea would be effective or not and use this information to make decisions about whether or not and how much urea to apply on the target plot. Farmers in the control group had to decide how they would use the given urea without knowing the EE status of their target plots.

III Analytical framework

A. Expected effectiveness to nitrogen fertilizer

Table 1 presents the summary of results of soil examination by EA. The Pox in soil as an index of phosphorus deficiency status was analyzed as per Schwertmann (Schwertmann 1964). The mean Pox values greatly varies across EAs from 36.1 mg/kg at EA10 to 547.5 mg/kg at EA1. Relatively high Pox values were observed at EA1, EA2, EA3, and EA4[5]. Soils of these four EAs were considered to be affected by volcanic soils, and thus, the Pox value of 300 mg/kg was applied as the threshold (θ) to judge the EE. For the remaining EAs, 100 mg/kg was used

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[4] Although our main objective was to give the information of EE status, we also provided the treated farmers with the Pox value and its ranking among the participants in the same EA. This is because farmers in the same EA tend to know plots of each other, and the additional information may help farmers relate the results of soil examination to the actual situations that they observe.

[5] Nishigaki *et al.* (2020) conducted soil survey covering our study site and found that sporadic volcanic soil exists in Betafo district in which the four EAs are located.

as the threshold. Applying this threshold, 8 out of 10 EAs embrace both high and low EE, implying that soil P deficiency status differs even within a village.

B. Econometric specification

Three specifications are used in the analysis. The first model is to examine the impact of intervention among the target plots by comparing the outcome variables between target plots of treated households and those of control households. Thus, this analysis used only target plot data. In our RCT setting, the impact of intervention can be obtained by simple comparisons of mean values. However, following the argument of McKenzie (2012), this study employs an ANCOVA model to improve analytical power[6].

$$Y_{ih2020} = \alpha_0 + \beta_1 T_{ih}^{high} + \beta_2 T_{ih}^{low} + \beta_3 Y_{ih2019} + \beta_4' PC_{ih} + \beta_5' HC_h + \beta_6' village + u_{ih} \ldots (1)$$

where Y_{ih2020} is one of outcome variables in target plot i of household h in the rainy season of 2019-2020. Two types of outcome variables are used in this model: binary variables and continuous variables. The binary variables are those for the adoption of urea, nitrogen fertilizer, and organic fertilizer in the target plot. These variables take a value of one if the target plot received these inputs. It is important to note that these variables capture only the adoption status of the target plot. Thus, they take a value of zero as long as the target plot does not receive these inputs even when a participant used these inputs in other plots than the target plot. Nitrogen fertilizer refers to any kind of chemical fertilizer products which include nitrogen as one of its nutrients such as NPK composite-type fertilizer and urea. The continuous outcome variables include rice yield in kg/ha, application rates of urea in kg/ha, nitrogen application rates in kg/ha which is calculated from the typical nutrients composition in each type of

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[6] ANCOVA stands for Analysis of Covariates. It improves analytical power especially when an outcome variable of interest has high variability and has non-zero but low autocorrelation. McKenzie (2012) gives income and consumption of households in poverty as examples for the appropriate cases of application of this model.

fertilizer product[7]. When the outcome variables are binary type, models become linear probability model where each coefficient, β, shows the marginal effect of change in one unit of each explanatory variable on the probability of adoption of each of those inputs. The key feature of the ANCOVA model is the inclusion of the outcome variable in the previous season, Y_{ih2019}, to control for the effects of pre-conditions of each plot. The inclusion of the lagged dependent variable enables us to interpret the effects as the impact on the change in outcome variables from the previous season.

As for the treatment variables, our treatment would affect farmers' decisions differently, depending on whether the information was high or low. Thus, two dummy variables of treatment status were separately included in the model. T_{ih}^{high} takes 1 if a participant was assigned to the treatment group and received information that urea would be effective in the target plot of his or her household. T_{ih}^{low} takes 1 if a participant belonged to the treatment group and information was low EE. These two dummy variables take 0 for those who belonged to the control group. Thus, we expect that β_1, the coefficient for T_{ih}^{high}, is positive, and significantly different from zero, but that β_2, the coefficient for T_{ih}^{low}, is not significantly different from zero.

In addition, plot level, household level, and village level control variables are included. PC_{ih} is a vector of plot level covariates that include plot size in ha, squared value of plot size. HC_h is a vector of household level covariates: household size, years in education of household head, age and sex of household head, log of per-capita value of asset, and risk preference of household head[8]. These variables should be included because EE might be correlated with some observable household characteristics due to the non-random selection of target plots. Village dummy variables to control unobserved factors attributable to village characteristics

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[7] For imputation of nitrogen amount, nitrogen is considered to account for 46% and 16% of the total weight in urea and NPK fertilizer available in the study area.

[8] Risk preference of household head was measured by a simple hypothetical game. The preference was scaled from 0 to 10 where smaller number indicates relative risk-averseness. When we could not find the household head at the time of interview, we conducted the game with another household member who responded to interview.

are also included as $village$. $\beta_3 - \beta_6$ are vectors of parameters to be estimated, α_0 is a constant term, and u_{ih} is the error term.

The major concern in estimating this model is the small number of EAs, which were the unit of sampling and hence standard errors must be clustered at this level. In order to deal with this problem, we employed wild cluster bootstrapping (WCB) suggested by Roodman *et al.* (2019).

The second model examines the impact of intervention within a household level by comparing the target plot with non-target plots of a household. Thus, unlike equation (1), all the rice plots cultivated by the sample households including upland rice plots were used for this analysis. The model specification is as follows.

$$Y_{ih} = \beta_1 I_{ih}^{high} + \beta_2 I_{ih}^{low} + \beta_3 NI_{ih}^{high} + \beta_4 NI_{ih}^{low}$$

$$+ \beta_5 size_{ih} + \beta_6 size\_sq_{ih} + \beta_7 uprice_{ih} + HHFE_h + u_{ih} \ldots (2)$$

where Y_{ih} is one of outcome variables in a plot i of a participating household h. The outcome variables include the quantity of urea, that of nitrogen, and rice yield. The units of these variables are the same as specification (1). All the plots are classified as either target plot or non-target plot. The target plots are further classified into four categories by expected effectiveness (EE) of nitrogen fertilizer and treatment status: namely target plots with high EE of treated households, target plots with low EE of treated households, target plots with high EE of control households, and target plots with low EE of control households. The corresponding binary dummy variables are denoted as $I_{ih}^{high}, I_{ih}^{low}, NI_{ih}^{high}$, and NI_{ih}^{low}. Note that in the case of treated households, the information about EE was provided to the households before planting rice, while in the case of control households, such information was not provided although the soil was sampled and the Pox value was obtained in the laboratory. Thus, these four dummy variables in equation (2) capture all the possible patterns of assignment status for target plots, setting non-target plots as the reference category. In this specification, β_1, β_2, β_3, and $\beta_4$are the parameters of interest. Each parameter indicates whether and how each type of assignment status has an effect on the outcome variables in comparison with non-target plots in the same household. In general, we expect that β_1 is positive and significantly different from zero, while β_2 is negative and significantly different from zero. But β_3 and $\beta_4$are not significantly different from zero.

Plot level control variables are also included. $size_{ih}$and $size\_sq_{ih}$ are plot size in ha and its squared value of plot i of a household h, and $uprice_{ih}$ is a dummy variable which takes a value of one if a plot is a rice plot in upland. Since upland rice cultivation is popular in the study area (Ozaki and Sakurai 2020) and many farmers in this dataset have rice plots both in lowlands and uplands, non-target plots include both types of rice plots. As the growing condition is different between the two, this dummy variable intends to capture the effect of being planted on uplands. $HHFE_h$ is household fixed effect that captures unobserved effects of a household's traits that commonly affect all rice plots. u_{ih} is the error term.

The third model is for household level impact. This model focuses on measuring the impact of intervention on household welfare.

$$Y_{h2020} = \alpha_0 + \beta_1 T_h^{high} + \beta_2 T_h^{low} + \beta_3' HC_h + \beta_4' village + u_h \dots (3)$$

where Y_{h2020} is one of outcome variables that include crop income per capita and monetary value of the total consumption per capita of household h. Data for outcome variables were collected in August 2020, approximately 3 months after the harvesting month of the year. T_h^{high} and T_h^{low} in (3) are dummy variables which decompose T_h by the types of information that a treated household receives. HC_h include the same list of variables in specification (1) as observable factors that also affect outcome variables. $village$ is a vector of dummy variables of village of residence. Since we do not have household level outcome variables in the previous year, we cannot apply ANCOVA specification to the household level analysis. However, in the case of rice yield and fertilizer applications, we use the values in the previous year at the target plot instead of household level data to control for the levels before the intervention.

IV. Results

A. Descriptive statistics about households

Table 2 presents descriptive statistics of participants' households. A household consisted of 5 people, and cultivated a total area of 0.49 ha of land on average. The number of rice plots was 3.5 per household on average, and one of them was the target plot whose mean size was 0.15 ha. The description indicates that the participants were small-scale, but had multiple choices of plots for fertilizer allocation. After randomization, 10 out of 35 households who belonged to the treatment group had plots with high EE and 25 of them had plots with low EE. Between the treatment and the control groups, there were no systematic differences with respect to these variables (see Table A1).

B. Descriptive statistics about outcomes

Table 3 shows descriptive statistics of rice yield and fertilizer use in the target plots. The number of plots was the same as the number of households because we targeted one plot from each household. In the last rainy season before the intervention, 20% of these plots had received any nitrogen-containing fertilizer, of which 17% was urea. After the intervention, the percentage of urea-applied plots was increased to 61%. This suggests that more than half of farmers are willing to use fertilizer if they can obtain it. The percentage of manure-applied plots little changed before and after the intervention. The average rice yield was 4795.22 kg/ha before the intervention, and 4548.10 kg/ha after the intervention.

After the intervention, urea was applied in 7 out of the 10 target plots or 70% in high EE sub-groups and 12 out of 25 plots or 48% in low EE sub-group (Table 4). We expect that the share of urea applied plots in the control group should be between the two treatment sub-groups. Although the share, 68.6 %, fell between the two, it is very close to the high EE group. Anyway, the shares are not statistically different as shown in the last column of the table.

C. Impact of intervention on fertilizer application in target plots

Table 5 presents the results of the regressions of specification (1) regarding fertilizer use at the target plots on the treatment variables. The impact of the intervention is examined by comparing between target plots of treated farmers and those of control farmers.

After controlling for the pre-intervention level of outcome variables, the result shows that receiving information of high EE did not affect urea application compared with control plots (columns (1) and (2)), but it had a significant positive impact on nitrogen application quantity by 41 kg/ha (column (4)). On the other hand, low EE information resulted in a significant decrease in the probability of urea application by 12% points and nitrogen application by 11% points compared with control plots (columns (1) and (3)). Moreover, low-EE information had a significantly negative impact on fertilizer purchase (column (6)). Please note that the adoption and the quantity of nitrogen fertilizer accommodate not only urea but also NPK as a source of nitrogen. No impact on the quantity of urea is found for either type of information though the signs of coefficients were consistent with the hypothesis (column (2)).

The insignificant impact of high-EE information on the use of urea can be attributed to the high adoption rate of urea among control farmers: 24 out of 35 farmers in the control group used the provided urea as shown in Table 4. Considering that the high-EE information had a significant impact on the application rate of nitrogen, its insignificant coefficients on urea use may be because 5 kg of urea was distributed to all participants equally before planting. Although 70% of farmers who received information of high-EE applied the given urea to their target plot, it was not sufficiently different from the percentage in the control group. On the other hand, low-EE information significantly reduced the use of urea because control farmers tended to use distributed urea to their target plots.

The fifth column shows that probability of using manure in the target plot declined by 22% points compared with the control group when farmers received information that would encourage urea application. This result indicates that farmers with high EE information substituted manure with nitrogen, i.e. urea and/or NPK.

The last column shows that there is no significant impact on rice yield in spite of the several significant changes in fertilizer use due to the intervention. However, if the decision of not using nitrogen fertilizer reduce the production cost without compromising yield, the information provision will contribute to the efficiency gain among rice farmers.

D. Impact of intervention on fertilizer allocation within a household

Table 6 presents regression results of specification (2). This model compares target plot and non-target plots in each household that had at least two rice plots controlling for unobserved household characteristics by household fixed effect. Hence, 10 households who had only one rice plot were excluded from the analysis. Including rice plots both in lowlands and uplands, the total number of observations was 207 from the total of 60 households.

We expect that in the case of positive information (i.e. high-EE information) farmers are likely to follow the information regardless of their subjective assessment of soil characteristic unless they have a very strong belief against the information. On the other hand, in the case of negative information (i.e. low-EE information), in which plots farmers will use urea cannot be predicted, and hence their decisions will not be different from control farmers who do not receive any information.

The first row shows the impact of the provision of high-EE information: it significantly increased the quantity of urea and the quantity of nitrogen applied to the target plot by 43.79

kg/ha and 53.42 kg/ha as shown in columns (1) and (2) respectively. These results imply that farmers followed the positive information as expected. As a result, it is found that rice yield was significantly higher in the target plot than non-target rice plots. The difference is 948.75 kg/ha on average after controlling for upland plots as well as household unobserved characteristics as shown in column (3).

The second row presents the impacts of low-EE information on the target plot. There are no significant differences between the target plot and non-target plots in terms of the quantity of urea, the quantity of nitrogen, or rice yield, which is also as expected. Since low-EE information does not tell in which plot the farmer should use urea or nitrogen unlike high-EE information, the insignificant effect seems to be natural.

The coefficients in the third and fourth rows are also estimated to be insignificant, suggesting that without information, participants in the control group evenly allocated fertilizer among rice plots within a household. The results imply that farmers do not know the effectiveness of nitrogen in their plots and providing such information will help their decisions.

E. Impact of intervention at household level

Table 7 shows the impact of the intervention on household level variables using specification (3). Outcome variables include the average rice yield, average intensities of application of urea and nitrogen to rice, crop income per capita, and monetary value of the total consumption per capita.

Column (1) shows that neither high-EE nor low-EE information affected rice yield at household level. But although it is not statistically significant, the sign and the size of the coefficient of high-EE seems to be reasonable. They did not have any impact on urea application rate at household level either as shown in column (2). However, nitrogen application rate in column (3) increased when a household received information that urea would be effective in their target plots. The results can be interpreted that farmers did not use more urea than they equally received, but they increased nitrogen use by purchasing if their plots are judged as high EE. The intensified nitrogen use was sufficient to have a statistically significant effect on the yield.

To see whether the intervention contributed to welfare improvement by enhancing rice production efficiency, two outcome variables were regressed on treatment variables. But neither crop income per capita nor consumption per capita were significantly affected by the information provision, as shown in columns (4) and (5). Since the impact on rice yield was not large enough, the intervention could not have significant effect on household welfare.

V. Robustness check

A. Impact of plot size

In the intervention, all the participants received information about the exact size of the target plot (see Figures A2 and A3) as well as the general instruction of fertilizer application regardless of the treatment assignment status (see Figure A1). The recommended rate of application was 5 kg of urea for 0.05 ha. The urea provided for free was not enough to cover all the area of the target plot for most participants as the average size of the target plot was 0.15 ha. Therefore, farmers might have given up using the urea just because the size of their plot is larger than 0.05 ha, areas that could be covered by the free urea. To see whether or not this was the case, an additional regression was run by using specification (1). In this model, instead of plot size variables, a dummy variable for the plot whose size is over 0.05 ha, and its interaction terms with treatment assignment variables were included. Results are presented in Table A6. None of three newly added variables are statistically significant, implying that whether the plot size was larger than 0.05 ha did not affect the farmers' decisions.

VI. Conclusion

The large variation of soil characteristics necessitates site-specific advice regarding fertilizer management because conventional blanket recommendation might result in disappointing outcome in some plots where crop yield response to the fertilizer is low due to inherent soil properties. However, what kind of site-specific information will influence farmers' soil fertility management and improve crop yield remain largely unknown. In order to answer this question, we created a unique binary indicator about fertilizer effectiveness and tested if such simple information could work. The indicator was based on Pox value in the soil and firmly supported by agronomic evidence. However, we did not know if such simple information can motivate farmers to shift from current practices with no or low fertilizer use to improved practice with more fertilizer.

We conducted a randomized controlled trial in Madagascar and found that the provision of plot-level simple information regarding expected effectiveness (EE) of nitrogen fertilizer could optimize farmers' fertilizer use and enhance rice yield: high EE information significantly increased application rate of nitrogen fertilizer and its consequent rice yield compared with the case of low EE information and no information.

Considering the general needs of increase in nitrogen use in SSA rice cultivation, this study made an important contribution to the discussion by showing that there is a possibility to simplify the design of intervention by focusing on a single soil property. Various attempts, including subsidy programs, credit lending and training about how to use fertilizer have been implemented in SSA to promote fertilizer use by farmers, but they are not so successful. The policy implication of this study is that even simple information will make conventional fertilizer policies more effective to promote fertilizer use.

The use of simple indicator of nitrogen effectiveness is the uniqueness of this study because prior studies dealt with multiple soil properties to show what and how much of mineral fertilizer to be applied in each plot. This idea is agronomically sound because increased number of soil properties in the information does not necessarily improve the accuracy of the information (Tsujimoto *et al.* 2019), but also practically important considering the cost and time to examine many soil properties and the feasibility of interventions with multiple soil properties. Of course, we should not simplify the reality too much, and agree with Burke *et al.* (2019)'s comments on Marenya and Barret (2009) suggesting that crop yield response is affected by complicated soil structure. With this respect, further studies to explore whether complex information that consisted of multiple soil properties leads to higher or lower impacts on farmers' practices than simple information based on a single soil property as used in this study, taking account of the cost of information generation, will be meaningful for both researchers and policy makers.

Limitations of this study are as follows. First, the experiment was implemented in only a few villages in the region and the number of observations is small. Considering criticism about external validity of many RCT studies in addition to the small sample problem, generalization of the results of this research will require a particular care. Some similar interventions with larger scale will be important to confirm the key findings from this study. Second, this study only examined the impact of information in the season of 2019-20 which started just after our intervention. Additional data in the following seasons would be useful to see whether the impacts would last without free fertilizer provision.

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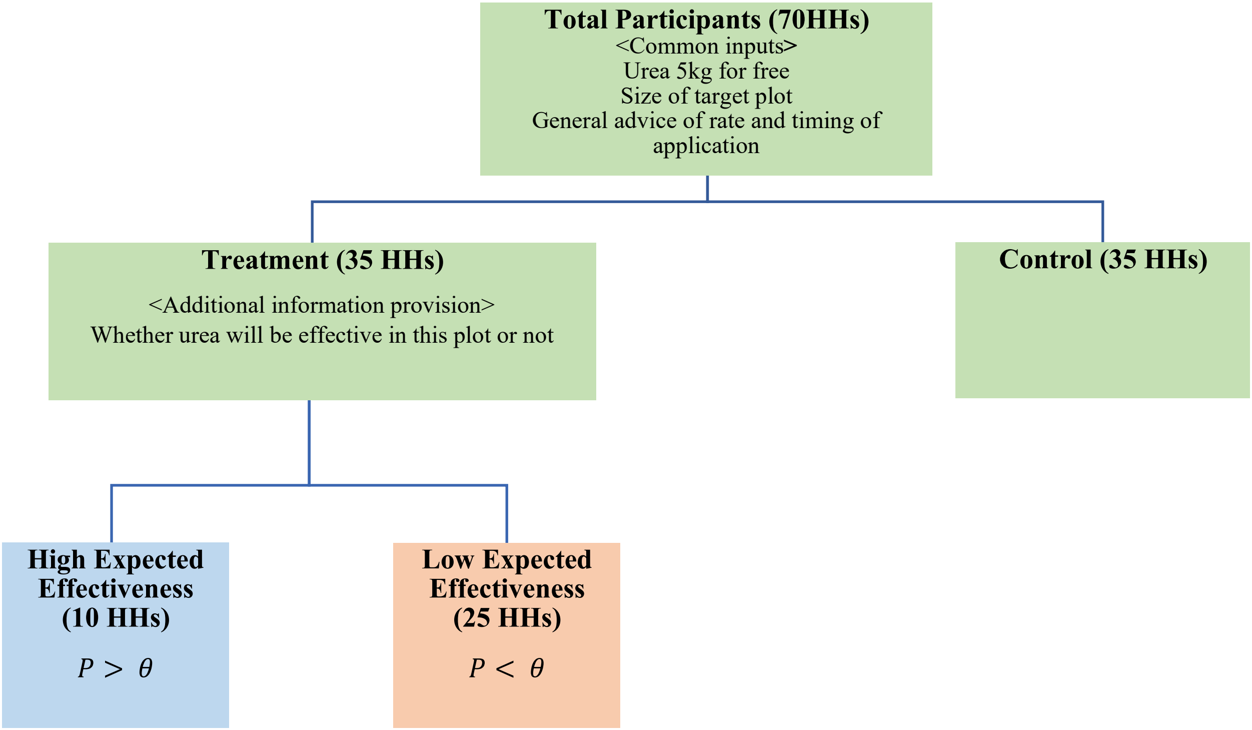
Figures and Tables

Figure 1: Location of study sties

Source) Authors created based on data obtained from Humanitarian Data Exchange (HDX) https://data.humdata.org/dataset/madagascar-administrative-level-0-4-population-statistics

Figure 2 Assignment Structure



Notes) P denotes the amount of phosphorus in soil in mg/kg. Phosphorus was measured as oxalate-phosphorus following Asai *et al*. (2020). θ is threshold value which defines the soil sample as either high EE or low EE. Two different thresholds were used because soils in 4 out of 10 EAs are considered to be affected by a volcano.

Table 1 Summary of variation of phosphorus amount by EAs

Villages	EA	Mean	S.D.	Min	Max	Volcanic soil	θ
1	1	547.53	228.82	228.27	823.08	Yes	300
1	2	335.54	175.34	66.56	576.31	Yes	300
2	3	321.71	145.13	94.16	586.60	Yes	300
2	4	316.25	117.60	136.88	481.96	Yes	300
3	5	122.38	38.51	98.60	166.81	No	100
3	6	74.74	26.55	44.61	108.24	No	100
4	7	64.13	29.81	26.69	116.71	No	100
4	8	57.29	22.09	30.26	89.78	No	100
5	9	37.14	11.97	22.76	57.83	No	100
5	10	36.13	12.04	25.02	63.22	No	100

Notes) Unit is mg/kg of dried soil. Phosphorus amount is measured as oxalate phosphorus.
S.D. stands for standard deviation.

Table 2 Descriptive statistics about participants' household

Variables	Unit	Overall (N=70)	Treatment High EE (N=10)	Treatment Low EE (N=25)	Control (N=35)
Household size	number	5.21 (1.82)	4.30 (1.06)	5.48 (2.35)	5.29 (1.51)
Sex of household head	%	92.86	90.00	92.00	94.28
Age of household head	years	46.57 (12.12)	46.30 (13.57)	47.44 (15.25)	46.03 (9.18)
Education of head	years	6.00 (3.20)	5.50 (2.76)	5.76 (3.53)	6.31 (3.13)
Total size of rice plots	ha	0.49 (0.58)	0.18 (0.24)	0.73 (0.79)	0.39 (0.37)
Number of rice plots	number	3.49 (1.56)	2.90 (0.99)	3.64 (1.66)	3.54 (1.62)
Size of target rice plot	ha	0.15 (0.15)	0.09 (0.08)	0.21 (0.22)	0.12 (0.08)
Value of asset per capita	10^3 MGA	146.46 (204.56)	201.34 (159.46)	145.45 (158.89)	131.50 (243.42)
Risk preference	0-10	5.53 (2.70)	6.90 (2.47)	5.36 (2.53)	5.26 (2.83)

Source) Authors.

Notes) MGA is local currency, standing for Malagasy Ariary. Standard deviations for continuous variables are in parenthesis.

T-test was conducted regarding size of target rice plot between treatment-high EE group and treatment-low EE group, and it detected a significant difference at 10% level.

Table 3 Descriptive statistics about outcome variables

Variables	Unit	Overall (N=70)	Treatment High EE (N=10)	Treatment Low EE (N=25)	Control (N=35)
Plot level (target plots)					
Before intervention					
Rice yield	kg/ha	4795.22 (2709.06)	6810.48 (2746.44)	4002.15 (2943.98)	4785.91 (2263.91)
Urea use	(0/1)	0.17	0.40	0.12	0.14
Urea application rate	kg/ha	30.69 (90.11)	49.90 (73.30)	24.87 (74.13)	29.35 (105.08)
Nitrogen use	(0/1)	0.20	0.50	0.12	0.17
Nitrogen application rate	kg/ha	16.21 (44.96)	33.19 (48.94)	12.44 (38.33)	14.04 (48.28)
Manure use	(0/1)	0.31	0.60	0.20	0.31
After intervention					
Rice yield	kg/ha	4548.10 (2651.25)	5984.01 (4016.77)	3581.68 (2306.09)	4828.15 (2205.97)
Urea use	(0/1)	0.61	0.70	0.48	0.69
Urea application rate	kg/ha	60.99 (103.66)	117.94 (111.50)	31.63 (57.41)	65.69 (120.74)
Nitrogen use	(0/1)	0.61	0.70	0.48	0.69
Nitrogen application rate	kg/ha	32.71 (58.64)	86.76 (93.19)	14.59 (26.40)	30.22 (55.51)
Manure use	(0/1)	0.36	0.50	0.28	0.37
Household level (after intervention)					
Rice yield at household level	kg/ha	4422.04 (2711.13)	6784.55 (3497.23)	3501.48 (2312.97)	4404.57 (2374.40)
Crop income per capita	10^3 MGA	167.21 (187.56)	91.06 (139.28)	190.45 (154.80)	172.37 (217.27)
Per capita consumption	10^3 MGA	246.99 (375.78)	319.07 (405.80)	168.88 (130.97)	282.19 (472.84)
Nitrogen quantity applied to all the rice plots	kg/ha	22.82 (33.05)	55.97 (67.22)	12.33 (15.41)	20.84 (21.09)
Urea quantity applied to all the rice plots	kg/ha	42.23 (48.71)	75.19 (69.89)	26.12 (33.85)	44.32 (46.89)

Source) Authors.

Notes) MGA is local currency, standing for Malagasy Ariary. Standard deviations for continuous variables are in parenthesis

Table 4 Urea adoption in the target plot by assignment status

	Adopt	Not Adopt	Total	%	Fisher's exact test
Treatment (Low EE)	12	13	25	48.0	
Treatment (High EE)	7	3	10	70.0	p = 0.243
Control	24	11	35	68.6	
Total	43	27	70	61.4	

Source) Authors

Table 5 Impact of soil characteristics information on outcome variables at target plots

	(1) Urea use (0/1)	(2) Urea quantity (kg/ha)	(3) Nitrogen use (0/1)	(4) Nitrogen quantity^{*1} (kg/ha)	(5) Manure use (0/1)	(6) Purchase of fertilizer (0/1)	(7) Rice yield (kg/ha)
Treatment (High EE)	-0.24 (0.15)	40.81 (41.73)	-0.23 (0.15)	41.02 (17.77)**	-0.22 (0.10)**	0.03 (0.13)	160.38 (884.27)
Treatment (Low EE)	-0.12 (0.07)*	-17.34 (13.83)	-0.11 (0.06)*	-13.99 (11.63)	-0.08 (0.05)	-0.21 (0.08)*	-756.16 (344.63)
Urea use in the last season (0/1)	0.24 (0.21)						
Urea quantity in the last season (kg/ha)		0.49 (0.26)					
Nitrogen use in the last season (0/1)			0.09 (0.13)			0.13 (0.06)	
Nitrogen^{*1} quantity in the last season (kg/ha)				0.88 (0.35)			
Manure use in the last season (0/1)					-0.19 (0.26)		
Yield in the last season (kg/ha)							0.52 (0.15) ***
Plot size (ha)	0.25 (0.90)	39.40 (86.62)	0.18 (0.91)	14.84 (39.62)	2.81 (1.01)**	1.45 (0.73)**	-10272.37 (4609.47)**
Plot size squared	-0.62 (0.63)	-23.14 (59.70)	-0.56 (0.65)	0.53 (23.53)	-2.21 (0.90)	-0.95 (0.58)**	7079.70 (3610.57)
Number of household members	-0.01 (0.04)	-0.52 (2.13)	-0.01 (0.04)	0.75 (1.90)	-0.05 (0.02)**	0.03 (0.02)	99.11 (106.10)
Age of household head (years)	< 0.01 (<0.01)	-0.21 (0.43)	< 0.01 (<0.01)	-0.28 (0.24)	-0.01 (0.01)**	-0.01 (< 0.01)*	32.18 (14.55)*

Sex of household head (0/1)	-0.01	-50.47	-0.04	-18.31	0.31	0.18	-1289.30
	(0.18)	(53.77)	(0.17)	(18.76)	(0.20)	(0.17)	(1813.48)
Years of education of household head	-0.01	0.31	-0.01	-0.40	-0.03	< 0.01	30.05
	(0.02)	(1.57)	(0.02)	(1.13)	(0.02)	(0.01)	(79.76)
Log of household asset value	0.37	92.01	0.28	69.12	-0.36	0.35	4551.56
	(0.57)	(56.73)	(0.54)	(53.20)	(0.33)	(0.37)	(2721.93)*
Risk preference (0 to 10)	-0.02	0.41	-0.02	1.40	-0.02	0.02	90.08
	(0.03)	(2.34)	(0.03)	(1.36)	(0.03)	(0.01)*	(127.63)
Village dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-0.02	-132.55	-0.56	-148.43	2.58	-0.75	-9450.84
	(1.54)	(154.44)	(1.12)	(153.86)	(0.79)	(0.85)	(5888.85)
Adj.R-Square	0.189	0.507	0.167	0.590	0.414	0.416	0.447
Observations[*2]	70	67	70	67	67	67	67

Notes)

[*1] Amount of nitrogen is imputed from any type of chemical fertilizer products that contain nitrogen in its composition. For imputation, urea (N46-P0-K0) and NPK (N11-P22-K16) were used.

[*2] The number of observations is different in (1) and (3) from other columns. This is because 3 observations were excluded in all but (1) and (3) as rice was not planted in the season of 2019-20 or only very small portion of the plot was used in these 3 observations. Since no or a little planting rice can be considered as a decision of not using urea provided from us in the target plot, these 3 observations were included in (1) and (3). However, since the rest the outcome variables should be considered as decisions related to rice cultivation, these 3 observations were excluded.

Robust standard errors clustered at EA level before wild bootstrapping are in parentheses. ***, ** and * indicate $p<0.01$, $p<0.05$ and $p<0.1$ obtained by wild bootstrapping.

Table 6 Impact of soil characteristics information on allocation of fertilizer within a household

	(1) Urea quantity (kg/ha)	(2) Nitrogen quantity[*1] (kg/ha)	(3) Rice yield (kg/ha)
Treatment variables			
Treatment (High EE) (0/1)	43.79 (19.09)**	53.42 (29.65)*	948.75 (474.35)**
Treatment (Low EE) (0/1)	15.26 (12.30)	7.23 (5.68)	115.70 (374.95)
Control (High EE) (0/1)	0.05 (24.17)	1.27 (10.92)	-538.95 (780.48)
Control (Low EE) (0/1)	38.89 (35.16)	16.07 (16.49)	765.99 (507.63)
Plot level covariates			
Plot size (ha)	-134.40 (49.10)***	-67.32 (22.80)***	-9506.06 (2645.23)***
Plot size squared	95.85 (36.97)**	47.58 (17.23)***	5314.64 (1871.00)***
Upland rice plot (0/1)	28.50 (11.04)**	15.34 (5.21)***	-759.86 (451.40)*
Household Fixed Effect	Yes	Yes	Yes
Observations	207	207	207
Number of groups	60	60	60

Note)

[*1] Amount of nitrogen is imputed from any type of chemical fertilizer products that contain nitrogen in its composition. For imputation, urea (N46-P0-K0) and NPK (N11-P22-K16) were used as major compositions of nutrients of each fertilizer products based on our field observations.

[*2] The number of groups are 60 which is different from the total number of participating households because 10 households had only one rice plot. To compare outcome variables in Robust standard errors clustered at household level are in parentheses. ***, ** and * indicate p<0.01, p<0.05 and p<0.01.

Table 7 Impact of soil characteristics information at household level

	(1) Rice yield at household level (kg/ha)	(2) Urea application rate at household level (kg/ha)	(3) Nitrogen^{*1} application rate at household level (kg/ha)	(4) Crop income per capita (10^3MGA)	(5) Consumption per capita in 3 months (10^3MGA)
Treatment variables					
Treatment (High EE)	545.29 (338.25)	6.54 (11.15)	20.84 (2.97)**	-66.05 (32.72)	-13.58 (149.33)
Treatment (Low EE)	-85.40 (221.00)	-6.69 (7.47)	-4.58 (6.41)	-33.59 (37.25)	-125.23 (60.74)
Other control variables					
Yield of target plot in the previous year	0.38 (0.05)***				
Urea application in target plot in the previous year		0.13 (0.13)			
Nitrogen application in target plot in the previous year			0.29 (0.25)		
Total size of rice plot (ha)	-4281.14 (1541.04)**	-31.95 (18.75)	-15.41 (10.65)	121.60 (128.88)	-503.40 (222.93)
Total size of rice plot squared	1064.22 (410.21)*	7.49 (4.27)	3.81 (2.58)	-15.57 (36.18)	192.56 (68.67)
Number of household members	154.05(128.11)	2.28 (1.66)*	1.35 (1.48)	-13.98 (10.38)	11.17 (30.06)
Age of household head (years old)	27.43 (20.17)	-0.29 (0.38)	-0.32 (0.27)	1.70 (1.61)	4.81 (6.36)
Sex of household head (0/1)	-177.12 (1769.20)	-14.15 (15.03)	-3.67 (6.27)	76.67 (28.35)*	64.10 (132.71)
Years of education of household head	80.58 (96.31)	1.20 (1.17)	0.52 (0.79)	0.13 (6.63)	-5.23 (14.86)
Log of household asset value	3221.17 (2523.62)	65.21 (32.33)**	51.69 (33.63)*	460.48 (172.14)**	-71.05 (580.09)
Risk preference (0 to 10)	56.15 (106.13)	0.35 (1.25)	0.59 (0.80)	-1.89 (9.27)	-2.17 (18.78)
Village dummy	Yes	Yes	Yes	Yes	Yes
Constant	-6168.03	-79.97	-95.38	-1118.02	359.78
Adj. R-Square	0.551	0.521	0.437	0.174	-0.174
Observations	70	70	70	70	70

Notes) ^{*1} Amount of nitrogen is imputed from any type of chemical fertilizer products that contain nitrogen in its composition. For imputation, urea (N46-P0-K0) and NPK (N11-P22-K16) were used as major compositions of nutrients of each fertilizer products based on our field observations.

Robust standard errors clustered at EA level before wild bootstrapping are in parentheses. ***, ** and * indicate $p<0.01$, $p<0.05$ and $p<0.1$ obtained by wild bootstrapping.

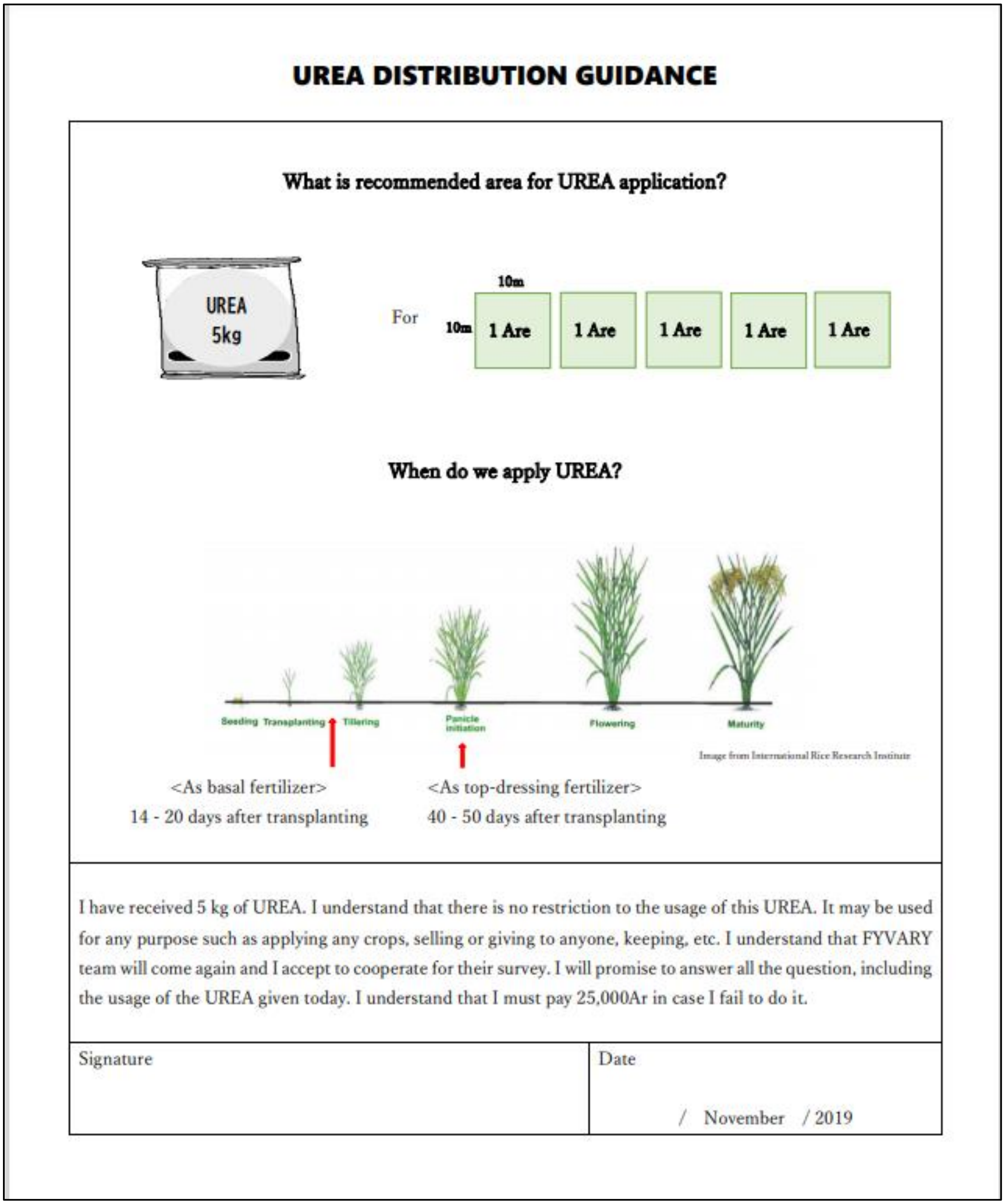
Table A1. Results of t-test for each variable

Variables	Unit	Control	Treatment	Pr(T > t)
Expected effectiveness (=1 if High)	%	34.29	28.57	0.613
Household size	people	5.29	5.14	0.746
Sex of household head (=1 if male)	%	94.29	91.43	0.648
Age of household head	years old	46.03	47.11	0.711
Years of education of household head	years	6.31	5.69	0.416
Total size of rice plots	hectare	0.39	0.58	0.190
The number of rice plots	number	3.54	3.43	0.761
Size of target rice plot	ha	0.12	0.17	0.147
Value of asset per capita	10^3 MGA	131.50	161.42	0.545
Risk preference (from 0 to 10)	score	5.26	5.80	0.404
Rice yield at household level (weighted)	kg/ha	4404.57	4439.50	0.958
Crop income per capita	10^3 MGA	172.37	162.05	0.820
Per capita consumption in 3 months	MGA	282.19	211.790	0.437
Rice yield at the target plot	kg/ha	4828.14	4268.09	0.381
Nitrogen use in the previous year (0/1)	%	17.14	22.86	0.557
Nitrogen application rate in the previous year	kg/ha	14.04	18.37	0.690
Urea use in the previous year (0/1)	%	14.29	20.00	0.533
Urea application rate in the previous year	kg/ha	29.35	32.03	0.902
Manure use (0/1)	%	31.43	31.43	1.000
Observations		35	35	

Source) Authors calculation from the dataset.

Notes) MGA is local currency, standing for Malagasy Ariary.

Figure A1. The instruction paper distributed to all participants



UREA DISTRIBUTION GUIDANCE

What is recommended area for UREA application?

When do we apply UREA?

Image from International Rice Research Institute

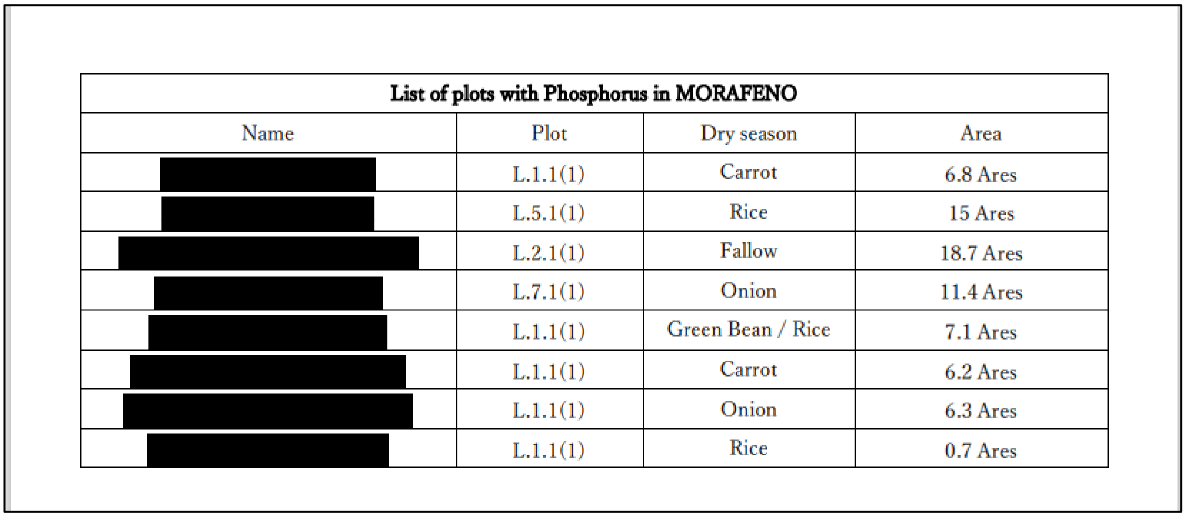
<As basal fertilizer>
14 - 20 days after transplanting

<As top-dressing fertilizer>
40 - 50 days after transplanting

I have received 5 kg of UREA. I understand that there is no restriction to the usage of this UREA. It may be used for any purpose such as applying any crops, selling or giving to anyone, keeping, etc. I understand that FYVARY team will come again and I accept to cooperate for their survey. I will promise to answer all the question, including the usage of the UREA given today. I understand that I must pay 25,000Ar in case I fail to do it.

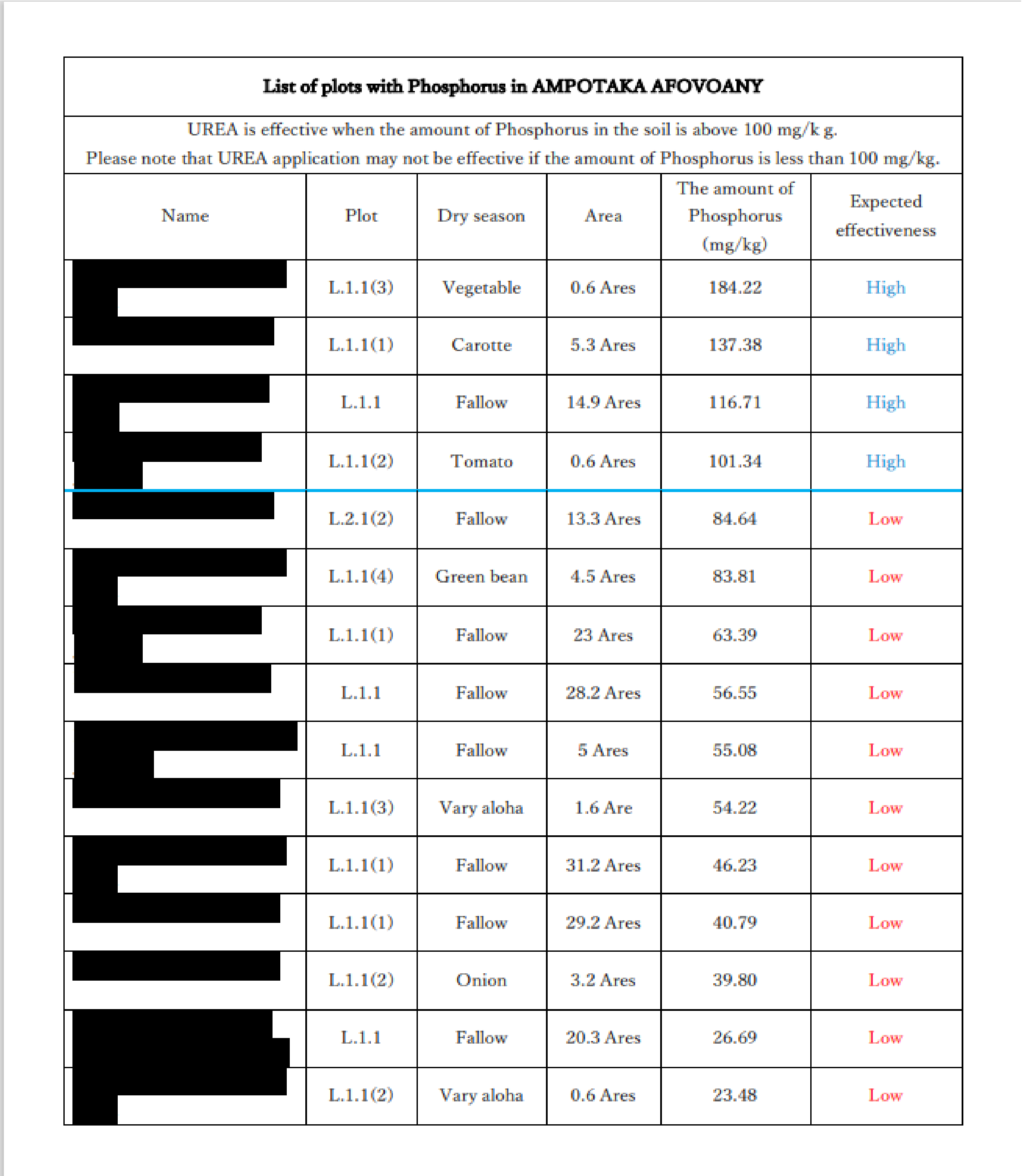
Signature	Date / November / 2019

Figure A2 An example of information provided to the control group



List of plots with Phosphorus in MORAFENO			
Name	Plot	Dry season	Area
[redacted]	L.1.1(1)	Carrot	6.8 Ares
[redacted]	L.5.1(1)	Rice	15 Ares
[redacted]	L.2.1(1)	Fallow	18.7 Ares
[redacted]	L.7.1(1)	Onion	11.4 Ares
[redacted]	L.1.1(1)	Green Bean / Rice	7.1 Ares
[redacted]	L.1.1(1)	Carrot	6.2 Ares
[redacted]	L.1.1(1)	Onion	6.3 Ares
[redacted]	L.1.1(1)	Rice	0.7 Ares

Figure A3 An example of information provided to the treatment group



List of plots with Phosphorus in AMPOTAKA AFOVOANY					
UREA is effective when the amount of Phosphorus in the soil is above 100 mg/k g. Please note that UREA application may not be effective if the amount of Phosphorus is less than 100 mg/kg.					
Name	Plot	Dry season	Area	The amount of Phosphorus (mg/kg)	Expected effectiveness
[redacted]	L.1.1(3)	Vegetable	0.6 Ares	184.22	High
[redacted]	L.1.1(1)	Carotte	5.3 Ares	137.38	High
[redacted]	L.1.1	Fallow	14.9 Ares	116.71	High
[redacted]	L.1.1(2)	Tomato	0.6 Ares	101.34	High
[redacted]	L.2.1(2)	Fallow	13.3 Ares	84.64	Low
[redacted]	L.1.1(4)	Green bean	4.5 Ares	83.81	Low
[redacted]	L.1.1(1)	Fallow	23 Ares	63.39	Low
[redacted]	L.1.1	Fallow	28.2 Ares	56.55	Low
[redacted]	L.1.1	Fallow	5 Ares	55.08	Low
[redacted]	L.1.1(3)	Vary aloha	1.6 Are	54.22	Low
[redacted]	L.1.1(1)	Fallow	31.2 Ares	46.23	Low
[redacted]	L.1.1(1)	Fallow	29.2 Ares	40.79	Low
[redacted]	L.1.1(2)	Onion	3.2 Ares	39.80	Low
[redacted]	L.1.1	Fallow	20.3 Ares	26.69	Low
[redacted]	L.1.1(2)	Vary aloha	0.6 Ares	23.48	Low

Table A2 Additional regression results using plot size dummy

	(1) Urea use (0/1)	(2) Urea quantity (kg/ha)	(3) Nitrogen use (0/1)	(4) Nitrogen quantity[*1] (kg/ha)	(5) Purchase of fertilizer (0/1)
Treatment (High EE)	-0.23	52.66	-0.25	35.73	-0.15
	(0.15)	(38.42)	(0.16)	(19.71)	(0.27)
Treatment (Low EE)	-0.16	9.13	-0.19 (0.14)	-41.37	-0.70
	(0.12)	(28.13)		(31.24	(0.37)
Urea use in the last season (0/1)	0.24				
	(0.23)				
Urea quantity in the last season (kg/ha)		0.52			
		(0.13)			
Nitrogen use in the last season (0/1)			0.08		0.03
			(0.14)		(0.13)
Nitrogen[*1] quantity in the last season (kg/ha)				0.88	
				(0.38)*	
Plot size is over 0.05ha (0/1)	0.02	32.32	-0.06	-11.64	-0.36
	(0.25)	(26.76)	(0.23)	(13.33)	(0.40)
plot size over 0.05ha x treatment (High EE)	-0.04	-3.42	<|0.01|	-1.18	0.24
	(0.17)	(13.28)	(0.17)	(6.16)	(0.33)
plot size over 0.05ha x treatment (Low EE)	0.01	-26.88	0.06	31.96	0.66
	(0.16)	(29.43)	(0.17)	(28.56)	(0.44)
Household level variables	Yes	Yes	Yes	Yes	Yes
Village dummy	Yes	Yes	Yes	Yes	Yes
Constant	-0.13	-158.30	0.24	-134.10	-0.51
	(1.52)	(143.84)	(1.38)	(135.97)	(0.96)
Adj.R-Square	0.163	0.507	0.109	0.604	0.414
Observations	70	67	70	67	67

Notes)

[*1] Amount of nitrogen is imputed amount from any type of fertilizer products that contain nitrogen in its composition. For imputation, urea (N46-P0-K0) and NPK (N11-P22-K16) were used.

[*2] The number of observations is different in (1) and (3) from other columns. This is because 3 observations were excluded in all but (1) and (3) as rice was not planted in the season of 2019-20 or only very small portion of the plot was used in these 3 observations. Since no or a little planting rice can be considered as a decision of not using urea provided from us in the target plot, these 3 observations were included in (1) and (3). However, since the rest the outcome variables should be considered as decisions related to rice cultivation, these 3 observations were excluded.

Robust standard errors clustered at EA level before wild bootstrapping are in parentheses. ***, ** and * indicate $p<0.01$, $p<0.05$ and $p<0.1$ obtained by wild bootstrapping.

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Vegetable Production and Its Impact on Smallholder Farmers' Livelihoods: The Case of the Central Highlands of Madagascar

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Despite the increasing economic and nutritional importance of vegetables in Madagascar, empirical evidence remains largely scarce. The objective of this study is thus to examine the impact of vegetable production on smallholder farmers' welfare and nutrition in the central highlands of Madagascar. Using yearly cross-sectional data, results reveal a positive association between market-oriented vegetable production and household's welfare and dietary diversity, which indicates such vegetable production is income generating while allowing farmers to diversify their nutritional intake. However, no evidence is found for less market-oriented households. Policy recommendations should emphasize on commercial vegetable-related strategies, farmers' skills and market access.

Key words: vegetable production, impact assessment, Madagascar

1. Introduction

Vegetable production can critically contribute to the welfare and the quality of diets of smallholder farmers in the central highlands of Madagascar (Minten, 2018). Particularly in rural areas, vegetable production provides high returns on land and labor, thus creates employment opportunities and incomes for rural smallholders. The demand for fresh vegetables has been increasing in recent years owing to increased urban and private companies' demand whereas a shift to more labor-intensive crops is progressively taking place in the study zones because of relative land scarcity. There is a possibility that these trends would expand the consumption level of vegetables in Madagascar, which is reportedly one of the lowest in Sub-Saharan Africa while offering a solution to the high chronic undernourishment rate of the country due to the high content of vitamins and essential micronutrients found in vegetables.

However, questions are being raised about agricultural production's contribution to nutrition. This link is less clear-cut than often assumed (Webb and Kennedy, 2014). In particular, agricultural production may affect the quality of the diets of rural smallholder farmers in two ways: (1) through the production of subsistence food crops households can consume directly, and (2) through the sale of agricultural goods that leads to increased income and hence food purchases and consumption (World Bank, 2007). This has led to a renewed interest in agricultural production and the need to show a more straightforward pathway from production to nutritional outcomes. Notwithstanding many studies on the links between agriculture and nutrition, empirical evidence of this relationship and the actual impact of vegetable production on income and nutritional security remain sparse (Webb and Kennedy, 2014; Yosef *et al.*, 2014).

The primary objective of this study is to examine the impact of vegetable production on smallholder farmers' welfare and nutritional wellbeing in the central highlands of Madagascar. To do so, we follow three steps. First, the study seeks to identify the determinants of vegetable production. Then, it estimates the impact of vegetable production on farmers' revenue, income, expenditure, and dietary diversity. Last, vegetable producers are categorized as to their approaches to the market to demonstrate how vegetable production affects their nutrition outcomes. Propensity score matching (PSM) and the multivalued treatment effect inverse-probability-weighted regression adjustment (IPWRA) are used to pinpoint the effect of vegetable production on household income and food security, and to emphasize the possible pathways to impact nutrition outcomes, respectively.

The results show that vegetable production impacts the household's income and nutritional wellbeing only when smallholder farmers are involved in selling a fraction or a totality of their products on the market.

This study makes a distinctive two-fold contribution to the literature. First, the actual impact of vegetable production on income and dietary diversity is examined. It has been widely

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pointed out that crop diversification tends to be effective in both generating income and improving dietary diversity of smallholders (Feliciano, 2019); however, few empirical studies have uniquely focused on the vegetable production (Thapa *et al.*, 2018; Krause *et al.*, 2019). Second, to give more insight into the plausible pathway through which vegetable production affects the quality of the diets of the households, the impact is further demonstrated by categorizing farmers in terms of their involvement in the market. This approach is a novel contribution to the agriculture-nutrition linkage literature.

2. Analytical Framework

In this study, a binary dummy variable for "vegetable growers" is used as the dependent variable: households cultivating at least one vegetable take the value of 1, whereas households who do not grow vegetables take the value of 0. Explanatory variables include household characteristics, geographical characteristics, land endowment, plot characteristics, and district dummies. Also, a multinomial logistic model is utilized where the dependent variable takes three categories: non-vegetable grower, less market-oriented vegetable grower, and market-oriented vegetable grower. The value of 0, 1, and 2 are assigned to each category of households, respectively. Specifically, market-oriented farmers are defined as farmers who are involved in commercializing a portion or the entire vegetable production to the market; while less market-oriented farmers are farmers who produce vegetables but consume the totality of their production instead of selling them.

In addition, considering the challenges of finding an instrumental variable that is both highly correlated with the vegetable production and uncorrelated with the error term of the outcome regression, propensity score matching (PSM) technique is used to estimate the impact of vegetable production on the household's livelihoods in order to control for the self-selection bias in vegetable production. To examine the robustness of the estimates to unobserved confounding factors, the Rosenbaum bounds approach (Rosenbaum, 2002) is applied exclusively for statistically significant results (Hujer *et al.*, 2004). In the case of three categorical choices mentioned above, a multivalued treatment effect model is adopted and the impact is estimated by inverse-probability-weighted regression adjustment (IPWRA) model. IPWRA is used for its potential to produce consistent estimates of the effects due to its double-robust property. The outcome variables used in the regression are the natural logarithm of monthly total revenue, income, and expenditure per capita, and three indicators of dietary diversity: the Household Dietary Diversity Score (HDDS), the micro-nutrient sensitive HDDS (MsHDDS), and the Food Consumption Score (FCS).

3. Data and Descriptive Statistics

To show empirical evidence of the impact of vegetable production on the household's livelihoods, 60 villages were randomly selected from 13 communes spread over 3 districts in the Vakinankaratra region of Madagascar. Ten households that grew lowland rice were randomly selected from each village for the survey. As a result, the number of sample households were 600. The data capture yearly agricultural activities from June 2018 to May 2019. Collected data include the household characteristics, agricultural practices, income from agricultural and non-agricultural activities, expenditure on food and non-food items, and food consumption respectively for the month and the week prior to the interview. With an attrition rate of 2% along with incomplete data, 570 households are retained for the analysis. Among the 570 households, 201 are considered as "vegetable growers" and 369 are considered as "non-vegetable growers" for the binary setting. Among the 201 "vegetable growers", 43 are less market-oriented and 158 are market-oriented.

Table 1 summarizes the descriptive statistics comparing vegetable growers with non-vegetable growers at the household level. With regard to the household characteristics, the differences between vegetable growers and non-vegetable growers are not significant except for one variable, namely household head's literacy in French. A significantly higher proportion of household heads with French literacy is observed among vegetable growers (71.64%) compared to non-vegetable growers (60.97%) at the 5% level of significance. On average, vegetable growers are located at a significantly higher altitude (1,310 m) than non-vegetable growers (1,210 m). Moreover, vegetable growers are significantly closer to big cities, with an average distance of 11.84 km, compared to their counterparts (14.56 km). In terms of land endowment characteristics, we divide the total parcel size owned by a household into quintiles. Among the quintile groups, only the 4th quintile (40-66 ares) shows a marginally significant difference between vegetable and non-vegetable growers. Concerning the plot characteristics, seven variables that are deemed important to influence the

Table 1. Descriptive statistics of vegetable growers and non-vegetable growers[1)]

Variables	Mean of all samples	Mean of vegetable growers	Mean of non-vegetable growers	Difference of the means	
Household characteristics					
Number of household members	4.80	4.90	4.74	0.16	
Dependency ratio (%)	42.14	40.40	43.09	-2.69	
Number of adult members (15 years old or above) in household	3.00	3.12	2.94	0.18	
Sex of household's head (1=male)	0.89	0.89	0.89	0.00	
Age of household head	47.21	47.19	47.23	-0.04	
Household head's literacy in French (%)	64.73	71.64	60.97	10.67	**
Two-headed household (%)	86.49	86.06	86.72	-0.66	
Owning a bicycle (%)	31.22	33.33	30.08	3.25	
Asset (Log of total value per capita in MDA[2)])	2.90	2.81	2.94	-0.13	
Geographical characteristics					
Altitude (10^3 m)	1.25	1.31	1.21	0.10	***
Distance from the closest big cities (km)	13.60	11.84	14.56	-2.72	***
Land endowment					
Parcel size (ares)	56.04	52.74	57.83	-5.09	
1st quintile (0-14 ares) (%)	20.35	23.38	18.69	4.69	
2nd quintile (15-24 ares) (%)	19.82	16.91	21.4	-4.49	
3rd quintile (25-39 ares) (%)	19.47	17.91	20.32	-2.41	
4th quintile (10-66 ares) (%)	21.40	25.87	18.97	6.90	*
5th quintile (66 ares or above) (%)	18.94	15.92	20.59	-4.67	
Plot characteristics					
Access to permanent water stream (%)	15.26	19.40	13.00	6.40	**
Access to seasonal water stream (%)	19.12	25.87	15.44	10.43	***
Household experienced any shock in lowland rice (%)	61.22	64.17	59.62	4.55	
Proportion of land considered as average fertility (%)	81.31	84.72	79.45	5.27	**
Proportion of land considered as low fertility (%)	4.64	4.24	4.87	-0.63	
Proportion of plot with volcanic soil (%)	30.75	30.64	30.81	-0.17	
Proportion of plot with ferralitic soil (%)	45.51	41.69	47.59	-5.90	**
District dummies					
Betafo (%)	51.40	61.19	46.07	15.12	***
Antsirabe 2 (%)	11.92	11.44	12.19	-0.75	
Mandoto (%)	36.66	27.36	41.73	-14.37	***
Number of observations	570	201	369		

Notes: 1) *, **, and *** indicate that the means are different at the significance level of 10%, 5%, and 1%, respectively.
2) MDA stands for Malagasy Ariary. 1 USD = about 3,614 MDA in December 2019.

farmers' decision to grow vegetables are selected. The access to permanent or seasonal water stream is significantly higher for vegetable growers compared to non-vegetable growers, respectively 19.40% compared to 13.00%, and 25.87 compared to 15.44%. Furthermore, the proportion of the land considered as average fertility is significantly higher for vegetable growers whereas the proportion of ferralitic soil is significantly lower. For district dummies, the district of Betafo holds a relatively greater number of vegetable growers (61.19%) compared to the non-vegetable growers (46.07%), while in the district of Mandoto, the frequency of vegetable growers (27.36%) is significantly lower compared to that of non-vegetable growers (41.73%). Nonetheless, there is no significant difference between both groups for the district of Antsirabe 2.

4. Results

1) The determinants of vegetable production

The first part of Table 2 shows the estimation results of the probit model for growing vegetables at household level, considering vegetable growers as one group. It shows that both the age of household head and its squared term are significantly correlated with vegetable adoption, suggesting that young and very old farmers are less likely to grow vegetables due to a possible lack of experience and strength respectively. Likewise, the variable "altitude" is also linked to vegetable cultivation, which may reflect the important role of temperature, rainfall, or other environmental factors in the cultivation's decision. It also displays that the distance from the closest big cities is negatively correlated with vegetable adoption. This result could be explained by the importance of market and the access to inputs.

The second part of Table 2 reports the multinomial logistic regression coefficients of the treatment model. The vegetable growing households are categorized into two: less market-oriented households (first group) and the market-oriented households (second group), in contrast with the control group of the non-vegetable growers.

Two variables are found to be closely associated with the first group. First, the household head's literacy in French is negatively correlated with less market-oriented households, which may reflect that less-educated household head is more prone to produce vegetable solely for their consumption. Second, household having experienced a shock in their lowland rice is positively associated with that group. It might be that the shock in lowland rice has reduced the amount of rice supposed to sustain the household and thus constraining them to produce vegetables only for self-consumption.

As for market-oriented vegetable growers, there is an inverse U-shape relationship with age just like the probit regression result for vegetable production. Also, the household head's ability in reading and writing French is positively associated with the group. This suggests the willingness of more educated household head to participate in the market. Moreover, there is a negative association between the distance from large cities and vegetables produced by market-oriented households. This implies the role played by the market and access to inputs in the decision of market-oriented vegetable production.

2) Impact of vegetable production

Table 3 shows the results after correcting for the selection bias by observable characteristics using the PSM approach. In our attempt to match the propensity score, the nearest-neighbor and the radius matching are used. Treating vegetable growers as a whole, the matchings yield comparatively similar results. Vegetable production significantly and positively influences total revenue from marketed crops per capita. In contrast, vegetable production has no significant impact on any other household economic welfare indicators. This lack of economic benefits from vegetables may be because the income from vegetable production equates with the income from other agricultural goods or other off-farm activities. On the other hand, vegetable production has a relatively strong correlation with the three indicators of the nutritional wellbeing of the household, namely HDDS, MsHDDS, and FCS. The results imply that vegetable production, considering vegetable producers as one group, improves household access to diverse foods with adequate macro and micronutrients.[1]

The second part of Table 3 reports the results of the causal effects of our categorized vegetable production on our outcome variables. Less market-oriented vegetable growers are not much different from non-vegetable growers in terms of either income or nutrition except the significantly negative effect on total revenue from marketed crops. In contrast, market-oriented vegetable growers have significantly higher revenue from marketed crops, total agricultural and non-agricultural income, and total household income (per capita). Thus, market-oriented vegetable production has a significant economic impact on rural households. Concerning the dietary diversity, as shown in Table 3, all the three indicators are significantly positive and relatively larger than those obtained from the binary cases (PSM).

These results indicate (1) vegetable production improves the quality of diets, but does not enhance income compared with non-vegetable growers, and (2) the impact of vegetable production comes from cash revenue from crop sales in the market, not from vegetable production itself, implying that

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[1] In order to confirm the robustness of the PSM results, Rosenbaum sensitivity test is conducted. The results (the value of Γ) are reported in Table 3. The value reflects the assumption about endogeneity in treatment assignment in terms of the odds ratio of differential treatment assignment due to unobserved covariates at 10% level. With an average value of $\Gamma=1.5$, it implies that the effects are relatively robust from hidden bias (Aakvik, 2001). Thus, all the results provide consistent evidence of the impact of vegetable production on the household's nutritional wellbeing.

Table 2. Determinants of vegetable production[1]

	Probit model		Multinomial logit model			
	Vegetable production		Less market-oriented		Market-oriented	
Independent variables	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
Household characteristics						
Number of household members	-0.030	(0.068)	-0.12	(0.19)	-0.046	(0.14)
Dependency ratio	0.22	(0.39)	0.41	(0.87)	0.35	(0.82)
Number of adult members (≥15 years old)	-0.0037	(0.085)	-0.070	(0.19)	0.025	(0.17)
Sex of household head (1=male)	0.15	(0.28)	0.10	(0.74)	0.26	(0.49)
Age of household head	0.069**	(0.027)	0.050	(0.063)	0.14***	(0.053)
Age squared of household head (10^3)	-0.74***	(0.26)	-0.51	(0.60)	-1.50***	(0.52)
Household head's literacy in French (1=yes)	0.13	(0.13)	-0.67*	(0.38)	0.55**	(0.27)
Two-headed household	-0.23	(0.27)	0.13	(0.66)	-0.60	(0.45)
Owning a bicycle (1=yes)	0.15	(0.11)	0.30	(0.36)	0.19	(0.22)
Asset (Log of total value per capita in MDA[2])	-0.041	(0.061)	-0.075	(0.17)	-0.081	(0.12)
Geographical characteristics						
Altitude (km)	1.25*	(0.72)	1.04	(1.33)	2.40	(1.59)
Distance from the closest big cities (km)	-0.028***	(0.010)	0.020	(0.023)	-0.061***	(0.022)
Land endowment						
2nd quintile (15-24 ares) (1=yes)	-0.27	(0.20)	-0.98	(0.67)	-0.24	(0.39)
3rd quintile (25-39 ares) (1=yes)	-0.16	(0.21)	-0.83	(0.56)	0.032	(0.43)
4th quintile (40-66 ares) (1=yes)	0.28	(0.21)	0.58	(0.51)	0.54	(0.42)
5th quintile (66 ares or above) (1=yes)	0.038	(0.25)	-0.49	(0.51)	0.37	(0.56)
Plot characteristics						
Access to permanent water stream	0.15	(0.19)	-0.57	(0.71)	0.40	(0.33)
Access to seasonal water stream	0.16	(0.18)	-0.73	(0.60)	0.42	(0.33)
Household experienced any shock in lowland rice	0.074	(0.11)	1.01***	(0.38)	-0.16	(0.21)
Proportion of land considered as average fertility	0.37	(0.25)	0.64	(0.75)	0.53	(0.47)
Proportion of land considered as low fertility	-0.22	(0.40)	-0.62	(1.79)	-0.29	(0.80)
Proportion of volcanic soil	-0.32	(0.23)	-0.69	(0.79)	-0.50	(0.42)
Proportion of ferralitic soil	-0.34	(0.24)	-0.18	(0.59)	-0.60	(0.46)
District dummies						
Antsirabe 2 (1=yes)	-0.68***	(0.26)	0.87	(0.63)	-1.47***	(0.54)
Mandoto (1=yes)	-0.20	(0.34)	0.62	(0.81)	-0.46	(0.70)
Constant	-2.90**	(1.20)	-4.97*	(2.92)	-5.88**	(2.41)
Total number of observations	570		570			

Notes: 1) *, **, and *** indicate that the means are different at the significance level of 10%, 5%, and 1%, respectively.
2) MDA stands for Malagasy Ariary. 1 USD = about 3,614 MDA in December 2019.

the revenue is used to buy diversified food items.

5. Conclusion

In this study, the impact of vegetable production on smallholder farmers' welfare and nutritional wellbeing has been assessed. We find that the category of market-oriented households benefit economically and nutritionally from vegetable production by agriculture-nutrition linkage through income generation. The result of the sensitivity analysis would seem to rule out unobserved factors which may influence the outcomes, suggesting that the findings are reasonably robust. Our findings also indicate the major role played by the closeness to the markets and experienced farmers.

In conclusion, more efforts are needed to diversify crops toward commercial vegetable production for its economic and nutritional importance while training farmers and addressing barriers constraining vegetable market access are

Table 3. Impact of vegetable production on household's livelihoods by PSM, and Multivalued Treatment Effects$^{1)}$

		Vegetable growers vs. Non-vegetable growers				Comparison with non-growers	
						Less market-oriented	Market-oriented
Variables	Unit$^{2)}$	PSM (Nearest-neighbor)		PSM (Radius caliper 0.1)		Multivalued treatment effects IPWRA	
Welfare indicators		Coef.	$\Gamma^{3)}$	Coef.	$\Gamma^{3)}$	Coef.	Coef.
Total revenue marketed crops	10^3 MDA/capita	1.58***	1.6	1.97***	>2	-1.29**	2.93***
Total value self-consumed crops	10^3 MDA/capita	0.14		0.11		0.060	0.13
Total agricultural income	10^3 MDA/capita	0.11		0.20		-0.049	0.27*
Total non-agricultural income	10^3 MDA/capita	0.13		0.25		0.07	0.45*
Total household income	10^3 MDA/capita	0.17		0.21		0.12	0.31**
Total value of food items consumed in the last month	10^3 MDA/capita	0.13		0.076		0.043	-0.078
Total value of non-food items consumed in the last month	10^3 MDA/capita	0.12		0.095		0.17	-0.14
The aggregated value of items consumed in the last month	10^3 MDA/capita	0.12		0.075		0.093	-0.11
Dietary diversity							
Household Dietary Diversity Score (HDDS)		0.43***	1.6	0.36***	1.7	-0.016	0.47**
Micro-nutrient sensitive HDDS (MsHDDS)		0.53***	1.5	0.33*	1.4	-0.39	0.46**
Food Consumption Score (FCS)		0.51		2.21*	1.1	1.24	3.01*

Notes: 1) *p<0.10, **p<0.05, ***p<0.01.
2) Units are in 10^3 MDA (Malagasy Ariary) per capita. 1 USD is about 3,614 MDA as of December 2019.
3) Rosenbaum bounds: Value of Γ under which results are still robust at the 10% level (only showed for statistically significant results).

recommended.

To explore the role of vegetables to fight against micronutrient deficiencies, further research is required to investigate the impact of vegetable production on health status of each of household members, especially on children.

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Comparison of Two Pathways Linking Agriculture to Child Health: Dietary Diversity and Micronutrient Intake in the Malagasy Highlands

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Rising micronutrient deficiencies threaten the well-being of preschool-aged children, as is the case for disadvantaged farmers in Madagascar. However, effective interventions to improve their nutritional status are still unknown. This study investigates the disjointed link between agriculture – food/nutrition security and food/nutrition security - nutritional status through a dual approach. Using a panel dataset, our result supports the link between production diversity – dietary diversity, and dietary diversity - improvement in children's wasting. Importantly, the finding highlights an association of own production of pulse with energy/micronutrient intake and that of energy/zinc intake with the reduction of undernourished and stunted child, respectively.

Key words: dietary diversity, micronutrient, child undernutrition

1. Introduction

"Hidden hunger" or "micronutrient malnutrition" has exacerbated the problem of food security in sub-Saharan Africa and has remained a silent obstacle for preschool children. In particular, micronutrient deficiency is a major contributor to premature death and cognitive disablement. This deficiency is prevalent among children in the central highlands of Madagascar, with a high prevalence of stunting (59.9%), wasting (6.0%) and underweight (40.1%) (INSTAT and UNICEF, 2019).[1)] However, effective interventions to address their micronutrient status are still unclear (Campos *et al.*, 2019). Hence, understanding the link between agriculture and improved nutritional outcomes for children is of strategic importance.

Research linking agriculture and nutrition has recently gained much attention for its global importance. Specifically, agricultural diversification is often recommended for its contribution to dietary diversification, which in turn is associated with improved nutritional status of individuals. However, no common understanding has been reached regarding its impact on dietary diversity (Sibhatu and Qaim, 2018). At the same time, supporting evidence indicating a link between dietary diversity and nutrient adequacy among children in developing countries has so far been inconclusive (Arimond and Ruel, 2004; Sié *et al.*, 2018). More recent studies have analyzed the relationship between agricultural diversification - household diets - and child nutritional outcomes (Bühler *et al.*, 2018; Chegere and Stage, 2020). Their findings suggest that production diversification significantly increases dietary diversity; yet, the latter explains only to a negligible extent the state of malnutrition among children.

To date, nearly all studies in this area contend that dietary diversity score can serve as a reliable proxy of dietary quality containing a range of micronutrients essential to the body (Arimond and Ruel, 2004). However, as a summary indicator, its appropriateness is of concern (Jones, 2017). That is, a diverse diet could: (i) be devoid of important micronutrients (Chegere and Stage, 2020); (ii) hide important variations in nutrient intakes (Jones, 2017); (iii) mask the heterogeneous effect of each food group; (iv) obscure underlying pathways with limited understanding of the influence of subsistence and market-based production; and (v) conceal the role of micronutrient intakes in improving a child's nutritional status.

With respect to (i) and (ii), the burden of collecting data on every micronutrient consumed leaves this area unexplored. Only one study has addressed the agriculture - food security - nutrition nexus from the perspective of micronutrient intake (Sekabira and Nalunga, 2020). However, the study does not investigate the role of food groups and their importance to

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1) These figures are of Vakinankaratra region, one of the regions belonging to the central highlands of Madagascar. Our study site is located in this region. Note that stunting rate is the highest in this region among 22 regions in Madagascar, whose average rate of child stunting is 41.6% (INSTAT and UNICEF, 2019). This is one of the reasons why we choose this study site.

human health. About (iii), only one study has analyzed the estimation of nutrient intakes by specifying food groups (Chegere and Stage, 2020). Yet, the study fails to assess the extensive role of each food group on micronutrient intake. As for (iv), although a handful of studies have distinguished the subsistence and income-generating pathways, they have not explicitly differentiated the impact of each food group (Muthini *et al*., 2020; Sekabira and Nalunga, 2020). Finally (v) implies the use of dietary diversity scores obscures the important role of caloric and micronutrient intake on child growth. Yet, limited studies have used the calorie and micronutrient intake measurements to assess the nutritional status of children thus far. Hence, there is an overall lack of empirical analyses to elucidate mediating pathways between the agriculture - food security - nutrition nexus. The present study aims to address these important gaps. The purpose is to unravel the link between agriculture, food/nutrition security, and child nutrition to formulate an effective intervention to address micronutrient deficiencies in children.

This study offers a more comprehensive contribution to the growing literature on agriculture - food security and food security - nutrition by taking three novel approaches. First, we use a twofold approach (the dietary diversity and the micronutrient intake approach) to trace the micronutrient intake pathway. Second, we single out the contribution of each food group on both dietary diversity and micronutrient intake to uncover their specific roles and to capture the heterogeneous linkage through both subsistence and market pathways. Third, we explore the association of diet quality in terms of calorie and micronutrient intake with child nutritional status.

2. Data and Analytical Framework

1) Data

This study uses an original panel dataset produced from household surveys conducted in January 2019 and in January/February 2020 as part of SATREPS project in which the authors participated. Each survey covers a total of 600 lowland rice producing households randomly selected from 60 villages in 3 out of 7 districts of the Vakinankaratra region in Madagascar. The surveys were implemented in the middle of rainy season, or the leanest season, and collected detailed information about agricultural activities and income in the previous dry season as well as household current situation at the time of interview including household-level food consumption (24-hour recall) from home production and market purchases, household characteristics and individual-level anthropometric measures and characteristics. It is worth noting that the stock of produced food is the lowest in the lean season, and it concerns most of the food groups. After eliminating the cases with incomplete data, we construct a balanced panel dataset of 510 households, which includes a pooled data of 395 anthropometric measurements of children under the age of 5 years from the two waves.[2]

Two categories of outcomes are evaluated in this study: household diet quality and child nutritional status.

The household dietary quality is assessed by household dietary diversification and micronutrient components in the diet. We use two indicators for household dietary diversification: Household Dietary Richness Score (HDRS) from 24-h recall, and Household Dietary Diversity Score (HDDS) from 24-h recall. HDRS is a raw count of any food crops and animal products consumed by the household, while HDDS is constructed on the basis of 12 food groups. Micronutrient components (Iron and Zinc) and calorie intake are calculated from the 24-h recall using food composition tables (FAO, 2020).

The indicators of child nutritional status are based on the anthropometric measurements as follows: (1) stunted, (2) wasted, (3) underweight, and (4) undernourishment (defined as either stunted, wasted, or underweight).[3]

Two explanatory variables are used as indicators of production diversity within a household: first, Agricultural Richness Score (ARS), which is the count of different food crops and animal products produced by a household; and second, Agricultural Diversity Score (ADS), which is the count of different food groups produced by a household, constructed using the 12 food groups of the HDDS.[4]

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[2] Since only children available at the time of the survey were measured, there are a lot of missing measurements. Hence, at the child level, the data are unbalanced very much and cannot be a good panel.

[3] Stunted is the case where height-for-age Z-score (HAZ) is less than -2 standard deviations (SD), wasted is the case where weight-for-height Z-score (WHZ) is less than -2 SD, and underweight is the case where weight-for-age Z-score (WAZ) is less than -2 SD. The Z-score was calculated according to the WHO Child Growth Standard 2006.

[4] During both surveys, 54% of sample households produced at least one of the 7 food groups: cereals (20%), tubers (23%), pulses (6%), vegetables (11%), milk (5%), egg (3%), and meat (5%). There was no household producing 5 food groups, namely fish, fruit, sugar, oil, or other miscellaneous foods such as tea and coffee. Therefore, we consider only 7 food groups for ADS. Also please note that 46% of sample households produced nothing because it is in the dry season.

2) Analytical framework

First, we examine the linkage of production diversity (ARS and ADS respectively) with household dietary quality (diversification as well as micronutrient components) and child nutritional status using household fixed effects (FE) model. Then, as a robustness check, we estimate a pooled Ordinary Least Square (OLS) model with village-level fixed effects and time fixed effects.

Second, using the same model, we disaggregate foods produced into food groups and investigate the linkage of the production of each food group with household dietary quality. In this analysis, we consider two sources of foods for consumption, market purchase and self-production, and respectively investigate their association with dietary diversity as well as micronutrient intakes.[5]

Third analysis is for the latter half of the linkage, namely between food consumption and child nutritional status, where using the household dietary quality variables as explanatory variables, its association with child nutritional status is estimated by a pooled OLS model.

3. Descriptive Statistics

Table 1 presents the summary statistics of outcome variables for the full sample. On a daily basis, a household consumes 4.6 food items and 4.0 food groups out of the 12 maximum possible food groups, which implies a shortage of 8 food groups. We also show results depicting the qualitative household food security, including energy and essential micronutrients (daily consumption per adult-male equivalent). We observe that the average intakes of energy and zinc are below the amount required for an adult male body, while that of iron seems to be sufficient.[6] Our second set of outcome variables consists of the nutritional status of children. Nearly 40 percent of children from our sampled household are stunted, approximately 20 percent are wasted, and more than 25 percent are underweight.[7] The percentage of undernourished children reaches about 57 percent.

Table 1. Summary statistics of outcome variables

	Mean	S.D.
Household Level Outcomes (N=510*2)		
Household Dietary Richness Score (24-h)	4.55	1.95
Household Dietary Diversity Score (24-h)	3.97	1.44
Energy (Kcal/per adult-male equivalent)	1977	1546
Iron (mg/per adult-male equivalent)	22.6	16.5
Zinc (mg/per adult-male equivalent)	9.59	6.92
Child Level Outcomes (N=373)		
Stunted (HAZ<-2)	0.39	0.49
Wasted (WHZ<-2)	0.20	0.40
Underweight (WAZ<-2)	0.29	0.46
Undernourished (at least one of the above three)	0.57	0.50

As for household characteristics, the descriptive statistics is given in Appendix Table.

4. Results and Discussions

1) Production diversity and dietary diversity

The results of the FE and pooled OLS models showing the influence of household agricultural production diversity on household dietary quality are presented in Table 2. As expected, we observe that ARS and ADS have positive and significant relationship with HDRS and HDDS collected from 24-h recall. However, neither ARS nor ADS has a significant relationship with energy and micronutrient intakes. The insignificant results imply that heterogeneity as to how to diversify food production may mask the contribution of specific food groups to the intake of micronutrients.

In addition, we regress agricultural diversity on child nutritional status. We observe insignificant associations except for ARS, which is positively and significantly associated with WHZ-score. These results may not imply the existence of a direct pathway linking agricultural diversity and child nutritional status but rather justify the two non-unified analyses of agricultural diversity – food diversity and food diversity – nutritional status.

Moreover, the results from disaggregating food crops and animal products into groups are presented in Table 3. With respect to the dietary diversification through the market, tuber, egg, and meat production tend to increase the 24-h dietary scores. Since these products are sold in the market to earn

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[5] Within the same food group, a household can consume both self-produced foods and market-purchased foods. We treat them as different kinds of foods and analyze their contributions to dietary quality separately.

[6] They are 2000 Kcal/day, 17.5 mg/day for iron, and 12 mg/day for zinc. We choose iron and zinc for our study since they, in addition to vitamin A, consist of micronutrient deficiency index for preschool children (Muthayya *et al.*, 2013). But vitamin A is not included in our study since it is distributed by the government in the study site in a program.

[7] These figures are not the same as those from INSTAT and UNICEF (2019) given in Section 1, particularly about the wasting. Although we cannot provide evidence, we consider that the difference should come from the fact that the INSTAT and UNICEF data covered the whole Vakinankaratra region including urban area and were collected after harvest period, while our data were only from rural area and collected during lean period. Since wasting reflects acute malnutrition in a short period, seasonality matters.

Table 2. Relationship of agricultural production diversity with household dietary diversity, energy and micronutrient intake and children nutritional status[1]

Dependent Variable	HDRS (24-h)				HDDS (24-h)				Energy Intake				Iron Intake				Zinc Intake				HAZ[2]		WHZ[2]		WAZ[2]		Undernourish[2]	
Expl. variables	F.E.		Pooled		F.E.		Pooled		F.E.		Pooled		F.E.		Pooled		F.E.		Pooled		Pooled		Pooled		Pooled		Pooled	
ARS (Agricultural	0.28^{**}		0.14^{**}		0.22^{***}		0.15^{***}		71.2		-69.3		0.73		-0.91		0.46		-0.26		-0.37		0.37^{*}		-0.06		-0.04	
Richness Score)	(0.11)		(0.06)		(0.07)		(0.04)		(105)		(58.7)		(1.38)		(0.63)		(0.56)		(0.31)		(0.27)		(0.22)		(0.18)		(0.04)	
ADS (Agricultural		0.27^{**}		0.17^{**}		0.20^{**}		0.17^{***}		12.58		-70.7		0.28		-0.97		0.11		-0.39		-0.23		0.22		-0.05		-0.04
Diversity Score)		(0.13)		(0.07)		(0.09)		(0.05)		(124)		(65.5)		(1.57)		(0.72)		(0.59)		(0.34)		(0.32)		(0.25)		(0.18)		(0.05)
Control Variables[3]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	393	393	370	370	389	389	370	370

Note: 1) Household Fixed Effects (F.E.) and pooled OLS model (Pooled) are used. Clustered standard errors at village level for F.E. and robust standard errors for Pooled are in parentheses; * $p<0.10$ ** $p<0.05$ *** $p<0.01$.
2) The dependent variables for nutritional status are HAZ-score, WHZ-score, WAZ-score, and binary dummy for at least one of stunting, wasting, and underweight.
3) Control variables are those shown in Appendix Table and a year dummy. For pooled OLS, Change of HH head dummy is replaced by variables referring to 4) and village fixed-effects are added.

Table 3. Relationship of each food group with household dietary quality[1]

Dependent Variable	HDRS (24-h)		HDDS (24-h)		Energy Intake		Iron Intake		Zinc Intake	
Explanatory variables	Foods bought in the market	Foods own produced	Foods bought in the market	Foods own produced	Foods bought in the market	Foods own produced	Foods bought in the market	Foods own produced	Foods bought in the market	Foods own produced
Cereal[2]	-0.15	-0.17	-0.16	-0.09	-82.1	-166.9	0.28	-2.47	0.10	-0.97
	(0.20)	(0.14)	(0.16)	(0.13)	(110.2)	(146.0)	(1.02)	(2.03)	(0.76)	(0.64)
Tuber[2]	0.44^{**}	0.06	0.31^{**}	0.07	155.2	-337.0	1.21	-1.45	1.04	-0.85
	(0.18)	(0.14)	(0.13)	(0.12)	(137.1)	(224.1)	(1.47)	(2.62)	(0.75)	(0.83)
Pulse[2]	-0.10	0.44^{**}	-0.19	0.40^{**}	-73.3	616.3^{***}	0.52	8.03^{***}	0.84	2.15^{**}
	(0.24)	(0.17)	(0.19)	(0.16)	(105.7)	(227.0)	(1.52)	(2.71)	(1.18)	(0.84)
Vegetable[2]	-0.21	0.58^{***}	-0.16	0.36^{**}	87.2	93.5	0.40	0.94	-0.49	-0.29
	(0.34)	(0.21)	(0.25)	(0.18)	(119.8)	(264.7)	(1.43)	(2.91)	(0.87)	(0.80)
Milk[2]	0.33	-0.02	0.25	0.10	-78.9	127.5	-3.36^{*}	-1.05	-1.45	0.64
	(0.32)	(0.25)	(0.25)	(0.21)	(147.1)	(164.5)	(1.79)	(1.95)	(1.25)	(1.01)
Egg[2]	0.86^{***}	-0.17	0.87^{***}	-0.07	23.9	165.0	0.60	-4.51	-0.00	-1.28
	(0.34)	(0.24)	(0.25)	(0.24)	(119.2)	(317.6)	(1.52)	(3.96)	(1.33)	(0.99)
Meat[2]	0.46	-0.19	0.49^{**}	-0.17	-27.1	--193.5	3.32^{*}	0.054	0.93	-0.11
	(0.29)	(0.19)	(0.24)	(0.16)	(192.2)	(297.1)	(1.84)	(3.13)	(1.12)	(0.91)
Control Variables[3]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020

Note: 1) Household Fixed Effects model is used. Clustered standard errors at village level are in parentheses; * $p<0.10$ ** $p<0.05$ *** $p<0.01$.
2) Dummy for household producing any food in this food group during the last dry season.
3) Control variables are socio-economic characteristics of the household shown in Appendix Table excluding those indicated as only for pooled OLS in note 4) and a year dummy.
4) Pooled OLS models give qualitatively similar results, but significance levels change in some cases. They are not in the table.

Appendix Table. Descriptive statistics

	mean	S.D.
Change of HH head in 2 years[1, 2]	0.01	0.09
--Male HH head[1, 2, 4]	0.89	0.32
--Age of HH head (years)[2, 4]	46.48	13.98
--Years in education of HH head[2, 4]	5.19	3.69
--Ability in French[1, 4]	0.63	0.48
--HH with two parents[1, 2, 4]	0.86	0.35
HH size[2]	4.85	1.94
Share of children	0.37	0.22
Share of old members (≧60)	0.15	0.31
Share of working woman	0.26	0.14
HH member in off-farm activities[1, 2]	0.29	0.22
# of plots used for lowland rice	1.64	0.96
# of plots used for upland rice	0.68	0.71
# of other plots	0.88	1.18
Home value per capita (ln MGA)[3]	2.78	1.56
Farm value per capita (ln MGA)[3]	2.76	1.55
Water available in dry season[1]	0.35	0.48
Crop sales in the market[1]	0.33	0.47
# of Observations (HHs)[2]	1,020	

Note: 1) A binary dummy variable.
2) HH stands for household.
3) Natural logarithm of Malagasy Ariary.
1 USD was about 3,780 MGA in April 2021.
4) Variables used only for pooled OLS.

cash income, their contribution to food consumption diversity is naturally through the market, or indirect linkage. On the other hand, as for dietary diversification through own-production, or direct linkage, pulse and vegetable production significantly increase HDRS and HDDS from the 24-h recall. However, the significant association is confirmed by pooled OLS regressions only in the case of pulse.

The second half of Table 3 is for the results on micronutrient intakes. We find that pulse production only has a significant positive association with the intake of calories, iron and zinc through own production pathway. The results are robust since they are confirmed by pooled OLS regressions. However, there is no other significant linkage with micronutrient intake.[8]

The insignificant association between vegetable production and energy or micronutrient intake might reveal the negligible amount of micronutrients (iron and zinc) contained in the consumed vegetables. In the case of tuber and egg, households tend to sell them and diversify their diets primarily through the purchase of sugar, coffee, and cereal, but the purchased food does not appear to increase the overall energy and micronutrient intake.

Hence, the findings imply that dietary diversity indicators may (i) miss out on important micronutrients; (ii) mask important variations in nutrient intakes; (iii) conceal the heterogeneous linkage of specific food groups; and (iv) mask the underlying pathway of micronutrient sources.

2) Diet quality and child nutrition outcomes

Table 4 presents the results of pooled OLS model regarding the association of household dietary diversification and child's nutritional outcomes. The table shows a positive association between HDDS recalled over a 24-h period with WHZ-score, suggesting that a diversified diet lowers the level of wasting in children. However, since small children do not necessarily consume the same food as adults, the observed associations are considered to be due to the household's awareness about nutrition, but may be partially attributed to pulse production.

We also analyze the relationship between energy and micronutrient intake either sourced from market or from own production (zinc and iron) on child's nutritional status in the same regression. The results show that the dummy of an adequate zinc obtained from own produced foods is positively and significantly associated with HAZ-score. Hence, the finding (v) displays the role of micronutrient intakes, in this case zinc, in improving stunting in children.

Table 4. Relationship of household dietary quality with child's nutritional status[1]

Explanatory variables	HAZ[2]		WHZ[2]		WAZ[2]		Undernourished[2]	
HDRS (24-h recall)	-0.10		0.26		0.08		-0.02	
	(0.17)		(0.18)		(0.08)		(0.02)	
HDDS (24-h recall)		-0.19		0.40*		0.09		-0.03
		(0.22)		(0.22)		(0.11)		(0.03)
Energy (market)[3]	0.93	0.96	-1.12	-1.13	-0.20	-0.18	-0.05	-0.06
	(0.74)	(0.75)	(0.77)	(0.78)	(0.31)	(0.31)	(0.10)	(0.10)
Energy (subsistence)[3]	-0.75	-0.71	0.61	0.54	-0.07	-0.08	-0.15*	-0.15*
	(0.48)	(0.48)	(0.55)	(0.55)	(0.25)	(0.26)	(0.08)	(0.08)
Zinc (market)[3]	-1.04	-0.96	0.87	0.73	-0.03	-0.05	-0.02	-0.02
	(0.69)	(0.70)	(0.62)	(0.64)	(0.31)	(0.32)	(0.10)	(0.11)
Zinc (subsistence)[3]	1.24*	1.28*	-0.52	-0.56	0.32	0.32	0.06	0.06
	(0.71)	(0.72)	(0.58)	(0.64)	(0.32)	(0.33)	(0.09)	(0.09)
Iron (market)[3]	0.40	0.40	-0.58	-0.54	-0.04	-0.02	-0.07	-0.07
	(0.64)	(0.62)	(0.62)	(0.60)	(0.27)	(0.27)	(0.08)	(0.08)
Iron (subsistence)[3]	0.29	0.28	-0.72	-0.70	-0.03	-0.02	0.07	0.07
	(0.60)	(0.60)	(0.63)	(0.63)	(0.33)	(0.33)	(0.08)	(0.08)
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variables[4]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of Observations[5]	393	393	370	370	389	389	370	370

Note: 1) Pooled OLS model is used. Robust standard errors in parentheses; * $p<0.10$ ** $p<0.05$ *** $p<0.01$.

2) The dependent variables for nutritional status are HAZ-score, WHZ-score, WAZ-score, and binary dummy for undernutrition (1 if at least one of stunting, wasting, and underweight).

3) Dummy variables representing an adequate energy and micronutrient for children, sourced either from market or subsistence.

4) They include a year dummy and the variables shown in Appendix Table excluding the change of household head dummy. In addition, characteristics of child (sex, age in months, etc.), mother's education, and sanitation characteristics are included.

5) Due to missing values, the number of observations differ for each regression analysis.

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[8] The significant estimates for milk and meat in the case of iron intake are not significant by pooled OLS regressions.

In addition, the result shows that (v) an adequate energy from the direct pathway significantly reduces the probability of being undernourished in children.

Therefore, even though we acknowledge that the two linkages are not joined, the result tends to seemingly show the associative link between pulse production – energy and micronutrient intake – and child nutritional status.

5. Conclusion

This study explores the association between farm production diversity and food diversity (micronutrient) as well as that of food diversity (micronutrient) and child nutritional status. The panel regression models show evidence of a positive linkage between production diversity and dietary diversity through both direct (own consumption) and indirect (market purchase) linkages. This study also supports a positive and significant association between household pulse production and calorie and micronutrient intake through the subsistence route. Both findings indicate the importance of assessing the micronutrient intake pathway and the disaggregation of production diversity into food groups. The pooled OLS model, on the other hand, highlights the importance of consuming self-produced caloric and micronutrient-rich food, particularly zinc, to improve overall child nutritional status and stunting in children, respectively. Thus, to enhance nutritional outcomes for children, policies should focus on promoting the production of micronutrient-rich crops such as pulses, particularly during the dry season.

A few limitations, however, remain in this study. First, the number of children under 5 years of age is limited in the sample, hence generalization of the results may belie the regional figure. Second, the food consumption data are from a household consumption survey and are not based on an individual level. Further research is encouraged to account for seasonal differences in household diets and to answer the question of whether off or on farm activities are more beneficial during the dry season.

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Abstract

It has been widely recognized that agriculture has the potential to contribute to rural household food security and nutrition in developing countries. However, studies that directly explore the link between agricultural productivity and farmers' nutrition are scarce. In this study, we examine how households' rice yield could affect their calories and micronutrients intake. To achieve this, we used three-years panel data of farm households collected in the Vakinankaratra region, one of the most important rice-producing regions of Madagascar. First, the results suggest that higher rice yield is significantly associated with an increase in calorie and micronutrients intake. Moreover, the results suggest that households with higher rice yield purchase more nutritious foods. Secondly, the results show that raising rice yield is a positive significant association with an increase in the share of the output sold and the cash revenue from rice sales. Therefore, we conclude that the market represents the channel through which increased staple foods production translates into improved nutritional outcomes. The findings of this study imply that interventions that improve rice yield and market access by farmers would contribute to improving households' nutritional outcomes.

Keywords: Rice, Agricultural productivity, Nutrition, Market access, Commercialization, Madagascar

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1 Introduction

It has been established that the growth of agricultural productivity and food production has helped to reduce hunger (Gödecke et al., 2018; Khoury et al., 2014; Pingali, 2012). Nevertheless, nutritional deficiencies, which are less related to general food shortages than to low dietary quality and diversity deficiencies, remain a major concern especially in Sub-Saharan Africa (SSA) and South Asia (FAO et al., 2021; Headey and Ecker, 2013; IFPRI, 2017). Furthermore, malnutrition is still among the major causes of premature deaths, infectious diseases, physical and mental growth retardation in children, and other types of health problems in developing countries (IFPRI, 2017).

Agriculture and nutrition are closely linked because the majority of undernourished people live in rural areas and many of them are smallholder farmers (Pinstrup-Andersen, 2007; Sibhatu et al., 2015). Recent literature has pointed the role of agriculture in improving nutritional outcomes. More specifically, it supports that increase in agriculture production, either from higher productivity (Darko et al., 2018; Kim et al., 2019; Slavchevska, 2015) or from increased commercialization (Carletto et al., 2017; Ogutu et al., 2019; Ruel et al., 2018; von Braun, 1995), is linked with improved nutrition.

At the macro-level several studies have shed light on the potential that increased productivity in agriculture should improve farm household's nutrition (Devkota and Upadhyay, 2013; Ogubdari and Awokuse, 2016). For example, Ogubdari & Awokuse (2016) examined the case of 41 countries in Sub-Saharan Africa (SSA) and found that an increase in agricultural value-added per hectare and cereal production per hectare contributes positively and significantly to food availability per capita in terms of weight, calorie, as well as protein supply.

At the household level, a systematic literature review of studies in South Asia by Shankar, Poole, & Bird (2019) found evidence that higher agricultural production per unit of land is significantly associated with improved household nutritional outcomes. For example, Morioka and Kondo (2017) suggested that the growth in productivity of agriculture in real terms has a positive impact on household food security in Nepal. Moreover, they found that the impact is stronger at the lowest levels of income. For a specific case of rice, Headey and Hoddinott (2016) found a significant association between rice productivity growth and child nutritional outcomes in Bangladesh. More specifically, they found evidence that rice yields predict the earlier introduction of complementary foods to infants after 6 months old as well as increases in their weight-for-height, but no improvements in their dietary diversity or height-for-age.

Studies in SSA that examine empirically the link between agricultural productivity and farm household nutrition, and in particular, the micronutrients intake are scarce. A study by Dzanku (2015) in Ghana found that the productivity of agriculture affects positively food expenditure. In the same vine, Darko et al. (2018) found that increase in maize yield per hectare has a positive impact on the household caloric intake in Malawi, though in terms of economic magnitude both the direct effect and economy-wide spillover effect of a percentage increase in agricultural productivity on the poverty and food security measures are small.

In general, although the potential of agricultural productivity and dietary diversity in improving food consumption has been recognized, there is little empirical evidence that they improve key measures of nutritional outcomes, such as micronutrients intake. More specifically, despite that a lot of effort has been done to induce a green revolution in rice production in SSA, empirical works that focus on the direct impact of household rice productivity on micronutrients intake at the household level are scarce. This paper seeks to fill this knowledge gap by exploring the nutritional impacts of lowland rice yield in the Vakinankaratra region of Madagascar.

The contribution of the paper is threefold: First, in Madagascar, rice is not one of the staple foods, but the only one, the most important staple food. This is different from other SSA countries, where there are several staple foods. As a result, many projects are aiming at the enhancement of rice productivity in Madagascar, and rice yield is relatively high compared with the cases of other SSA countries. However, its consequences on rice producers' nutritional status are poorly examined. Moreover, it is known that the nutritional status of farm household members is low in Madagascar (FAO et al., 2021). For example, in terms of the prevalence of stunting among children under 5 years old, Madagascar is one of the worst ten countries in the world according to the World Bank (World Bank, 2019). To the best of our knowledge, however, no study examines the relationship between rice productivity and nutritional status in the Malagasy context. The dearth of nutritional and agricultural data in Madagascar has undoubtedly been a constraint to exploring such a relationship. Second, one of the major limitations in most studies that use a seven-day recall questionnaire to capture rural households' consumption is that they are not free from seasonality effect. Seasonality in the reported data may lead to an overestimation or underestimation of the effects of the variables of interest. The data used in this paper is collected both during lean season and just after the harvest. Therefore, we used the weighted average of both seasons. This allows us to reduce the effect of the seasonal patterns of consumption on our estimates. Third, as opposed to the previous studies, we used panel data which allows us to remove the endogeneity due to unobserved time-invariant factors that can be correlated with both rice productivity and nutritional outcomes.

The remainder of this paper is organized as follows: Section 2 provides an overview of agriculture and nutrition in Madagascar. Section 3 lays out the conceptual link between agriculture and nutrition at the farm level and develops concrete research hypotheses. Section 4 describes the data used in this paper and the econometric approach used to test the hypotheses. Section 5 presents and discusses the results, and Section 6 concludes the paper.

2 Background on agriculture and nutrition in Madagascar

2.1 Agricultural production in Madagascar

Agriculture employed 74% of Madagascar's population and accounted for almost 23% of GDP in 2019 (FAO, 2019). It is characterized by extensive agricultural production and is very susceptible to climate hazards (Harvey et al., 2014). The production is carried out by small family farms, with approximately 85% of farmers cultivating rice (GRiSP[1], 2013). In Madagascar rice is produced mainly in rain-fed lowland plots where water can be retained during the rainy season[2], consequently, rice production is highly seasonal, with the vast majority of production taking place in the rainy season, and production in the dry season constrained by lack of water.

Figure 1 uses FAO production data to show the trends in rice yields and chemical fertilizers used in agriculture in Madagascar between 1961 and 2020. Before 2000 rice yield in Madagascar was stagnated like other African countries, but since 2000 Madagascar has experienced rapid growth of rice yield to catch up with Asia (Figure 1a). As shown in Figure 1b, the quantity of nitrogen used in agriculture began to be increasing exponentially since 2000, which interestingly

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[1] GRiSP: Global Rice Science Partnership

[2] Rice production has been extended to upland plots since the early 2000s with the introduction of new varieties that are cold and drought tolerant (Raboin et al., 2014). More than half of lowland rice producers grow upland rice recently in the study site (Ozaki and Sakurai, 2020).

corresponds to the high growth in rice yield in Figure (1a) although we do not have any evidence of their causal relationship. In fact, the use of chemical fertilizers for rice is still limited. For example, according to the world bank data, fertilizer consumption in agriculture is approximately only 12.6 kg/ha of arable land in Madagascar. This application rate is much lower than in Asian countries, such as 149 kg/ha for Thailand, 318 kg/ha for Indonesia, 236 kg/ha for Bangladesh, and about 415 kg/ha for Vietnam in 2018 (World Bank, 2019). For the case of rice production, a previous study in our study site shows that almost 75% of lowland rice plots received no chemical fertilizer at all, and even if they use some, the application rate is less than 40 kg/ha (Ozaki and Sakurai, 2021).

2.2 Dietary and nutrition trends in Madagascar

Like other countries of sub-Sahara Africa, Madagascar is permanently threatened by food insecurity. Figure 2 uses FAO Food Balance Sheets to plot trends in food supply and nutritional status of households in Madagascar. This figure needs to be treated with caution because there may be systematic errors in FAO Food Balance Sheets, particularly misreporting of production for foods that are traded little (Headey and Hoddinott, 2016). Though the prevalence of undernourished people is declining over time, it remains high with more than 40% of the total population in 2020 (Figure 2a). The daily energy supply though higher than the minimum requirement remains lower than the dietary energy requirement defined by FAO (Figure 2b). Also, there are some malnutrition problems in Madagascar. For example, Figure 2a shows that since 2015, the prevalence of anemia among women of reproductive age is higher than 37% while the proportion of children under 5 years old who are stunted is more than 42% approximately.

Rice is the main staple food in Madagascar: the per-capita annual rice consumption was estimated to be 157kg in 2018, making it one of the highest in the world for rice consumption per capita (FAO, 2018). This implies that rice represents an important source of calorie intake. For example, in 2018 rice's contribution to the daily calorie supply was 1075 kcal/per capita, which represents 56% of the total calorie consumption (FAO, 2018). Furthermore, rice is also known as one of most important income sources for most farm households in Madagascar (World Bank, 2016). Therefore, we expect that the increase of household cash revenue that would follow the increase of rice yield will be translated into an enhanced purchase of food unproduced by the household, specifically highly nutritious food.

3 Conceptualizing the linkages between rice productivity household nutritional outcomes

The linkage between agriculture production and nutrition, in general, is quite complex and highly context-specific. Moreover, there are many interactions among the different pathways that connect agricultural production to nutritional outcomes. A review by Gillespie et al.(2019) identified six routes of this linkage that can be summarized into three main channels: (a) food production, which can affect the food available for household consumption as well the price of diverse foods; (b) agricultural income for expenditure on food and non-food items; and (c) women's empowerment, which affects income, caring capacity and practices, and female energy expenditure.

In general, the literature suggests that the effect of income on nutrition is very heterogeneous. Some studies found that the income elasticity of nutrition is declining or tend close to zero (Colen et al., 2018; Ogundari and Abdulai, 2013; Salois et al., 2012; Skoufias et al., 2011), while other recent studies in low- and middle-income countries demonstrate that agricultural income growth contributes effectively to improved nutrition (Carletto et al., 2015; Gillespie et al., 2019; Pingali and Sunder, 2017).

Figure 3 provides a simplified picture of how an increase in rice production per unit would improve the farmers' nutritional outcomes in Madagascar. Rice production may have a direct effect on the farm household calory intake through the Pathway (1). However, while an increase in food production increases food availability, it does not guarantee that the quality, variety, or nutritional value of the food will increase. To achieve this, it is necessary that the growth in rice production induces an increase in cash revenue (Pathway 2). More specifically, this would imply that higher rice productivity via farmers' adoption of improved inputs and management practices may improve the nutritional status of nutritionally vulnerable households by enhancing their cash revenue, which provides better access to more diverse or nutritious foods through the market.

However, there is another possibility. The increase in rice productivity may free up additional land for the production of other crops, which could improve the nutrition directly through dietary diversification and indirectly through higher cash income (Pathway 3). This would contribute to improving the farm household either through direct consumption or increased cash revenue.

From this conceptual framework we postulate the following hypotheses:

(1) Increased households' rice yield is associated with higher energy intake by households.
(2) Increased households' rice yield is associated with higher micronutrients intake by households.

With respect to the mechanism through which increased households' rice productivity improves the households' micronutrients intake, we postulate two additional hypotheses:

(3.1) Increased households' rice yield is associated with larger purchases of highly nutritious foods.

(3.2) Increased households' rice yield is associated with a higher households' cash revenue.

4 Method and data

4.1 Method

In order to test the hypotheses postulated above, we model the relationship between nutritional outcomes and rice yield as:

$$N_{ivt} = \delta_0 + \delta_1 y_{ivt} + \delta_2' X_{ivt} + \delta_3' T_t + \delta_4' T_t * V_v + \mu_i + \varepsilon_{ivt} \quad (1)$$

where N_{ivt} refers to nutritional outcome for household i in village v of year t and y_{it} to household i*'s* rice yield in natural logarithm. The parameter of interest is δ_1, representing the effect of rice yield on the household's nutritional outcomes. X is a vector of time-variant household and farm characteristics, including household socio-demographics, and asset variables. T_t is a vector of time dummies for the years 2018, 2019, and 2020, which captures all structural changes such as economic growth, improvements of communication and transportation infrastructure, and climate shocks. Interaction terms between year dummies (T_t) and village dummies (V_v) are also added to control for time varying village specific effects such as drought and low temperature. μ_i is household fixed effect, which is to control for time-invariant factors that can be correlated with both yields and nutritional outcomes (e.g. water availability, soil quality, climate, household preferences, and cultural practices). While Equation (1) controls for a wide range of observable factors, we acknowledge that empirical estimates of the effects of rice yield on nutrition could still be biased by unobservable time-variant factors that simultaneously influence rice yields and nutrition outcomes. Also, an important concern is that the relationship between agricultural productivity and nutritional status may not run in one direction. On the contrary, individuals in better nutritional status and health are likely to be able to perform more strenuous activities with fewer breaks, and hence have higher productivity (Egbetokun et al., 2012; Gkiza and Nastis, 2017). This means that we must treat the results below as suggestive rather than definitive evidence on the linkages between rice productivity and nutritional outcomes at the household level.

4.2 Data

This study used data collected by the FertilitY sensing and Variety Amelioration for Rice Yield (FyVary) Project led jointly by the Japan International Research Center for Agricultural Sciences and the Malagasy Ministry for Agriculture, Livestock and Fishing (MINAE). One of the major goals of this project is to increase the rice yield under low fertility conditions through rapid diagnosis of soil fertility and the development of nutrient-use-efficient breeding lines. The project site is the Vakinankaratra region in central Madagascar, one of the most important rice-producing regions of this island country in terms of volume. The sample households were chosen following two steps: First, a census survey was conducted in 60 villages across 3 out of the 6 districts of the Vakinankaratra region from December 2017 to January 2018. The villages were selected proportionally to the size of each district. Second, from the households listed in the census, 10 lowland rice-growing households were randomly selected in each of 60 villages. This yielded an initial sample size of 600 households.

The data collected includes demography, agricultural input and output, monthly rice purchases and sales, monthly expenditure of food and non-food items, 7-day and 24-hour recall questionnaire about food consumption, and non-agricultural/off-farm activities. To capture the dry season activities as well as the seasonality in food consumption, farmers were interviewed at least twice every year: the first round after the harvest and the second during the lean season. The data covers three rice productions in years of 2018, 2019, and 2020. We kept households that appear at least twice during the three years, then additional exclusion of households with missing values yielded to an unbalanced panel of 1587 observations including 487 households that appear in each of the three years. Since total number of observations should have been 1800 in three years, the attrition rate is 11.8%, or less than 4% per year on average, which suggests a moderate attrition.

4.3 Variables and summary statistics

Table 1 shows the summary statistics of the key variables and some control variables. The lowland rice yield (kg/ha) is the variable of interest of this study. Since some farmers have several plots, we computed the average yield weighted by the plot size. On average, the yield of lowland rice for our sample is 3363.4 kg/ha, which is close to the regional average yield of 3000-3500 kg per ha during the period of study (WFP, 2019). Moreover, Table 1 shows that more than 54% of households in our sample sell rice, which suggests that a large number of farmers in the study site obtain cash revenue from lowland rice production. Also, Table 1 shows that only 20% of the total output is sold. However, it is worth noting that selling rice does not mean that those farmers produce sufficient rice for self-consumption. In fact, many farmers purchase rice during the lean season in Madagascar (Minten et al., 2006). In this study, we found that more than 43 % of the sample is at the simultaneously seller and buyer rice (Table 1). We also controlled for some farming characteristics variables including the number of other crops, the income from other farming activities such as dry season farming, non-rice crops, and upland rice cultivation.

As for household wealth, the summary statistics in Table 1 show that the average size of total land cultivated is 0.88 hectares and the average livestock holding is 2.75 TLU, which suggests that our sample is composed of smallholder farmers. Household socio-demographic variables include the age of the household head, number of children under 5 years old, number of children between 6-15 years old, and the number of adult members. In addition, when we analyze household food consumption and expenditure, we include two more control variables: one is the identity of the respondent to reduce the effect of a possible measurement error, taking 1 if the respondent is different from the person who knows better about household food consumption; the other is a binary variable to control for unordinary food consumption in the 24 hours before the interview (for example a day of ceremony or feast).

The summary statistics of the outcome variables are shown in Table 2. In total, we have 7 survey rounds during the three years for the consumption data. Therefore, we calculated the average value of outcome variables weighted by the household size in AE (Adult Equivalent). First, monthly the food consumption and rice purchases are presented the panel A of Table 2. It shows that the food consumption is 48583.4 MGA per AE, which is equivalent to USD 0.42 per/AE/ day. The food consumption of non-purchased is converted into MGA. The market plays an important role in food consumption, with an average food purchase of 30769.6 MGA per AE, which is equivalent to 63% of the total food consumption. On average, households in this sample purchase 5.43 kg/AE of rice per month, which increases approximately 6% during the lean season. Additionally, the panel B of Table 2 shows that a large share of the of household budget is allocated to staple foods group, follows by meat and fish.

Panel C of Table 2 presents households' calories and micronutrients intake calculated based on 24-hour dietary recall. On average, the sample calories intake is 2640 kcal/day/AE, which is approximately equivalent to the standard requirement for an appropriate active life for an adult. However, the prevalence of calorie deficiency is 45%, which suggests that a high number of undernourished people should be included this sample. In terms of micronutrients, we concentrate on iron, zinc, and vitamin A, for which deficiencies are particularly widespread in Sub-Saharan Africa (Mason et al., 2015). For this sample the average iron intake is 14.32 mg/day/AE, which is closed to the recommended[3] amount while zinc intake is lower than the recommended level of 11 mg/day/AE WHO (2005). A striking observation in Table 2 is that on average the vitamin A intake is 221 μg RAE/day/AE, which is far below the standard requirement of 800 μg RAE/day/AE defined the WHO (2005).

5 Results and Discussion

The effects of rice productivity on the calorie and micronutrients intake are shown in Table 3. First, the results show that raising rice yield has a positive and significant impact on household energy intake (Column 1 of Table 3). For instance, an increase of rice productivity by 1% is associated with an increase of the calorie intake per AE by 0.18 % approximately. This result supports our Hypothesis (1) that higher households' rice yield is associated with higher energy intake. Additionally, the results in columns (1) and (2) of Table A1 in the appendix show that there is a significant impact of household's rice yield on food consumption per AE, and more specifically rice consumption per AE. Furthermore, the results in column (5) of Table A1 of the appendix shows households with higher rice yield purchase less rice during the lean season. Consistent with the Pathway (1) in Figure 3, higher rice productivity contributes to the increase of the amount of food that is available for households.

Second, columns (2)-(4) of Table 3 show that the rice productivity elasticities of micronutrients intake are positive and significant across all the micronutrients of interest. For example, an increase of rice productivity by 1% is associated with an increase of zinc intake by

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[3] WHO (2005) recommend a daily amount of iron of 8.7mg/day for men over 18 years old and 14.8mg/day for women aged 19 to 50.

0.11%, iron intake by 0.75%, and vitamin A intake by 0.19%. These results support our Hypothesis (2) that an increase in lowland rice productivity improves farm households' nutritional outcomes. Not only does higher productivity increases calorie intake, but it also improves the household micronutrient intake. However, the effect size of the observed effects remains low. For instance,(Ozaki and Sakurai, 2021) found in this study site that farmers who adopt chemical fertilizers increase their rice yield by 30%, which is interestingly close to one standard deviation of rice in this study. The increase in rice yield that follows this adoption would increase the households' zinc intake and Vitamin A intake by 0.3 mg/day/AE and 12.54 µg RAE/day/AE respectively, which is still not enough to satisfy their daily standard requirements.

Furthermore, consistent with this result, column (5) suggests that increased household rice yield is associated with a higher household dietary diversity score. For example, a coefficient of 0.7 in column (5) of Table 3 suggests that an increase of the rice yield by 10% will increase the Household dietary diversity score (HDDS) by 0.067 ($0.7 \times \ln [1.1]$) food groups. A hypothetical increase of rice yield by one standard deviation- approximately a 38 % increase relative to the sample mean- would increase the HDDS by only 4.26 % relative to the sample mean. This low effect size is consistent with the low elasticities in most of the micronutrient intake.

To understand the transmission channel of the observed effects, we estimate the impact of rice yield on the monthly food expenditure per AE. The results are shown in Table 4. Columns (1) and (2) of Table 4 show that rice yield does not significantly affect the purchase of staple foods (e.g., rice and maize), tuber, and pulses. However, and interestingly, we observe a positive and significant effect on the purchase of micronutrient-rich food groups such as vegetables, fruits, and meat/fish (columns (3)-(6). For example, an increase of rice yield per ha by 1% is associated with an increase of the purchase of vegetables by 0.45%, fruits by 0.57%, and meat/fish by 0.65 %.

Consistent with columns (3)-(6), the results in column (3) of Table A1 shows that there is a positive association between rice yield and the total consumption from purchased foods. These results support our our Hypothesis (3.1) that an increase in the households' rice yield is associated with more purchases of highly nutritious foods.

As discussed in the previous section (3), for a higher yield to be translated into more purchases of highly nutritious foods, it is necessary that the increase in yield induces higher cash revenue. Therefore, to deepen our analysis, we estimate the effect of rice yield on the household level of commercialization and the cash revenue from lowland rice sales. The results of the econometric estimation are presented in Table 5. First, columns (1)-(3) of Table 5 show that the coefficients of rice yield on the decision to sell as well as on the share of rice that is sold are positive and significant. For example, a coefficient of 31.14 in column (2) suggests that an increase of household's rice yield by 10% is associated with an increase of the share of rice sold by 3 points percentage. The magnitude of the observed impact is quite high. For instance, a hypothetical increase in the rice yield by one standard deviation- approximately 38% relative to the sample mean - would be associated with an increase of the share of the rice sold by 50%. Moreover, columns (4) and (5) show that the increase in rice sales is translated into higher cash revenue. Consistent with the effect size of columns (2) and (3), there is a strong association between household's rice yield and cash revenue obtained from rice sales. For example, an increase in rice yield by 1% is associated with an increase in cash revenue by 4.75%. The strong effect of rice productivity on the income seems surprising but consistent with the low level of commercialization shown in the descriptive statistics: If we assume that local demand for rice is fixed, low commercialization - 20% in this sample - implies low pressure on prices, and then higher revenues for farmers who sell rice.

Moreover, we investigate the effect of market access on rice sales. To do so, we used the household location to the main road, more specifically the distance. Since location is time-invariant, we used the interaction term between the distance and household rice yield. The results in Table 5 suggest that distance from the main road affect negatively the rice commercialization and the cash revenue from sales at the highest level of rice yield. This result suggests that market access remains a significant constraint to rice commercialization for households in this sample.

Furthermore, to check the validity of Pathway (3) shown in Figure 3, we estimated the effect of rice yield on the other sources of income. The results are shown in column (1) of Table A2 of the appendix. It suggests that raising lowland rice yield does not significantly associated with the income from the production of the other crops. One possible explanation is that lowland plots are generally small and rice production is far below the self-sufficient quantity in the study site. Furthermore, household's rice yield does not significantly affect off-farm income (column (1) of Table A2 in the appendix).

Overall, the results of this study are consistent with previous studies that agriculture production contributes to the farm household nutritional outcome through crop commercialization (Ogutu et al., 2019). However, this study goes further by showing that commercialization could be enhanced by boosting crop yield. More specifically, the positive effects on calories and nutrients suggest that the additional cash revenue that follows the increase in rice yield improves households' economic access to food and dietary quality. Households with higher rice productivity do not only access to energy-dense foods (including rice itself), but also purchase foods that contribute to improved micronutrients intake, such as vegetables, fruits, meat, and fish.

6 Conclusion and policy implications

Nutritional deficiencies remain the main cause of several health problems in Sub-Sahara Africa. Improving agricultural productivity has a prominent role to play in alleviating malnutrition among the poorest in this part of the world. This has motivated the academics, practitioners, and policy communities to gear up to improve the productivity of major staple food crops such as rice in this region. However, how the increase of staple crop productivity translates into more micronutrients intake at the household level is not well investigated. In this study, we aim to fill this gap by exploring the association between lowland rice yield and energy and micronutrients intake. To achieve this, we used three-years panel data of smallholder farmers collected in the Vakinankaratra region of Madagascar. Moreover, we have used a household fixed-effect model to control for unobservable time-invariant factors that may correlate with both nutritional outcomes and rice yield. Additionally, we controlled for several time-variant variables including the other sources of income, household asset, and socio-demographic, year-village dummy variables.

First, the results suggest that an increase in rice yield is significantly associated with an increase in calorie and micronutrients intake. Second, our regression supports that the linkage between rice productivity and nutritional outcomes is through the market in the following way: (i) higher rice yield is significantly associated with higher commercialization of rice in the market, (ii) rice yield is positively and significantly associated with household cash revenue, and (iii) higher rice yield is significantly associated with a higher purchase of nutritious food.

The findings of this study have important policy implications. First, though the effect size of rice yield on the micronutrients intake is low, significantly raising the productivity of rice, which is the most important crop for farm households, would benefit nutrition policies in rural Madagascar in the short run. Second, local strategies to improve farm household market participation are likely to benefit rural households' nutrition. In particular, market-related infrastructures would be important to this by facilitating farmers' commercialization of the additional production that follows the increase in yield.

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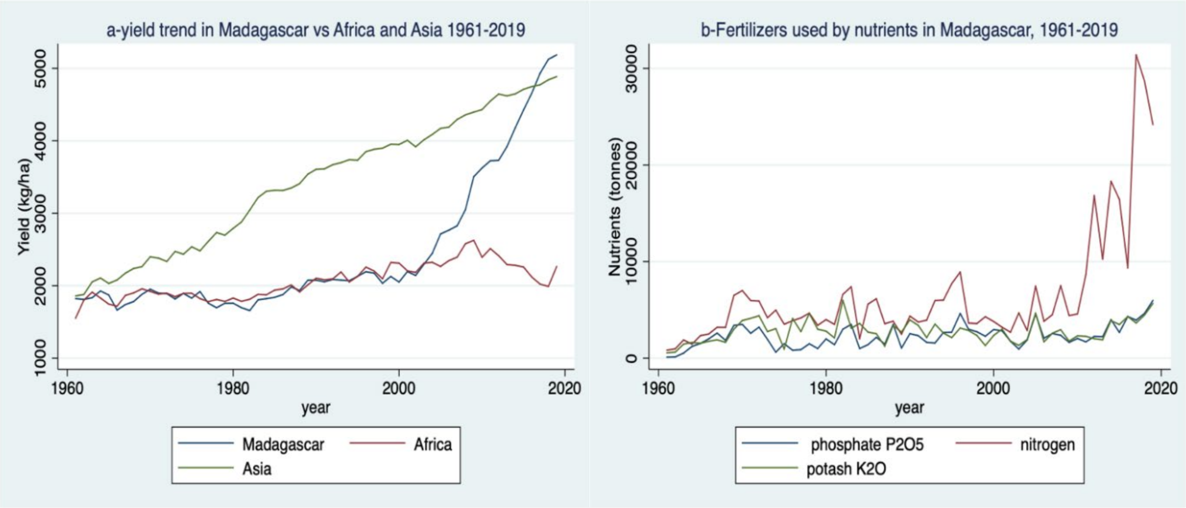
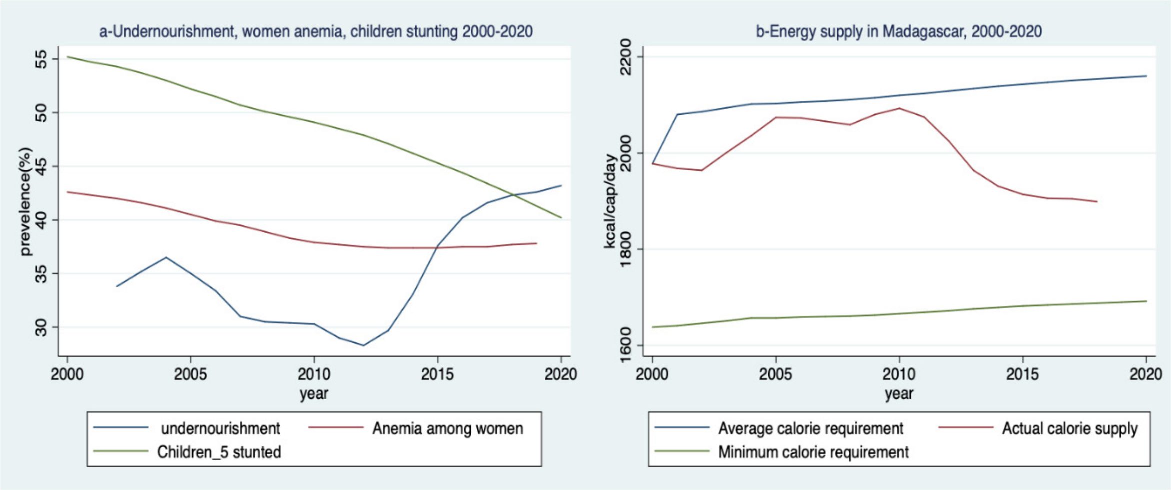
Tables and Figures

Figure 1: Trends in rice yields and chemical fertilizers used in agriculture in Madagascar, 1961–2020



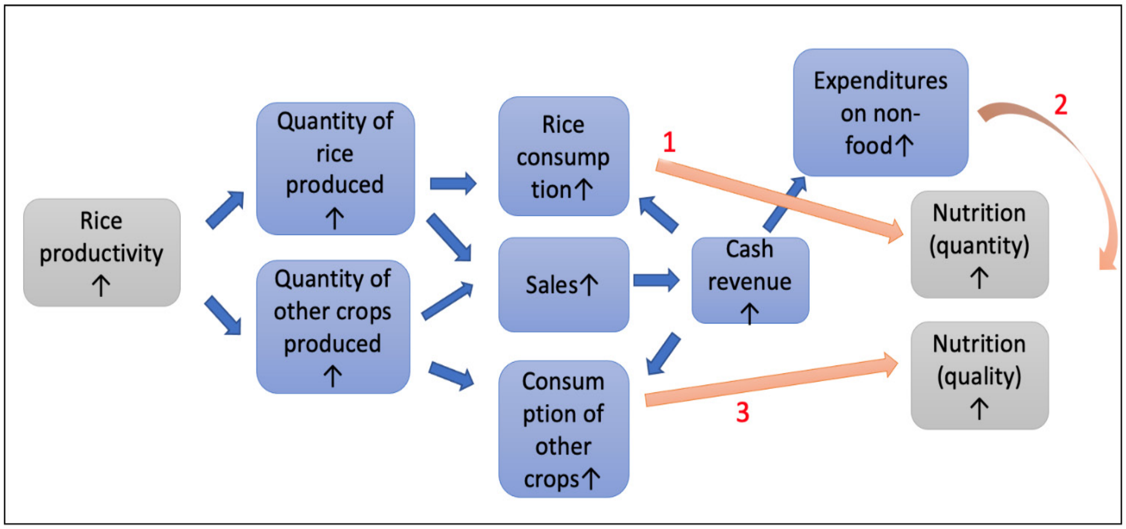
Source: Constructed by authors based on the FAO data, 2021.

Figure 2: Trends in the Average dietary energy requirement and nutritional status in Madagascar, 2000-2020



Source: Constructed by authors based on the FAO food balance sheets, 2021.

Figure 3: Linkage between rice yield and farm household nutrition outcomes



Source: Constructed by authors

Table 1: Summary statistics rice production and households' characteristics

	2018	2019	2020	All	
Variables	mean	mean	mean	mean	Standard deviation
	(1)	(2)	(3)	(4)	(5)
Lowland rice yield (kg/ha)	3432	3203.6	3455.7	3363.4	1294.17
Lowland production (kg/AE)	230.46	236.2	247.3	237.8	454.79
Total land size for lowland rice (ha)	0.32	0.29	0.28	0.3	0.57
Number of lowland rice plots	1.7	1.62	1.72	1.68	0.92
Commercialization of lowland rice (1/0)	0.57	0.58	0.48	0.54	0.49
Share of the lowland rice production sold (%)	20.88	18.94	20.67	20.17	27.44
Cash revenue from lowland rice sales (1000 MGA/AE)	45.20	30.90	61.26	45.57	173.95
Household buys rice (1/0)	0.88	0.84	0.79	0.84	0.36
Household buys and sells rice in a year (1/0)	0.48	0.46	0.34	0.43	0.49
Crop diversification [a]	1.52	1.74	2.13	1.79	1.58
Income from other farm activities (1000 MGA/AE)	232.0	143.22	178.47	185.51	382.91
Off-farm income (1000 MGA/AE) [b]	227.57	336.22	360.32	306.30	406.80
Age of the household's head	53.16	46.66	47.45	49.19	69.79
Number of children under 5 years old	0.67	0.61	0.54	0.61	0.76
Number of children between 6-15 years old	1.4	1.32	1.29	1.34	1.22
Number of adult members	2.92	2.91	2.91	2.91	1.24
Household size (in AE)	3.69	3.55	3.63	3.62	1.41
Consumption questionnaire respondent [c] (1/0)	0.35	0.52	0.39	0.42	0.49
Yesterday was a special day (1/0)	0.04	0.05	0.00	0.03	0.18
Total size of land cultivated (ha)	0.87	0.9	0.88	0.88	3.57
Livestock holdings (Tropical Livestock Unit, TLU)	2.77	2.74	2.74	2.75	3.21
Distance to the main road (km)	5.37	5.44	5.40	5.40	5.09
Value of total asset (1000 MGA/AE)	144	149.22	162.42	151.6	296.0
Number of Observations	550	529	508	1587	

Note: AE is Adult Equivalent. MGA: Malagasy Ariary is Malagasy currency (1 MGA = US$ 0.00026 as of July 27th, 2021).

[a] Crop diversification is the number of other crops cultivated.

[b] The income from other farming activities includes income from dry season farming, non-rice crops, and upland rice cultivation.

[c] Consumption questionnaire respondent takes 1 if the respondent is different from the person who knows better about household consumption and 0 otherwise.

Table 2: Summary statistics of consumption and micronutrients supply

	2018	2019	2020	All	
Variables	mean	mean	mean	mean	Standard deviation
	(1)	(2)	(3)	(4)	(5)
A. Food consumption					
Consumption of purchased food (1000 MGA/month/AE)	33.96	23.45	34.74	30.77	20.75
Consumption of non-purchased food (1000 MGA/month/AE)	13.96	19.77	19.99	17.81	14.27
Total food consumption (1000 MGA/month/AE)	47.92	43.23	54.73	48.58	23.98
Total rice consumption (1000 MGA/month/AE)	24.50	24.02	28.31	25.55	11.20
Monthly rice purchased rice (kg/month/AE)	6.54	5.82	3.83	5.43	9.37
Monthly (average) rice purchased rice during lean season (kg/month/AE)	7.07	6.70	3.40	5.78	7.58
B. Purchase of different food groups					
Staple foods (1000 MGA/month/AE)	13.35	6.30	14.33	11.31	11.98
Pulses (1000 MGA/month /AE)	1.27	1.43	1.06	1.26	1.47
Tubers and Roots (1000 MGA/month/AE)	0.40	1.02	1.24	0.87	1.61
Vegetables (1000 MGA/month/AE)	1.92	2.25	2.17	2.20	8.8
Fruits (1000 MGA/month/AE)	0.53	1.06	0.53	0.71	3.81
Meat and Fish (1000 MGA/month/AE)	5.80	3.81	4.53	4.73	6.75
C. Diet quality, Energy, and micronutrients intake					
Household Dietary Diversity Score (HDDS)[a)]	5.030	5.213	5.643	5.290	1.114
Calorie intake (kcal/day/AE)	2639.1	2567.2	2783.5	2661.9	834.9
Prevalence of undernourishment (%)[b)]	50.6	46.3	38.3	45.2	49.8
Iron intake (mg/day/AE)	14.27	13.84	14.89	14.32	8.89
Zinc intake (mg/day/AE)	9.60	7.60	9.20	8.81	4.53
Vitamin A intake (μg RAE/day/AE)	236.90	166.70	258.60	220.70	190.0
Number of Observations	550	529	508	1587	

Note: AE is Adult Equivalent. MGA: Malagasy Ariary is Malagasy currency (1,000MGA = US$ 0.026 as of July 27th, 2021). RAE is retinol activity equivalents

[a)] HDDS is number of different food groups consumed during the 24 hours preceding the survey [0-12]

[b)] The percentage of the household with calorie consumption lower that 2,500kcal/day/AE.

Table 3: Impact of household's rice yield on the calories and micronutrients intake (Household fixed effects)

VARIABLES	Energy	Zinc	Iron	Vitamin A	HDDS
	(1)	(2)	(3)	(4)	(5)
Lowland rice yield (Ln)	0.183***	0.115***	0.750***	0.190***	0.697***
	(0.026)	(0.034)	(0.039)	(0.043)	(0.074)
Age of the household's head	-0.000	0.000***	-0.000**	-0.000***	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of children under 5 years old	-0.074***	-0.027	0.044	-0.015	-0.023
	(0.026)	(0.035)	(0.038)	(0.036)	(0.081)
Number of children between 6-15 years old	-0.057***	-0.051**	-0.025	0.004	-0.023
	(0.019)	(0.025)	(0.030)	(0.017)	(0.064)
Number of adult members	-0.041**	-0.056***	-0.052**	-0.014	0.022
	(0.017)	(0.019)	(0.025)	(0.017)	(0.057)
Consumption questionnaire respondent [a] (1/0)	0.011	0.024	0.013	0.001	-0.104
	(0.023)	(0.027)	(0.033)	(0.025)	(0.073)
Yesterday was a special day (1/0)	0.015	-0.017	0.136	0.063	0.074
	(0.069)	(0.075)	(0.082)	(0.051)	(0.201)
Value of farm asset per AE (ln)	0.048	-0.032	0.066*	0.042	0.049
	(0.032)	(0.025)	(0.039)	(0.025)	(0.073)
Livestock holdings (TLU)	0.006	0.0020	-0.0010	-0.002	0.018
	(0.003)	(0.003)	(0.007)	(0.007)	(0.016)
Total off-farm income per AE (ln)	-0.001	-0.007	0.006	0.003	0.012
	(0.003)	(0.004)	(0.009)	(0.004)	(0.012)
Total size of land cultivated (ln)	0.000	0.018	0.034	-0.022	-0.019
	(0.024)	(0.027)	(0.041)	(0.022)	(0.087)
Total plot size for lowland rice (ln)	0.007	0.005	0.016	0.014	0.070
	(0.020)	(0.018)	(0.025)	(0.020)	(0.064)
Crop diversification	0.007	-0.013	0.015	0.005	0.091
	(0.016)	(0.014)	(0.018)	(0.014)	(0.062)
R-squared	0.236	0.215	0.408	0.405	0.325
Observations	1,587	1,587	1,587	1,587	1,587

Note: From columns (1) to (4) the dependent variables are in logarithm.

[a)] Consumption questionnaire respondent takes 1 if the respondent is different from the person who knows better about household consumption and 0 otherwise.

[b)] Crop diversification is number of other crops cultivated.

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at the village level in parentheses. Number of households in the panel is 550.

Table 4: The impact of rice yield on the purchase of different food groups(Household fixed effects)

VARIABLES	Staple food	Pulse	Tuber	Vegetables	Fruits	Meat and Fish
	(1)	(2)	(3)	(4)	(5)	(6)
Lowland rice yield (Ln)	-0.024	0.374	0.288	0.456***	0.575**	0.658***
	(0.245)	(0.239)	(0.249)	(0.171)	(0.253)	(0.139)
Age of the household's head	-0.002***	-0.000	-0.002	0.000	0.001***	0.000
	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.001)
Number of children under 5 years old	-0.232	0.246	0.005	-0.022	0.407*	-0.141
	(0.225)	(0.255)	(0.233)	(0.124)	(0.220)	(0.121)
Number of children between 6-15 years old	0.238	-0.118	-0.095	-0.267***	0.280*	-0.114
	(0.180)	(0.138)	(0.216)	(0.082)	(0.161)	(0.098)
Number of adult members	-0.099	-0.163	-0.020	-0.064	-0.115	-0.019
	(0.149)	(0.202)	(0.133)	(0.072)	(0.157)	(0.084)
Value of farm asset per AE (ln)	-0.030	0.401	-0.159	0.233	0.226	0.467***
	(0.278)	(0.286)	(0.236)	(0.167)	(0.263)	(0.138)
Livestock holdings (TLU)	-0.052	0.026	-0.029	-0.028	0.019	-0.002
	(0.037)	(0.045)	(0.054)	(0.023)	(0.045)	(0.021)
Total off-farm income per AE (ln)	0.052	-0.012	-0.007	-0.021	0.008	0.014
	(0.045)	(0.031)	(0.043)	(0.016)	(0.029)	(0.030)
Total size of land cultivated (ln)	-0.588***	-0.204	-0.611**	-0.150	-0.027	0.154*
	(0.211)	(0.230)	(0.243)	(0.114)	(0.222)	(0.088)
Total plot size for lowland rice (ln)	0.157	0.186	0.229	0.070	0.105	0.085
	(0.165)	(0.185)	(0.212)	(0.090)	(0.202)	(0.087)
Crop diversification [a]	0.163	-0.197	-0.086	-0.106*	-0.238*	-0.094
	(0.146)	(0.134)	(0.151)	(0.055)	(0.139)	(0.067)
R-squared	0.443	0.289	0.481	0.233	0.232	0.210
Observations	1,355	1,103	807	1,587	1,587	1,587
Number of households in the panel	532	517	450	550	550	550

Note: Dependent variables are natural logarithm of the expenditure on the purchased food.

a) Crop diversification is number of other crops cultivated.

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at the village level in parentheses.

Table 5: The effect of rice yield on rice commercialization and households' cash revenue (Household fixed effects)

VARIABLES	Commercialization (1/0)	The share of the rice sold (%)	Conditional share of the rice sold (%)	Cash revenue from rice sales (ln)	Conditional cash revenue from rice sales (ln)
	(1)	(2)	(3)	(4)	(5)
Lowland rice yield (ln)	0.405**	31.141***	47.253***	4.753***	2.981**
	(0.165)	(9.083)	(16.962)	(1.692)	(1.120)
Age of the household’s head	-0.000***	-0.011*	0.246*	-0.002***	0.002
	(0.000)	(0.007)	(0.140)	(0.001)	(0.014)
Number of children under 5 years old	-0.044	0.910	0.487	-0.446	-0.106
	(0.028)	(1.623)	(2.282)	(0.274)	(0.114)
Number of children between 6-15 years old	0.005	0.472	0.617	-0.101	-0.233**
	(0.026)	(1.260)	(2.567)	(0.259)	(0.099)
Number of adult members	-0.006	-0.341	1.465	-0.152	-0.017
	(0.022)	(1.343)	(1.873)	(0.240)	(0.082)
Value of farm asset per AE (ln)	0.014	0.608	1.815	0.281	0.261**
	(0.037)	(2.546)	(3.272)	(0.404)	(0.128)
Livestock holdings (TLU)	-0.007	-0.079	-0.175	-0.049	0.009
	(0.008)	(0.303)	(0.745)	(0.078)	(0.028)
Distance to main road*Rice yield (ln)	-0.054**	-3.331***	-4.633**	-0.575***	-0.277**
	(0.021)	(1.146)	(2.121)	(0.214)	(0.137)
Total size of land cultivated (ln)	0.016	-1.071	-0.374	0.124	0.023
	(0.039)	(1.802)	(2.997)	(0.376)	(0.085)
Total off-farm income per AE (ln)	-0.002	0.412	0.376	0.000	0.016
	(0.004)	(0.384)	(0.452)	(0.050)	(0.026)
Total plot size for lowland rice (ln)	0.037	-0.914	-5.892**	0.549*	0.297**
	(0.029)	(1.279)	(2.905)	(0.277)	(0.136)
Crop diversification [a]	0.017	1.088	1.986	0.160	0.098
	(0.019)	(1.132)	(2.469)	(0.191)	(0.073)
R-squared	0.214	0.216	0.356	0.220	0.401
Observations	1,587	1,587	865	1,587	865
The number of households in the panel	550	550	386	550	386

Note: [a)] Crop diversification is number of other crops cultivated.
The dependent variable in columns (3) and (5) are conditioned on commercialization =1.
*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at the village level in parentheses.

Appendix

Table A 1: The effect of rice yield on food consumption and rice purchases (Household fixed effects)

VARIABLES	Total food consumption per AE	Total rice consumption per AE	Consumption on purchased food per AE	Total rice purchase per AE	Rice purchase during lean season
	(1)	(2)	(3)	(4)	(5)
Lowland rice yield (Ln)	0.117***	0.123***	0.183***	-0.071	-0.678***
	(0.038)	(0.028)	(0.064)	(0.068)	(0.077)
Age of the household's head	0.000***	-0.000	-0.000	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of children under 5 years old	-0.030	-0.056*	-0.082	0.055	-0.042
	(0.030)	(0.031)	(0.052)	(0.056)	(0.116)
Number of children between 6-15 years old	-0.093***	-0.087***	-0.075**	0.009	0.029
	(0.023)	(0.024)	(0.035)	(0.046)	(0.081)
Number of adult members	-0.091***	-0.090***	-0.092***	-0.045	-0.065
	(0.015)	(0.020)	(0.022)	(0.039)	(0.047)
Value of farm asset per AE (ln)	0.095***	0.009	0.091**	0.113*	0.054
	(0.029)	(0.030)	(0.035)	(0.059)	(0.112)
Livestock holdings (TLU)	0.010*	0.006	0.004	-0.002	-0.005
	(0.006)	(0.005)	(0.007)	(0.009)	(0.017)
Total off-farm income per AE (ln)	0.009	0.003	0.013	0.007	-0.004
	(0.006)	(0.005)	(0.008)	(0.009)	(0.012)
Total size of land cultivated (ln)	0.047**	0.013	-0.034	-0.062***	-0.033
	(0.023)	(0.024)	(0.040)	(0.023)	(0.030)
Total plot size for lowland rice (ln)	-0.008	0.014	0.017	0.030	0.006
	(0.017)	(0.017)	(0.029)	(0.035)	(0.037)
Crop diversification [a)]	0.010	0.008	0.032	0.001	-0.006
	(0.014)	(0.017)	(0.020)	(0.033)	(0.041)
R-squared	0.291	0.247	0.317	0.310	0.361
Observations	1,587	1,587	1,587	1,587	1,587
Number of households in the panel	550	550	550	550	550

Note: The dependent variables are in in natural logarithm.

[a)] Crop diversification is number of other crops cultivated.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Robust standard errors clustered at the village level in parentheses.

Table A 2: The impact of household's rice yield on the rice availability, other sources of income (Household fixed effects)

VARIABLES	Off-farm income per AE	Income from other farm activities	Income from other crops
	(1)	(2)	(3)
Lowland rice yield (Ln)	-0.116	-0.151	-0.250
	(0.156)	(0.281)	(0.299)
Age of the household's head	-0.000	0.005***	0.004***
	(0.000)	(0.001)	(0.001)
Number of children under 5 years old	0.256	0.430	0.395
	(0.174)	(0.306)	(0.298)
Number of children between 6-15 years old	0.040	-0.080	0.061
	(0.110)	(0.289)	(0.182)
Number of adult members	0.191	0.049	-0.416*
	(0.156)	(0.179)	(0.215)
Value of farm asset per AE (ln)	0.333	0.360	-0.333
	(0.249)	(0.239)	(0.256)
Livestock holdings (TLU)	0.053	0.078	0.075*
	(0.039)	(0.056)	(0.040)
Total size of land cultivated (ln)	-0.122	0.228	0.201
	(0.164)	(0.405)	(0.252)
Total plot size for lowland rice (ln)	-0.072	0.042	0.175
	(0.112)	(0.242)	(0.225)
Crop diversification [a)]	-0.102	-0.211	0.757***
	(0.101)	(0.149)	(0.189)
R-squared	0.275	0.340	0.634
Observations	1,587	1,587	1,587

Note: The dependent variables are in in natural logarithm. Income from other farm activities include income from dry season cropping, other crops in the main season, upland production. Income from other crops include income from all other crops excluding rice.

[a)] Crop diversification is number of other crops cultivated.

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered a t the village level in parentheses. The number of households in the panel is 550

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Development of a Motivation Scale in Rural Madagascar[1]: The Challenges of Psychometrics in Impoverished Populations of Developing Countries

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This series of studies initially aimed to develop a scale to measure the motivation, based on the self-determination theory, of rural farmers in Madagascar toward an agricultural training program. Considering the low rate of literacy, the Likert scales were designed to be administered orally. However, there were several unforeseen challenges in psychological measurement that hindered the development of the scales. Despite several revisions, responses to the questions lacked sufficient variance for the first four studies. The scale produced in the fifth study attained marginally satisfactory variance and internal consistency. The final version of the scale asked questions in the second person and measured the respondents' frequency of thoughts, instead of their degree of agreement with a first-person statement as is common in many scales. The possible reasons behind the lack of variance when answering in degrees are discussed. The challenges involved in the quantitative psychological measurement of impoverished populations, as well as considerations for future research in poverty contexts are also discussed.

Keywords: psychometrics, development aid, poverty, reflective ability, self-determination theory

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Introduction

In the field of development aid, which seeks to alleviate poverty and the difficulties associated with it, there is a growing interest towards psychology. For example, a recent edition of the *World Development Report* (World Bank, 2015), one of the most influential publications in the field, is subtitled *Mind, Society, and Behavior* and illustrates in detail how the understanding of the psychological factors of aid beneficiaries is important in making aid more effective. While the report cites several empirical studies that utilize psychological scales that have been translated from English into the local languages, most of the studies are published in economics journals, and the validity of the measurements seem questionable in many cases. For example, Laajaj et al. (2019) examined data of the Big Five Index (e.g., McCrae & Costa, 1997), which is frequently used in development economics research, from 23 low- and middle- income countries, and found that the reliability was low and factor structure was incongruent in most cases. There have been very few rigorous psychological studies that have been conducted with impoverished populations (Davis & Williams, 2020; Sayanagi, 2017; Sayanagi & Aikawa, 2016), and consequently there are no psychological measures that have been developed in the contexts of development aid or poverty.

This paper reports on a series of five studies conducted with the objective of developing a psychometric scale to measure the motivation of farmers participating in an agricultural training program in Madagascar. This scale was a necessary step in conducting research with the aim of identifying factors that would make the training more effective. The process of developing the scale highlighted the challenges of psychological measurement with impoverished populations, many which were unforeseen as there were no studies that addressed the issue of psychometrics in such populations at the time this research was initiated.

Madagascar is one of the poorest countries in the world, with around 75% of the population estimated to live below the international poverty line of $1.90 in 2019 (World Bank, 2020). As Ximenes, Cidade, & Silva (2019) point out, research in poverty contexts can be challenging for several reasons, including: "[the] lack of psychometric scales adapted to the poor population; the low level of education of those being researched…; and the lack of validation of scales for the [local] language," among others. One of the challenges that the current study initially addressed was illiteracy. Madagascar has a relatively low literacy rate at 74.8% as of 2018 (UNESCO Institute of Statistics, n.d.), but the literacy among farmers targeted for this study was expected to be lower. Therefore, the measure was designed to be administered orally as a structured interview, a strategy that is commonly utilized in development economics studies as seen in part of the studies in Laajaj et al. (2019). However, there were further unforeseen challenges that hindered the development of the scale. These difficulties will be described in detail, and their implications on conducting psychological research on the extremely poor will be discussed.

Psychological literature on the poor

The majority of psychological studies on poverty have been conducted in the context of health and education, especially on the negative effects of poverty on developmental, cognitive, and educational outcomes and how to alleviate those negative effects. For example, an influential review by Yoshikawa, Aber, & Beardslee (2012) concludes that poverty has a negative effect upon children's and youths' mental, emotional, and behavioral health and suggests strategies to mediate those effects. A longitudinal study by Shelleby et al. (2014) indicates that children's family incomes at age 2–3 indirectly but significantly predicted conduct problems and emotional problems at age 7–8. While studies such as Heckman, Pinto, & Savelyev (2013) and Reynolds, Ou, Mondi, & Giovanelli (2019) demonstrate that early childhood interventions are effective in alleviating poverty in later stages of life, few studies focus on shorter-term alleviation of poverty, for example through the identification of factors that could facilitate an adult's escape from poverty. Moreover, most studies have been conducted on the relatively poor in industrialized countries. Very few studies have been conducted on people who live below the international poverty line.

It is important to stress that many do not consider poverty to be caused by psychological factors such as deficient cultural or personality traits. An influential review and treatise by the Nobel Prize-winning economist Amartya Sen asserts that the structural lack of opportunity is a major cause (Sen, 1999). However, as Sayanagi (2017) argues, impoverished people often tend to have behavioral patterns that hinder their escape from poverty. Haushofer & Fehr (2014) review the effects of poverty and posit that decision-making under impoverished conditions hinder the alleviation of poverty. In sum, poverty may not be caused by psychological factors, but psychological states that occur under poverty work against the escape from poverty. Identifying these behavioral and psychological states through psychological research and defining strategies to work through them could help to alleviate poverty.

Many programs in development aid aim to change the behavior of the beneficiaries so that they will adopt skills or techniques that will enable them to become more profitable: psychological theories on motivation would be suited for this purpose, and as Sayanagi (2017) has reviewed, self-determination theory (SDT: Ryan & Deci, 2017) and the theory of planned behavior (TPB: Ajzen, 1991), both theories on motivation, have been employed to some extent. However, there are still very few psychological studies, and research paradigms are yet to be established. There have been no psychological measures that have been developed in the context of extreme poverty, and as aforementioned, validity is often questionable when simply translating existing scales (Laajaj et al., 2019).

Self-determination theory

As discussed above, motivational theories would be a good fit for application in the field of development aid. SDT is a broad theory that encompasses not only motivation, but also basic psychological needs and well-being. The theory is known for highlighting the undermining effect (e.g., Deci, 1971; Lepper, Greene, & Nisbett, 1973), in which giving expected rewards diminishes intrinsic motivation and consequently decreases behavior after the rewards are withdrawn. A comprehensive meta-analysis by Deci, Koestner, and Ryan (1999) demonstrates that the undermining effect is robustly observed in industrialized nations.

While there are no academic reports on the undermining effect in extreme poverty, the authors have encountered several experts who agree that it is a problem in the field of development aid. In many aid projects, incentives are used to encourage people to train in skills that would help them earn more money. However, in many cases once the project ends and incentives are discontinued, the participants cease doing what they have been trained. SDT could provide guidelines to prevent the undermining effect from occurring, for example by structuring programs so that beneficiaries are not solely motivated by incentives. Furthermore, Sayanagi (2017) proposes a theoretical framework based upon SDT on facilitating sustainable behavioral change.

There have been some SDT studies that have been conducted to samples that include impoverished people in Africa (e.g., Czaicki, Dow, Njau, & McCoy, 2018; van Egmond, Berges, Omarshah, & Benton, 2017). However, the measures used in these studies were translations of existing scales, and as will be seen later, there seem to be issues in measurement.

Organismic integration theory (OIT), a subtheory of SDT, outlines a taxonomy of motivation (Ryan & Deci, 2017). There are two general types of motivation: intrinsic motivation, in which behavior is driven by internal states such as curiosity, interest, and enjoyment; and extrinsic motivation, in which behavior is enacted to meet external demands such as rewards or social acceptance. Extrinsic motivation has several categories that can be placed on a continuum that spans from controlled to autonomous. The most controlled type of motivation is *external regulation*, in which behavior is typically enacted to attain rewards or avoid punishment. Next on the continuum, *introjected regulation* is a relatively controlled type of motivation. Behavior is enacted to avoid feelings of guilt or shame, or to attain ego enhancement. A relatively autonomous type of motivation is *identified regulation*. Behavior is enacted by a conscious endorsement of the value underlying the action. Sayanagi & Aikawa (2016) have proposed a further subdivision of identified regulation, self-oriented and other-oriented, speculating that outcomes would differ between the two. The most autonomous form of extrinsic motivation is *integrated regulation*, which occurs when the value of the behavior has been fully assimilated with the self. The current study endeavored to develop subscales for all of the above regulation types except for integrated because it rarely occurred in the Kenyan farmers surveyed by Sayanagi & Aikawa.

The studies in this paper endeavored to develop a psychological scale for motivation based on SDT. The issues that arose during the research and their implications are discussed.

The current research project

This series of studies was conducted as part of a larger research project which goal is to develop techniques that would improve rice production in Madagascar, and then to extend[2] those techniques to Sub-Saharan rice-producing countries. The authors are part of a team that is responsible for identifying psychosocial factors that lead to more effective extension of such techniques. The scale reported in this paper is one of the necessary steps in conducting this research and could be used in other development aid studies as well.

Overview of data collection

All data were collected on sites of a farmer training program that extends efficient rice-grow-

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[2] To "extend" agricultural techniques, or "agricultural extension," is to introduce and educate new techniques to farmers. The current research project is developing new rice breeding materials that produce higher yields in the local soil, which is infertile, and also techniques for more effective fertilizer usage.

Table 1 Characteristics of survey respondents from each study

	n (M/F)	Cellphone owners	Age Average (SD) range	Education Ave years (SD) range	Cash deficit Ave mo. (SD) range	Food deficit Ave mo. (SD) range
Study 1	24 (4/20)	6 (25%)	46.46 (12.29) 25–77	6.42 (3.01) 0–13	3.88 (3.17) 1–12	3.38 (3.38) 0–11
Study 2	54 (22/32)	27 (50%)	39.54 (11.76) 21–63	8.15 (3.69) 2–15	3.69 (2.27) 0–12	3.41 (2.67) 0–12
Study 3	31 (12/19)	7 (23%)	40.73 (13.55) 20–72	6.60 (2.39) 4–13	4.53 (2.97) 0–12	3.40 (2.16) 0–8
Study 4	105 (66/39)	30 (29%)	41.90 (14.73) 18–79	7.38 (3.51) 0–16	3.15 (2.29) 0–12	2.71 (2.24) 0–12
Study 5	24 (18/6)	12 (50%)	51.92 (11.20) 23–69	7.20 (2.78) 3–13	2.92 (1.53) 0–7	2.08 (1.26) 0–5

Notes. Cellphone ownership was verified by asking participants' phone numbers.
Number of months with cash and food deficits was measured by asking whether the participants had experienced any deficit for each of the past 12 months. Thus, this measure does not take into account the severity of the deficit: it could be just 1 day in the particular month, but it also could be the whole month; it could be a slight deficit, but also could be an extreme deficit.

ing techniques in several regions across Madagascar. The program, Projet d'Amélioration de la Productivité Rizicole (PAPRIZ) is jointly operated by the Madagascar Ministry of Agriculture, Livestock, and Fisheries (MAEP) and Japan International Cooperation Agency (JICA).[3] PAPRIZ was selected because its aims are similar to those of the current research project, and it can be regarded as a model case for extending rice-growing techniques to farmers in Madagascar.

Participants for the current studies were recruited as follows. First, candidate sites for the surveys were selected by the PAPRIZ headquarters. There were unique objectives for each survey, which were considered in selecting the sites. Also, the locations of the sites were taken into account so that the survey itineraries would be manageable. Farmers were recruited through local agents such as local government employees who oversaw the training and local farmers who had broad social networks. No cash or material stipends were distributed to the interviewees.

Characteristics of survey participants from each study are shown in Table 1. In addition to gender and age, statistics on cellphone ownership, education, and numbers of months within the past year with cash and food deficits are reported to illustrate the degree of poverty. According to the World Bank (n.d.), mobile cellular subscription rates in Madagascar were 40.57% in 2018, so apart from Study 2 and 5, the participants of this study had average or lower ownership rates within the country. Compulsory education is 8 years, but the average years of education exceeds 8 years in only Study 2. Most participants reported going short of cash and/or food within the past year. While the cash and food deficit measure does not necessary reflect the severity of the deficit (see footnote of

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[3] The current research project was partially funded by JICA, but the research was conducted independently: i.e., there was no mandate or obligation to conduct a study on PAPRIZ.

Table 1), taken with the aforementioned indices, it can be reasonably assumed that a part of the participants are indeed extremely poor.

Apart from the scale reported in this paper, the surveys included questions on interviewees' farming, financial situation, and family members, among others. All interviews were conducted one farmer at a time. There were some sections of the survey in which one of the Japanese co-authors interviewed in English with one of the Malagasy co-authors interpreting, but most parts of the survey, including the scale reported in this paper, were conducted in Malagasy by one of the Malagasy co-authors.[4] While the time required for the scale reported in this paper generally was within 10 minutes per interviewee, times ranged between 30 minutes to 150 minutes for the complete survey package. The variance in interview times was mainly because the length of the survey section on farming varied and was especially shortened from Study 4.

Ethical considerations

All interviews were conducted in line with the Ethical Principles of Psychologists of the Japanese Psychological Association (n.d.). Informed consent was obtained, either in written form or by an audio recording. Special care was taken so that no interviewees were coerced into participating. Mindful of the possibility that the local agent who recruited the farmers may have pressured some participants, interviewees were assured that they could discontinue the interview without consequence if they did not wish to talk. Also, as Narayan, Patel, Schaff, Rademacher, and Koch-Schulte (2000) state, in many cases participants hold the false hope that foreign researchers will give them a stipend for the day or provide material aid later (pp. 24–25). Interviewees were informed that there would be no such distributions, and that they were free to leave if they were not satisfied with the arrangement.

Study 1

Method

Development of items. The items were modeled after the self-regulation questionnaire (SRQ) paradigm widely used in SDT studies (the original SRQ was developed by Ryan & Connell, 1989). SRQ items typically state a reason for engaging in a target activity and ask the degree to which respondents agree. Items in this study were derived from Sayanagi & Aikawa (2016) where farmers in a comparable training project in Kenya gave reasons for their participation. The derived items were reviewed by the Malagasy co-authors to affirm their relevance in the context of Malagasy culture and farming.

Items were devised for internal, other-oriented identified, self-oriented identified, introjected, and external regulation. Two items for each regulation style were developed. The 10 items are shown in Table 2. Interviewees would answer on a 4-point Likert-like scale from "Do not agree at all" to "Strongly agree." The items and answers were translated into Malagasy by the co-authors. The translation was verified through back-translation

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[4] Some may wonder if conducting the questionnaire in groups, with the researcher reading the questions and respondents answering by marking circles on paper would be better, as it would be more efficient and be less prone to social desirability biases. However, the authors, who include researchers with extensive experience surveying Malagasy farmers, believe that such group sessions would not be viable because many of the farmers would not be able to easily understand the syntax of the questions. Indeed, questions often needed to be repeated or clarified during the interviews.

Table 2 Items and descriptive statistics of motivation scale from Study 1 (n=24)

Item	Mean	SD
Internal regulation		
1. I participate because I enjoy the activities of PAPRIZ.	3.96	0.20
6. I participate because I feel PAPRIZ activities are interesting.	4.00	0.00
Other-oriented identified regulation		
2. I participate because I feel PAPRIZ activities will help improve our community.	4.00	0.00
7. I participate because I feel PAPRIZ will help my family.	4.00	0.00
Self-oriented identified regulation		
3. I participate because I feel that PAPRIZ will improve my skills as a farmer.	4.00	0.00
8. I participate because I feel that I can learn many things from PAPRIZ activities.	4.00	0.00
Introjected regulation		
4. I participate because I don't want to miss chances that other people will have.	3.92	0.28
9. I participate because I think PAPRIZ activities will help me get ahead of others.	4.00	0.00
External regulation		
5. I participate because I want to become rich.	4.00	0.00
10. I continue to participate because there are people that tell me I must.	1.00	0.00

by another Malagasy researcher who is not a co-author. In the interviews, the items were administered in the order that they are numbered in Table 2.

Participants. Twenty-four farmers participated in this study (see Table 1). The number of participants was small for this study because time was required to train the interviewers, especially on the extensive section on farming which is not reported in this paper, and procedures for contacting farmers were not established so thus it took more time to gain access to them.

Survey dates and location. This survey was conducted in the Vakinankaratra region of Madagascar in late August to early September of 2017.

Results and brief discussion

Descriptive statistics for all 10 items are shown in Table 2. Variance was zero for 8 of the items, and very small for the 2 other items. All 5 subscales were psychometrically unsuitable, as they cannot detect individual differences. One possible reason for the lack of variance is that the statements were too weak. However, the items might have been difficult to understand, as interviewers reported instances in which items had to be repeated or explained.

Study 2

Method

Revision of items. Considering the possibility that the statements were too weak, the expressions of the items were made more extreme. For example, the clause "very much" was added to Item 1, "I participate because I enjoy the activities of PAPRIZ" (see Supplementary Table 1 for all items). Since the changes to the items were minor, there was no back-translation for this study. In the interviews, the items were administered in the order that they are numbered in Supplementary Table 1.

Participants. Fifty-four farmers participated in this study (see Table 1). This was a relatively affluent sample, with cellphone ownership rates higher than the national average, and average education exceeding the mandatory schooling of eight years. However, the average number of months in which participants experienced food and cash deficits during the past year both exceeded 3 months, highlighting the level of poverty among rural farmers in Madagascar.

Survey dates and location. This survey was conducted in the Vakinankaratra region in February 2018.

Results and brief discussion

Descriptive statistics are shown in Supplementary Material Table 1. Distributions were still very skewed, and all 5 subscales were unsuitable. The interviewers observed that the respondents seemed to be confused because the items were first-person statements but were being read to them by a second person. Thus, the authors concluded that the reason for lack of variance was not that the statements were too weak, but because the respondents were not able to grasp the perspective of the statements. Additionally, the authors speculated that the respondents were having difficulty answering in degrees on the four-point Likert-like scale.

Study 3

Method

Revision of items and questioning method. Statements were changed from first person to second person (see Supplementary Material Table 2). Changes were minor, so there was no back-translation. Additionally, the method of questioning was altered. Items were presented as yes-no questions, and then for example if the respondent answered "yes," they would be prompted, "Is that a strong yes or a weak yes?" "Strong no" was scored as 1 point, "weak no" 2 points, "weak yes" 3 points, and "strong yes" 4 points. In the interviews, the items were administered in the order that they are numbered in Supplementary Material Table 2.

Participants. Thirty-one farmers participated in this study (see Table 1). Cellphone ownership was lowest and average number of months with cash deficit was highest for this sample. This is thought to be the effect of the widespread flooding in the area during the past year due to cyclones.

Survey dates and location. This survey was also conducted in the Vakinankaratra region in late August to early September of 2018.

Results and brief discussion

Descriptive statistics for the 10 items are displayed in Supplementary Material Table 2. There was no apparent improvement in terms of increasing the variance of the responses, and none of the five subscales were suitable.

However, the interviewers reported that the participants seemed to understand better because there were fewer instances in which they needed to repeat the questions. Thus, one possibility that was considered as the cause for the lack of variance was that the reasons that farmers were participating in PAPRIZ were somewhat obvious, and the items would not be answered otherwise. The project taught participants to use seeds of improved varieties of rice and trained more effective planting and weeding techniques. Many farmers reported that the yield of their crops had increased by two to three times, while the amount of seeds required decreased. In other words, participation in PAPRIZ would clearly help their families (Item 7), improve their farming skills (Item 3), and help them get ahead of other farmers (Item 9). However, this line of thinking was deemed inconclusive as other items were not so obvious: PAPRIZ training and activities are not inherently fun or enjoyable (Item 1), and because the fields of the interviewees in this study were relatively small, it would be unrealistic to think that one would get rich from just the farming techniques (Item 5).

Study 4

Method

Revision of items and questioning method. Before revising the items, an alternative method of questioning was considered, namely, paired comparisons (Bradley & Terry, 1952). However, this method was not chosen because the scores obtained would be nonparametric and would greatly limit future research designs. Additionally, it would be difficult to evaluate the reliability and validity of the scale. Thus, the authors elected to continue development as a Likert-like scale.

Considering the possibility that the items used in the previous studies were over-sensitive to PAPRIZ participants, new items were added (see Supplementary Material Table 3). To address the issue of the lack of variance, a new method of questioning was introduced after approximately a quarter this study had been completed.

New items were based on farmer answers in Sayanagi & Aikawa (2016) and also the Treatment Self-Regulation Questionnaire (TSRQ: Williams, Grow, Freedman, Ryan, and Deci, 1996). The TSRQ was chosen because it included items regarding choice and life goals that are not included in other versions of the SRQ. While there were concerns that some of the statements were too abstract and difficult for the farmers to answer, the authors decided to use the items and observe respondents' reactions to assess their appropriateness. New items were not added for internal regulation and other-oriented identified regulation because the authors believed that the existing items already covered the breadth of the concepts. The original items were retained to examine how the interviewees would respond to the new questioning method. All new items were translated from English to Malagasy by the co-authors and verified through back-translation by a Malagasy researcher who is not a co-author.

The new method was initially a "yes, no, or neutral" question, but because no farmers answered "neutral" after a number of trials, a modification was added. The question would be presented as a yes-no question, and when the respondent gave their answer, the interviewer would prompt "Do you really think so *all of the time*?" If the answer to the prompt was no, or if there was hesitation of approximately one second or more in answering yes, the answer would be treated as "neutral." Approximately three quarters of the participants of this study were questioned with the modified method. The scoring scheme for this method was, a "no" would be scored as 1 point, "neutral" 2 points, and "yes" 3 points. In the interviews, the items were administered in the order that they are numbered in Supplementary Material Table 3.

Participants. A total of 105 farmers were interviewed for this study (Table 1). The number of participants increased because the larger survey in which this study was embedded substantially shortened its interview section on agriculture, allowing the survey team to interview more farmers. Also, the survey itinerary was longest of the five studies.

Survey dates and locations. Interviews were conducted in the Itasy and Analamanga regions of Madagascar in early March 2019.

Results and brief discussion

Descriptive statistics of all of the items are shown in Supplementary Material Table 3. There was no apparent difference between the participants who answered as a yes-neutral-no question and those with the new "do you think so all the time?" prompt, so the results are not reported separately. The distributions were very skewed, and the 5 subscales were still not fit for usage.

In regard to the method of questioning, the authors observed that while there was no increase in variance, it seemed easier for the interviewees to respond in terms of frequency (i.e., "do you think so all the time") than in degree as in the first two studies (i.e., "how much do you agree with this statement").

Study 5

Method

Revision of items and questioning method. Items were revised so that they would ask how frequently they thought like each respective statement. This is a strategy that is sometimes used in interview scales to younger children (e.g., Stocker & McHale, 1992). Respondents were asked "How often do you think this way?" to each respective item. Interviewees answered to a 4-point Likert-like scale: "never" was scored as 1 point, "only sometimes" 2 points, "most of the time" 3 points, and "all of the time" 4 points. In the interviews, the items were administered in the order that they are numbered in Table 3.

All of the items were reconsidered. Past items that were deemed as irrelevant or too abstract were omitted, but others that had a reasonable chance of being understood were retained and rephrased. Two new items (items 14 and 15) were proposed based upon farmer interviews that were conducted in a different part of this survey. The new items are presented in Table 3. All of the items were re-translated from English into Malagasy by the co-authors and verified through

Table 3 Items and descriptive statistics of motivation scale from Study 5 ($n=24$)

Item	Mean	SD
Internal PLOC ($\alpha=.64$)		
1. How often do you participate because you want to enjoy the activities of [the project]?	3.71	0.55
6. How often do you participate because [the project's] activities are interesting?	3.42	0.78
Other-oriented identified PLOC ($\alpha=.66$)		
2. How often do you participate because you want to help improve your community?	3.04	0.81
7. How often do you participate because you want to help your family?	3.17	0.76
15. How often do you participate because you want to help others?	3.08	0.83
Self-oriented identified PLOC ($\alpha=.55$: .63 for 3 & 8 only)		
3. How often do you participate because you want to you improve your skills as a farmer?	3.50	0.59
8. How often do you participate because you feel that you can learn from [the project's] activities?	3.00	0.78
13. How often do you participate in [the project's activities] because it's the best thing for you to do?	2.75	1.33
Introjected PLOC ($\alpha=.42$)		
4. How often do you feel that if you don't participate, you would miss chances that other people might have?	2.50	1.29
9. How often do you participate because [the project's] activities will help you get ahead of others?	3.17	0.82
12. How often do you participate in [the project's] activities because if you didn't, people would think you are not a good farmer?	1.67	0.92
External PLOC ($\alpha=.42$: .60 for 5 & 14 only)		
5. How often do you participate in [the project] because you want the project to make you rich?	2.71	1.20
10. How often do you participate in [the project's] activities because there are people that tell you that you must?	1.04	0.20
11. How often do you participate in [the project's] activities because other people would be unhappy if you didn't participate?	1.17	0.38
14. How often do you participate because you want to receive inputs from [the project]?	2.46	0.93

back-translation by a Malagasy researcher who is not a co-author.

Participants. Twenty-four farmers were interviewed in this study (Table 1). The number was small for this study because: 1) due to the objectives of the larger survey, sites that were struggling in collecting participants for PAPRIZ training were selected, thus there were fewer farmers to begin with; 2) the survey itinerary was short compared with past surveys; and 3) due to unexpected circumstances, recruiting of interviewees did not go as planned.

Survey dates and location. Interviews were conducted in the Vakinankaratra region in late August to early September 2019.

Results and brief discussion

Descriptive statistics are shown in Table 3. While the distributions of some items are still skewed, the skewedness was acceptable for most items, so Cronbach's alpha was computed for each of the 5 subscales. After deleting some items to improve internal consistency, 4 of the subscales reached tolerable levels, exceeding .60. Only the introjected regulation subscale was not satisfactory. Alpha coefficients are also reported in Table 3. Ultimately, the remaining items were all based upon farmers' interview statements.

General Discussion

A marginally satisfactory measure, which shall tentatively be named the SRQ for agricultural training in developing countries, has been put forward. Future studies should aim to improve the scale, especially the introjected regulation subscale that did not reach tolerable internal consistency. All final items are based on farmer responses and can be considered to have some degree of content validity. However, other aspects of validity are yet to be confirmed. Especially, whether this method of asking the frequency of thinking of certain types of motivation validly reflects the strength of the motivation is still unclear and should be investigated in future studies. The scale could be tested with different training schemes by changing the project name in the items.

Apart from scale development, this series of studies sheds light on the challenges of conducting quantitative psychological studies with impoverished populations. These challenges are not just relevant to SDT studies such as this, but any studies that endeavor to quantitatively measure psychological constructs in such contexts.

First, the lack of variance in participants' responses to Likert-like scales indicate that traditional questioning methods may not be appropriate. Other studies conducted in the context of poor populations in Africa using translations of existing scales have also reported skewed distributions (Czaicki et al., 2018; van Egmond et al., 2017). In this study, what ultimately worked was a method that asked in second person instead of first person and the frequency of occurrence instead of degree of agreement. One possible reason that there was no variance in the responses for Studies 1–4 is the lack of *reflective ability* of the participants. In order to respond to an item in a psychometric scale adequately, one must be able to not only understand the superficial syntax, but also to reflect upon the statement's relevance to themselves. This would involve metacognition, a relatively high-order cognitive task. Additionally, thinking in degrees or in relative terms is considered a more abstract and complex cognitive task (Thomas, 1980, p. 461). It may be difficult for people who have had limited opportunities for education to adequately reflect upon their degree of agreement. It may also be that living in poverty was a restraint on the respondents' cognitive capacities (see Dean, Schilibach, and Schofield, 2017; Haushofer & Fehr, 2014 for reviews).

Validation of the new scale and method will be challenging: there are no existing scales that can be validated against. Simply translating questionnaire measures that are used in industrialized nations may not result in accurate measurement, as previously discussed regarding the Big Five index (Laajaj et al., 2019) and SDT scales (Czaicki et al., 2018; van Egmond et al., 2017).

To address these issues it would be important that more research in the context of extreme poverty be conducted, and in doing so the establishment of ethical guidelines for conducting research in such contexts needs to be considered. While there are still few psychologists that conduct such research, interest is growing. For example, a former president of the American Psychological Association has called out for more psychologists to become involved (Davis & Williams, 2020). The JPA's ethical guidelines (n.d.) to which this study adhered has no explicit statements on researching impoverished subjects. While the authors of this study considered the guidelines to be satisfactory and that sufficient informed consent was obtained in these studies, there were some potential issues worth noting. First, as two of the authors/interviewers are foreigners, some interviewees may have held the false hope that they would be given something at the end of the interview. Indeed, a number of the interviewees asked for confirmation afterwards if there would really be no stipend, despite having been explicitly informed otherwise beforehand. It should also be noted that farmers who held such false hopes might have shunned opportunities to earn cash through manual labor to participate in the interview, resulting in a financial loss to the already impoverished farmer. Second, as the PAPRIZ is a three-year training program, some farmers may have had the false hope that they were candidates to receive additional training after the scheduled end of the program. Third, while the authors made clear that they were independent from PAPRIZ and JICA and thus all interviews would be confidential, some interviewees may have suspected that their answers would be shared with the program staff, which is probable considering the tightly knitted communities of the farmers. These are not just ethical but also methodological issues, as they also may have biased the responses towards what the farmers perceived to be desirable to the interviewers.

Addressing these challenges is important for the field of psychology, as most contemporary theories claim to be universal despite the absence of evidence from impoverished populations in developing countries. Additionally, the advance of psychological research in these contexts could lead to the understanding of the psychological mechanisms behind extreme poverty and the identification of psychological factors that would alleviate poverty. While accessing impoverished populations in developing countries would also be a challenge, it would be possible if done in collaboration with aid agencies that already have a presence in the field. As aforementioned, there is demand for psychological perspectives in the field of development aid. Japan is one of the world leaders in official development assistance (Organization for Economic Co-operation and Development, 2020), and there are also numerous

Japanese non-government organizations that are active, so there are potential opportunities for Japanese researchers to get involved. Many other industrialized countries also have strong presences in development aid, and psychologists from such countries also could seek chances to enter the field. This would be an important contribution to not just the field of development aid but also society in general, and it is hoped that this paper will interest readers to join this worthy cause.

*Supplementary Material is available on J-Stage.

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Role of "mediator-cum-actor" in rural advisory service: Case from Madagascar rice technical assistance project

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Abstract

Farmer trainers who received formal technical training by the development assistant projects are expected to act as "mediator-cum-actors" working with local lay farmers. Then, involving third parties such as governments and NGOs, an Agricultural Knowledge Information/Innovation System is to be constructed, resulting in autonomous sustainable development after the project is completed.

Keywords: Mediator-cum-actors, Agricultural Knowledge Information/Innovation System, Madagascar, Technology transfer, Rice farming

Introduction

Classic agricultural extension (advisory service) theory has been based on the assumption of the dissemination of technologies developed as public goods (i.e., neither excludable nor rivalrous, and available free to all) by public institutions to an unspecified number of homogeneous farmers. Therefore, the technologies that have been advocated for use in extension programs are standardized and systematized so that they can be used by all farmers within the recommendation domain and can be expected to produce the same results for all those who follow the relevant manual.

However, even in developing regions, the socio-economic structure of farming and rural communities is diverse and the effectiveness of “packaged” technologies remains limited. Even when farmers are growing the same crop in the same village, the significance of that crop in their lives will differ, as will their relevant business goals. Individual farmers have always attempted to optimize the various individual technologies (both traditional and modern) available to them, to fit their individual situations and specific objectives.

Even if a technology that has been developed is used in a different way than intended by an extension project, if its use is beneficial to the farmers concerned, it may deserve to be evaluated as an (unintended) positive impact of that project. Conversely, even when a technology is disseminated as its developers intended, it may become inappropriate due to changes in the production environment or socioeconomic conditions. This is because, even where technological rationality exists, there is no guarantee of business or social rationality.

In other words, the final goal of extension should not be limited to the transfer of knowledge and technology, but the development of the ability to understand, and apply, the scientific principles behind the technology.1)

Transition from a technology transfer model to an innovation system 2)

1. The emergence of AKIS

In the EU countries, the role of agriculture in the environment and quality of life began to be questioned in the late 1980s, and Agricultural Knowledge Information/Innovation Systems (AKIS) were proposed as an alternative to existing unilinear technology transfer. An AKIS is defined as a group of organizations and individuals engaged in decision-making, problem-solving, and technological innovation through the creation, transformation, communication, storage, recovery, integration, dissemination, and use of knowledge and information, comprising all those involved in agriculture. This concept is extremely close to the "ba (place)" proposed by Nonaka and Konno (1999, p.161), that is, relationality based on a physical, virtual, or mental place that serves as a platform for knowledge creation and utilization, and for knowledge asset retention. Knowledge, information, and technology do not exist in isolation, but are situation-dependent. To utilize these intellectual assets, rather than merely accumulate and compile them, organizations and individuals who share the same objectives, thoughts, and spaces must collaborate in a relational manner. This thought process implies that AKIS are not unusual in agricultural and rural communities in Japan, or in many developing countries, and that "village meetings" have successfully fulfilled the same function as AKIS. Hence, what is the significance of mentioning AKIS? The underlying aim of agriculture is to realize integrated value (economic, ecological and environmental, and livelihood value); the scope of agriculture cannot be confined to a village, and relevant problematic issues transcend the scope of what can be handled at a “village meeting.” Similarly, the comprehensive and flexible approach of AKIS is necessary for extension field activities to realize comprehensive value.

The actors that make up AKIS are diverse, and they do not need to all have the same interests or be organized with a specific agenda. They can be composed of anything from a small group of people with shared aspirations to an international network of common interest. The easiest way to visualize this is through local agriculture. This is a group, at the unit of local administration or small settlement, with a common vision of agricultural and rural community. If we broaden the scope of interest to include the environment, food, and international cooperation, AKIS can also include traders and processors, consumers, environment-related citizen groups, fair trade companies, and grassroots-level private-sector activists.

2. Multidimensional model of extension

In recent years, one of the most important changes in the environment surrounding extension (agricultural advisory services) has been the trend toward privatization. The privatization of extension services has been progressing since the 1980s against the background of i) fiscal austerity, and diversification and the sophistication of technological needs in developed countries and ii) structural adjustment policies, the export-oriented development of specialty crops, and the formation of business-driven supply chains in developing countries.

The advantages of privatization were seen as allowing extension services to be provided timely and to be flexibly adapted to individual needs, custom made quality, and avoiding the arbitrary selection of beneficiaries and service contents and policy orientation. Conversely, disadvantages include the fact that farmers who cannot pay for the services cannot receive them, that services are biased toward certain profitable commodity crops, that regions with poor market accessibility are not targeted, and consequently, that economic disparities among farmers and regions are widened.

In other words, while public extension services can target the poor and socially vulnerable, they can also be a vehicle for politics of interest inducement. Conversely, private extension services can respond to attentive needs of customers but do not provide services that are not profitable. A strategy intended to utilize the advantages and avoid the disadvantages of both public and private extension services involves the use of NGOs and farmer organizations that have a quasi-public character. The roles of these organizations include: 1) to identify and delineate farmers' problems, needs, and solutions; 2) to monitor and evaluate services provided by public and private organizations; 3) to partially finance services provided by public and private organizations; 4) to provide services; and 5) to connect public and private organizations and farmers.

The role of the "mediator-cum-actor" in AKIS3)

1. The importance of the brokering role

As mentioned in the previous section, the increased privatization of extension services and higher diversity among the stakeholders surrounding the farmers has heightened expectations for AKIS as a new extension model. However, for these systems to function effectively, the role of those who can link stakeholders with different backgrounds, needs, and objectives becomes particularly important.

In the conventional technology transfer model, rural communities are composed of relatively homogeneous farm households, and active interaction between farmers and non-farm households is not assumed. In recent years, however, rural communities have become increasingly diversified. Meanwhile, connections that transcend spatial constraints have been expanding through the Internet and other means. This phenomenon is similar in developing countries. Even in villages without electricity, mobile phones are spreading among lay farmers using solar panels as a power source, and some leading farmers have even adopted the use of computers. There are also increasing opportunities to engage with travelers interested in supporting developing countries and fair-trade businesses (Fig. 1).

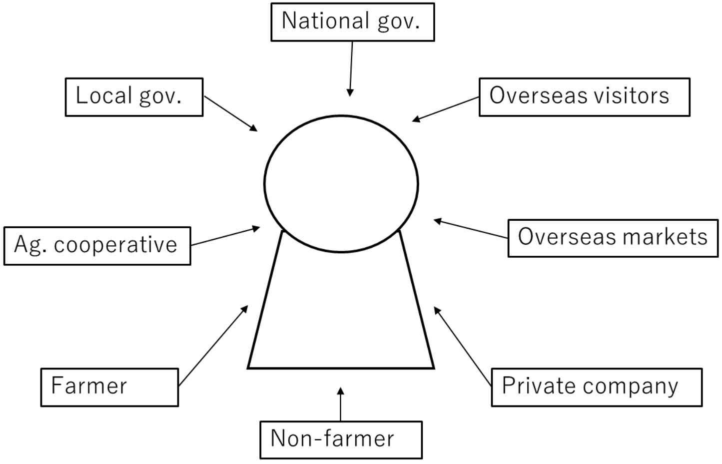

Fig. 1. Stakeholders around the farmers

In short, there are expectations that, as a multidimensional development support initiative, AKIS can formulate and facilitate a series of processes, from the identification of needs (regarding who requires what), to the search for resources (regarding where they are and who has what), and the building of networks (regarding the business opportunities and social contributions generated when two parties are connected).

2. Extension personnel as “mediators-cum-actors”

The key "brokerage role" in AKIS can be better understood by drawing on a method of family therapy in clinical psychology known as “reflecting processes,” developed by Norwegian psychiatrist Tom Andersen and his colleagues. This method is characterized by its interactive (reflective) nature, in which, in a clinical context, the interviewed client observes the interviewing therapist and other members of the therapy team talking about themselves from a third-party perspective. In other words, the observer is observed.

First, supporters, who are mediators-cum-actors (i.e., they understand the situation from the farmers' perspective while having no direct stake), join in the discussion of local issues among the farmers involved (who are the actors). The supporters participate mainly to learn from the actors, but also share their own knowledge and outsider views when requested. The role expected of the supporters is to make the actors aware (of issues and potentials of which they were unaware). A third party, such as a researcher who has no vested interest in the persons concerned, observes this exchange from a slight distance and organizes the problematic issues from a more objective standpoint. Next, a team of experts consisting of mediators-cum-actors and a third party (with the addition of experts of different profession/discipline as necessary) analyzes the problematic issues from an expert standpoint. The actors view this process from a distance. Although there are naturally conflicts of interest and disagreements among the actors, viewing discussion of their own issues from various perspectives from the position of a third-party allows them to relativize the issues and consider from a different perspective. This further encourages discussion among the actors themselves, and the needs and potentials that were previously only vaguely perceived are highlighted and become evident, leading to the sharing of problematic issues. This process also maintains a healthy level of tension for the expert team, as they are being watched by the actors. At the end of the process, all members collaborate to consider solutions. It can be said that at this stage, for the first time, a “place” has been created for collaboration toward the solution to common problems while respecting each other's differences. All that remains is to optimally combine the skills, wisdom, and networks of each party, including those who are not actors (Fig. 2).

The specific problems of agricultural and rural communities cannot be summed up by single issues such as markets, employment, the environment, or aging populations. They are a complex intertwining of multiple issues and possibilities within a unique cultural and historical context. No two sets of problems are the same, just as family problems differ from one family to another. Additionally, although the actors must be proactive, the problems of agricultural and rural communities cannot be solved by the actors alone. This is reminiscent of family problems, and the reflecting processes approach, which was developed as a family therapy, is expected to also be effective in solving problems in agricultural and rural communities.

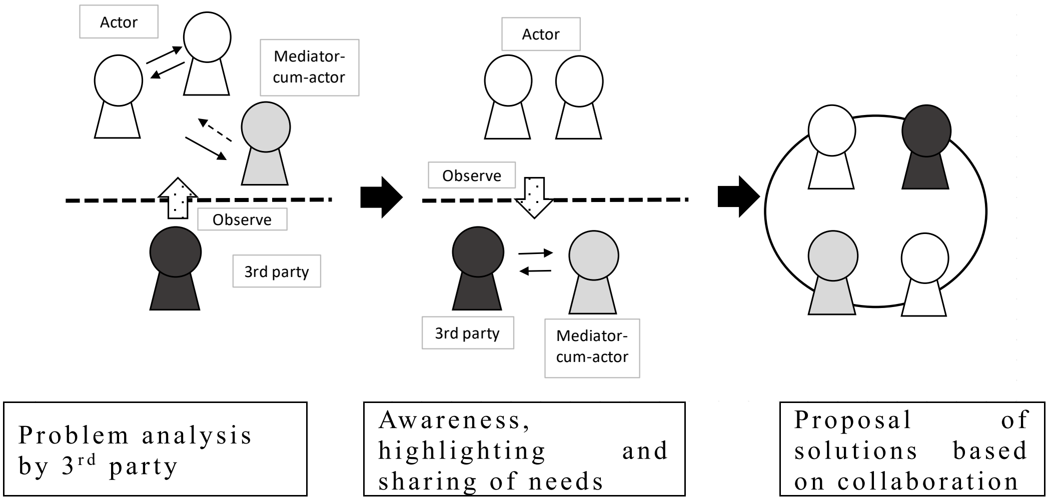

Fig. 2. The role of mediators-cum-actors in agricultural support

Potential of "farmer trainers" as mediators-cum-actors

The author has investigated extension activities in Madagascar conducted as part of the SATREPS project “Breakthrough in Nutrient Use Efficiency for Rice by Genetic Improvement and Fertility Sensing Techniques in Africa (2017-2022).” The research team carried out a series of interview surveys at the sites of a JICA technical cooperation project, “Project for Rice Productivity Improvement and Management of Watershed and Irrigated Area (PAPRIZ Phase 2).”

In Madagascar, there are no full-time extension officers, and staff from the regional offices of the Ministry of Agriculture provide technical guidance as part of their administrative duties. However, budget constraints make sufficient activity on their part unlikely. The PAPRIZ 2 Project, therefore, trains farmer trainers to promote technology dissemination. For an initial two years, farmer trainers who have received instruction in rice cultivation technology delivered as part of the Project are given training materials (seeds. fertilizer, and other teaching materials), which they use to train neighbor farmers under the supervision of the Project. In the third and subsequent years, although the Project does not intervene in the training, the farmer trainers may provide training at the request of local people in some cases. Farmers who have received training from farmer trainers are expected to pass the technology on to their neighbors, thus creating the prospect of sustainable and autonomous technology dissemination even after the Project is completed.

This article hypothetically examines how information is communicated among farmers, based on field interviews conducted in August 2018.

1. Method of selection of farmer trainers

The PAPRIZ 2 Project aims to disseminate irrigated rice cultivation technologies, therefore, its recommendation domain is based on existing irrigation zones (périmètre d'irrigation), as is the selection of farmer trainers. The irrigation zone in which the study site is located covers three villages (fokontany). The zone has a water users' association with 128, 52, and 40 members in the three villages, totaling 220 members. The Project aims to assign one farmer trainer for roughly every 50 households, and the local Department of Agriculture (DRAE) was asked to select four farmer trainers. The DRAE technical staff, familiar with the situation in the irrigation zone, recommended Mr. A who had been the elected head of the water users' association in the irrigation zone since 2012. The term of the head being five years with no term limit, Mr. A was in his second term as of August 2018. Mr. A recommended his younger brother Mr. B, cousin Mr. C, and friend Mr. D as the other three trainers. The four of them were taken on as farmer trainer candidates and, after undergoing training by DRAE, they were awarded certificates (see photo) and certified as official trainers.

REPOBLIKAN'I MADAGASIKARA

MINISTERA EO AMBANY FIADIDIAN'NY REPOBLIKA MISAHANA NY FAMBOLENA SY FIOMPIANA

PAPRIZ 2

MARI-PANKASITRAHANA
TANTSAHA MPAMPIOFANA TEKNIKA PAPRIZ

Atolotra an' Andriamatoa

RAFANOMEZANTSOA Philibert

monina ao Antsirabe I,

Noho ny fanarahany atsakany sy andavany ny « ***Fiofanana haitao teknika PAPRIZ*** » nataon'ny tetikasa PAPRIZ 2, ***Tetikasa Fanatsarana ny Famokaram-bary, Fitantanana Sahandriaka sy lemaka voatondraka*** izay tetikasan'ny Ministera eo ambany fiadidian'ny Repoblika misahana ny Fambolena sy Fiompiana MPAE.

Ity Fankasitrahana ity dia omena azy ary manandanja sy azo ampiasaina araka izay ilàna azy.

Natao teto Antsirabe ny 29 Septambra 2017

Ny Tetikasa PAPRIZ 2
NAKAMURA Hirotaka

Ny DRAE Vakinankaratra
Voahangy
RAKOTONDRANAIVO Joséane Voahangy

Photo. Farmer trainer certificate

It should be noted that the Project has set out certain criteria for the selection of trainers, and in principle, the decision is made through discussions among the farmers. However, in the case of this study, there was no process of selection at a farmers' meeting, with relatives and friends being selected instead. And also, they do not conduct training for ordinary farmers alone, but often work in teams. From the perspective of disseminating the technology over a wide area, the

Project considers this way of selecting and training farmer trainers to be undesirable, because there is a risk that dissemination will be limited to residential areas of farmer trainers and biased to favor their close people. This point is discussed later, because it concerns the effectiveness, efficiency, and sustainability of the technology dissemination method after the completion of the project.

2. Farmer training by farmer trainer A

Below are some examples of autonomous training by farmer trainers from the third year onward, since when no support from the Project is provided. First, approximately one month before the training, a poster prepared by DRAE is displayed in the village hall and other places to attract farmers. When farmers ask for training, the request is accepted on the condition that approximately 10 farmers attend and that they provide the necessary materials (certified seeds and fertilizer) themselves. Training is provided in response to requests from villages outside the irrigation zone if they are within walking distance.

Initial training consists in classroom-based learning at the village hall or elementary school. A *kamishibai* (picture-story show) created by the Project is used to explain the theory and cultivation methods, and pamphlets are distributed. If a computer is available at the training site, a VCD video produced by the Project and commercially available is shown. Following the class learning, there are four field demonstrations in principle: nursery preparation, transplanting, fertilizing, and harvesting. The demonstrations are normally held on Mr. A's plot, which is well managed, but they may be held at a plot prepared by one of the farmers being trained. The basic premise of the training is the learning of theory and practice through attending all the sessions of a classroom and field demonstrations. However, in practice, some participants attend only one or the other. In particular, the number of participants in the harvest demonstration is small. The different participation rates according to the content of the technology thus reflect the different interests of farmers. Harvesting methods and drying and packaging are important technologies for post-harvest loss reduction and quality improvement. However, in the area where the study was conducted, most of the farmers are small-scale farmers who mainly produce rice for their own consumption, and these technologies are perhaps of little interest to them.

In Madagascar, the dense transplanting of large seedlings of 30 days or more is common, and farmers find it difficult to accept the benefits of the sparse planting of younger seedlings even when the advantages are explained in the classroom sessions. However, they find themselves convinced when they see Mr. A's plot. They realize the superiority of younger seedlings when, as they return to the same plot for weeding, they see that the rice plants that looked weak when transplanted are growing well. Meanwhile, they can see that the weeds that sparse planting have allowed to flourish can be dealt with cleanly using a rotary weeder if the rice is planted in wide straight rows.

According to Mr. A, farmers' comments after the training included that the quantity of seeds and the amount of weeding labor decreased while yields increased, and that, although things seemed difficult during the classroom sessions, they were easy in practice. No complaints of failure were received. As a follow-up, Mr. A visits the participating farmers’ plots and gives advice on weeding and other matters. In the pamphlet prepared by the Project, the amount of fertilizer to be applied is uniform regardless of soil conditions, but farmers are taught to change the amount of fertilizer applied according to the fertility of their land by Mr. A. The farmers are instructed to examine their soil and use a small amount of fertilizer for black soil, a standard amount for red soil, and compost for gray soil because chemical fertilizer alone is not effective for this least fertile soil. It seems that even ordinary farmers have a rough understanding of the relationship between soil color, texture, and fertility.

Mr. A has been featured on TV and the radio and seems to have become a local celebrity. He says that he feels proud when a farmer with whom he is not acquainted greets him and says that he saw him on TV. He says that his plot is growing so well that passing farmers often seek him out and ask him to teach them. If he cannot go to a training session himself, he sends his son (a high school graduate who received computer training in a local city, including how to use basic software, before returning to his village to farm). Although he is not a certified trainer, he seems to have a certain credibility because he is Mr. A's son and has an academic background.

3. Relationship between trainers

The three farmer trainers other than Mr. A have not been featured in the media, and they themselves feel that their credibility with other farmers is weak. Sometimes, when conducting training alone, they were unable to answer the farmers' questions. They often ask Mr. A to accompany them when they conduct training, and usually, two or three of them work as a team to conduct it. The numbers of field demonstration by them in total were: nursery preparation 6 times, transplantation 6, and weeding 3 in 2017; and 4, 4, and 2 in 2018.

Mr. A can recall almost everything in the pamphlet and can give explanations without consulting it. The other three trainers need to consult the pamphlet when giving explanations and cannot teach anything that is not included in it. During demonstrations, Mr. A explains what he is doing and why as he works, but the other three have difficulty interacting with questions from the farmers while showing operations. Thus, they often read the explanation in the pamphlet while instructing the farmers to practice operations in field.

Many questions from farmers relate to the quantity of seed required for the seedling beds, transplant spacing, and the quantity and frequency of fertilizer application in the main field. It seems that, for many of the farmers, the classroom sessions alone do not allow confirmation of whether the type of fertilizer and the standard quantity in the manual are suitable for their own plot or of whether the expected outcomes will be obtained. In addition to sharing his own experiences, Mr. A makes specific suggestions based on the soil conditions of the farmer's demo plots. The other trainers have difficulty doing this. As such, it is necessary to make appropriate judgments as needed on the plots during demonstrations under different conditions to improve training quality of farmer trainers. It is assumed that less experienced trainers learn this by working with experienced trainers (through on-the-job training).

Mr. A makes efforts to confirm the yield of the plots where demonstrations were conducted by asking the farmers after harvest. So far, there have been no cases of complaints of poor results from the farmers who have been trained. However, some farmers do not adopt the Project's methods even after receiving training. In such cases, there is no compulsion to follow the manual, but attempts are made to convince them, for example, by encouraging them to participate in the next year's training. There have apparently been cases in which farmers are convinced after repeating the process several times.

4. Farmers' information network

Table 1 and Figure 3 show how information about technology was disseminated from Mr. A. He received PAPRIZ Phase 1 technical training in 2012 and passed on the technology to his son in the same year. Since then, he has continued the training almost every year. The numbers shown in Table 1 are limited to the training he has conducted alone; from 2016, he has increasingly teamed up with other trainers, and these sessions have not been counted. Although this is thus something of an underestimation, information was passed on to a cumulative total of 76 people between 2012-17 (Table 1).

Table 1. Rice production technology information transfer originating from farmer trainer (A) (2012-2017)

	A	F1	F2	No. of getting ripple-effect info from sources other than F1 & F2	Cumulative no. of farmers
	No. of farmers to whom technology was passed on				
2012	1	0	-	0	1
2013	0	2	-	0	3
2014	15	0	0	0	18
2015	13	0	0	1	32
2016	0	5	0	3	40
2017	4	10	9	13	76
Total	33	17	9	17	NA

A: Farmer trainer, received technical instruction from JICA in 2012
F1: Son of A, received technical instruction from A in 2012
F2: Ordinary farmer, received technical guidance from A in 2014

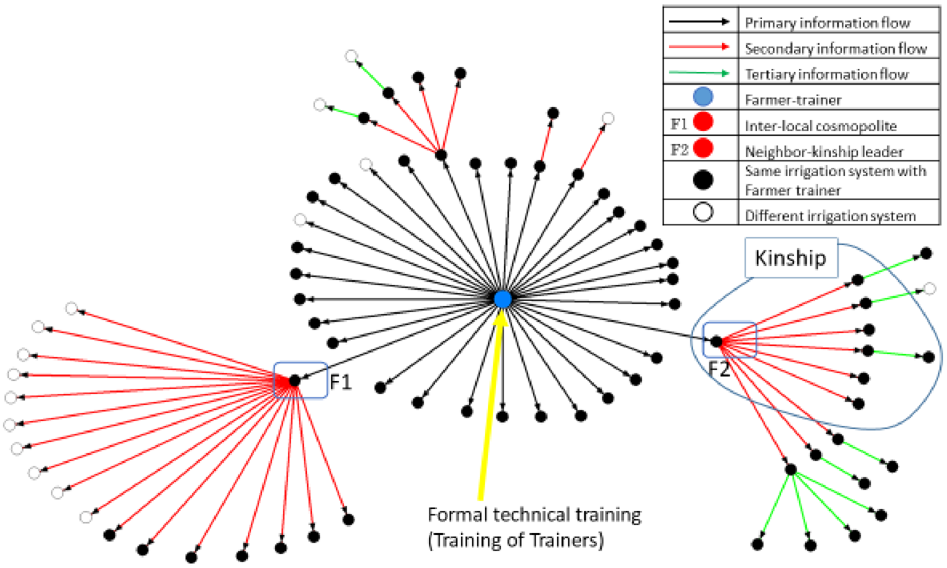

Fig. 3. Information transfer from farmer trainers in the PAPRIZ project

The center of the figure represents A in Table 1
F1 in Table 1
F2 in Table2

For information transfer among farmers to spread in a ripple effect, it is expected that farmers who received training teach neighbor farmers in an informal manner. In reality, however, only five of the 33 farmers who learned from Mr. A passed the information on to other farmers (Figure 3). The most frequently heard reason for farmers not teaching the technology to other farmers despite recognizing its merits themselves was that they had never been asked to do so. They were also afraid that the person they teach would fail and lose revenue, which would be blamed on them. Many respondents indicated that, even if they were willing to teach, they were not confident in doing so after only one trial. The area in which the study was conducted has a cold highland climate, and only one crop of rice is grown per year, with hailstorms and other disasters being common. The inference is that the experience of several rounds of rice cultivation is required for new methods to be properly adopted.

In this context, two relatively influential farmers were identified. F1 in Table 1 is Mr. A's son (21 years old and single at the time of the survey, with computer training after high school graduation); the people he taught in 2013 and 2016 were acquaintances from the same village, but in 2017, he went to teach in another village on behalf of his father. He is not certified as a farmer trainer, so this can be considered informal farmer training. Let us categorize this kind of information transfer to an unspecified number of strangers away from the place of residence, as "inter-local cosmopolite type" information transfer.

The other relatively influential farmer (F2) is a close friend of Mr.

A (50 years old, married, middle school graduate, full-time farmer), who gives demonstrations on his own plot at the request of neighbor farmers. He does not use any teaching materials, only demonstrates his practices on his own plot and, of the nine people who learned from him, six were relatives. Those who learned from him are also teaching other farmers, which shows a certain influence. Let us call this case "neighbor-kinship type" information transfer.

Comparing the two types, although the "neighbor-kinship type" is limited in the spatial spread of information, because it involves close and continuous relationships, it is promising in feedback and passing on information to the next generation. The frequent exchange of information among a small number of people with a close and continuous relationship is effective for technological improvement and the discovery of new issues. Contrastingly, in the "inter-local cosmopolite type," the flow of information tends to be one-way, although it can be expected to spread over a wide area in the short term. However, communication with little feedback carries the risk of the transmission of misinformation. The spread of misinformation is a major negative aspect in the diffusion of technology. Therefore, continuous follow-up by local administrative agencies and/or NGOs with accurate information is necessary.

The "neighbor-kinship" and the "inter-local cosmopolite" of information transfer are complementary for technology dissemination. Bearing this in mind regarding selecting farmer trainers and developing training methods is expected to lead to the proposal of efficient and effective dissemination methods. Furthermore, regarding information transmission between farmers, it is still necessary to clarify whether any information is omitted, added, or changed in the indirect transmission process it is still necessary to clarify what kind of technology is difficult to transmit and what kinds of misunderstandings are likely to occur.

Conclusion

Farmer trainers who have received formal training and have certificates from the Project can be described as "mediators-cum-actors." They use manuals and pamphlets prepared by the Project to provide instruction in the fields of farmer groups that wish to receive training, but they do not simply tell the farmers what is written in the manuals. The production environments, i.e., soil fertility and water condition, differs from plot to plot, and the materials available to farmers also vary according to economic and market conditions.

In other words, the Project (the third party) only creates standard technical guidelines, and the farmer trainers (mediators-cum-actors)4) must make minor changes to the content of the instructions and devise instructional methods based on their own judgment each time they conduct training. Feedback of this type of information to the Project is expected to lead to the revision of the manual and improvement of the training methods. Ordinary farmers who voluntary communicate information are "actors." It is possible to expect self-sustaining development even after the Project is completed as a result of the formation of an AKIS by these "actors" and "mediators-cum-actors" with the involvement of "third parties" such as local governments and/or NGOs.

Notes

1) The postwar extension system in Japan started with the Agricultural Improvement Promotion Act promulgated in 1948, and Hidetoshi Isobe, the first Director General of the Agricultural Improvement Bureau, described its significance as follows. “A more fundamentally important factor in extension is the training of farmers in scientific ways of looking at things, of thinking, and of making comparisons. Technological instruction in the past has only taught how things should be done, not why they are done in that way; farmers were not completely convinced and were not taught how to adapt to circumstances. Extension should be intended to improve agriculture and farmers' livelihoods by their impact on farmers' voluntary will and reason; this is nothing short of a kind of educational enlightenment movement." (Agricultural Improvement Bureau, Ministry of Agriculture and Forestry 1949)

2) This section is based on Yokoyama (2014).

3) This section is based on Yokoyama (2017).

4) A farmer trainer is an "actor" in their capacity as farmer and a "mediator" in their capacity as trainer. Interviews also confirmed that field demonstrations constitute an opportunity to teach and learn through exchanging information and opinions of other farmers, which is among the motivations for participating in the training. The division of roles between "actor" and "mediator" is not fixed.

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Acknowledgements:

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Representative Institutions

JIRCAS

MINAE

Partner Institutions

高知大学
Kochi University

東京大学
THE UNIVERSITY OF TOKYO

Laboratoire des Radioisotopes
Université d'Antananarivo

FOFIFA

PRIMATURE
ONN
OFFICE NATIONAL DE NUTRITION

Supported by

SATREPS
Science and Technology Reasearch Partnership
for Sustainable Development Program

JICA

JST

MESUPRES
Ministère de l'Enseignement Supérieur
et de la Recherche Scientifique

ANNEX 3

Appendix 2 PROJECT DESIGN MATRIX (PDM) **Version 0, Drafted on Sep 27, 2016**

Project Title:The Project for Breakthrough in Nutrient Use Efficiency for Rice by Genetic Improvement and Fertility Sensing Techniques in Africa
Implementing agencies (Madagascar): Ministry to the Presidency in charge of Agriculture and Livestock (MPAE), National Center of Applied Research and Rural Development (FOFIFA), Radioisotopes Laboratory of University of Antananarivo (LRI) and National Nutrition Office (ONN)
Implementing agencies (Japan): Japan International Research Center for Agricultural Sciences (JIRCAS), Kyoto University (Kyoto U), The University of Tokyo (Tokyo U)
Target groups: Researchers/Technicians/Extension workers of the implementing agencies of Madagascar
Final beneficiaries: Farmers in the target area
Target area: Vakinankaratra Region, Analamanga Region
Project period: 5 Years (2017-2022)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions
Overall Goal			
Developed techniques are used by farmers in the target area.	Developed breeding materials and/or fertilizer management practices are used by xx farmers in the target area. Developed breeding materials are officially released as varieties in Madagascar.	Documents from the implementing agencies and published research articles Survey at the project site	
Project Purpose			
Rice production techniques to improve nutrient use efficiency under low-input and low-fertility soil conditions for dissemination are developed.	Developed breeding materials and fertilizer management practices based on field nutrient characteristics are appreciated by xx% of rice farmers that participate in adoptation trials in the target area.	Project reports Technical manuals Policy recommendation Published articles	-Political and social conditions do not get greatly unstable in Madagascar. -Developed techniques, field nutrient maps, and policy recommendation are promoted in the extension scheme of the target area by GOM. -Enhanced extension scheme and seed production system by the PaprizII and PHRD projects are sustained.
	User manuals of developed techniques and recommendation for the extension policies are compiled. Over 25 research articles including xx top-authored ones by the Malagasy researchers related to the project outputs are published.		
Outputs			
1 Evaluation techniques and geographical maps of field nutrient fertility characteristics are developed.	1-1. Soil and spectral analytical methods that are applicable to the rice fields in the target area are established. 1-2. Inter-field scale maps for the fertilizer application are developed. 1-3. The developed evaluation methods are transferred to the extension workers in the xx regions of Madagascar.	Project reports, technical manuals and related research articles	1. The Policy recommendation by the Project is accepted by GOM.
2 Breeding materials to improve grain yield and nutrient use efficiency under low-input and low-fertility soil conditions are developed.	2-1. At least two breeding lines to improve nutrient acquisition capacity and utilization efficiency by xx % relative to the conventional varieties in the target area (or recurrent parents) are developed. 2-2. At least two DNA markers for QTLs related to nutrient acquisition capacity and utilization efficiency of rice are developed. 2-3. At least two genes and their mechanisms related to nutrient acquisition capacity and utilization efficiency of rice are identified.	- ditto -	
3 Fertilizer management techniques using genetic resources for nutrient-efficient rice production are developed.	3-1. Fertilizer management practices that improves nutrient use efficiency by xx % are developed. 3-2. xx varieties that show high performance responding to the field nutrient conditions are selected. 3-3. The developed fertilizer management techniques are transferred to xx extension workers in the target regions of Madagascar.	- ditto -	

4 A policy recommendation is compiled to promote the extension of developed techniques for rice production in the target area.	4-1. Socioeconomic factors for the dissemination of fertilizer management techniques and varieties in the target area are identified. 4-2. The effect of improved rice cultivation techniques on household income and human nutrition are quantified based on over xx household survey in the target area. 4-3. The policy recommendation is reflected in the implementation plan to promote the extension of developed techniques in the target area.	Project reports, policy recommendation and related research articles	
Activities	Inputs		
	The Japanese side	The Malagasy side	
1-1 Enhance research capacity on soil and plant nutrition and on GIS and remote sensing 1-2 Develop evaluation techniques and inter-field scale maps for the SOC in rice fields 1-3 Develop evaluation techniques and inter-field scale maps for the major nutrient deficiencies in rice fields 1-4 Develop *on-site* evaluation techniques for nutrient characterization of rice fields and its application 2-1 Enhance research capacity on phenotyping and genotyping for rice breeding 2-2 Select prominent donors and identify QTLs and its DNA markers 2-3 Select donors (including Pup1 lines) and crossing with varieties by MAS, followed by the field evaluation 2-4 Identify physiological/morphological mechanism of nutrient deficient tolerance and genetic functions of underlying genes 3-1 Enhance research capacity on fertilizer management 3-2 Identify short- to mid- term effect of fertilizer application and its interaction with several soil types in the target area 3-3 Develop fertilizer management techniques based on nutrient characteristics of rice fields 3-4 Identify effect of genetic resources responding to field nutrient conditions 4-1 Enhance research capacity and database of socioeconomic survey 4-2 Identify dissemination factors for the improved rice cultivation techniques 4-3 Analyze impact of inter-field scale fertility information and effective fertilizer management techniques on rice yield, production efficiency, and household welfare 4-4 Analyze impact of the improved rice productivity on the human nutrition	1. Dispatch of experts; A long-term expert (Project coordinator) and short-term experts (researchers and post-doctral researchers in specific fields) 2. Training of the counterpart researchers in Japan, Madagascar and/or third countries 3. Equipment and materials necessary for the Project 4. Necessary recurrent cost for the Project	1. Counterpart personnel and technical and administrative staff members 2. Facilities necessary for the implementation of the Project (laboratories, experimental fields, project offices, greenhouses etc.) 3. Available data and information related to the Project 4. Necessary recurrent cost for the Project	1. Installation of research equipment is not greatly delayed. 2. Preparation of laboratories is not greatly delayed for the installation of research equipment. 3. Significant turn over of Malagasy counterparts does not occur.
			Preconditions

Annex 1 PROJECT DESIGN MATRIX (PDM)

Version 1, Jan 17, 2017

Project Title:The Project for Breakthrough in Nutrient Use Efficiency for Rice by Genetic Improvement and Fertility Sensing Techniques in Africa
Implementing agencies (Madagascar): Ministry to the Presidency in charge of Agriculture and Livestock (MPAE), National Center of Applied Research and Rural Development (FOFIFA), Radioisotopes Laboratory of University of Antananarivo (LRI) and National Nutrition Office (ONN)
Implementing agencies (Japan): Japan International Research Center for Agricultural Sciences (JIRCAS), Kyoto University (Kyoto U), The University of Tokyo (Tokyo U)
Target groups: Researchers/Technicians/Extension workers of the implementing agencies of Madagascar
Final beneficiaries: Farmers in the target area
Target area: Vakinankaratra Region, Analamanga Region
Project period: 5 Years (2017-2022)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions
Overall Goal			
Developed techniques are used by farmers in the target area.	Developed breeding materials and/or fertilizer management practices are used by xx % of farmers in the target area. Developed breeding materials are officially released as varieties in Madagascar.	Documents from the implementing agencies and published research articles Survey at the project site	
Project Purpose			
Rice production techniques to improve nutrient use efficiency under low-input and low-fertility soil conditions for dissemination are developed.	Developed breeding materials and fertilizer management practices based on field nutrient characteristics are appreciated by xx% of rice farmers that participate in adoptation trials in the target area. User manuals of developed techniques and recommendation for the extension policies are compiled. Over 25 research articles including xx top-authored ones by the Malagasy researchers related to the project outputs are published.	Project reports Technical manuals Policy recommendation Published articles	-Political and social conditions do not get greatly unstable in Madagascar. -Developed techniques, field nutrient maps, and policy recommendation are promoted in the extension scheme of the target area by GOM. -Enhanced extension scheme and seed production system by the PaprizII and BVPI-PHRD projects are sustained.
Outputs			
1 Evaluation techniques and geographical maps of field nutrient fertility characteristics are developed.	1-1. Soil and spectral analytical methods that are applicable to the rice fields in the target area are established. 1-2. Inter-field scale maps for the fertilizer application are developed. 1-3. The developed evaluation methods are transferred to the extension workers in the xx regions of Madagascar.	Project reports, technical manuals and related research articles	1. The Policy recommendation by the Project is accepted by GOM.
2 Breeding materials to improve grain yield and nutrient use efficiency under low-input and low-fertility soil conditions are developed.	2-1. At least two breeding lines to improve nutrient acquisition capacity and utilization efficiency by xx % relative to the conventional varieties in the target area (or recurrent parents) are developed. 2-2. At least two DNA markers for QTLs related to nutrient acquisition capacity and utilization efficiency of rice are developed. 2-3. At least two genes and their mechanisms related to nutrient acquisition capacity and utilization efficiency of rice are identified.	- ditto -	
3 Fertilizer management techniques using genetic resources for nutrient-efficient rice production are developed.	3-1. Fertilizer management practices that improves nutrient use efficiency by xx % are developed. 3-2. xx varieties that show high performance responding to the field nutrient conditions are selected. 3-3. The developed fertilizer management techniques are transferred to xx extension workers in the target regions of Madagascar.	- ditto -	

4 A policy recommendation is compiled to promote the extension of developed techniques for rice production in the target area.	4-1. Socioeconomic factors for the dissemination of fertilizer management techniques and varieties in the target area are identified. 4-2. The effect of improved rice cultivation techniques on household income and human nutrition are quantified based on over xx household survey in the target area. 4-3. The policy recommendation is reflected in the implementation plan to promote the extension of developed techniques in the target area.	Project reports, policy recommendation and related research articles	
Activities	Inputs		
	The Japanese side	The Malagasy side	
1-1 Enhance research capacity on soil and plant nutrition and on GIS and remote sensing	1. Dispatch of experts; A long-term expert (Project coordinator) and short-term experts (researchers and post-doctral researchers in specific fields) 2. Training of the counterpart researchers in Japan, Madagascar and/or third countries 3. Equipment and materials necessary for the Project 4. Necessary recurrent cost for the Project	1. Counterpart personnel and technical and administrative staff members 2. Facilities necessary for the implementation of the Project (laboratories, experimental fields, project offices, greenhouses etc.) 3. Available data and information related to the Project 4. Necessary recurrent cost for the Project	1. Installation of research equipment is not greatly delayed. 2. Preparation of laboratories is not greatly delayed for the installation of research equipment. 3. Significant turn over of Malagasy counterparts does not occur.
1-2 Develop evaluation techniques and inter-field scale maps for the SOC in rice fields			
1-3 Develop evaluation techniques and inter-field scale maps for the major nutrient deficiencies in rice fields			
1-4 Develop *on-site* evaluation techniques for nutrient characterization of rice fields and its application			
2-1 Enhance research capacity on phenotyping and genotyping for rice breeding			
2-2 Select prominent donors and identify QTLs and its DNA markers			
2-3 Select donors (including Pup1 lines) and crossing with varieties by MAS, followed by the field evaluation			
2-4 Identify physiological/morphological mechanism of nutrient deficient tolerance and genetic functions of underlying genes			
3-1 Enhance research capacity on fertilizer management			
3-2 Identify short- to mid- term effect of fertilizer application and its interaction with several soil types in the target area			
3-3 Develop fertilizer management techniques based on nutrient characteristics of rice fields			
3-4 Identify effect of genetic resources responding to field nutrient conditions			
4-1 Enhance research capacity and database of socioeconomic survey			
4-2 Identify dissemination factors for the improved rice cultivation techniques			Preconditions
4-3 Analyze impact of inter-field scale fertility information and effective fertilizer management techniques on rice yield, production efficiency, and household welfare			
4-4 Analyze impact of the improved rice productivity on the human nutrition			

Annex 1 PROJECT DESIGN MATRIX (PDM)

Version 2, Oct5, 2017

Project Title:The Project for Breakthrough in Nutrient Use Efficiency for Rice by Genetic Improvement and Fertility Sensing Techniques in Africa (Projet FY VARY)
Implementing agencies (Madagascar): Ministry to the Presidency in charge of Agriculture and Livestock (MPAE), National Center of Applied Research and Rural Development (FOFIFA), Radioisotopes Laboratory of University of Antananarivo (LRI) and National Nutrition Office (ONN)
Implementing agencies (Japan): Japan International Research Center for Agricultural Sciences (JIRCAS), Kyoto University (Kyoto U), The University of Tokyo (Tokyo U), Yamashi Eiwa Univ.
Target groups: Researchers/Technicians/Extension workers of the implementing agencies of Madagascar
Final beneficiaries: Farmers in the target area
Target area: Vakinankaratra Region, Analamanga Region, Alaotra-Mangoro Region
Project period: 5 Years (2017-2022)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions
Overall Goal (3 years after the end of the Project)			
Developed techniques are used by farmers in the target area.	Developed breeding materials and/or fertilizer management practices are used by 500 or more farmers in the target area. Developed breeding materials are officially released as varieties in Madagascar.	Documents from the implementing agencies and published research articles Survey at the project site	
Project Purpose			
Rice production techniques to improve nutrient use efficiency under low-input and low-fertility soil conditions for dissemination are developed.	Developed breeding materials and fertilizer management practices based on field nutrient characteristics are appreciated by 50% of rice farmers that participate in adoption trials in the target area. User manuals of developed techniques and recommendation for the extension policies are compiled. Over 25 research articles including 5 top-authored ones by the Malagasy researchers related to the project outputs are published.	Project reports Technical manuals Policy recommendation Published articles	-Political and social conditions do not get greatly unstable in Madagascar. -Developed techniques, field nutrient maps, and policy recommendation are promoted in the extension scheme of the target area by GOM. -Enhanced extension scheme and seed production system by the PaprizII and BVPI-PIIRD projects are sustained.
Outputs			
1 Evaluation techniques and geographical maps of field nutrient fertility characteristics are developed.	1-1. Soil and spectral analytical methods that are applicable to the rice fields in the target area are established. 1-2. Inter-field scale maps for the fertilizer application are developed. 1-3. The developed evaluation methods are transferred to at least 20% of extension service in the target regions of Madagascar.	Project reports, technical manuals and related research articles	1. The Policy recommendation by the Project is accepted by GOM.
2 Breeding materials to improve grain yield and nutrient use efficiency under low-input and low-fertility soil conditions are developed.	2-1. At least two breeding lines to improve nutrient acquisition capacity and utilization efficiency by 20% relative to the conventional varieties in the target area (or recurrent parents) are developed. 2-2. At least two DNA markers for QTLs related to nutrient acquisition capacity and utilization efficiency of rice are developed. 2-3. At least two genes and their mechanisms related to nutrient acquisition capacity and utilization efficiency of rice are identified.	- ditto -	

3 Fertilizer management techniques using genetic resources for nutrient-efficient rice production are developed.	3-1. Fertilizer management practices that improves nutrient use efficiency by 20 % are developed. 3-2. At least two varieties that show high performance responding to the field nutrient conditions are selected. 3-3. The developed fertilizer management techniques are transferred to at least 20% of extension service in the target regions of Madagascar.	- ditto -	
4 A policy recommendation is compiled to promote the extension of developed techniques for rice production in the target area.	4-1. Socioeconomic factors for the dissemination of fertilizer management techniques and varieties in the target area are identified. 4-2. The effect of improved rice cultivation techniques on household income and human nutrition are quantified based on 500 or more household survey in the target area. 4-3. The policy recommendation is reflected in the implementation plan to promote	Project reports, policy recommendation and related research articles	
Activities	Inputs		
	The Japanese side	The Malagasy side	
1-1 Enhance research capacity on soil and plant nutrition and on GIS and remote sensing 1-2 Develop evaluation techniques and inter-field scale maps for the SOC in rice fields 1-3 Develop evaluation techniques and inter-field scale maps for the major nutrient deficiencies in rice fields 1-4 Develop *on-site* evaluation techniques for nutrient characterization of rice fields and its application 2-1 Enhance research capacity on phenotyping and genotyping for rice breeding 2-2 Select prominent donors and identify QTLs and its DNA markers 2-3 Select donors (including Pup1 lines) and crossing with varieties by MAS, followed by the field evaluation 2-4 Identify physiological/morphological mechanism of nutrient deficient tolerance and genetic functions of underlying genes 3-1 Enhance research capacity on fertilizer management 3-2 Identify short- to mid- term effect of fertilizer application and its interaction with several soil types in the target area 3-3 Develop fertilizer management techniques based on nutrient characteristics of rice fields	1. Dispatch of experts; A long-term expert (Project coordinator) and short-term experts (researchers and post-doctral researchers in specific fields) 2. Training of the counterpart researchers in Japan, Madagascar and/or third countries 3. Equipment and materials necessary for the Project 4. Necessary recurrent cost for the Project	1. Counterpart personnel and technical and administrative staff members 2. Facilities necessary for the implementation of the Project (laboratories, experimental fields, project offices, greenhouses etc.) 3. Available data and information related to the Project 4. Necessary recurrent cost for the Project	1. Installation of research equipment is not greatly delayed. 2. Preparation of laboratories is not greatly delayed for the installation of research equipment. 3. Significant turn over of Malagasy counterparts does not occur.

Annex 1 PROJECT DESIGN MATRIX (PDM)

Ver3, 17092020

Project Title:The Project for Breakthrough in Nutrient Use Efficiency for Rice by Genetic Improvement and Fertility Sensing Techniques in Africa (Projet FY VARY)

Implementing agencies (Madagascar): Ministry to the Presidency in charge of Agriculture and Livestock (MPAE), National Center of Applied Research and Rural Development (FOFIFA), Radioisotopes Laboratory of University of Antananarivo (LRI) and National Nutrition Office (ONN)

Implementing agencies (Japan): Japan International Research Center for Agricultural Sciences (JIRCAS), Kyoto University (Kyoto U), The University of Tokyo (Tokyo U), Yamashi Eiwa Univ. (Yamanishi

Target groups: Researchers/Technicians/Extension workers of the implementing agencies of Madagascar

Final beneficiaries: Farmers in the target area

Target area: Vakinankaratra Region, Analamanga Region, Alaotra-Mangoro Region

Project period: 5 Years (2017-2022)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions
Overall Goal (3 years after the end of the Project)			
Developed techniques are used by farmers in the target area.	Developed breeding materials and/or fertilizer management practices are used by 500 or more farmers in the target area. Developed breeding materials are officially released as varieties in Madagascar.	Documents from the implementing agencies and published research articles Survey at the project site	
Project Purpose			
Rice production techniques to improve nutrient use efficiency under low-input and low-fertility soil conditions for dissemination are developed.	Developed breeding materials and fertilizer management practices based on field nutrient characteristics are appreciated by 50% of rice farmers that participate in adoption trials in the target area. User manuals of developed techniques and recommendation for the extension policies are compiled. Over 25 research articles including 5 top-authored ones by the Malagasy researchers related to the project outputs are published. Developed fertilizer management practice(s) are tested >500 farmers' fields, and the factors of farmers' adoption and effect under farmers' management practices are identified.	Project reports Technical manuals Policy recommendation Published articles	-Political and social conditions do not get greatly unstable in Madagascar. -Developed techniques, field nutrient maps, and policy recommendation are promoted in the extension scheme of the target area by GOM. -Enhanced extension scheme and seed production system by the PaprizII and BVPI-PHRD projects are sustained.
Outputs			
1 Evaluation techniques and geographical maps of field nutrient fertility characteristics are developed.	1-1. Soil and spectral analytical methods that are applicable to the rice fields in the target area are established. 1-2. Inter-field scale maps for the fertilizer application are developed. 1-3. The developed evaluation methods are transferred to at least 20% of extension service in the target regions of Madagascar.	Project reports, technical manuals and related research articles	1. The Policy recommendation by the Project is accepted by GOM.

2	**Breeding materials to improve grain yield and nutrient use efficiency under low-input and low-fertility soil conditions are developed.**	**2-1. At least two breeding lines to improve nutrient acquisition capacity and utilization efficiency by 20% relative to the conventional varieties in the target area (or recurrent parents) are developed.** **2-2. At least two DNA markers for QTLs related to nutrient acquisition capacity and utilization efficiency of rice are developed.** **2-3. At least two genes and their mechanisms related to nutrient acquisition capacity and utilization efficiency of rice are identified.**	**- ditto -**	
3	**Fertilizer management techniques using genetic resources for nutrient-efficient rice production are developed.**	**3-1. Fertilizer management practices that improves nutrient use efficiency by 20 % are developed.** **3-2. At least two varieties that show high performance responding to the field nutrient conditions are selected.** **3-3. The developed fertilizer management techniques are transferred to at least 20% of extension service in the target regions of Madagascar.**	**- ditto -**	
4	**A policy recommendation is compiled to promote the extension of developed techniques for rice production in the target area.**	**4-1. Socioeconomic factors for the dissemination of fertilizer management techniques and varieties in the target area are identified.** **4-2. The effect of improved rice cultivation techniques on household income and human nutrition are quantified based on 500 or more household survey in the target area.** **4-3. The policy recommendation is reflected in the implementation plan to promote the extension of developed techniques in the target area.**	**Project reports, policy recommendation and related research articles**	

Activities		**Inputs**		
		The Japanese side	**The Malagasy side**	
1-1	**Enhance research capacity on soil and plant nutrition and on GIS and remote sensing**	**1. Dispatch of experts; A long-term expert (Project coordinator) and short-term experts (researchers and post-doctral researchers in specific fields)** **2. Training of the counterpart researchers in Japan, Madagascar and/or third countries** **3. Equipment and materials necessary for the Project** **4. Necessary recurrent cost for the Project**	**1. Counterpart personnel and technical and administrative staff members** **2. Facilities necessary for the implementation of the Project (laboratories, experimental fields, project offices, greenhouses etc.)** **3. Available data and information related to the Project** **4. Necessary recurrent cost for the Project**	**1. Installation of research equipment is not greatly delayed.** **2. Preparation of laboratories is not greatly delayed for the installation of research equipment.** **3. Significant turn over of Malagasy counterparts does not occur.**
1-2	**Develop evaluation techniques and inter-field scale maps for the SOC in rice fields**			
1-3	**Develop evaluation techniques and inter-field scale maps for the major nutrient deficiencies in rice fields**			
1-4	**Develop *on-site* evaluation techniques for nutrient characterization of rice fields and its application**			
2-1	**Enhance research capacity on phenotyping and genotyping for rice breeding**			
2-2	**Select prominent donors and identify QTLs and its DNA markers**			
2-3	**Select donors (including Pup1 lines) and crossing with varieties by MAS, followed by the field evaluation**			
2-4	**Identify physiological/morphological mechanism of nutrient deficient tolerance and genetic functions of underlying genes**			

3-1 Enhance research capacity on fertilizer management			
3-2 Identify short- to mid- term effect of fertilizer application and its interaction with several soil types in the target area			
3-3 Develop fertilizer management techniques based on nutrient characteristics of rice fields			
3-4 Identify effect of genetic resources responding to field nutrient conditions			
4-1 Enhance research capacity and database of socioeconomic survey			
4-2 Identify dissemination factors for the improved rice cultivation techniques			**Preconditions**
4-3 Analyze impact of inter-field scale fertility information and effective fertilizer management techniques on rice yield, production efficiency, and household welfare			
4-4 Analyze impact of the improved rice productivity on the human nutrition			

Annex 1 PROJECT DESIGN MATRIX (PDM)

ver4. 30Sep, 2021

Project Title:The Project for Breakthrough in Nutrient Use Efficiency for Rice by Genetic Improvement and Fertility Sensing Techniques in Africa (Projet FY VARY)

Implementing agencies (Madagascar): Ministry of the Agriculture and Livestock (MINAE), National Center of Applied Research and Rural Development (FOFIFA), Radioisotopes Laboratory of University of Antananarivo (LRI) and National Nutrition Office (ONN)

Implementing agencies (Japan): Japan International Research Center for Agricultural Sciences (JIRCAS), Kochi University (Kochi U), The University of Tokyo (Tokyo U), Yamashi Eiwa Univ. (Yamanishi

Target groups: Researchers/Technicians/Extension workers of the implementing agencies of Madagascar

Final beneficiaries: Farmers in the target area

Target area: Vakinankaratra Region, Analamanga Region, Alaotra-Mangoro Region

Project period: 5 Years (2017-2022)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions
Overall Goal (3 years after the end of the Project)			
Developed techniques are used by farmers in the target area.	Developed breeding materials and/or fertilizer management practices are used by 500 or more farmers in the target area. Developed breeding materials are officially released as varieties in Madagascar.	Documents from the implementing agencies and published research articles Survey at the project site	
Project Purpose			
Rice production techniques to improve nutrient use efficiency under low-input and low-fertility soil conditions for dissemination are developed.	Developed breeding materials and fertilizer management practices based on field User manuals of developed techniques and recommendation for the extension policies Over 25 research articles including 5 top-authored ones by the Malagasy researchers Developed fertilizer management practice(s) are tested >500 farmers' fields, and the	Project reports Technical manuals Policy recommendation Published articles	-Political and social conditions do not get greatly unstable in Madagascar. -Developed techniques, field
Outputs			
1 Evaluation techniques and geographical maps of field nutrient fertility characteristics are developed.	1-1. Soil and spectral analytical methods that are applicable to the rice fields in the target area are established. 1-2. Inter-field scale maps for the fertilizer application are developed.	Project reports, technical manuals and related research articles	1. The Policy recommendation by the Project is accepted by GOM.
2 Breeding materials to improve grain yield and nutrient use efficiency under low-input and low-fertility soil conditions are developed.	2-1. At least two breeding lines to improve nutrient acquisition capacity and utilization efficiency by 20% relative to the conventional varieties in the target area (or recurrent parents) are developed. 2-2. At least two DNA markers for QTLs related to nutrient acquisition capacity and utilization efficiency of rice are developed. 2-3. At least two genes and their mechanisms related to nutrient acquisition capacity and utilization efficiency of rice are identified.	- ditto -	
3 Fertilizer management techniques using genetic resources for nutrient-efficient rice production are developed.	3-1. Fertilizer management practices that improves nutrient use efficiency by 20 % are developed. 3-2. At least two varieties that show high performance responding to the field nutrient conditions are selected.	- ditto -	

4	A policy recommendation is compiled to promote the extension of developed techniques for rice production in the target area.	4-1. Socioeconomic factors for the dissemination of fertilizer management techniques and varieties in the target area are identified. 4-2. The effect of improved rice cultivation techniques on household income and human nutrition are quantified based on 500 or more household survey in the target area. 4-3. The policy recommendation is reflected in the implementation plan to promote the extension of developed techniques or knowledge in the target area.	Project reports, policy recommendation and related research articles	
Activities		Inputs		
		The Japanese side	The Malagasy side	
1-1	Enhance research capacity on soil and plant nutrition and on GIS and remote sensing	1. Dispatch of experts; A long-term expert (Project coordinator) and short-term experts (researchers and post-doctral researchers in specific fields) 2. Training of the counterpart researchers in Japan, Madagascar and/or third countries 3. Equipment and materials necessary for the Project 4. Necessary recurrent cost for the Project	1. Counterpart personnel and technical and administrative staff members 2. Facilities necessary for the implementation of the Project (laboratories, experimental fields, project offices, greenhouses etc.) 3. Available data and information related to the Project 4. Necessary recurrent cost for the Project	1. Installation of research equipment is not greatly delayed. 2. Preparation of laboratories is not greatly delayed for the installation of research equipment. 3. Significant turn over of Malagasy counterparts does not occur.
1-2	Develop evaluation techniques and inter-field scale maps for the SOC in rice fields			
1-3	Develop evaluation techniques and inter-field scale maps for the major nutrient deficiencies in rice fields			
1-4	Develop *on-site* evaluation techniques for nutrient characterization of rice fields and its application			
2-1	Enhance research capacity on phenotyping and genotyping for rice breeding			
2-2	Select prominent donors and identify QTLs and its DNA markers			
2-3	Select donors (including Pup1 lines) and crossing with varieties by MAS, followed by the field evaluation			
2-4	Identify physiological/morphological mechanism of nutrient deficient tolerance and genetic functions of underlying genes			
3-1	Enhance research capacity on fertilizer management			
3-2	Identify short- to mid- term effect of fertilizer application and its interaction with several soil types in the target area			
3-3	Develop fertilizer management techniques based on nutrient characteristics of rice fields			
3-4	Identify effect of genetic resources responding to field nutrient conditions			
4-1	Enhance research capacity and database of socioeconomic survey			
4-2	Identify dissemination factors for the improved rice cultivation techniques			Preconditions

4-3	**Analyze impact of inter-field scale fertility information and effective fertilizer management techniques on rice yield, production efficiency, and household welfare**			
4-4	**Analyze impact of the improved rice productivity on the human nutrition**			

ANNEX 4

SUMMARY REPORT

Name: RABENARIVO Michel

Objective: development of evaluation techniques and geographical maps of the field nutrient fertility characteristics in target region of Madagascar for SATREPS –Madagascar project (Fy-Vary).

The training at JIRCAS and Kyoto University permit to acquire a new knowledge and skill about simple and rapid method for the acquisition of data to evaluate and survey soil fertility.

Period: 26 July 2017 – 1 September 2017

Achievement in Kyoto-University:

Training at Kyoto University with Dr Naouki for the:

1- Using of rapid technic to assess soil fertility

Standardization of soil sampling and preparation for the following analysis:

For water soluble nutrient

- Midori – kun: test paper for the nutrient (phosphorus and nitrogen) and soil chemical characteristics (pH)

Alternative method:

- Pack test for the evaluation rapid of soil properties and fertilities

? COD (Chemical Oxygen Demand): an index of organic contamination

? $P0_4^{2-}$ (phosphate)

? NO_3^- (Nitrate)

? NH_4^+ (Ammonium)

? NO_2 (Nitrite)

2- Rapid determination of soil sand content by using Nylon mesh method (maximum 2 days)

3- Determination of soil color class using MUNSEL CHART and Soil color reader SPAD -503

4- Determination of magnetic sensibility (indicator of magnetic mineral in the soil)

5- Electric conductivity measurement using conductivity meter

6- Use of compact potassium ion meter to determine the pH, salt, Na^+, NO_3, Ca^{2+}, K^+ conductivity

Achievement in JIRCAS:

1- With Dr Asai

Soil available nitrogen assessment (using 2 types of technics):

? Rapid assessment (2 days of measurement) of available N using (pack test)

? Long 40 days of anaerobic soil incubation to determine available N

2- With Dr Kensuke Kawamura

? Acquisition of spectral data Using Visible and Near Infrared Spectrometer (VIS-NIR-SWIR) of 64 Malagasy soil samples

- Acquisition of field spectro-radiometer for the chlorophyll and biomass measurement
- Treatment of the spectrum for the calibration and prediction of data using MATLAB software
- Operation to pilot drone and to take photo of the field
- Image processing using photoscan software for mapping 3D

Activity pictures with captions:

Test rapid for the nitrate at Kyoto University

Acquisition of spectral data (JIRCAS)

Use of SPAD in the field

Soil incubation (40 days) for Available N

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN (“Fy Vary” Satreps project)

Name: ANDRIAMANANJARA Andry, Laboratoire des RadioIsotopes-Université d’Antananarivo

Objective: The main objective of this training/exchange is to develop remote sensing techniques for evaluating field characteristics and soil properties. The planned activities during this training were: (i) operation of drone; (ii) digital mapping and extraction of geographical parameters using 3D mapping software and airborne imagery; (iii) operation skill of High-Resolution Spectroradiometer; (iv) soil analysis using spectral data from field spectrometer; (v) development of easy assessment method for nitrogen-supplying capcity of soils.

Period: 26th August – 01st September 2017

Achievement in Kyoto-U: This training was carried out with Dr. Naoki at Kyoto University. We acquired knowledge of the simplified tools/techniques used for the assessment of physical and chemical soil properties. These simple and accessible methods for soil properties included: (1) “Midori-kun” for water-soluble N, P, and K in soil; (2) Measurement of soil sand content with nylon mesh; (3) Estimation of soil total nitrogen by oxydol; (4) Soil color analysis using Munsell color chart and inexpensive color sensor; (5) Estimation of magnetic minerals in Malagasy soils. For the sand content analysis, higher correlation was found between conventional and simplified approaches.

Achievement in JIRCAS.: This research and training were conducted with Dr.Kensuke and Dr Asai. We also acquired an advanced knowledge on Visible–Near–Infrared scpectroscopy (Vis-NIR) approach for physico-chemical properties of Malagasy soils with Dr. Kensuke. This approach included: the operation skill of portable Vis-NIR spectro-radiometer; Spectra data acquisition; modelling of soil nutrient properties using spectral data and laboratory measurement. The preliminary result reported higher prediction accuracy in total N and total C and acceptable prediction accuracy for oxalate P.

Operation skills on imagery analysis was also acquired during this training. The training started from the use of drone, imagery data acquisition and processing with Agisoft Photoscan software.

Competence on available nitrogen assessment was obtained with Dr. Asai. Mineral nitrogen measurement on Malagasy soil could be done using incubation and simplified methods.

Activity pics with captions:

	
Operation of drone with Dr. Kensuke (Photo: Yasu)	Soil scanning using Vis-NIR spectroscopy with Dr. Kenuke (Photo Yasu)

	
Soil analysis with Dr. Naoki (Photo: Andry)	Available N measurement with Dr. Asai (Photo: Andry)

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN (« Fy Vary » Satreps project)

Name: TOJO MANDAHARISOA Sarah, FOFIFA

Objective: Strengthening the capacity in rice breeding through the "Fy Vary" project.

Period: 3th October – 10th November 2017

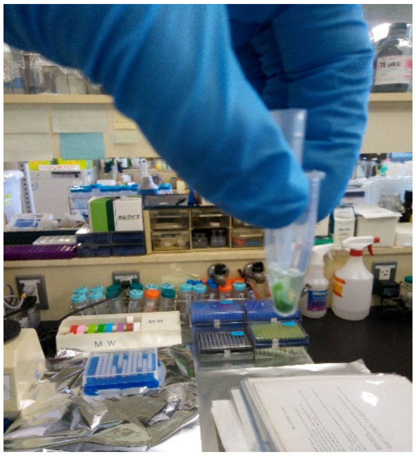
Achievements :

All the lab work at JIRCAS was led by Juan-san and Matsuda-san.

- DNA and RNA extraction: We have prepared the DNA of Malagasy variety for genome sequencing at the IRRI. We have also tried some protocols of DNA extraction in order to identify the more appropriate of the lab work in Madagascar. The best one was using CTAB protocol with dry leaves by silica gel. Since RNA is not stable, the extraction was more difficult compared to DNA extraction.
- PCR and RT-PCR respectively for DNA and RNA extraction
- Phosphorus analysis and data processing (with Matthias-san): the purpose of that work was to modelling the P uptake of some varieties (Nerica4, DJ, DJI) in high P and low P condition by acid digestion of root, shoot and seed. With basic data analysis, we can say that Nerica has a low P uptake.
- Crossing varieties

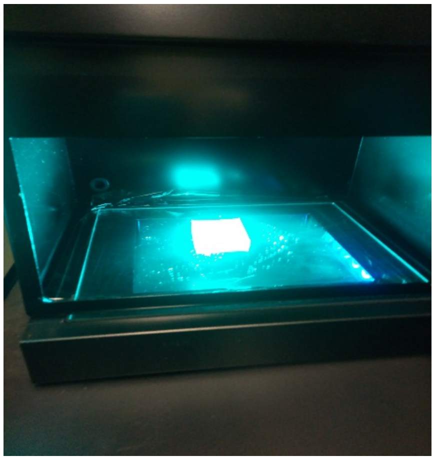
Activities pictures

Phosphorus analysis (photo: Sarah)



DNA extraction using fresh leaves and tips for grinding (photo: Sarah)

DNA extraction by separating the aqueous phase (photo: Sarah)



Running gel electrophoresis (photo: Sarah)

Summary report of research and training in Japan (“FyVary” SATREPS project)

Name: Michel RABENARIVO, Laboratoire des RadioIsotopes (LRI), Université d’Antananarivo

Period: 22nd August – 17th September 2018

Objective: The main objective of this training was to learn the key techniques of output 1 in the development of evaluation techniques and geographical maps of field nutrient fertility characteristics using drone image. The activities during this visits were: 1) Drone image analyses for mapping of yield in heterogenous small holder fields of FyVary projects (Behenjy and Antohobe), 2) Field hyperspectral measurements at canopy scale on paddy under different fertilizer treatments, and 3) hyperspectral data analyses during cropping season 2017-2018.

Achievement in Kyoto-U: Exchange of knowledge and discussion about conventional and rapid analysis of soil properties combined with remote sensing technic with Dr. Moritsuka and Dr. Kawamura. Discussion about the selection of promising simple technic to evaluate soil properties and for the next research topic.

Achievement in JIRCAS: The training and research are realized with Dr. Kawamura of JIRCAS using several methods on remote sensing and GIS. The main achievments were:

- Development of the GIS map at Behenjy using a 50 cm spatial resolution Digital Terrain Model (DTM) (Figure 1)
- Training on map creation by Photoscan and Pix4D software using the images taken from drone by RGB and multispectral camera, respectively.
- Mapping of Digital Surface Model (DSM) and ortho-mosaic images of RGB and NDVI in two areas at FyVary project (Behenjy and Antohobe regions) using Pix4D software.
- Training on field hyperspectral measurements to acquire canopy reflectance of plant grown and extraction using a portable spectro-radiometer MS-720
- Partial least squared (PLS) regression with wavebands selection to estimate agronomic parameters from canopy reflectance data obtained in Feb-March 2018 using Matlab software

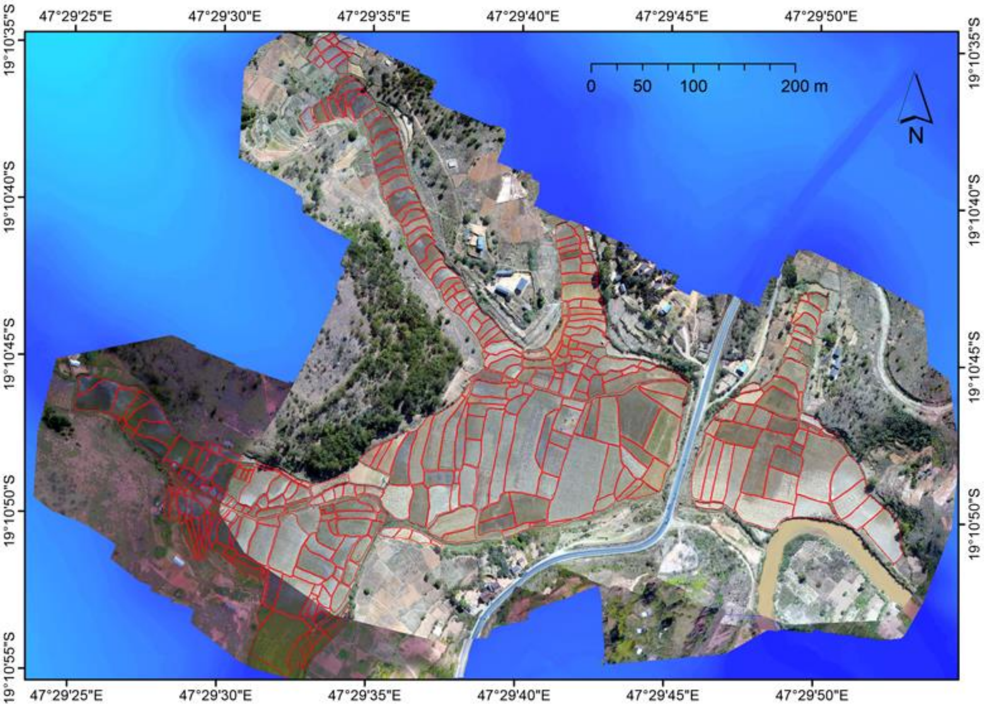


Figure 1. GIS map at Behenjy

Activity pics

<table>
<tr><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Training of data acquisition using spectroradiometer and data analysis</td><td>Meeting with Dr. Moritsuka at Kyoto Univerity</td></tr>
</table>

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN
("Fy Vary" Satreps project)

Name (s):

- RAKOTONDRAMANANA Mbolatantely Fahazavana – FOFIFA Rice Research Department Madagascar
- RANAIVO Harisoa Nicole – FOFIFA Rice Research Department Madagascar Madagascar

Objective(s) :
The main objective of this training/exchange is to improve our skills as a researcher- breeder in the output 2 of the FY VARY Project. The first purpose of this training was that we would be able to manage and conduct manipulations in the new laboratory in Ambatobe, then to train our co-workers in output 2. The second aim was Enhance Capacity of Marker assisted selection to improve adaptation of Malagasy rice varieties to low-input conditions.

The planned activities during this training were:

1- Genotyping: DNA marker analysis by PCR using SSR marker and Real-time PCR using KASP marker.
2- DNA extraction: TPE and TPS methods.
3- Crossing and back-cross of breeding lines
4- Statistical Analysis: QTL and GWAS analysis using R.
5- Phosphorus Digestion
6- Field works : harvest, roots counting, roots digging

Period: August 6th – September 29th

Achievement in JIRCAS: The training was carried out with

- DR MATTHIAS WISSUWA who trained us about experimental design and subsequent statistical analysis such as the software statistix ; Development of a workplan for the 2018-2019 field season in Madagascar. Phosphorus digestion using acid methods (HNO3 and HCL) then colorimetric method by using a specific machine and finally determination of Phosphosrus concentration by calculation.

- DR JUAN PARIASCA TANAKA who trained us about DNA extraction using different methods: TPS and TPE. Genotyping by electrophoresis and PCR using sofisticated machines, materials and markers. Use of two different Markers: SSR marker by running agarose gel and KASP marker for Real-time PCR. Elaboration of new protocol depending on the chemical reagents and materials available in the new laboratory in Madagascar.

- DR KATSUHIKO KONDO who trained us about doing crosses of the rice breeding materials such as X265 with promoting Genomic prediction accession and back-cross of selected NDJ lines with Nerica 4. F1 populations from these crosses will be tested if they are successfull or not then they will be grown in Japan.

Achievement at Tokyo University: This training was carried out with Dr Kanegae and Dr Ryokei Tanaka from Laboratory of Biometry and Bioinformatics of Tokyo University. We acquired knowledge of using R software especially using script of R-QTL and R-GWAS statistical analysis.

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN (“Fy Vary” Satreps project)

Name: RAKOTOSON Tovohery, Laboratoire des RadioIsotopes-Université d’Antananarivo

Objective: The main objective of this training/exchange is to conduct experiments for the identification of root and rhizosphere processes for enhanced phosphorus uptake. The planned activities during this training were: (i) rhizobox experiments using P deficient soil and rice genotypes with contrasting P uptake capacity in Madagascar, (ii) fine-scale analysis of root systems excavated from soil using scanned root images and the WinRhizo software, (iii) collection of rhizosphere and rhizosheath soil and analysis of genotype-induced changes in soil-P fractions, (iv) collection of root exudates and analysis of exudate composition using GC-MS, (v) development of easy P solubilization assays using root exudates or exudate components as solubilizing agents.

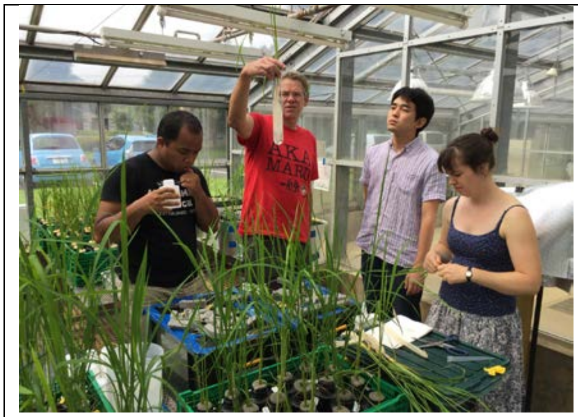
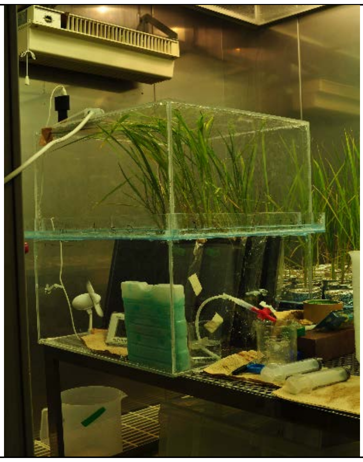
Period: 6th June – 31st August 2018

Achievement in Kyoto-U: This training was carried out with Dr. Naoki at Kyoto University. We acquired knowledge of the simplified tools/techniques used for the assessment of physical and chemical soil properties such as soil color analysis using Munsell color chart and inexpensive color sensor and other techniques compiled in a handbook that was shared to us.

Achievement in JIRCAS: This research and training were conducted with Dr Wissuwa, Dr Tanaka and Dr Holtz and permitted to deepen our knowledge and skills in terms of rhizosphere mechanisms identification. Specifically, the technic of 13-Carbon labeling and phosphatase activity measurement by zymography were learned through assisting Dr Holtz. Root exudates collection technique in 0.01M $CaCl_2$ was also learned. In addition to the planned activities, an additional set of experiments permitted to learn the determination of parameters necessary to run P uptake model calculation such as the C_{min} value or the ion concentration at which the ion influx (uptake by plant roots per unit of surface and time) is equal to zero with Dr Tanaka and Dr Wissuwa, C_L value (P concentration in soil solution) with a new protocol involving the use of Diffusive Gradient in Thin film technique (DGT) that can overcome the detection limits of colorimetric method. Most of the data output are being under process.

During the stay, Dr. Tsujimoto and I summarized the results of previous pot experiments, and submitted the manuscript entitled “"Pronounced effect of farmyard manure application on P availability for rice plants in P deficient soils with low total C and low pH as assessed by isotope technique" to the Journal of Plant Nutrition and Soil Science.

Activity pics with captions:

 Nutrient solution sampling (C_{min} experiment)		13-Carbon labelling (rhizobox experiment)

Summary report of research and training in Japan (“fyvary” SATREPS project)

Name: Njato Michaël RAKOTOARISOA, FOFIFA/Département de Recherche Rizicole – Tsimbazaza, Antananarivo

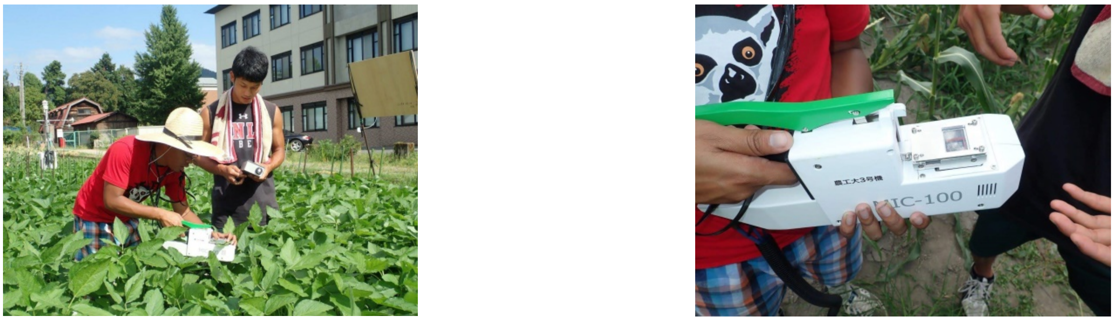
Period: 22th July – 07th September 2018

Objective: The main objective of this training was to improve the research skills and key technique of researcher of output 3 in the development of optimized fertilization techniques for yield improvement under low-productive lowland ecosystems of Madagascar. The planned activities during this training were: measurements of nitrogen content and 15N content of grain, stem and soil from the on-going field trials in Madagascar by using organic elemental analyser and mass-spectrometer and quantification of nitrogen dynamics under the lowland ecosystems of Madagascar; technical learning for in-situ physiological evaluation techniques for rice growth.

Achievement in Kyoto-U: The training was carried out with Dr Yu Tanaka, assistant professor at the Crop sciences laboratory - Kyoto University. During training, we improved basic knowledge in crop physiology through article paper reading. Moreover, we acquired the knowledge about biomass production and photosynthesis by using new instrument for the gas exchange measurement: “MIC-100” on soybean plant. We had also learn about the “deep learning technology”, which is a subset of artificial intelligence in the field that often uses statistical techniques to give computers the ability to learn with data, without being explicitly programmed.

Achievement in JIRCAS: The research and training were supervised by Dr Tsujimoto and Dr. Asai. We learned about technical preparation of 15N samples (packaging of soil, grain and stem). Operation skills to analyse N and C content by using NC analyser was also acquired. I discussed the results of field trials in the previous season (2017-2018) and the planning of the coming season trials (2018-2019) with Japanese counterparts in Output3 group.

Pictures:



Gas exchange measurement on soybean plant using MIC 100 at Kyoto university

Taking picture in rice paddy fields for deep learning technology at Kyoto University

separation of partial grain filled and sterile grain

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN (« FY VARY » - Satreps Project

Name: RINASOA Seheno ,Laboratoires des radioIsotopes – Université d’Antananarivo

Objective : The main objective of this internship was to conduct an experiment to identify the release of phosphorus under the application of different types of organic matter , on different types of soil. The experiment included sequential analysis of soluble P, Fe and pH of soils during the 45-day-incubation using 6 soils and two organic matters collected from Madagascar .

Period : 6th June – 31st August 2018

Achievement in Kyoto University: The visit was carried out with Dr Naoki at Kyoto University : (i) we acquired knowledge of the simplified tools/techniques used for the assessment of physical and chemical soil properties such as analysis using Munsell color chart (ii) we also visited the Soil Science laboratory, Experimental farms and also gave a seminary.

Achievement in JIRCAS : The experiment was carried out at the laboratories of Dr Yasuhiro Tsujimoto, under the supervision of Dr. Tomohiro Nishigaki, Dr. Yasuhiro Tsujimoto and Dr. Tovohery Rakotoson. This experiment allowed to know the principles of use of ICP for the measurement of the elements in the pore water of soils. We also tested the use of the malachite green method and confirmed its applicability for the detection of low P concentration in pore waters of submerged soil because the ICP could not detect the low concentration of P. More than four hundred tubes have been used and the main analyzes were: pH soil water, P olsen in incubated soil, Fe content in interstitial water and phosphorus in this water. As a result, I successfully collected necessary data to identify the mechanism of releasing P for different type of the soil under application of different type of organic matter . It confirmed that the response to OM application was affected by varying soil P , total Cand Ph and the different quality of applied OM significantly affect P releasing by observing the change of Ph,the olsen-P of incubated soil and the amount of P releasing and Fe in the pore water.

Activity pics with captions:

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN ("FY VARY" SATREPS PROJECT/OUTPUT 4)

Names: - RAFALIMANANTSOA Jules, Responsible research and Development at ONN
- RAZAFIMBELONAINA Harisoa, Researcher, FOFIFA/DRD

In Japan**:** 4rd June – 13th June 2019

I- OBJECTIVE

In the Output4 of the SATREPS-Madagascar project, the main objective of this training/exchange is to propose a policy recommendation to promote the extension of developed technical for rice production in the target region of Madagascar to improve household food and nutrition in collaboration among JIRCAS and Ministry of Agriculture through the National Center of Applied Research and Rural Development (FOFIFA) and National Nutrition Office (ONN).

II- Achievement in JIRCAS and JICA Tsukuba center conducted with Dr Shiratori

The discussion was focused on a brief presentation of activities progress state in Output 4 as well as the precision of adding questionnaires that are not included in the survey sheets. We discussed about the Survey Solutions concerning the survey contains. In that case, it will be necessary to add questionnary to obtain and to highlight any problems related to the effects of climate change. In this case, the analysis of the vulnerability of farmers to the farming system is relevant in order to identify the socio-economic and nutritional problems at the community level. Regarding to the own research on food and nutrition security, the layout of research content is very relevant. Also, the discussion focused in the feasibility of monitoring and supervision of the head quarter to comment or rectify the wrong data collected at the community level and stored in Survey solution. Finally, we acquired knowledge of operation skill of a computer-assisted personal interviewing software using Survey Solutions like the exporting data to excel or to Stata, the designer, the reading of the questionnaires.

The second presentation was carried out with the expert of nutrition at JICA Tsukuba center. The observation of the lecture on "nutritional improvement through agriculture" helped us to improve the nutrition knowledge. The presentation was focused on the survey module related to the scale of measuring food insecurity experienced (FIES survey module) counts eight questions that relate to people's access to adequate food and can be easily integrated to various types of household surveys. Indicators of the three dimensions of food security have been well explained and these three dimensions make it possible to determine the prevalence of food insecurity, to define the household dietary diversity score and the prevalence of under-nutrition. The presentation was coupled with 24-hour recall simulation exercises to determine the food and nutritional status of households in relation to product availability at the household level.

Summary report of research and training in Japan (« FyVary » SATREPS project)

Name: Hobimiarantsoa RAKOTONINDRINA, Laboratoire des Radioisotopes (LRI)-Université d'Antananarivo

Period: 1st July – 26th July 2019

Objective: The main objective of this training was to improve the research skills of output 1 in the development of simple and quick evaluation techniques for soil nutrient characteristics for rice production systems in Madagascar. The planned activities during this training were: (1) simple evaluation techniques for soil chemical properties using soil colorimetric sensor and magnetic sensor, (2) soil particle size distribution analysis by conventional and simplified methods, (3) use of new instrument to detect soil and plant nutrients, (4) soil phosphorus (P) retention analysis, (5) spectral data analysis for soil nutrient prediction.

Achievement in Kyoto University: this training was carried out with Dr. Naoki Moritsuka. We acquired knowledge of using simplified method to analyze particle size distribution as "Nylon mesh" sieving for sand content assessment, and improved basic knowledge of conventional method like "pipette method" for soil texture analysis.

Additionally, we learned about soil color measurement in lab by using simplified tools such as colorimetric sensor "CR-20" which is more accurate than conventional tool as "Munsell color chart" and can be used to predict indirectly soil nutrient content and about magnetic sensor for magnetic susceptibility in lab and in fields and its correlation with soil elements including Al and Fe. We also visited the Soil laboratory at the university and experimental farms cropping system in lowland.

Achievement in JIRCAS: this training was carried out with Dr. Yasuhiro Tsujimoto, Dr. Aung Zaw Oo and Dr. Kensuke Kawamura. The main achievements were:

- Tests in different ways to use new instrument "portable XRF" for assessing soil and plant nutrients efficiently such as P concentration following time of scan, soil samples status (0.2 mm / 2 mm), crushed and without crushed grain samples.
- Method of soil P retention capacity in laboratory.
- Vis-NIRS spectral data analysis using Matlab software with partial least squares (PLS) regression: removal of outliers, Genetic Algorithm (GA)-PLS analysis for oxalate extractable P and organic carbon prediction.
- Discussion in deep regarding determination of geographical and land management factors which can be used for soil nutrient modeling in watershed scale, e.g., elevation, slope, fertilizer application.

Pictures:

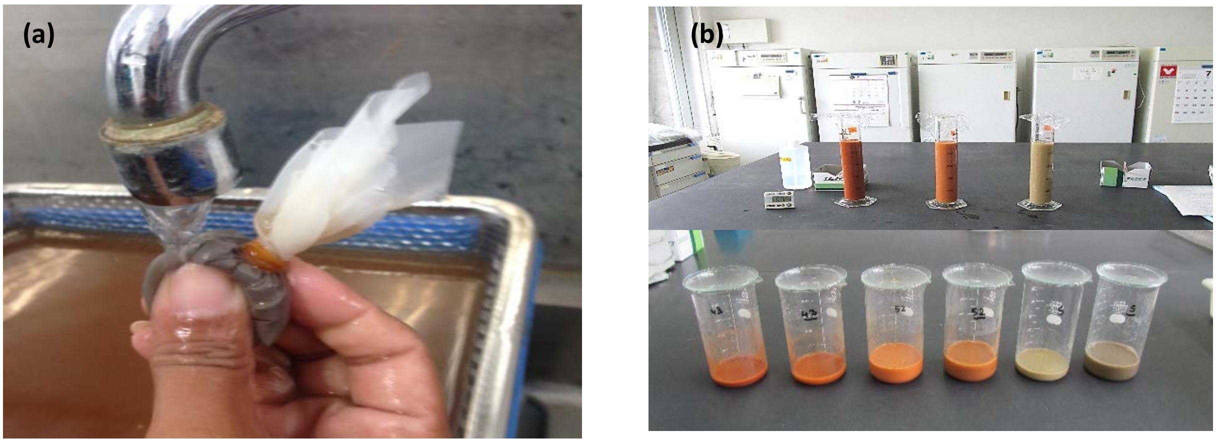


Figure 1: (a) simplified (Nylon mesh) and (b) conventional methods for particle size distribution analysis in Kyoto university lab

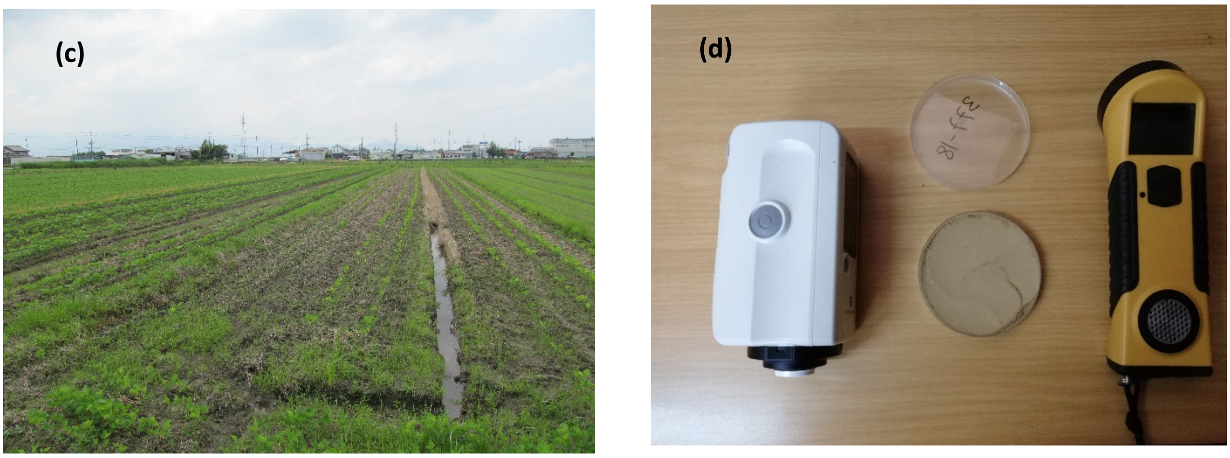


Figure 3: (c) soya bean field experiment in Nara (crop rotation with rice), (d) CR-20 colorimetric tool and magnetic sensor

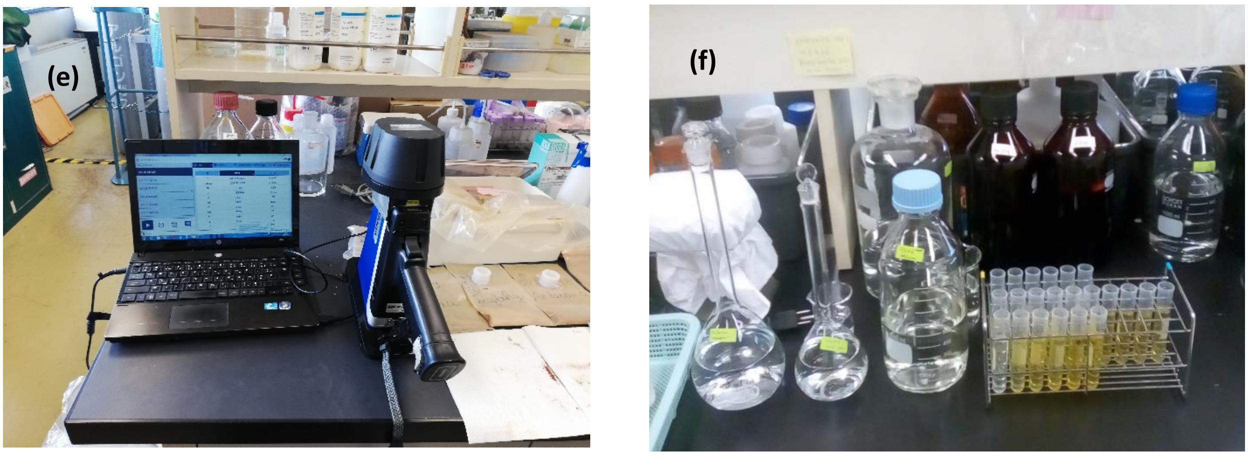


Figure 2: (e) XRF machine for P detection in soil and plant, (f) soil P retention analysis in JIRCAS lab

Summary report of research and training in Japan, « Fy Vary » SATREPS project

Name : Marie-Paule Razafimanantsoa, Laboratoire des Radioisotopes, Université d'Antananarivo

Period : June 30th to July 16th

Objective : to improve skills in the use of simple and rapid assessment techniques for soil and plant analysis.

Achievement in JIRCAS

This training was supervised by Dr Yasuhiro Tsujimoto
A new instrument, « portable XRF » was used to assess the contents of soil and plant nutrient.
The results showed good correlations to the chemical elements contents in the sample.
A series of scenarios have been carried out to determine the appropriate method to determine the macro element contents, in particular Phosphorus, which are the two main elements studied in our research.
For the soil:
Scenario 1: Scanning sieved soil at 2mm
Scenario 2, scanning crushed soil at 0.2mm
For the plant:
First scenario: scan uncrushed grains
Scenario 2: Scanning grain powders
Each sample in any condition was scanned in 3 replicates
The general conclusion is that the detection limit is better with crushed samples than with non-crushed samples, statistical tests were done.

Achievement in Kyoto University

A method using nylon mesh was tested to determine the sand content of a soil sample.
Two scenarios were tested by changing the duration of the washing time. The results obtained were compared with the results of conventional physical analysis.

Pictures

After weighing, soil samples in the nylon mesh

Sample washing

Portabe XRF

Sample ready to scan with XRF

Summary report of Training in Japan (« FyVary » SATREPS project)

Name: RAHARINIVO Viviane, Department of Rice Research (DRR)-FOFIFA

Period: 6thAugust – 13rd September 2019

Objective: The main objective of this training was to enhance of research capacity on molecular rice breeding for yield improvement under low-productive lowland ecosystems of Madagascar. The planned activities during this training were: (1) Genotyping rice breeding lines in the Madagascar varieties, genetic backgrounds by PCR-electrophoresis basis method, real-time PCR basis method, and selection of promising lines, (2) Crossing the selected lines with the parental Madagascar variety, (3) Technical learning for gene editing by CRISPR-Cas9 system.

Achievement in JIRCAS:

Genotyping rice breeding lines in the Madagascar varieties genetic backgrounds by PCR-electrophoresis

This training was under supervisor of with Dr. Toshiyuki Takai and Dr. Kondo. DNA from 96 F2 individual plants, including parents NDJ123, and X265 was extracted. 576 SSR markers have been used for parental polymorphism survey.

Among the 576 primers, 104 primers were recognized as polymorphism between parent NDJ123 and X265. Seven (07) polymorphic primers for chromosome 7 were used for genotyping F_2 population. PCR was carried out in a 384 well plates with the following conditions: pre-denaturation at 95ºC for 3 min; followed by 36 cycles of denaturation at 95ºC for 30 s, annealing for 30 s (annealing temperature determined by primer pair sequence, usually 55ºC), and extension at 72ºC for 1 min; with a final extension at 72ºC for 5 min. The amplified products were electrophoresed on 3% of agarose gels, and visualized by gel imaging camera.

Genotyping rice breeding lines in the Madagascar varieties genetic backgrounds by real-time PCR

Real-time PCR, it is same principle of amplification, but instead of looking at bands on a gel at the end of the reaction, the process is monitored in “real-time”. Literally, the reaction is placed in to a real-time PCR machine that watches the reaction occur with a camera or detector.

PCR and real-time PCR are highly useful to identify the plants carrying desirable genome of interest.

Strengthen the crossing method

This training was carried out with Dr Toshiyuki Takai, it focused on the cross by using the selected lines with the parental Madagascar variety by using water bath method at 43^{o}C to emasculate the rice plant.

Achievement in JIRCAS Ischigaki: this training was carried out with Dr.Takuma Ishizaki and Dr Toshiyuki Takai the main achievements was the use of *Agrobacterium*-mediated transformation in Rice. For this we had skill concerning the following subject:

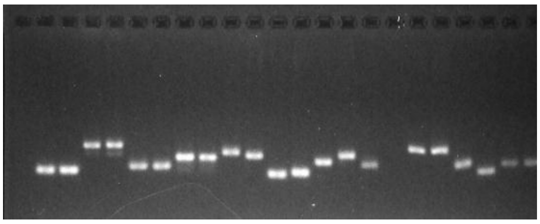
- Electroporation method: it focused on the introduction of plasmid DNA into *Agrobacterium tumefacien*. In the process, small volume sample with high resistance are exposed to pulses with very high electrical field strengths. The short, high voltage pulses create temporary holes or pores in the cell membrane, through which plasmid DNA can diffuse into the cell. Then holes close after removal of the electrical field and period of regeneration. The inserted plasmid DNA can then be transcribed and replicated in the cell.
- Inoculation of *Agrobacterium* to rice callus. It focused by using rice embryon from young seed and inoculated by *Agrobacterium*.

We also accomplished the preparation method of culture media used for tissue culture and transformation. Petri dishes (9 cm in diameter) were used, and all dishes were sealed with medical surgical tape.

Illustration

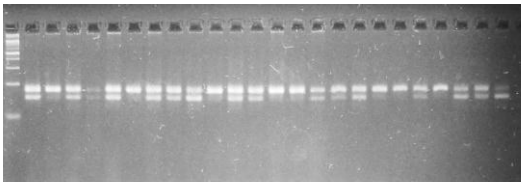
Rice crossing

Collected leaf sample for DNA extraction



Parental polymorphism

Lab work DNA extraction, PCR



F_2 Genotyping

Summary report of research and training in Japan ("Fy Vary" SATREPS project)

Name: Njato Michaël RAKOTOARISOA, FOFIFA/Département de Recherche Rizicole – Tsimbazaza, Antananarivo

Period: 06th August – 14th September 2019

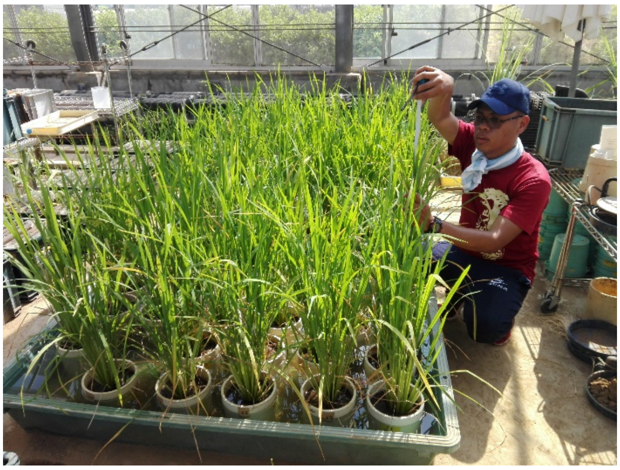
The main objective of this internship was to develop skills of writing the research results as a manuscript for submission to an international refereed journal. In addition, we conducted a pot experiment about P dipping in order to understood well the mechanism of root morphology under localized P application, and P root dipping slurry.

Achievement in Kyoto-University: The training was carried out with Dr Yu Tanaka, assistant professor at Kyoto University (Crop sciences laboratory). During training, we harvested rice crop at the field experiment for a better understanding of biomass weight and harvesting process of the laboratory.

Achievement in JIRCAS: The strategy and steps for writing scientific research article was supervised by Dr Tsujimoto. I had learned about how to write each article session and how to organize data and turning it into knowledge. Results of P dipping experiment conducting in Madagascar during two seasons (2017-2018 and 2018-2019) was analysed during the training. We acquired the notion of referencing by using citation to develop your own argument. One of the important things is to locate your project within an existing field of scientific research. Weather and temperature data were analysed to determine new parameters: the Growing degree days (GDD) and the Cooling degree days (CDD) in order to determine the effect of P dipping treatment on shortening the rice crop duration.

The pot experiment was conducted with Dr Aung Zaw Oo in a greenhouse at Japan International Research Center for Agricultural Science (JIRCAS), Tsukuba, Japan. Two different soil types (weathered soil and volcanic soil) was used to test the effect of P dipping slurry relative to P incorporation. A total of 6 pots were filled with 11 kg of soil. The harvesting was done at the beginning of September and root biomass was collected following a specific method in order to avoid root scorching.

Activity with captions:



Measure of plant height and tiller no.

root biomass collection

Collecting sample for P retention

raising seedling for next pot experiment

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN « FY VARY » - Satreps Project

Name: ANDRIANARY Haja Bruce, Laboratoires des radio-Isotopes – Université d'Antananarivo

Period: 7 August 2019 - 13 September 2019

Objective: The main objective of this training was to improve 1) skills in technical learning for remote sensing to evaluate rice growth and 2) digital imagery analysis and deep learning for evaluating rice growth.

Activities and achievement in JIRCAS:

1) Testing different ways to use the "portable XRF" for assessing total P contents of soils efficiently in different times of X-ray emissions (60/ 120/ 160 seconds) and in different particles size of the samples (0.2/ 2 mm). As a result, we found that 160s duration with 0.2 mm particle size had the highest correlation with the data obtained by chemical analysis.
2) Data analysis conducted using 2018-2019 data to elucidate the correlation between grain yield and the early growth stage of rice and changes in the canopy coverage and biomass. Then, obtained the techniques to calculate the Radiation Use Efficiency and the light Interception during rice growth periods.
3) Learned spectral data analysis (measured by MS 720 Spectroradiometer) to predict rice biomass: Spectral pre-treatment, outlier analysis, and creating model using Partial Least Squares (PLS) regression analysis on MATLAB. To estimate rice biomass, Full Spectrum PLS (FS-PLS) and Iterative Stepwise Elimination PLS (ISE-PLS) were performed on the reflectance (observed spectral data) and the First Derivated reflectance (FDR).

Activities and achievement in Kyoto: The activity in Kyoto University was realized with Dr Yu TANAKA about deep learning method from the sampling method and the canopy photo shooting, up to the modelling. Rice biomass was estimated using pictures (from normal camera) taken from above the rice canopy. Deep learning analysis was performed using Neural Network Console (NNC) Software.

Figure 2: Soil nutrients measurement using the portable XRF

Figure 1: Biomass sampling for the deep learning

SUMMARY REPORT OF RESEARCH AND TRAINING IN JAPAN
(“Fy Vary” SATREPS project)

Name : RANAIVO Harisoa Nicole – FOFIFA Rice Research Department-Madagascar
Objective(s) : The main objective of this short term training in JIRCAS was to select and characterize breeding lines for Malagasy low -input conditions using the markers assisted selection approach.
Period: July 1st – August 29th 2022

The planned activities during this training period were

- Selection of best upland breeding lines in populations developed from Malagasy varieties and preparation of seed transfer
- Develop marker sets for transfer to FOFIFA, based on all identified loci, and candidate genes
- Training in QTL mapping, linkage map construction and marker assisted selection and RNA-extraction, for gene expression analysis of FYVARY varieties.
- QTL mapping of field performance traits, and root traits including root branching

Achievement during the stay in Japan (JIRCAS)

1) **Selection of upland breeding lines - Ishigaki**

Upland breeding evaluation and selection was carried out together with Dr Matthias (Senior Scientist in JIRCAS) in Ishigaki. Lines were selected according to its tolerance to Phosphorus deficiency tolerance. Several lines derived from the cross between DJ123 and X265, and CG34 and WAB exhibited longer panicles and higher yields. In addition, seeds of selected breeding lines were sown to continue their field performance evaluation and marker selection in the next cropping season. In addition, seeds of selected breeding lines were examined by the Japanese Plant Quarantine Office, and will be hand-carried in our way home.

2) **QTL analysis in the cross DJ123 x Nerica 4**

This training was carried out with Dr Matthias Wissuwa, Dr Pariasca-Tanaka Juan and Dr Ueda. QTL for the cross DJ123 x Nerica 4 was confirmed, and thanks to the markers training and close supervision, a manuscript summarizing all the results was submitted during this training period. As a main result of this manuscript, one peak related to early seedling vigor was detected on chromosome 9. Candidate lines were selected and characterized in detail in the field and greenhouse. Root scanning was carried out and the images will be analyzed using the Win-Rhizo software.

3) **Characterization of root traits in elite breeding lines**

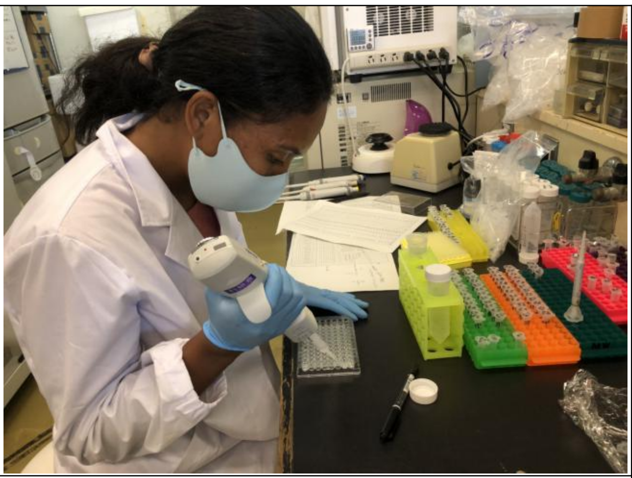
Characterization of root and shoot traits of elite breeding lines were performed under different P concentration in nutrient solution experiment, and field condition. Phosphorus content was determined through P digestion (nitrate/perchloric acid), using colorimetric method (Molybdenum blue).

4) **Expression of Pup1-related genes in the FyVary32 cultivar**

An experiment aiming to characterize the expression of Pup1-related genes in the FyVary32 cultivar was carried out for 35 days under hydroponic condition. Shoot, root and crown tissue were collected for RNA extraction. RNA was isolated using RNA iso protocol and RT_PCR performed. Gene expression for the PsTOL1 gene was performed for a set of samples. Due to time constraint complete expression profile will be conducted by the research team members.

Ongoing research: Thanks to this training in Japan, papers were submitted but ongoing paper related to roots traits and Phosphorus deficiency is on progress, based on the experiment that I have been done during my stay here in JIRCAS.

Illustrations of the carried activities

		
Root sampling from nutrient solution experiment in JIRCAS	Phosphorus measurement in microplate reader using molyblue method	
		
Plant digging out at Hachimantai field for root and shoot characterization	Upland rice selection and harvest in Ishigaki	
		
Preparing tubes for Phosphorus digestion	PH measurement of the nutrient solution	

Name: RAKOTONDRAMANANA Mbolatantely Fahazavana, FOFIFA/ Rice research Department.
Period: 04th July-29th August 2022

Objective:

The main objective of this training was to characterize the newly released varieties FyVary32, FyVary85 and high Zinc lines for Madagascar. To achieve the purpose, the following activities were planned: 1) Training in marker assisted selection using Pup1-related markers, and RNA extraction to determine their expression; 2) Field and greenhouse experiments to determine P uptake and root traits of FyVary32 and FyVary85; 3) Acid digestion and ICP analysis of the high zinc lines from Madagascar 2021 experiments in order to confirm the results from the XRF and to calibrate the XRF on rice grain and straw zinc analysis, 4) Analysis of Zn grain content of elite breeding lines to select potential high-zinc candidate lines for transfer to Madagascar.

Achievments in Jircas:

Upland breeding evaluation and selection was carried out together with Dr Matthias in Ishigaki. Several lines derived from the cross between DJ123 and X265, and CG34 and WAB exhibited longer panicles and higher yield. In addition, seeds of selected breeding lines were sown to continue their field performance evaluation and marker selection in the next cropping season.

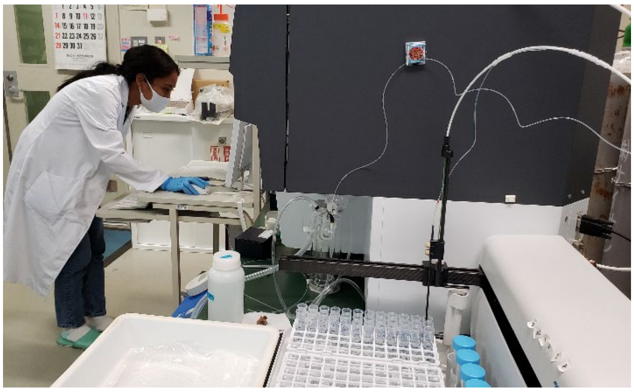
The characterization of the FyVary varieties was done in the field of Tsukuba and in greenhouse under nutrient solution with the supervision of Dr Matthias WISSUWA and Dr Juan TANAKA. The FyVary lines was compared with X265, DJ123 and N4 under different level of P and in different time point of sampling. The phenotyping of roots was performed by counting the number of roots and root scanning. The root images will be analyzed using the Win-Rhizo software.
To characterize the expression of Pup1-related genes in the FyVary32 cultivar an experiment was carried out for 35 days under hydroponic condition. Shoot, root and crown tissue were collected for RNA extraction. RNA was isolated and RT_PCR performed. Gene expression for the PsTOL1 gene was performed for a set of samples.

Grain of advanced breeding lines from DJ123*X265 and DJ123*N4 were analyzed for their zinc content analysis. In addition, different tissues from X265 and the high-zinc lines IRIS1008, IRIS79 (reported in previous study of Genomic Selection and the GWAS analysis) were sampled in detail (panicle, flag leaf, young leaf, old leaf) in three times points (heading, 15 days after flowering and maturity stages) for physiological study. The purpose of this study is to distinguish the strategy of each breeding line in term of zinc uptake, translocation and loading in the plant and the grain. Moreover, Zn content were determined in straw and grain samples of those lines from Madagascar experiments confirm the results from the XRF analysis (performed in Madagascar). The results from the ICP analysis will be used to calibrate the XRF in Madagascar. Tissues were digested using nitrate and perchloric acid, filtered and injected into a ICP equipment.

Crosses between IRIS1008 and X265 were done to get new population for future study. These cross will allow us to select X265 grain type lines which are liked by the Malagasy farmers but with high zinc. QTL mapping will be done in the future to extend the research about zinc biofortification.

Activities with captions:

1-sample preparation for acid digestion



2-ICP analysis

3-RNA Extraction

4-crossing process

Summary report of training and research in Japan (“Fy Vary” SATREPS project)

Name: ANDRIAMANANJARA Andry, Laboratoire des Radio-Isotopes (LRI)-University of Antananarivo

Period : 15th July – 30th August 2022

Objectives:

The objectives of this training were (i) to conduct soil analysis for physicochemical properties of experimental soils (P and N fractionation) after 5 years nutrient management under different soil P availability, (ii) to perform statistical analysis for on-farm trial for validation of optimized FYM application method on 40 sites in Behenjy, and starting the manuscript preparation on on-farm trial practiced on 40 sites in Behenjy, and (iii) to manage all processes related to the GHG measurement in flooded rice field.

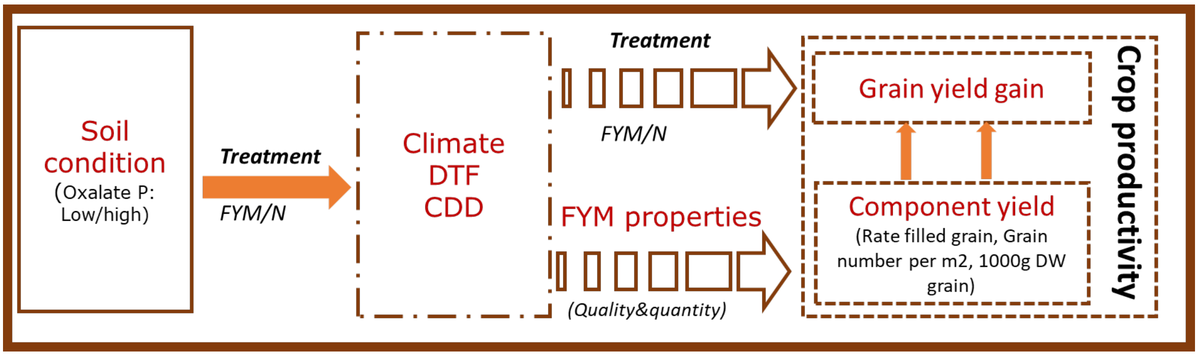
Achievement in JIRCAS

Data handling for validation of optimized FYM application method on 40 sites: This training was carried out with Dr. Asai Hidetoshi. The main activities were:

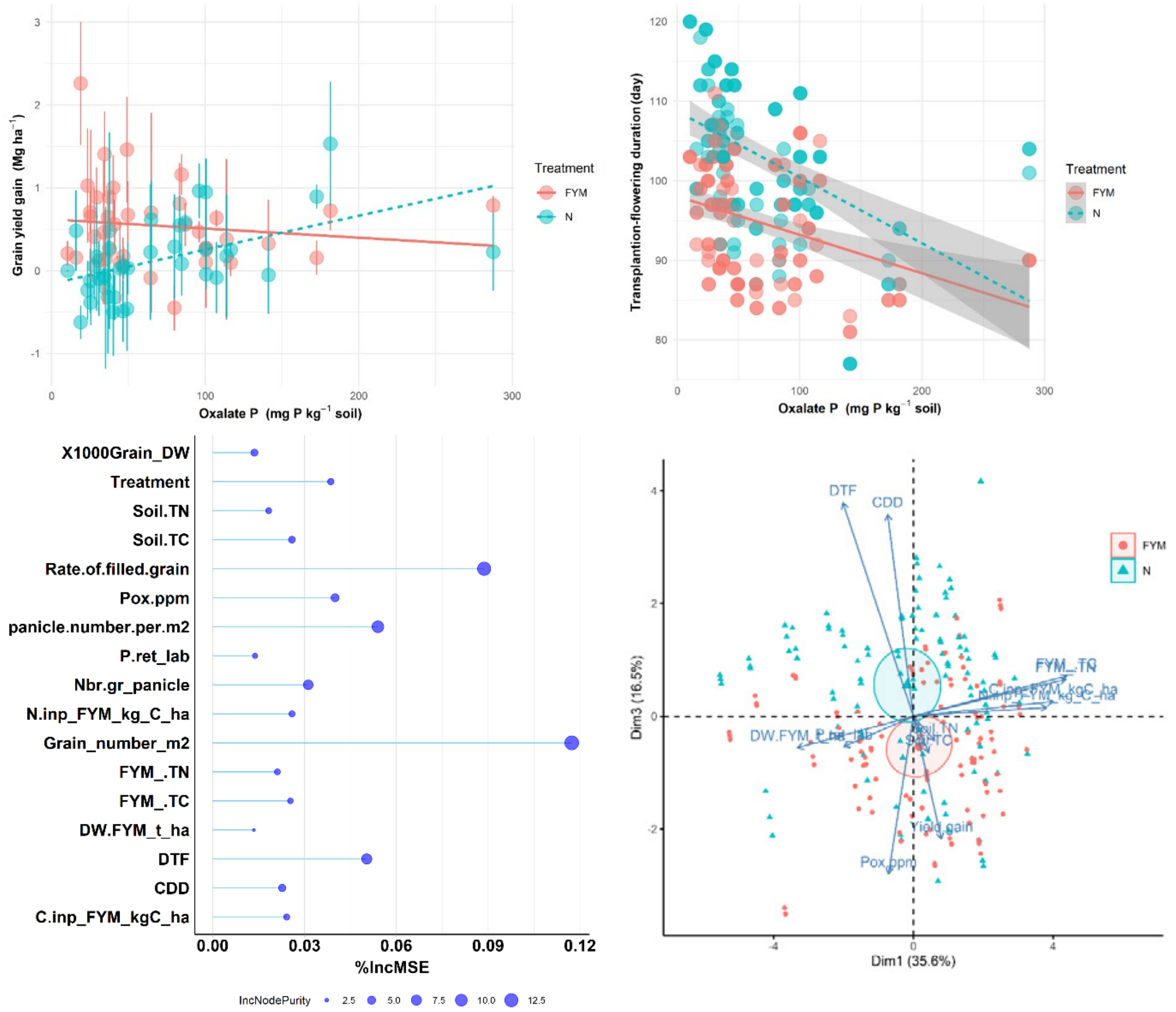
-Compilation of all collected data and calculation of different parameters related to the grain yield (components of grain yield), plant parameters (transplanting and flowering dates), soil parameters (Oxalate P, total C, and total N), and climate parameter (Cold degree day, Duration between Transplanting and Flowering dates).

- Statistical analysis using different tests (simple linear regression, nonlinear regression, analysis of variance, correlation, …) and multivariate analyses (as Bayesian analysis).

-Writing of draft of paper (“Farmyard manure influences rice productivity in lowland flooded rice conditions”).



Conceptual scheme of research question assuming the indirect effect of soil P condition on grain yield gain by shortening DTF/CDD under FYM application, and the related direct effect of component yield.



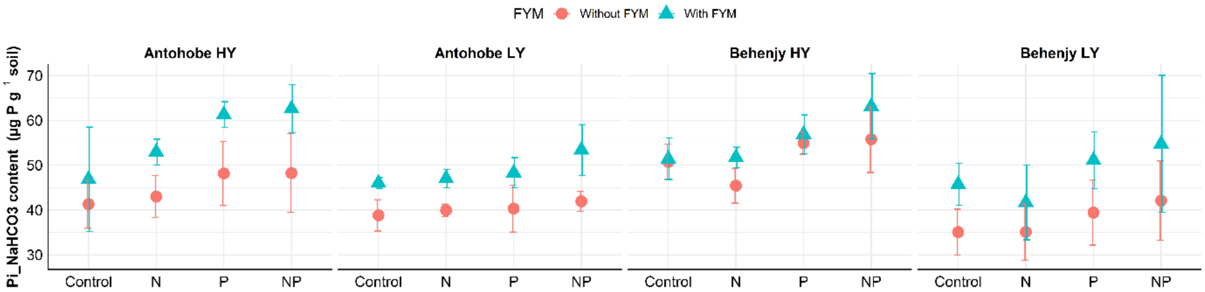
Rice productivity as affected by FYM, soil type and climate parameters.

Chemical analysis of experimental soils (P and N fractionation) after 5 years nutrient management under different soil P condition

This research activities were conducted with Dr. Asai Hidetoshi and Dr. Tomohiro Nishigaki. The main activities were:

- Preparation of soil and reagents required for P fractionation analysis according to Hedley method (Hedley et al., 1982) modified by Nishigaki.
- Extraction procedure using the four reagents estimating different P fractions according to theirs availability.
- Measurement of different P fractions using Molybdenum Blue Method.

Extraction procedure for P fractionation

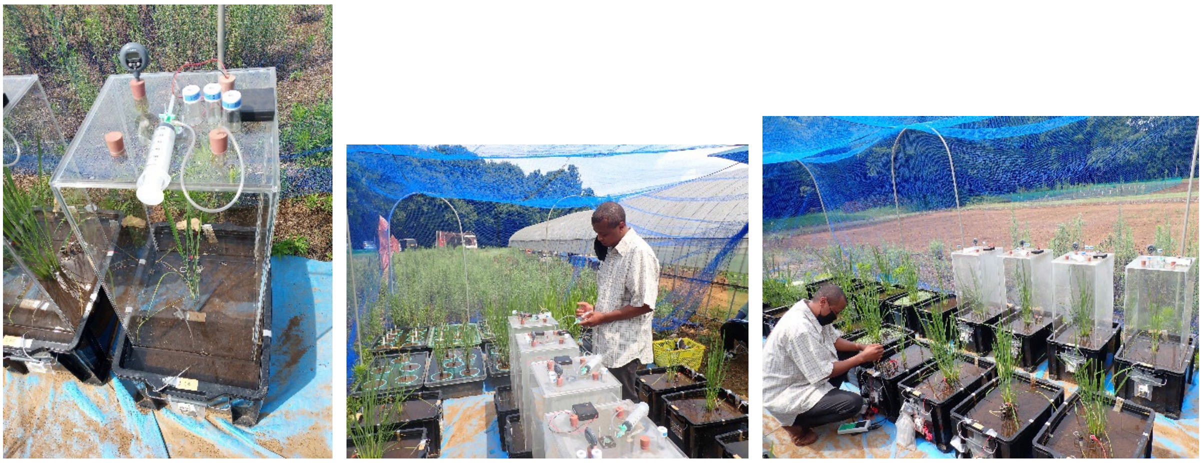


Inorganic NaHCO3-P as affected by FYM and mineral fertilizer treatments in four studied areas.

<u>*Assessment of Greenhouse gaz (GHG) in flooded rice :*</u> The training was carried out with Dr. Aung Zaw Oo. The main activities were:

- Visiting National Institute of Agro-environmental research: I was in contact of the head of department and informed of advanced different equipments involved in the GHG measurement. Measurement of GHG (CH4, CO2, and N2O) are performed using Specific Gaz Chromatography (GC)
- Measurement of GHG in flooded rice pot experiment: The tested treatments of the pot experiment were Control, P-dipping, High FYM, Low FYM (with 04 replications) in order to assess the potential of P-dipping approach in term of GHG emission. The different steps of the GHG assessment are: preparation of the vials (under vacuum), sampling of the GHG using 4-6 air chambers, and measurement of GHG in GC.

Visiting NIAE: Gaz chromatography, automatic GHG sampling



GHG sampling and plant parameters measurements in pot experiment

Summary report of Training in Japan (« FyVary SATREPS project)

Name: RAHARINIVO Viviane, Department of Rice Research (DRR)-FOFIFA

Period: 12nd August – 31st August 2022

Objective: The main objective of this training was to mastered 1) crossing methods under high temperature and dry conditions, 2) strengthen genotyping process activity and 3) using software for genetic analysis

Activities and achievement in JIRCAS:

1- Crossing methods under high temperature and dry conditions.

This training was under the supervision of Dr. Toshiyuki Takai. This activity focused on the cross rice by using water bath method at 43°C to emasculate rice plant and cross under high temperature and dry condition, it is an improved method achieved in JIRCAS. This method avoids the impact of anther dehiscence and disperse pollen grains because of high temperature, which reduce pollen numbers on the stigma and, eventually, the fertility rate.

2- Genotyping of TBQ3-32, this activity supervised by Dr. Toshiyuki Takai, this activity focused on sowed 96 X 2 plants followed by DNA extraction and genotying process.

3- Deep learning for genetic analysis, this training was carried out by Dr. Sakata.

QTL mapping was performed using AntMap Ver.1.2 software and Windows QTL cartographer 2.5 software.

Phenotyping data and genotyping data of lines from AZ-97 and X265 will be analyzed using learned software.

Pictures

Figure 1: Crossing under high temperature and dry condition

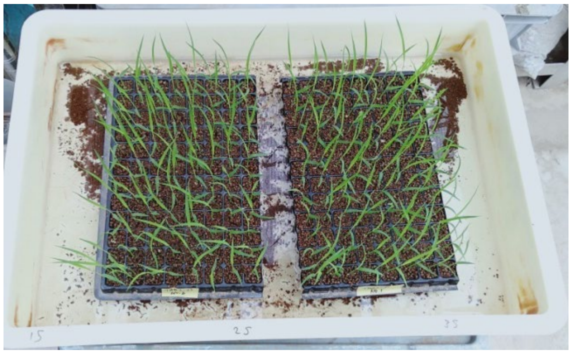


Figure 2: Sprout seed before sowing and seedling plant for leaf sampling

Figure3: Agarose electrophoresis of PCR product for genotyping

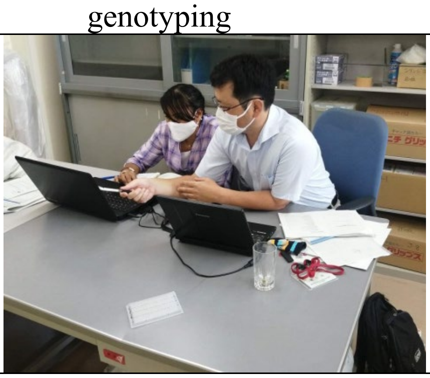


Figure 4: Learn of genetic analysis software with Dr Sakata

Annex 5 Media Coverage

*The online links which are valid as of Aug31, 2022 are shown.

- The kick-off meeting of the project, held on October 5, 2017 was broadcasted on radio (9 programs), TV (4 programs), and featured in newspaper (4 articles) and online journal (1 article).

- An article on the joint statement of the summit meeting between Japan and Madagascar held on December 3 to 6, 2017 was posted on the website of the Ministry of Foreign Affairs of Japan (MOFA). In the summit, the President of Madagascar expressed his appreciation on the activities of this project as mentioned in the "Cultural, academic, and human exchange" section of the joint leaders' statement of the two countries when he visited Japan.
  https://www.mofa.go.jp/mofaj/files/000313749.pdf

- The joint press conference between JIRCAS President and the Secretary General of the Ministry of Agriculture and Livestock held on March 1, 2018 was broadcasted on radio (1 program) and TV (2 programs) in Madagascar.

- The unveiling ceremony of the genetic analysis laboratory, breeding facility, and the remote sensing and soil analysis laboratory constructed under the project, which was held on March 1, 2018 and attended by the Minister of Agriculture, Livestock and Fisheries, was broadcasted on TV (1 program) and featured in newspaper (1 article).

  TVM (17:29-19:38)
  https://www.youtube.com/watch?v=h5gdcmcH6jQ

- The research activities of Dr. TSUJIMOTO Yasuhiro, Fy Vary Project leader, including an overview of the project, was featured in a newspaper (LE Soleil) article in Senegal on July 4, 2019.
  http://lesoleil.sn/japon-tsukuba-terre-dinnovations-agricoles/

- The research activities of Dr. TSUJIMOTO Yasuhiro, Fy Vary Project leader, including an overview of the project, was featured in a newspaper (EgyptToday) article in Egypt on July 5, 2019.
  https://www.egypttoday.com/Article/3/72471/Could-developing-agriculture-in-Egypt-s-Delta-be-part-of

- The 3rd Joint Coordination Committee (JCC) meeting held on July 12, 2019 was broadcasted on TV (1 program) and reported in newspaper (2 articles). The partner country's representative and Dr. Tsujimoto were interviewed, and the project overview and progress were also reported.

MidiMadagasikara
http://www.midi-madagasikara.mg/societe/2019/07/15/projet-fy-vary-les-changements-climatiques-pris-en-compte/

MTV Vaovao
https://www.youtube.com/watch?v=krfXUKtEUpY

- The workshop for mid-term evaluation of the project including overview and results to date held on December 12, 2019 was broadcasted on radio (2 programs), TV (3 programs) and reported in newspaper (2 articles).

TVM (21:18-23:41)
https://www.youtube.com/watch?v=qDS1gTRzqz0

KOLO TV (38:54-41:53)
https://www.youtube.com/watch?v=fepDPgfLohQ

Midi Madagasikara (p9)	L'Express (p7)
	

2019

9

Projet "Fy Vary"

Une amélioration variétale pour augmenter la productivité

Le projet « *Fy Vary* », mis en œuvre depuis mai 2017 dans la région de Vakinankaratra, pour une période de cinq ans, s'inscrit dans le cadre du Partenariat de Recherche sur la Science et la Technologie pour le Développement Durable (SATREPS), financé par la JICA (Agence Internationale de Coopération Japonaise) et JST ou Japan Science and Technology ainsi que Madagascar. L'objectif consiste à élaborer les techniques de production de riz pour améliorer le rendement de productivité même dans les conditions de sols à faible apport en intrants et peu fertiles. Pour ce faire, « *une amélioration variétale de semences par le biais de la biologie moléculaire, entre autres, a été menée en collaboration avec le centre de recherche FOFIFA. Ce qui a permis de sélectionner dix lignées prometteuses. Si ces résultats de recherche sont confirmés, on peut procéder à l'homologation et à la diffusion de variétés de semences de riz plus performantes au profit des petits paysans* », a expliqué Yasi Tsujimoto, le chef de projet « *Fy Vary* », lors d'une évaluation à mi-parcours de ce projet hier à l'hôtel Colbert.

Sélection participative. Le directeur général de FOFIFA, le Pr Razafinjara Lala Aimé, a rajouté que la variété X 265 est très prisée par les paysans. « *L'application d'une nouvelle technique dans le processus d'amélioration variétale tout en maintenant les meilleurs caractéristiques de ce X 265, a contribué à l'obtention d'une variété stable en 2 à 3 ans seulement contre 8 à 9 ans pour la méthode conventionnelle. En outre, une sélection variétale participative, a été effectuée grâce aux consultations des paysans pour que le résultat obtenu puisse bien correspondre à leurs besoins* », a-t-il enchaîné. Notons que le projet « *Fy Vary* » a mis en place un nouveau laboratoire génétique et une infrastructure de croisement au sein de FOFIFA afin d'accélérer la sélection du riz pour le développement de nouvelles variétés à Madagascar.

Fertilité de sols. Par ailleurs, le projet a installé des équipements de recherche sur les sols et de télédétection permettant de réaliser l'évaluation de la fertilité des sols. En fait, « *cette technique consiste à identifier l'état des éléments nutritifs composant les sols. On peut citer, entre autres, le phosphore, le carbone et l'azote. On peut ensuite améliorer le dosage des engrais à utiliser après avoir détecté les nutriments qui manquent* », a souligné le Chef du projet « *Fy Vary* ». Le développement d'une technique de gestion des engrais, n'est pas en reste dans le but d'améliorer l'efficacité de l'utilisation de ces engrais et le rendement de productivité de riz dans les sols pauvres en phosphore. Et toujours dans le cadre de la coopération entre Madagascar et le Japon, le projet « *Fy Vary* » a contribué au renforcement de capacité de la recherche sur le riz à Madagascar. Ainsi, 21 chercheurs malgaches ont été formés au Japon sans compter les missions effectuées par des chercheurs japonais dans la Grande île.

Navalona R.

FILIÈRE RIZICOLE

Introduction de variété de riz pour les sols fertiles

Faire avancer le développement par les personnes et les technologies, c'est l'objectif que se fixent les initiateurs du projet FY VARY (Fertility sensing and Variety Amelioration for RiceYeld) ou détection de la fertilité et amélioration variétale pour le rendement du riz. Pour ce faire, une évaluation des résultats du projet a été effectuée avant-hier à Antaninarenina. Étant à mi-parcours, le FY VARY, qui a débuté en 2017, sera finalisé d'ici trois ans.

Le projet, financé à hauteur de 12,7 milliards d'ariary pour une durée de cinq ans, sera mis en œuvre dans les régions Vakinankaratra, Analamanga et Alaotra-Mangoro. « *FY VARY vise à développer des techniques de production de riz pour améliorer l'efficacité d'utilisation de nutriments dans les conditions de sols à faibles intrants et peu fertiles à Madagascar, et sera principalement mis en œuvre dans les régions des Hautes Terres centrales. Pour cela, le projet comprend quatre axes de recherche, dont le développement de techniques d'évaluation et de cartographie des caractéristiques en termes de nutriments de champs* », explique le docteur Tsujimoto Yasuhiro, chef de projet.

H.R.

- The visit to the project's test fields on Jan 27, 2020 was reported in 3 newspaper articles highlighting the P-dipping technology and other promising technologies for improving rice production in the country.

  MidiMadagasikara
  http://www.midi-madagasikara.mg/societe/2020/01/27/madagascar-japon-un-bond-pour-la-filiere-riz-dici-a-deux-ans/

  Les Nouvelle (p11)

  Projet Fy Vary

  Phase de test pour la technique P-dipping

- The technology developed by the project such as P-dipping, the promising rice varieties as well as the interviews of counterparts and cooperating farmers were featured in a TV program on February 22, 2020.

- The phosphorus dipping treatment of transplanted seedlings, which facilitates improvement in rice yield and avoidance of cold damage, was featured in a newspaper article published on May 15, 2020 and JST news on June 1, 2020.

  JST News (June 1st, 2020)
  https://www.jst.go.jp/pr/jst-news/backnumber/2020/202006/pdf/2020_06_p06-07.pdf

- Newspaper articles (3) published on January 27, 2021 featured the FOFIFA researchers and laboratories developed by the Project. The featured contents were followed by the MINAE official FACEBOOK video.
  https://web.facebook.com/watch/?v=455935952246809

- The visit of Minister of MINAE, Minister of Internal Affairs, Governor of Vakinankaratra, and Ambassador of Japan to the Project trial site was broadcasted on radio (3 program) and TV (2 programs) on February 26, 2021, and reported in 2 newspaper articles on Feb 27, 2021.

Midi Madagasikara

SOCIETE 27 février 2021

Projet Fy Vary : La vulgarisation de la technique rizicole japonaise sur la bonne voie

Temps de lecture : 2 min.

Les producteurs sur les Hautes terres s'imprègnent petit à petit du P-dipping. Cette technique accélère la croissance initiale du riz ainsi que la date de la floraison de la récolte.

La démonstration du P-dipping du projet Fy Vary s'est tenue à Behenjy avec tous les acteurs concernés.

Des avancées. Le P-dipping, qui consiste à imprégner les jeunes touffes de riz dans un mélange composé de boue, d'eau et d'engrais phosphaté juste avant le repiquage, commence à être adopté par les paysans. Bien que nous soyons encore dans la phase de test et que cette technique japonaise du projet Fy Vary ne soit pas encore homologuée, les résultats sont déjà palpables du côté de Behenjy dans la région de Vakinankaratra. En effet, cette technique permet de réduire significativement la quantité d'engrais utilisée par les riziculteurs, soit jusqu'au tiers, tout en augmentant la production rizicole. C'est durant une séance de démonstration de cette technique à Behenjy que l'Ambassadeur du Japon à Madagascar, Yoshihito Higuchi, a fait savoir que cette technique contribue activement à l'autonomisation alimentaire de la Grande Île. *« Le changement climatique cause beaucoup de perturbations dans le calendrier cultural. Il est donc très important de raccourcir le cycle de production tout en améliorant la productivité»,* a-t-il souligné

L'application de cette technique peut se faire dans toutes les conditions climatiques des hautes terres centrales. Sous les conditions plus froides des hautes terres telles que Behenjy et Ambohibary, l'augmentation de la production est de 20% à 30% en moyenne par rapport à l'application conventionnelle d'engrais. *« Cette technique ne demande qu'une faible quantité d'engrais à appliquer sur la parcelle et permet de réduire les dépenses. Le Triple super phosphate ou TSP est, jusqu'ici, le seul type d'engrais utilisé pour cette pratique »,* témoigne Nivo Mampionondraibe, une paysanne du côté de Behenjy. Le ministre de l'Agriculture, de l'élevage et de la pêche, Lucien Ranarivelo, quant à lui, a félicité les chercheurs malgaches au niveau du Centre national de recherches appliquées au développement rural (FOFIFA) d'avoir apporté leur savoir-faire dans la mise en œuvre de ce projet. Il a indiqué que la vulgarisation de cette technique à l'échelle nationale pourrait se faire d'ici deux ans après son homologation.

Narindra Rakotobe

- The 5th Joint Coordination Committee (JCC) meeting held on Oct 12, 2021 was featured in radio broadcast (1), TV coverage (5), newspaper articles (2) and online article (1).

KOLO TV(37:17-38:19)
https://www.youtube.com/watch?v=Si4Fpc5bzPk

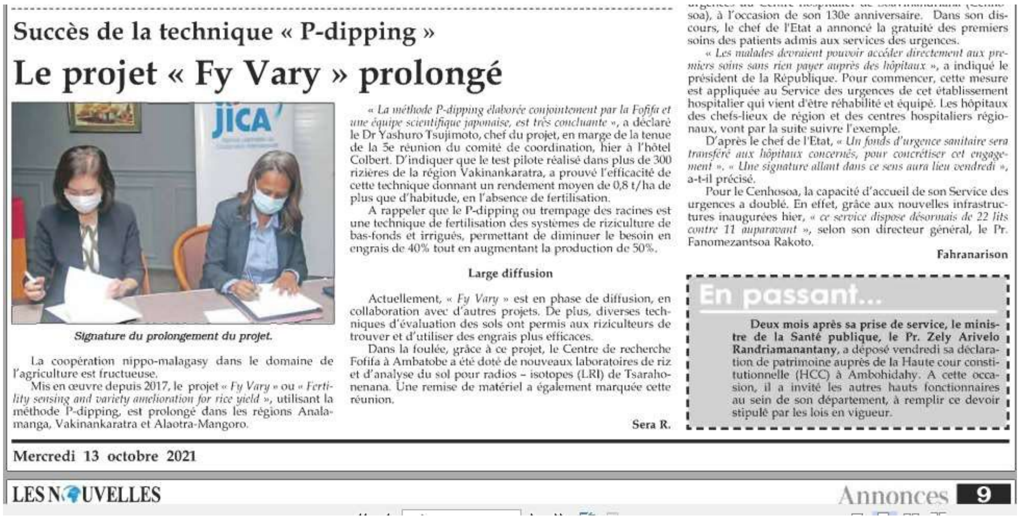
iBC News (28:50:-32:11)
https://youtu.be/WnchcA_07K0

TNTV News (13:17-16:13)
https://www.youtube.com/watch?v=lw8nZj5ADDw

Le Jite (21:15-23:54)

https://youtu.be/K2-gd7XpklY

Les Nouvelles (p8)



Succès de la technique « P-dipping »

Le projet « Fy Vary » prolongé

Signature du prolongement du projet.

La coopération nippo-malagasy dans le domaine de l'agriculture est fructueuse.

Mis en œuvre depuis 2017, le projet « *Fy Vary* » ou « *Fertility sensing and variety amelioration for rice yield* », utilisant la méthode P-dipping, est prolongé dans les régions Analamanga, Vakinankaratra et Alaotra-Mangoro.

« *La méthode P-dipping élaborée conjointement par la Fofifa et une équipe scientifique japonaise, est très concluante* », a déclaré le Dr Yashuro Tsujimoto, chef du projet, en marge de la tenue de la 5e réunion du comité de coordination, hier à l'hôtel Colbert. D'indiquer que le test pilote réalisé dans plus de 300 rizières de la région Vakinankaratra, a prouvé l'efficacité de cette technique donnant un rendement moyen de 0,8 t/ha de plus que d'habitude, en l'absence de fertilisation.

A rappeler que le P-dipping ou trempage des racines est une technique de fertilisation des systèmes de riziculture de bas-fonds et irrigués, permettant de diminuer le besoin en engrais de 40% tout en augmentant la production de 50%.

Large diffusion

Actuellement, « *Fy Vary* » est en phase de diffusion, en collaboration avec d'autres projets. De plus, diverses techniques d'évaluation des sols ont permis aux riziculteurs de trouver et d'utiliser des engrais plus efficaces.

Dans la foulée, grâce à ce projet, le Centre de recherche Fofifa à Ambatobe a été doté de nouveaux laboratoires de riz et d'analyse du sol pour radios – isotopes (LRI) de Tsarahonenana. Une remise de matériel a également marquée cette réunion.

Sera R.

soa), à l'occasion de son 130e anniversaire. Dans son discours, le chef de l'Etat a annoncé la gratuité des premiers soins des patients admis aux services des urgences.

« *Les malades devraient pouvoir accéder directement aux premiers soins sans rien payer auprès des hôpitaux* », a indiqué le président de la République. Pour commencer, cette mesure est appliquée au Service des urgences de cet établissement hospitalier qui vient d'être réhabilité et équipé. Les hôpitaux des chefs-lieux de région et des centres hospitaliers régionaux, vont par la suite suivre l'exemple.

D'après le chef de l'Etat, « *Un fonds d'urgence sanitaire sera transféré aux hôpitaux concernés, pour concrétiser cet engagement* ». « *Une signature allant dans ce sens aura lieu vendredi* », a-t-il précisé.

Pour le Cenhosoa, la capacité d'accueil de son Service des urgences a doublé. En effet, grâce aux nouvelles infrastructures inaugurées hier, « *ce service dispose désormais de 22 lits contre 11 auparavant* », selon son directeur général, le Pr. Fanomezantsoa Rakoto.

Fahranarison

En passant...

Deux mois après sa prise de service, le ministre de la Santé publique, le Pr. Zely Arivelo Randriamanantany, a déposé vendredi sa déclaration de patrimoine auprès de la Haute cour constitutionnelle (HCC) à Ambohidahy. A cette occasion, il a invité les autres hauts fonctionnaires au sein de son département, à remplir ce devoir stipulé par les lois en vigueur.

Mercredi 13 octobre 2021

LES NOUVELLES Annonces 9

L'Express de Madagascar (p6)

6 A LA UNE

RIZICULTURE

Le projet Fyvary fait ses preuves

Le projet Fyvary continue son petit bonhomme de chemin. Les résultats sont notables.

PHOTO D'ARCHIVES DE L'EXPRESS DE MADAGASCAR

Des techniques de riziculture améliorées permettent d'augmenter le rendement à l'hectare.

Le projet Fyvary (FertilitY sensing and Variety Amelioration for Rice Yield), en partenariat avec le Japon, a débuté en mai 2017 pour une période de cinq ans. Le projet vise à développer des techniques de production du riz pour améliorer l'efficience d'utilisation des nutriments dans les conditions de sols à faibles intrants et peu fertiles à Madagascar et est principalement mis en œuvre dans les Régions du Vakinankaratra, Analamanga et Alaotra-Mangoro.

Le projet est mis en œuvre en partenariat avec le ministère de l'Agriculture et de l'élevage, celui de l'Enseignement supérieur et de la recherche scientifique, le FOFIFA, le LRI et l'ONN et le Japan International Research Institute for Agricultural Sciences (JIRCAS). Une réunion de comité de coordination conjointe s'est tenue hier à l'hôtel Colbert Antaninarenina. Quatre techniques de production rizicole en particulier ont été rapportées comme performantes après des tests-pilotes sur terrain.

« *Il y a la technique P-dipping, une méthode novatrice mais facile à utiliser pour les petits exploitants agricoles. Cela consiste à tremper les racines de jeunes plants de riz dans un liquide boueux préparé en mélangeant une petite quantité d'engrais phosphaté et de la terre de rizière, puis transplanter* » a rapporté le chef de projet de la partie japonaise.

Le test pilote a été mis en œuvre dans plus de trois cent champs des agriculteurs de la région de Vakinankaratra. Le résultat a confirmé que la technique était particulièrement efficace dans les champs qui étaient à faibles intrants et à faible rendement. Le projet a en outre développé de nouvelles variétés de riz adaptées au bas-fond en répétant les expérimentations sur les champs des agriculteurs dans plusieurs endroits différents pendant plus de 5 ans. Diverses techniques d'évaluation des sols permettent aux agriculteurs d'utiliser les engrais plus efficacement, en fonction des caractéristiques propriétés physico-chimiques de leurs champs. Quatrièmement, une analyse unique au Projet pour allier la riziculture à la nutrition humaine a été menée. Le projet apporte une contribution à la recherche et au développement dans le secteur agricole du pays en créant de nouveaux laboratoires pour la sélection du riz et pour l'analyse des sols.

Recueillis par Mirana Ihariliva

- The release of new rice Varieties, FyVary 32 and FyVary 85, was reported on TV and featured in 6 newspaper articles published from November 4 to December 17, 2021.

Orange
https://actu.orange.mg/fy-vary-32-et-fy-vary-85-deux-nouvelles-varietes-de-riz-pour-ameliorer-la-productivite-rizicole/

Le JITE (33:43-36:43)

https://www.youtube.com/watch?v=hwN49aaNJ-Y

MINAE official Facebook

- The Fy Vary Project was promoted in a TVM on Nov 28, 2021.

Other online articles and materials

Project Promotion Video
https://www.youtube.com/channel/UC7XWJIDVAWm63A-m8kgJeMw

2016.3.17.
Agriculture Minister of Madagascar Visits JIRCAS
https://www.jircas.go.jp/en/reports/2015/r20160317

2018.3.6
Courtesy visit to the Director-General of Ministry of Agriculture, Livestock and Fisheries of Madagascar
https://www.jircas.go.jp/en/reports/2017/r20180306

2018.10.5
Visit of Minister Randriarimanana of Madagascar to JIRCAS
https://www.jircas.go.jp/en/reports/2018/r20181005

2018.10.9
Bilateral Meetings with the Agriculture Ministers of Madagascar and Senegal
https://www.jircas.go.jp/en/reports/2018/r20181009

2019.5.20
Inauguration of the research facilities developed by the SATREPS Madagascar Project
https://www.jircas.go.jp/en/reports/2019/r20190520

2019.9.2
Bilateral Meeting of JIRCAS and Minister Lucien Ranarivelo of Madagascar
https://www.jircas.go.jp/en/reports/2019/r20190902_0

2019.12.17
SATREPS FY VARY Project Holds Workshop in Madagascar
https://www.jircas.go.jp/en/reports/2019/r20191217_0

2020.4.23
Phosphorus dipping treatment of rice seedlings increases yield and avoids cold damage —Towards stable rice production in Africa with minimal fertilizer input—
https://www.jircas.go.jp/en/release/2020/press202001

2020.5.14
Contributing to food security in Madagascar by developing rice cultivation technology that improves fertilizer use efficiency
https://www.jircas.go.jp/en/program/program_d/blog/20200602

2021.3.10
COVID-19 and Field-oriented International Research Collaboration
https://www.jircas.go.jp/en/program/program_d/blog/20210310

2021.4.28
Addressing Low Fertilizer Inputs and Nutrient-poor Soils for Improving Rice Production in Africa
https://www.jircas.go.jp/en/program/proc/blog/20210428

2021.7.7
Rice Cultivation Technology to Overcome Soils with Poor Nutrient Supply
https://www.jircas.go.jp/en/program/proc/blog/20210707

2021.7.13
Using Organic Materials to Overcome Low Productivity of Rice Cultivation in Madagascar
https://www.jircas.go.jp/en/program/proc/blog/20210713

2021.11.26
New Rice Varieties Released in Madagascar
—FyVary varieties show high productivity under nutrient deficiencies—
https://www.jircas.go.jp/en/release/2021/press202117

2021.12.20
Field Crops Research Special Issue on Sustainable Productivity Enhancement of Rice-based Farming Systems in Africa
https://www.jircas.go.jp/en/program/proc/blog/20211220

2022.3.29
Fy Vary Project Promotional Video
https://www.jircas.go.jp/en/program/proc/blog/20220329

2022.4.4
Translating Psychometric Scales in Developing Countries
https://www.jircas.go.jp/en/program/proc/blog/20220404

2022.5.19
Workshop on Rapid Soil Fertility Evaluation Technology Held in Madagascar
https://www.jircas.go.jp/en/reports/2022/r20220519

2022.5.20
New Rice Varieties Developed by JIRCAS Introduced to the President of Madagascar
https://www.jircas.go.jp/en/reports/2022/r20220520

2022.6.13
Genomic Prediction of Zinc Biofortification Potential in 3000 Gene Bank Accessions to Increase Grain Zinc Concentrations in Rice
https://www.jircas.go.jp/en/program/proc/blog/20220613

2022.6.22
Discovered Rice Gene Region Associated with Low Soil Fertility Tolerance in Small Farm Conditions in Madagascar
https://www.jircas.go.jp/en/program/proc/blog/20220622