Micro-dose Placement of Phosphorus Induces Deep Rooting of Upland Rice

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Abstract

Purpose

Upland rice production is often constrained by phosphorus deficiency (P) and drought events. Methods are needed to maximize P use efficiency, while promoting deep root development to mitigate drought. This study evaluates micro-dose P placement as a technique to enhance drought resilience of upland rice, thereby hypothesizing that P placement enhances deep root development, stimulated by the local P supply in the planting hole, compared to broadcast P.

Methods

Two pot experiments were conducted using P deficient upland soil in Tanzania (Expt.1) and Madagascar (Expt.2), with factorial combinations of P doses (control and two P levels), application method (placement versus broadcast), rice varieties (DJ123 & NERICA4) and water regimes (field capacity and drying periods).

Results

Micro-dose P placement strongly boosted the establishment of upland rice and enhanced P recovery rates (4- to 5-fold) and fertilizer use efficiency (9- to 14-fold) compared to broadcast P. Micro-dose P placements significantly enhanced the fraction of roots found at largest depth (>30 cm, Expt. 1; >15 cm, Expt. 2) by 22- to 33%. Surprisingly, shoot P concentrations were markedly lower under P placement than under broadcast at equivalent P doses or equivalent biomass, indicating a Piper-Steenbjerg effect.

Conclusion

This study is first in showing the enhanced deep rooting after P placement, and suggests replication at field scale where subsurface moisture may yield stronger benefits than in pots. The depleted shoot P concentrations induced by vigorous plant establishment under P placement may, however, counteract benefits at later growth stages and need further attention.

Introduction

One third of the rice (*Oryza* spp.) area in sub Saharan Africa (SSA) is cultivated by smallholder farmers in low-input, rainfed (non-irrigated) upland systems. With a total production of only 4 M t upland rice compared to the 30 M t of total rice production per year in SSA (Diagne et al. 2013b; FAOSTAT 2018), upland rice is often cultivated in marginal environments with suboptimal management practices (Tanaka et al. 2017; Niang et al. 2017; Senthilkumar et al. 2018). Exploitable yield gaps of rice are largest in upland systems (Kwesiga et al. 2020), where drought events and phosphorus (P) deficiency form two major challenges that are often co-occurring (Diagne et al. 2013; Mueller et al. 2012). There is a strong need for sustainable intensification of the existing rice growing areas in SSA by a more efficient use of the available resources such as water and nutrients (Saito et al. 2013; van Oort et al. 2015; Zenna et al. 2017).

Current low P fertilizer recovery rates and persistently low purchasing power of many smallholder rice farmers preclude a drastic improvement of P use in rice-based systems. A more efficient P application method has been developed for several crops, by localizing the P dose (Nziguheba et al. 2016). A micro-dose P placement implies a localized application of a small P dose to a small surface or sub-surface area, often combined with seeds into the planting hole (ICRISAT 2009; Nkebiwe et al. 2016; Vandamme et al. 2018). The P is rather immobile in soils and P sorption is reduced under small localized P placements due to the local saturation of the binding sites (Fe and Al oxyhydroxides). Hence, such localized micro-dose P applications form an option towards sustainable P management (Malhi et al. 2001; Margenot et al. 2016; Nziguheba et al. 2016; Oo et al. 2020). This method of combining fertilizers with seeds in the planting hole is also referred to as pop-up fertilization (Olsson et al. 2018).

The technique of micro-dose P placement has been successfully tested and adopted for several cereals such as maize, millet, and sorghum (van der Eijk et al. 2006; Aune and Bationo 2008; Bagayoko et al. 2011; Camara et al. 2013; Bielders and Gérard 2015; Ibrahim et al. 2016a). However, micro-dose P placement in direct seeded rice systems has only been studied and evaluated in a few cases in Tanzania and Benin (Bayan and Lourduraj, 2000; De Bauw et al., 2019; Garrity et al., 1990; Vandamme et al., 2018) and, to our knowledge, it is only adopted in upland rice growing areas of Madagascar (Raboin et al. 2014; Andriamananjara et al. 2018). Phosphorus micro-dose placement strongly benefits shoot establishment and grain yield in direct seeded rice systems (De Bauw et al. 2019; Vandamme et al. 2018), following a high fertilizer efficiency and P recovery from the soil. In theory, P placements provide the P initially needed by the seedlings (He et al. 2003; Sanusan et al. 2009), resulting in an increased early root growth, which gives the plant a competitive advantage early on in the growth period. Through this early root development, it was argued that plants can take up more of the water and other nutrients that are present in the soil (Ibrahim et al. 2015a; Ibrahim et al. 2015b).

As the intensity and frequency of dry spells are expected to increase in many regions of SSA (Cook et al. 2014; Zhao et al. 2015), multiple studies have highlighted the importance of deep roots for drought resistance and drought avoidance in future crops (Uga et al. 2011; Maeght et al. 2013; Lou et al. 2015). Plants with deep roots are able to access water from deeper soil layers, which enables the plants to tolerate droughts by drought avoidance (Fukai and Cooper 1995; Uga et al. 2013). Therefore, modifying the root distribution of rice from shallow to deep rooting by genetic selection is a promising strategy for drought-resistance breeding (Gowda et al. 2011; Uga et al. 2011). In addition, soil management practices can also promote deeper rooting of crops in acid upland soils (Garrity et al. 1990; Haefele et al. 2016). To this end, effects of P banding on deep root development have yet been observed in multiple crops (Singh et al. 2005; Nkebiwe et al. 2016; Hansel et al. 2017), but implications of micro-dose P placements on root development of upland rice were never assessed. In this regard, it has been hypothesized that an increase in root growth after P placements can result in enhanced drought resistance (ICRISAT 2015). However, this was never confirmed before. Additionally, it is also unclear how such P placements can influence water acquisition and how this affects plant performance under drought.

This study was set up to evaluate micro-dose P placements as a method to counteract drought effects in rice systems, thereby hypothesizing that P placement enhances deeper rooting stimulated by the local P supply in the planting hole, compared to broadcast P. Pot experiments were set up by using P deficient upland soil in large pots, and including factorial combinations of P doses, P application method (placement versus broadcast), rice varieties, and water regimes (field capacity and dry periods). Shoot growth, root distribution, fertilizer efficiency, and P content of the rice shoots was determined.

Materials & Methods

Two pot experiments were conducted in Tanzania and Madagascar, using P deficient upland soil (Table 1), in a full factorial design of five P treatments (a zero P control (NoP), two rates of micro-dose P placement (Micro1 & Micro2), a small dose of P broadcasting (SubP), and a high dose of P broadcasting (PlusP)), two contrasting water regimes (permanent Field Capacity vs. Drying Periods) and two upland rice varieties (DJ123 & NERICA4). A summary of the similarities and differences of the imposed treatments in both experiments is presented in Table 1.

Pot Experiment 1

Soil preparation, P treatments, and pot filling

The pot trial was conducted in a greenhouse located at Sokoine University of Agriculture in Morogoro (6°50′53.9″S, 37°39′31.3″E; Tanzania). Average daily minimum and maximum temperatures during the experiment were 21.9 and 33.4 °C, respectively. A P-deficient soil (0.035 mg P L^{-1} in soil solution, measured by Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Agilent7700X) after a water extraction; 1:10 solid:liquid ratio; 24 hours equilibration; 30 minutes centrifugation at 2000 g; and 0.45 µm membrane filtration) was collected from an upland rice field in Matombo (Tanzania), on which P deficiency was previously ascertained. Characteristics of the soil are presented in Table 2. After sampling the P deficient rice field (0–30 cm), the bulk soil was shade dried, crushed to an aggregate size of 4 mm, and amended with salts of NH_4NO_3, KCl, $CaCl_2$, $MgSO_4$, $ZnSO_4$, $CuSO_4$, H_3BO_3 and Na_2MoO_4 at rates of 37 mg N kg^{-1}, 95 mg K kg^{-1}, 16 mg Mg kg^{-1}, 21 mg S kg^{-1}, 3.5 mg Zn kg^{-1}, 0.04 mg B kg^{-1}, 0.08 mg Cu kg^{-1}, and 0.03 mg Mo kg^{-1} soil, to avoid any nutrient deficiency other than P.

As P generally accumulates in the topsoil, no P was initially added to the bulk soil in order to mimic a P deficient subsoil at the bottom layer of the pots across treatments. Large pots of 10.5 L (height: 55 cm, diameter: 16 cm) were first filled with 7.3 kg of the P deficient soil. To avoid downwards P transport by wetting the whole pot at once, this bottom layer of mimicked subsoil was first watered to field capacity (38% w/w, based on the water retention curve of this soil) before adding the treated top layers of soil. To this end, the remaining of the bulk soil was subjected to different P amendments to obtain five different P treatments.

The top soil layer of 16 pots was amended with a large amount of ground Triple Super Phosphate (TSP) (70.8 mg P $kg_{topsoil}^{-1}$ or 354 mg P per pot) up to a P concentration of 0.5 mg P L^{-1} in soil solution (PlusP), which was based on a previously determined P adsorption isotherm. Briefly, the soil was dried and sieved. Replicate samples of 3 g were suspended in 30 mL water and amended with KH_2PO_4 at various rates between 0–60 mg L^{-1}. The soils were equilibrated with an end-over-end shaker for 24 h followed by centrifugation and filtration (0.45 µm) and analyzed for P by ICP-MS. The top soil layer of 16 other pots was amended with a lower amount of ground TSP (25.0 mg P $kg_{topsoil}^{-1}$ or 125 mg P per pot) up to a P concentration of 0.1 mg P L^{-1} in soil solution (SubP). The top soil layer of the remaining pots (i.e. 48 pots) was not amended with TSP as this upper soil layer was later used for a control without P amendments and two rates of micro-dose placements. Salt of $CaCl_2$ was broadcasted to equalize the amended Ca in all treatments. Pots were filled with 5 kg of treated topsoil, affixed on top of each subsoil. The thickness of the layer of the subsoil was 30 cm and that of the topsoil was 20 cm. Pots were then irrigated to bring the whole pot to field capacity (38% w/w). For the two rates of micro-dose P placement (i.e. Micro1 & Micro2), 0.06 g and 0.12 g of recompressed TSP powder were locally applied together with the seeds in the planting hole of the non-amended topsoil. These micro-dose placement rates correspond with amendments of 12 mg P pot^{-1} and 24 mg P pot^{-1}, respectively, and they are equivalent to an application rate of 3 and 6 kg P ha^{-1}, when plants are conventionally spaced at 20 x 20 cm.

Sowing, maintenance, and water treatments

One pre-germinated seed of each variety was sown into the pots (1 cm depth) at the center of the surface. The two upland varieties used in the trial were NERICA4 and DJ123, because of their contrasting performance under P deficiency. NERICA4 is an upland rice variety developed by the Africa Rice Center (AfricaRice) using interspecific crosses between *Oryza sativa* (Asian rice) and *Oryza glaberrima* (African rice). NERICA4 is known for its robust performance under droughts, but it is relatively susceptible to low P availability (De Bauw et al., 2019b, 2019a; Koide et al., 2013). The root system of the latter variety was previously characterized as having relatively limited number of nodal roots, able to penetrate to deep layers (De Bauw et al. 2020). DJ123 is an upland rice variety from the *aus* group, originating from Bangladesh. This variety was previously found to perform well under P deficient soils and it was suggested to have a high phosphorus acquisition efficiency (PAE) (Saito et al. 2015; Nestler and Wissuwa 2016; Vandamme et al. 2016b; Mori et al. 2016), in this work defined and assessed by the amount of P taken up per unit of root mass. DJ123 was previously observed to have a large number of nodal roots and longer root hairs (Nestler et al. 2016).

Two top dressings of NH_4NO_3 (in solution) were applied at a rate of 349 mg N per pot at 21 and 34 days after sowing (DAS). An additional top dressing of $ZnSO_4$, $ZnCl_2$, KCl, and $MgSO_4$ were added to each pot at rates of 0.27 g Zn, 0.58 g K, 0.16 g S, and 0.11 g Mg at 21 and 34 DAS.

Pots were daily irrigated to field capacity (based on pot weight, 38% w/w) until 25 DAS, and two contrasting water treatments were then initiated and maintained until the end of the trial. Half of the pots were daily irrigated to field capacity (FC), while the other half was subjected to drying periods (DP) to mimic drying cycles during erratic rainfall. To do so, pots were watered up to field capacity after a period of ca. six days of drying, and drying spells were repeated 5-fold until harvest. Each treatment combination was replicated four times.

Plant development was monitored by measuring plant height and counting tillers and leaves twice a week. At 52 DAS, shoots were cut, oven dried (60 °C), weighed, and manually ground by mortar. The P concentrations in the shoot tissues were then determined by Inductively Coupled Plasma Optical Emission Spectrometry analysis (Thermo Scientific iCAP 7000 series) after digestion in hot (120°C) HNO_3 and total P content of the shoot was calculated. Immediately after removing the shoot, the soil cylinder was carefully taken out of the pot and precisely cut into three segments. One part comprised a segment (A) from 0 to 15 cm depth which included the '*shallow roots*'; another segment (B) comprised soil from 15 to 30 cm depth including the '*intermediate roots*'; and the last segment incorporated the '*deep roots*' below a depth of 30 cm. The latter segment (C) was defined according to most rice studies, where deep roots are defined as roots below 30 cm (Kato et al. 2006, 2013; Gowda et al. 2011). For each soil segment, roots were carefully washed out by gently shaking the soil segments on a 2 mm net in water. After removing the soil from the roots, the roots from each segment were oven dried (60°C) and weighed to determine root distribution and biomass allocation.

Pot Experiment 2

A second pot trial was conducted in a greenhouse located at the Laboratoire des Radio Isotopes (19°12'37''S; 47°29'13''E; Madagascar). Average daily minimum and maximum temperatures during the experiment were 15 and 26 °C, respectively. A P-deficient soil (0.006 mg P L^{-1} in soil solution, measured by ICP-MS after a 1 mM $CaCl_2$ extraction; 1:10 solid:liquid ratio; 5 days equilibration; 30 minutes centrifugation at 2000 g; and 0.45 µm membrane filtration) was collected from the top 20 cm of an upland rice field in Behenji (Madagascar). Characteristics of the soil are presented in Table 2. The bulk soil was shade dried, crushed to an aggregate size of 4 mm and limed with $Ca(OH)_2$ from a pH of 4.2 to 5.4, in order to avoid toxicity of Al and Mn. After liming, the bulk soil was amended with salts of NH_4NO_3, KCl, $MgSO_4$, $ZnCl_2$, $CuSO_4$, H_3BO_3 and $(NH_4)_6Mo_7O_{24}$ at rates of 33 mg N kg^{-1}, 95 mg K kg^{-1}, 15 mg Mg kg^{-1}, 20 mg S kg^{-1}, 2.5 mg Zn kg^{-1}, 0.04 mg B kg^{-1}, 0.08 mg Cu kg^{-1}, and 0.03 mg Mo kg^{-1} soil, to avoid any nutrient deficiency other than P. Application of ammonium nitrate was later split in two additional doses of 33 mg kg^{-1} soil at 22 DAS and one 34 DAS.

Pots of 5.5 L (height: 30cm, diameter: 16cm) were then filled with 2.5 kg of the P deficient soil, mimicking a subsoil layer from 15-30 cm. Later, 2.5 kg of topsoil was added to the pots (i.e. 0-15 cm) after establishing the different P treatments by mixing powdered TSP into this topsoil. For the NoP, Micro1, and Micro2 treatments no P fertilizer was initially added to the topsoil. For the suboptimal broadcast, 10 mg P kg^{-1} soil (corresponding to 25 mg P pot^{-1}) was mixed in the soil, corresponding to a P concentration of 0.01 mg L^{-1} in a 1:10 1 mM $CaCl_2$ extract (SubP). For the large rate of P broadcasting, 100 mg of P kg^{-1} soil (corresponding to 250 mg P pot^{-1}) was mixed into the soil, up to a P concentration of 0.02 mg L^{-1} (PlusP). The same two varieties as used in Expt. 1 (i.e. NERICA4 & DJ123) were then planted, and the same two micro-dose placements were established at similar application rates (i.e. 12 and 24 mg P per pot).

Half of the pots were daily maintained at Field Capacity (FC; 43% w/w) while the other half was subjected to the local precipitation pattern during the growing season (DP). The weather data was retrieved from

New_LocClim (longitude 47.483°, latitude -19.2°, altitude 1480 masl), using the single point mode and the nearest neighbor method (LocalClimateEstimator (FAO 2001)). To simulate the temporal precipitation distribution and drying periods, water was added according to the amount of rainy days per month. Doing so, pots were watered to field capacity at an interval of four days between 1 and 12 DAS, and at an interval of two days between 12 and 49 DAS. Each treatment combination was replicated four times.

At 49 DAS, plants were harvested to measure shoot growth, P concentration, and P content of the shoots with identical methods as in Expt. 1. For this experiment, roots were collected from two segments over depth: the '*shallow roots*' (0-15 cm) and the combination of intermediate and deep roots (>15 cm), in this experiment referred to as '*deeper roots*'.

Data analysis

A provisional indicator of the agronomic efficiency of the P fertilizer at 52 DAS was calculated as *AEP = (biomass with P – biomass without P)/amount of P applied*, expressed in [g g^{-1}]. The apparent P recovery from the fertilizer was calculated as P_{rec} = *(Shoot P content with P – Shoot P content without P)/amount of P applied*, expressed in percentage. The partial soil P balance was assessed as $P_{balance}$ = *Shoot P content / amount of P applied*, expressed in percentage (Fixen et al. 2015). The shoot P uptake per unit root mass was calculated as a measure of phosphorus acquisition efficiency (PAE).

All statistics were computed in R version 4.0.2 (R Development Core Team, 2012). Three-way ANOVAs (Type III, using 'aov' from the {stats} package) were performed on the shoot and root variables with water regime, P treatment, and variety as fixed factors and each combination included four replicates. Means and standard errors of the mean ($\frac{\sigma}{\sqrt{n}}$, with σ = standard deviation and n = the number of observations) were calculated for every treatment combination and significance between treatment means was determined by calculating the Least Significant Difference (LSD). Plots of shoot mass, relative root mass distribution, and tissue P concentration were created using 'ggplot' from the { ggplot2 } package.

Results

Rice establishment and shoot growth

Shoot weights were lower in Expt. 2 compared to Expt. 1, which might be related to the different growth conditions but also to the soil P supply (Figure 1). The most P deficient soil was that of Expt. 2, suggested by the much lower P concentrations in soil solution (Table 1). In both experiments, all P application methods enhanced rice development at early stages compared to the control (NoP), which was most pronounced in the most P deficient soil (i.e. Expt. 2). The highest broadcast rates (PlusP) consistently yielded largest shoot mass production.

Shoot weight under Micro2 was equal to that under Micro1 for Expt. 1, while this was largest for Micro2 in Expt. 2. The shoot weight with SubP broadcast (125 mg P) did not significantly differ from that under micro-dose placements in Expt. 1, despite the much higher P dose in this broadcast application. In contrast, the shoot weight of SubP in Expt. 2 (25 mg P) was consistently lower than that under both placement rates, where the highest placement rate was equal as in the broadcast P (SubP). (Figure 1)

Drying periods slightly reduced biomass production compared to permanent field capacity in both experiments. Largest effects of soil water were found when shoot biomass under field capacity were largest, i.e. at high P supply and more with higher yielding DJ123 than with NERICA4. In contrast, only the shoot growth under SubP in Expt. 2 increased under drying period compared to field capacity (Figure 1).

During the first weeks of plant establishment, a fast initial shoot development was indeed observed for both placement rates. Increments of tiller and leaf number under both placement rates were similar to that with PlusP, however, these growth curves of rice plants receiving P placements started to level off from the growth curves of the rice that received the highest broadcast rates after ca. 40 DAS in Expt. 1 and 30 DAS in Expt. 2 (Figure S1 & S2, Supplementary Information).

Phosphorus uptake and tissue concentration of the rice shoots

Similar to shoot weight, total P content was consistently lowest without P application (NoP) and largest under PlusP (Table 3 & Table 4). In Expt. 1, the P content under SubP was higher than the P content under Micro1 and Micro2 for DJ123, while this was not the case for NERICA4 (Table 3). In Expt. 2, shoot P content under both P placement rates was similar to SubP. However, the significance of these differences depended on both variety and water treatment (Table 4), as DP increased the P content under SubP only and DJ123 acquired more P under Micro2 which was not the case for NERICA4.

The P concentration in the shoot tissue observed in Expt. 1 was consistently lowest under both rates of micro-dose placement compared to that under broadcast and this contrasts the opposite trends for the effects of placement on shoot yield (Figure 2 & Figure S3, Supplementary Information). The P concentration was higher in NERICA4 than in DJ123 (Table 3). For Expt. 2, P concentrations in the shoot tissue were also very low for the P placements (below values of SubP and PlusP), and these concentrations were similar to the control values of NERICA4 (NoP), but slightly higher than the control value of DJ123 (NoP) (Table 4, Figure 2 & Figure S2, Supplementary Information).

The PAE was consistently lowest for DJ123, in Expt. 1 (Table S1, Supplementary Information), while this was only the case for NoP and SubP in Expt. 2. In Expt. 2, the PAE of DJ123 was larger than NERICA4 under PlusP only (Table S2, Supplementary Information).

Fertilizer efficiency, apparent P recovery, and P balances

In both experiments (Table 3 & Table 4), a very large fertilizer efficiency (AEP) and apparent P recovery (P_{rec}) have been observed for both micro-dose placements. However, both parameters were consistently largest with Micro1 (12 mg P) compared to Micro2 (24 mg P).

The partial soil P balance ($P_{balance}$) of the P application methods was consistently highest under Micro1, followed by Micro2. These (Micro1 & Micro2) were consistently larger compared to the partial P balance under SubP and PlusP (Table 3 & Table 4). For Expt. 1, the partial P balance at 52 DAS consistently exceeded the value of 100% under Micro1, while this only occurred under Micro2 in DJ123 grown under Field Capacity (Table 3). The partial P balance never exceeded 100% in Expt. 2 (Table 4).

Root distribution

The root mass distribution of the upland rice in both experiments was affected by water, variety, and P management. In Expt. 1, drying periods (DP) decreased the fraction of the shallow roots while it increased the fraction of deep roots compared to field capacity (FC) (Figure S5, Supplementary Information). In Expt. 1, DJ123 had a smaller fraction of shallow roots and a larger fraction of deep roots compared to NERICA 4 (Figure S5, Supplementary Information). In Expt. 2, a similar effect of drying periods (DP) on deep rooting was only found for NERICA4 (Figure S6, Supplementary Information), and it was not consistently significant for all P treatments (Figure 5).

Interestingly, both rates of micro-dose P placements in Expt. 1 (Micro1 & Micro2) decreased the fraction of the shallow roots, while it strongly increased the fraction of the deep roots, compared to all other P treatments (i.e. NoP, SubP, and PlusP) by on average 22% (Figure 3). For Expt. 2, a similar trend was observed under field capacity (FC), as both rates of micro-dose placements indeed displayed the lowest fractions of shallow roots and highest fractions of deeper roots (here all roots deeper than 15 cm) (Figure 4). However, the effect of drying periods (DP) in Expt. 2 overruled the effect of placements, and hence the difference of shallow root fractions under Micro2 compared to SubP and PlusP was not significant under DP while it was indeed significant under FC (Figure 4).

Accordingly, the absolute root mass in the deepest layer was consistently largest under both placement rates (Micro1 and Micro2) in Expt. 1 (Table 3). Similar for Expt. 2, largest values of absolute root mass in the deeper layers (>15cm) were observed for both placement rates (Table 4), and the specific treatment ranking depended on the water treatment.

Discussion

Effects of micro-dose P placement on P deficiency and deep rooting of upland rice

This work corroborates earlier findings that micro-dose P placements boost the initial establishment of upland rice on P deficient soils (Vandamme et al. 2018). Such initial benefits of micro-dose P placements were previously also observed for lowland rice (De Bauw et al. 2019), maize (Richards et al. 1985), pearl millet (Muehlig-Versen et al. 2003), sorghum (Aune and Ousman 2011) and other crops like groundnut, sesame and cowpea (Ousman and Aune 2011). Indeed, micro-dose P placements result in a high P recovery and a high agronomic efficiency of P fertilizers, and the P content in the rice shoot often exceeds the amount of P applied (Vandamme et al. 2018).

As far as known, two observations are new and call for attention. The first is the markedly low P concentration in the rice tissue after P placements, despite the strong growth under the micro-dosed P. This was most apparent when plotting shoot P concentrations against the yielded shoot dry matter, illustrating that placements versus broadcast data separate out across all rates, soils, and genotypes (Figure 2, Figure S3, Figure S4). The low P concentration in the tissue may indicate that micro-dose P placements enhanced the internal P use efficiency of the rice at initial stages, following the fast growth boost (Vandamme et al. 2016a). The combination of a higher biomass with lower tissue nutrient concentration also points to a Piper-Steenbjerg effect (Wikstrom 1994), which is explained as follows. Low tissue P concentrations occur when the fast growth of plants grown in an initially higher P medium (locally after placement) eventually leads to a more rapid depletion of external P than the slow growth of plants grown in an initially lower P medium. However, this effect is less pronounced in more extremely deficient conditions, where the tissue P concentrations without P amendments generally remain very low (i.e. Expt. 2). As the shoot P content exceeds or approximates the amended dose of P by the placements after 52 DAS (Table 3, Expt. 1) this study indicates that the available P from the micro-dose placements (both at an application rate of 12 and 24 mg P per planting hole) quickly becomes insufficient to the fast growing rice plants (roots and shoots), resulting in the observed drop in shoot P concentration at later stages. Indeed, growth curves of the tiller and leaf number under placements were observed to flatten off compared to P broadcasts at large rates, from ca. 35 DAS in these pot trials and this was also observed for field-grown rice (De Bauw et al. 2019; Vandamme et al. 2018). Such declining effects of micro-dose P placements over time compared to broadcasts were also observed for millet (Muehlig-Versen et al. 2003) and maize (Eghball and Sander 1989). The latter decrease in growth indicates a P deficiency at later stages under P placements, and hence special attention should be given in P deficient soils to avoid P limitations during the later stages of the rice cropping cycle when placing micro-doses of P, possibly by additional P management at later growth stages.

The second new observation is that deep rooting of rice is stimulated by micro-dose P placements. It is well known that plants enhance their rooting depth in response to dryer conditions (Comas et al. 2013). For lowland rice an enhanced deep rooting was already observed in response to water saving techniques (De Bauw et al., 2019). For upland rice, a response in root elongation and rooting depth to drought was previously also observed (Asch et al. 2005; Kato et al. 2006; Kano et al. 2011; Suralta et al. 2016), and such deep root response of upland rice to drying periods is now also confirmed in this work. The latter response might have a two-fold reason since P availability in upper layers would also decrease under drying conditions.

Interestingly, we observed that P placements also enhance deep rooting of upland rice, both in absolute and relative terms (Figures 3 and 4; Tables 3 and 4). Such responses of deep rooting to P placements were previously reported when P was banded in deeper layers (Singh et al. 2005; Nkebiwe et al. 2016; Hansel et al. 2017), or when P was locally placed in deeper layers of the soil (Fatondji et al. 2008; Ibrahim et al. 2015; Weerarathne et al. 2015). Accordingly, morphological changes of rice roots to localized P applications were previously observed by He et al. (2003), and they argued that the relative root allocation of rice is favored in the soil layer with high-phosphorus supply. However, the enhancement of deep rooting in response to micro-dose P placements in the planting hole was never reported before. The mechanisms contributing to such deep rooting after basal micro-dose P placements have not yet been confirmed, but this deep rooting might be explained by an osmotic response to the local higher salt concentration at the seedling base, as drought and salt responses are strongly related within plants (Maheswari et al. 2012; Niu et al. 2016; Forni et al. 2017). Another explanation would be that nodal root elongation over depth is stimulated over lateral elongation, following the local P saturation at the root base. In other words, a localized P application after placement results in a local P hotspot and a P deficient bulk soil. Hence, plants would not benefit from extended root proliferation in such a deficient topsoil layer after P placements, resulting in a decrease of root allocation to this layer so stimulating deep rooting. Further research would thus benefit from unraveling these mechanistic effects of micro-dose P placements on root development and root distribution.

This response of deep rooting after P placements has strong implications for enhancing the drought resilience of upland rice and possibly also in other crops, as deep rooting is known to enhance drought avoidance (Gewin 2010; Gowda et al. 2011). Such effects of micro-dose placements on drought avoidance were here not clearly presented in the shoot weights. However, in the field these effects are expected to become larger than in pots because subsurface soils in the field may have more water than in the closed pots for obvious reasons. In the field, micro-dose placements of fertilizers have been reported to result in rapid early growth and better crop performance under drought conditions (Tabo et al. 2006, 2007), which might be related to such an enhanced rooting depth. Additionally, micro-dose P placements in upland rice were previously observed to induce end-of-season drought escape following faster maturity of the rice under P placements (Vandamme et al. 2018). Hence, following these observed root responses and the fast maturity after placements, this technique of micro-dose P placements could indeed be used as a sustainable management practice to enhance the resilience of upland rice, and possibly also other crops to droughts.

Agronomic implications on micro-dose P placement

According to the P status of the soil, different rates of micro-dose P placements mattered for growth and P content in Expt. 2, but not in Expt. 1 where differences in growth and P content between the two placement rates were minor. Such minor differences among placement rates were previously also observed for rice in De Bauw et al. (2019) and Vandamme et al. (2018), and this study now suggests that rate effects after P placements will indeed only appear when the soil is extremely deficient in P. Lower rates of P placements will result in a higher P use efficiency, and it was therefore argued that low placement rates are preferred above higher rates (van der Eijk et al. 2006; Bielders and Gérard 2015; Aune et al. 2017). However, using such small application rates of 12 mg P per plant (3 kg ha^{-1}) on the field, seasonal P balances of rice will often be negative, while seasonal P balances were sometimes observed to be positive when placing rates of 24 mg P per plant (6 kg ha^{-1}) (De Bauw et al., 2019). Therefore, it was argued that micro-dosing increases the risk of soil nutrient depletion in low-input cropping systems, and that seasonal balances should be considered (Bagayoko et al. 2011; Ibrahim et al. 2016b; Blessing et al. 2017). Further research should thus determine the appropriate application rates of micro-dose P placements for different soil types in order to avoid P deficiency at later stages, and prevent further mining of the available P stocks in the already deficient soils (De Bauw et al. 2019; Margenot et al. 2016). In this regard, larger placement rates should not compromise on the emergence of the crop due to germination failure or salt injury of the seedlings (Muehlig-Versen et al. 2003; Vandamme et al. 2018). To achieve this, larger rates or multiple doses of P could possibly be placed further from the planting hole, or small rates of micro-dose P placements in the planting hole could possibly be combined by additional broadcasts of locally available rock phosphate (Muehlig-Versen et al. 2003), or practices of conservation agriculture such as organic amendments (Aune and Coulibaly 2015). Additionally, it should be considered that the implementation of placements by traditional manual methods is labor intensive, reducing the net profit (Vandamme et al. 2018). However, the development of new mechanical tools like 'Fertiseeders' reduce labor input by 80% when placing fertilizers together with seeds in the planting hole, thereby justifying the implementation of fertilizer placements on the field (Africa Rice Center 2018).

Differences in P uptake efficiency and drought stress tolerance between rice varieties

The variety DJ123 indeed displays a faster growth and a higher absolute P uptake capacity (Vandamme et al. 2016b, a) compared to NERIC4, likely following a fast root development (De Bauw et al. 2020). However, despite the consistent higher P uptake capacity, the PAE of DJ123 often remains relatively low compared to the inefficient variety NERICA4 (Table S1, Supplementary Information). For DJ123, these results on PAE contradict those by Mori et al. (2016) and Wissuwa et al. (2020) who found that this genotype generally displays a higher PAE than NERICA4 under P deficient conditions and suggested DJ123 as a potential donor of traits towards enhanced root P uptake efficiency. This was recently also contested by Rakotoson et al. (2020), and hence, our results additionally suggest that this hypothesis is not consistently true.

Conclusions

This work highlights the opportunities of micro-dose P placements towards more efficient P management in rice cultivation on low P upland soils as it strongly boosts rice establishment, while increasing the fertilizer use efficiency and P recovery. We found that P placements enhance deep rooting of upland rice, and hence the technique of P placements can serve as a management strategy to enhance P use in upland rice, while mitigating effects of dry periods and increasing the resilience of upland rice to droughts. Therefore, the technique of micro-dose P placement should be considered when developing new decision support tools designing site-specific nutrient recommendations for rice (Bado et al. 2018; Saito et al. 2019). Future field studies should be conducted to validate whether P placements can indeed mitigate drought events in upland rice systems by improving root water acquisition on the field, and the observed root responses to P placements should be assessed in other crops. The low P concentrations in the rice shoots after P placements indicate that additional P management is needed to overcome P deficiency in the later stages of the rice cropping cycle and to avoid further P mining when placing micro-doses of P in deficient soils. To this end, multiple years of on-field validation trials are needed to draft sustainable and site-specific recommendations on P management utilizing the technique of micro-dose P placement. Doing so, contrasting rates of micro-dose P placements should be tested for multiple crops (Aune et al. 2017) along a wide gradient of soil P availability.

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References

Africa Rice Center ARC (2018) Africa Rice Center (Africa Rice) Annual Report 2018: Sustainable rice production in the face of climate emergency. Abidjan, Côte d'Ivoire

Andriamananjara A, Rakotoson T, Razanakoto OR, et al (2018) Farmyard manure application in weathered upland soils of Madagascar sharply increase phosphate fertilizer use efficiency for upland rice. F Crop Res 222:94–100. https://doi.org/10.1016/j.fcr.2018.03.022

Asch F, Dingkuhn M, Sow A, Audebert A (2005) Drought-induced changes in rooting patterns and assimilate partitioning between root and shoot in upland rice. F Crop Res 93:223–236. https://doi.org/10.1016/j.fcr.2004.10.002

Aune JB, Bationo A (2008) Agricultural intensification in the Sahel – The ladder approach. Agric Syst 98:119–125. https://doi.org/10.1016/J.AGSY.2008.05.002

Aune JB, Coulibaly A (2015) Microdosing of Mineral Fertilizer and Conservation Agriculture for Sustainable Agricultural Intensification in Sub-Saharan Africa. In: Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa. Springer International Publishing, pp 223–234

Aune JB, Coulibaly A, Giller KE (2017) Precision farming for increased land and labour productivity in semi-arid West Africa. A review. Agron Sustain Dev 37:1–10. https://doi.org/10.1007/s13593-017-0424-z

Aune JB, Ousman A (2011) Effect of seed priming and micro-dosing of fertilizer on sorghum and pearl millet in western sudan. Exp Agric 47:419–430. https://doi.org/10.1017/S0014479711000056

Bado VB, Djaman K, Mel VC (2018) Developing fertilizer recommendations for rice in Sub-Saharan Africa, achievements and opportunities. Paddy Water Environ 16:571–586. https://doi.org/10.1007/s10333-018-0649-8

Bagayoko M, Maman N, Pale S, et al (2011) Microdose and N and P fertilizer application rates for pearl millet in West Africa. African J Agric Res 6:1141–1150. https://doi.org/10.5897/ajar10.711

Bayan HC, Lourduraj AC (2000) Phosphorus management in rice and rice based cropping systems - A review. Agric Rev 21:89–96

Bielders CL, Gérard B (2015) Millet response to microdose fertilization in south–western Niger: Effect of antecedent fertility management and environmental factors. F Crop Res 171:165–175. https://doi.org/10.1016/J.FCR.2014.10.008

Blessing OC, Ibrahim A, Safo EY, et al (2017) Fertilizer micro-dosing in West African low-input cereals cropping: Benefits, challenges and improvement strategies. African J Agric Res 12:1169–1176. https://doi.org/10.5897/ajar2016.11559

Camara BS, Camara F, Berthe A, Oswald A (2013) Micro-dosing of fertilizer - a technology for farmers' needs and resources. International Academic Journals Pub

Comas LH, Becker SR, Cruz VM V, et al (2013) Root traits contributing to plant productivity under drought. Front Plant Sci 4:442. https://doi.org/10.3389/fpls.2013.00442

Cook BI, Smerdon JE, Seager R, Coats S (2014) Global warming and 21st century drying. Clim Dyn 43:2607–2627. https://doi.org/10.1007/s00382-014-2075-y

De Bauw P, Mai TH, Schnepf A, et al (2020) A functional-structural model of upland rice root systems reveals the importance of laterals and growing root tips for phosphate uptake from wet and dry soils. Ann Bot 126:789–806. https://doi.org/10.1093/aob/mcaa120

De Bauw P, Vandamme E, Lupembe A, et al (2019a) Architectural Root Responses of Rice to Reduced Water Availability Can Overcome Phosphorus Stress. Agronomy 9:11. https://doi.org/10.3390/agronomy9010011

De Bauw P, Vandamme E, Lupembe A, et al (2019b) Anatomical root responses of rice to combined phosphorus and water stress – relations to tolerance and breeding opportunities. Funct Plant Biol 46:1009. https://doi.org/10.1071/fp19002

De Bauw P, Vandamme E, Senthilkumar K, et al (2019c) Combining phosphorus placement and water saving technologies enhances rice production in phosphorus-deficient lowlands. F Crop Res 236:177–189. https://doi.org/10.1016/J.FCR.2019.03.021

Diagne A, Alia DY, Amovin-Assagba E, et al (2013a) Farmer perceptions of the biophysical constraints to rice production in sub-Saharan Africa, and potential impact of research. In: Realizing Africa's rice promise. CABI, Wallingford, pp 46–68

Diagne A, Amovin-Assagba E, Futakuchi K, Wopereis MCS (2013b) Estimation of cultivated area, number of farming households and yield for major rice-growing environments in Africa. In: Realizing Africa's rice promise. CABI, Wallingford, pp 35–45

Eghball B, Sander DH (1989) Distance and Distribution Effects of Phosphorus Fertilizer on Corn. Soil Sci Soc Am J 53:282–287. https://doi.org/10.2136/sssaj1989.03615995005300010051x

FAO (2001) New_LocClim

FAOSTAT (2018) FAOSTAT. http://www.fao.org/faostat/en/#home. Accessed 23 Mar 2018

Fatondji D, Pasternak D, Woltering L (2008) Watermelon production on stored rainwater in Sahelian sandy soils. African J Plant Sci 2:151–160

Fixen P, Brentrup F, Bruulsema TW, et al (2015) Nutrient/fertilizer use efficiency: Measurement, current situation and trends. In: Drechsel P, Heffer P, Magen H, et al. (eds) Managing Water and Fertilizer for Sustainable Agricultural Intensification, first. International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI), Paris, p 257

Forni C, Duca D, Glick BR (2017) Mechanisms of plant response to salt and drought stress and their alteration by rhizobacteria. Plant Soil 410:335–356. https://doi.org/10.1007/s11104-016-3007-x

Fukai S, Cooper M (1995) Development of drought-resistant cultivars using physiomorphological traits in rice. F Crop Res 40:67–86. https://doi.org/10.1016/0378-4290(94)00096-U

Garrity DP, Mamaril CP, Soepardi G (1990) Phosphorus requirements and management in upland rice-based cropping systems. In: Phosphorus requirements for sustainable agriculture in Asia and Oceania. Proceedings of a symposium, 6-10 March 1989. International Rice Research Institute, pp 333–347

Gewin V (2010) Food: An underground revolution. Nature 466:552–553

Gowda VRPV, Henry A, Yamauchi A, et al (2011) Root biology and genetic improvement for drought avoidance in rice. F Crop Res 122:1–13. https://doi.org/10.1016/j.fcr.2011.03.001

Haefele SM, Kato Y, Singh S (2016) Climate ready rice: Augmenting drought tolerance with best management practices. F Crop Res 190:60–69. https://doi.org/10.1016/j.fcr.2016.02.001

Hansel FD, Amado TJC, Ruiz Diaz DA, et al (2017) Phosphorus Fertilizer Placement and Tillage Affect Soybean Root Growth and Drought Tolerance. Agron J 109:2936–2944. https://doi.org/10.2134/agronj2017.04.0202

He Y, Liao H, Yan X (2003) Localized supply of phosphorus induces root morphological and architectural changes of rice in split and stratified soil cultures. Plant Soil 248:247–256. https://doi.org/10.1023/A:1022351203545

Ibrahim A, Abaidoo RC, Fatondji D, Opoku A (2016a) Determinants of fertilizer microdosing-induced yield increment of pearl millet on an acid sandy soil. Exp Agric 52:562–578. https://doi.org/10.1017/S0014479715000241

Ibrahim A, Abaidoo RC, Fatondji D, Opoku A (2015a) Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. F Crop Res 180:29–36. https://doi.org/10.1016/j.fcr.2015.04.022

Ibrahim A, Abaidoo RC, Fatondji D, Opoku A (2016b) Fertilizer micro-dosing increases crop yield in the Sahelian low-input cropping system: A success with a shadow. Soil Sci Plant Nutr 62:277–288. https://doi.org/10.1080/00380768.2016.1194169

Ibrahim A, Pasternak D, Fatondji D (2015b) Impact of depth of placement of mineral fertilizer micro-dosing on growth, yield and partial nutrient balance in pearl millet cropping system in the Sahel. J Agric Sci 153:1412–1421. https://doi.org/10.1017/S0021859614001075

ICRISAT (2015) Fertilizer microdosing: Increases agriculture productivity

ICRISAT - (2009) Fertilizer Microdosing: Boosting Production in unproductive lands

Kano M, Inukai Y, Kitano H, Yamauchi A (2011) Root plasticity as the key root trait for adaptation to various intensities of drought stress in rice. Plant Soil 342:117–128. https://doi.org/10.1007/s11104-010-0675-9

Kato Y, Abe J, Kamoshita A, Yamagishi J (2006) Genotypic Variation in Root Growth Angle in Rice (Oryza sativa L.) and its Association with Deep Root Development in Upland Fields with Different Water Regimes. Plant Soil 287:117–129.

https://doi.org/10.1007/s11104-006-9008-4

Kato Y, Tajima R, Homma K, et al (2013) Root growth response of rainfed lowland rice to aerobic conditions in northeastern Thailand. Plant Soil 368:557–567. https://doi.org/10.1007/s11104-012-1538-3

Koide Y, Pariasca Tanaka J, Rose T, et al (2013) Qtls for phosphorus deficiency tolerance detected in upland nerica varieties. Plant Breed 132:259–265. https://doi.org/10.1111/pbr.12052

Kwesiga J, Grotelüschen K, Senthilkumar K, et al (2020) Rice Yield Gaps in Smallholder Systems of the Kilombero Floodplain in Tanzania. Agronomy 10:1135. https://doi.org/10.3390/agronomy10081135

Lou Q, Chen L, Mei H, et al (2015) Quantitative trait locus mapping of deep rooting by linkage and association analysis in rice. J Exp Bot 66:4749–4757

Maeght J-L, Rewald B, Pierret A (2013) How to study deep roots—and why it matters. Front Plant Sci 4:299. https://doi.org/10.3389/fpls.2013.00299

Maheswari M, Yadav SK, Shanker AK, et al (2012) Overview of plant stresses: Mechanisms, adaptations and research pursuit. In: Crop Stress and its Management: Perspectives and Strategies. Springer Netherlands, pp 1–18

Malhi SS, Zentner RP, Heier K (2001) Banding increases effectiveness of fertilizer P for alfalfa production. Nutr Cycl Agroecosystems 59:1–11. https://doi.org/10.1023/A:1009889218829

Margenot AJ, Singh BR, Rao IM, Sommer R (2016) Phosphorus fertilization and management in soils of Sub-Saharan Africa. In: Lal, Rattan and Stewart BA (ed) Soil Phosphorus . CRPC Press, p p.151-208

Mori A, Fukuda T, Vejchasarn P, et al (2016) The role of root size versus root efficiency in phosphorus acquisition in rice. J Exp Bot 67:1179–89. https://doi.org/10.1093/jxb/erv557

Muehlig-Versen B, Buerkert A, Bationo A, Roemheld V (2003) PHOSPHORUS PLACEMENT ON ACID ARENOSOLS OF THE WEST AFRICAN SAHEL. Exp Agric 39:307–325. https://doi.org/10.1017/S0014479703001261

Mueller ND, Gerber JS, Johnston M, et al (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257. https://doi.org/10.1038/nature11420

Nestler J, Keyes SD, Wissuwa M (2016) Root hair formation in rice (Oryza sativa L.) differs between root types and is altered in artificial growth conditions. J Exp Bot 67:3699–3708. https://doi.org/10.1093/jxb/erw115

Nestler J, Wissuwa M (2016) Superior Root Hair Formation Confers Root Efficiency in Some, But Not All, Rice Genotypes upon P Deficiency. Front Plant Sci 7:1935. https://doi.org/10.3389/fpls.2016.01935

Niang A, Becker M, Ewert F, et al (2017) Variability and determinants of yields in rice production systems of West Africa. F Crop Res 207:1–12. https://doi.org/10.1016/j.fcr.2017.02.014

Niu X, Hu T, Zhang F, Feng P (2016) Severity and duration of osmotic stress on partial root system: effects on root hydraulic conductance and root growth. Plant Growth Regul 79:177–186. https://doi.org/10.1007/s10725-015-0123-1

Nkebiwe PM, Weinmann M, Bar-Tal A, Müller T (2016) Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. Elsevier B.V.

Nziguheba G, Zingore S, Kihara J, et al (2016) Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. Nutr Cycl Agroecosystems 104:321–340. https://doi.org/10.1007/s10705-015-9729-y

Olsson ME, Gustavsson KE, Svensson SE, Hansson D (2018) Different types of organic pop-up fertilizers in carrot cultivation: Effects on the concentrations of polyacetylenes and sugars. Sci Hortic (Amsterdam) 230:126–133. https://doi.org/10.1016/j.scienta.2017.10.010

Oo AZ, Tsujimoto Y, Rakotoarisoa NM, et al (2020) P-dipping of rice seedlings increases applied P use efficiency in high P-fixing soils. Sci Rep 10:1–10. https://doi.org/10.1038/s41598-020-68977-1

Ousman A, Aune JB (2011) Effect of seed priming and micro-dosing of fertilizer on groundnut, sesame and cowpea in western Sudan. Exp Agric 47:431–443. https://doi.org/10.1017/S0014479711000068

R Development Core Team (2012) R: A Language and Environment for Statistical Computing

Raboin L-M, Randriambololona T, Radanielina T, et al (2014) Upland rice varieties for smallholder farming in the cold conditions in Madagascar's tropical highlands. F Crop Res 169:11–20. https://doi.org/10.1016/J.FCR.2014.09.006

Rakotoson T, Holz M, Wissuwa M (2020) Phosphorus deficiency tolerance in Oryza sativa: Root and rhizosphere traits. Rhizosphere 14:. https://doi.org/10.1016/j.rhisph.2020.100198

Richards JE, Bates TE, Sheppard SC (1985) The effect of broadcast P applications and small amounts of fertilizer placed with the seed on continuously cropped corn (Zea mays L.). Fertil Res 6:269–277. https://doi.org/10.1007/BF01048800

Saito K, Nelson A, Zwart SJ, et al (2013) Towards a better understanding of biophysical determinants of yield gaps and the potential for expansion of the rice area in Africa. In: Realizing Africa's rice promise. CABI, Wallingford, pp 188–203

Saito K, Vandamme E, Johnson J-M, et al (2019) Yield-limiting macronutrients for rice in sub-Saharan Africa. Geoderma 546–554. https://doi.org/10.1016/j.geoderma.2018.11.036

Saito K, Vandamme E, Segda Z, et al (2015) A Screening Protocol for Vegetative-stage Tolerance to Phosphorus Deficiency in Upland Rice. Crop Sci 55:1223. https://doi.org/10.2135/cropsci2014.07.0521

Sanusan S, Polthanee A, Seripong S, et al (2009) Rates and timing of phosphorus fertilizer on growth and yield of direct-seeded rice in rain-fed conditions. Acta Agric Scand Sect B - Plant Soil Sci 59:491–499. https://doi.org/10.1080/09064710802368694

Senthilkumar K, Tesha BJ, Mghase J, Rodenburg J (2018) Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. Paddy Water Environ 16:749–766. https://doi.org/10.1007/s10333-018-0666-7

Singh DK, Sale PWG, Routley RR (2005) Increasing phosphorus supply in subsurface soil in northern Australia: Rationale for deep placement and the effects with various crops. In: Plant and Soil. Springer, pp 35–44

Suralta RR, Kano-Nakata M, Niones JM, et al (2016) Root plasticity for maintenance of productivity under abiotic stressed soil environments in rice: Progress and prospects. F Crop Res. https://doi.org/10.1016/j.fcr.2016.06.023

Tabo R, Bationo A, Diallo Maimouna K, et al (2006) Fertilizer microdosing for the prosperity of small-scale farmers in the Sahel: Final report. Niamey, Niger

Tabo R, Bationo A, Gerard B, et al (2007) Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. In: Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities. Springer Netherlands, pp 201–208

Tanaka A, Johnson JM, Senthilkumar K, et al (2017) On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. Eur J Agron 85:1–11. https://doi.org/10.1016/j.eja.2016.12.010

Uga Y, Okuno K, Yano M (2011) Dro1, a major QTL involved in deep rooting of rice under upland field conditions. J Exp Bot 62:2485–2494. https://doi.org/10.1093/jxb/erq429

Uga Y, Sugimoto K, Ogawa S, et al (2013) Control of root system architecture by DEEPER ROOTING 1 increases rice yield under drought conditions. Nat Genet 45:1097–1102. https://doi.org/10.1038/ng.2725

van der Eijk D, Janssen B, Oenema O (2006) Initial and residual effects of fertilizer phosphorus on soil phosphorus and maize yields on phosphorus fixing soils: A case study in south-west Kenya. Agric Ecosyst Environ 116:104–120. https://doi.org/10.1016/J.AGEE.2006.03.018

van Oort PAJ, Saito K, Tanaka A, et al (2015) Assessment of rice self-sufficiency in 2025 in eight African countries. Glob Food Sec 5:39–49

Vandamme E, Ahouanton K, Mwakasege L, et al (2018) Phosphorus micro-dosing as an entry point to sustainable intensification of rice systems in sub-Saharan Africa. F Crop Res 222:39–49. https://doi.org/10.1016/j.fcr.2018.02.016

Vandamme E, Rose T, Saito K, et al (2016a) Integration of P acquisition efficiency, P utilization efficiency and low grain P concentrations into P-efficient rice genotypes for specific target environments. Nutr Cycl Agroecosystems 104:413–427. https://doi.org/10.1007/s10705-015-9716-3

Vandamme E, Wissuwa M, Rose T, et al (2016b) Genotypic Variation in Grain P Loading across Diverse Rice Growing Environments and Implications for Field P Balances. Front Plant Sci 7:1435. https://doi.org/10.3389/fpls.2016.01435

Weerarathne LVY, Suriyagoda LDB, Marambe B (2015) Barnyard grass (Echinochloa crus-galli (L.) P.Beauv) is less competitive on rice (Oryza sativa L.) when phosphorus (P) is applied to deeper layers in P-deficient and moisture-limited soils. Plant Soil 391:1–17. https://doi.org/10.1007/s11104-015-2383-y

Wikstrom F (1994) A theoretical explanation of the Piper-Steenbjerg effect. Plant, Cell Environ 17:1053–1060. https://doi.org/10.1111/j.1365-3040.1994.tb02028.x

Wissuwa M, Gonzalez D, Watts-Williams SJ (2020) The contribution of plant traits and soil microbes to phosphorus uptake from low-phosphorus soil in upland rice varieties. Plant Soil 448:523–537. https://doi.org/10.1007/s11104-020-04453-z

Zenna N, Senthilkumar K, Sie M (2017) Rice Production in Africa. In: Rice Production Worldwide. Springer International Publishing, Cham, pp 117–135

Zhao T, Dai A, Zhao T, Dai A (2015) The Magnitude and Causes of Global Drought Changes in the Twenty-First Century under a Low–Moderate Emissions Scenario. J Clim 28:4490–4512. https://doi.org/10.1175/JCLI-D-14-00363.1