Manipulation of Localised Nutrient Placement to Enhance Synergistic Effects of Nitrogen and Phosphorus for Rice

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Abstract

Background: Point application of fertiliser containing only immobile phosphorus (P) at a site distant from crop roots may limit plant P capture and grain yield. We investigated whether a localised application of P together with nitrogen (N) could offset this limitation in rice (Oryza sativa L.). We postulated that N in this combined fertiliser would stimulate root proliferation, thereby promoting uptake of P.

Results: We conducted a pot experiment using three localised nutrient supply treatments (N-only, P-only, and combined N and P) applied at sites near (3 cm) and distant (10 cm) from rice seedlings. We also tested the effects of homogeneous NP supply. Grain yields were similar between the homogeneous NP supply and localised N-only supply, regardless of placement distance. P-only supply with 10 cm placement reduced grain yield by 30%. Root length density was considerably greater around the placement site in the localised N-only treatment compared to the P-only at both placement distances. Hence, localised combined N and P supply offset reductions in yield and nutrient uptake realised under the P-only supply with 10 cm placement. Root mass density and root/shoot dry weight ratio were greater under the localised N-only supply than in the NP combination with 3 cm placement. Hence, localised combined N and P supply with 3 cm placement enhanced grain yield (by 33%) than the N-only supply.

Conclusion: The synergistic effects of localised fertilisation with N and P can be maximised through precise manipulation of specific placement distances for favourable root architecture and high crop yield.

Background

Crop yield improvements over recent decades have been closely associated with the wide application of chemical fertilisers (Tilman et al. 2011; Ladha et al. 2016), especially those containing N and P. Diverse loss pathways (N) and low biological availability (P) often reduce fertiliser use efficiency and threaten the health of the ecosystem environment (Chien et al. 2009; Simpson et al. 2011). These problems are particularly severe when fertiliser is provided with suboptimal placement, such as through broadcast application on the soil surface (Afroz et al. 2015; Huda et al. 2016). Designs for sound nutrient management systems should fully consider the methods used to supply each fertiliser nutrient component.

Nutrient distributions in most agricultural soils are temporally and spatially heterogeneous (Day et al. 2003; Hodge 2006; Stevens et al. 2006). Vertical nutrient stratification in the soil profile is common in locations with long histories of broadcast fertilisation and little deep-plough tillage (Howard et al. 1999; Lynch 2011). Nutrient concentrations and crop root densities decrease substantially with depth in these soils (Ma et al. 2007). Local application of fertiliser in the subsoil can enhance both the nutrient content in this depth zone and fertiliser nutrient bioavailability when synchronised with increased soil water contents (Jackson and Caldwell 1992; 1996), especially in water-limited regions (Ma et al. 2009). To exploit and survive in nutrient-rich microenvironments, crop roots exhibit morphological and physiological

adaptive strategies that facilitate nutrient acquisition (Drew 1975; Robinson 1994). This important mechanism explains the beneficial effects of local fertiliser application as a method to improve grain yields of many crops, including wheat (Trapeznikov et al. 2003), maize (Kume et al. 2006), and rice (Kapoor et al. 2008; Miah et al. 2016). However, local application of fertilisers does not always enhance crop yield and nutrient uptake, even when subterranean roots respond positively by proliferating in a nutrient-rich patch (Hodge 2004; Hill et al. 2006; Nkebiwe et al. 2016). The performance of local fertiliser application varies with crop species, fertiliser source type, and specific placement within the soil profile.

Fertiliser placement is an important factor that determines the distance between crop roots and local fertiliser dose; it directly influences (i) the plastic response of roots to fertiliser, and (ii) nutrient uptake. The diffusion movement capacity in diverse soils is lowest for P fertiliser due to a series of sorption or fixation processes involving Fe, Al, and Ca (Schachtman et al. 1998; McLaughlin et al. 2011; Schröder et al. 2011). Hence, crop roots may not effectively absorb fertiliser P when the dose is applied in low P soils at points distant from crop roots (Ma et al. 2009; Lu et al. 2018). This application will reduce crop yield, in comparison with P broadcast fertilisation. In rice, placement of a monocalcium phosphate dose 12 cm from individual rice seedlings causes a significant lag in dry matter accumulation and P uptake on day 25 after transplantation compared to P broadcast fertilisation (Lu et al. 2019). In rape, locating compound fertiliser doses 15 cm below rape seeds significantly reduced plant growth during early stages, in comparison with fertiliser incorporation through the soil (Su et al. 2015). Identification of the optimal placement of mobile P fertiliser is crucial for high crop yields and high nutrient uptake. Recent studies have demonstrated that placement of fertiliser at locations near the crop root zone can maximise crop yield potential and fertiliser use efficiency by promoting a favourable synchronisation between nutrient diffusion and root development (Cassman et al. 2002; Chen et al.,2011).

Previous studies have shown that, in comparison with separate applications of N and P, localised fertilisation with both nutrients combined can improve crop growth and P uptake by stimulating root proliferation and altering the rhizosphere pH (Li et al. 2014). For example, found that supplying nitrate-only fertiliser enhanced wheat root length density, in comparison to P-only fertilisation in acidic subsoils (Weligama et al. 2008). In maize, root length density was greater when ammonium and P were supplied together in a localised manner, in comparison with patches enriched with P alone (Jing et al. 2012). These observations raise two questions: (i) Can a localised combined supply of N and P at a distant placement location reduce rice yield losses that result from localised supplies of P-only fertiliser under flooded conditions? (ii) Can a localised combined supply of N and P at a proximate placement location enhance rice yields, in comparison with either localised N-only supply or uniform N and P supplies? We aimed to examine the effects of localised supplies of various nutrient combinations at two different placement sites on (i) rice grain yield and (ii) root plastic responses.

Results

Grain yield

The rice grain yield did not significantly differ between treatments LN (both placement sites) and UNP (Fig. 1). The rice grain yield also did not significantly differ between treatments LP (3 cm placement site) and UNP. The rice grain yield in treatment LP with 10 cm placement was reduced by 30.4%, in comparison with treatment UNP (Fig. 1). Treatment LNP with 10 cm placement offset the yield reduction obtained under treatment LP, whereas yields were similar under treatments LNP and UNP (Fig. 1). Treatment LNP with 3 cm placement realised the highest grain yield, which was 32.9% greater than the yield in treatment UNP (Fig. 1).

Grain and straw nutrient concentration and total above-ground nutrient uptake

Treatment LNP with 3 cm placement enhanced the grain P concentration in comparison with treatment UNP; however, this enhancement not observed for treatments LN and LP with 3 cm placement (Table 2). With 10 cm placement, none of the localised nutrient supply types affected grain P concentration (Table 2). The straw P concentration was unaffected by localised nutrient supply type with both 3 cm and 10 cm placements (Table 2). Hence, the total P uptake was similar to the trend in rice grain yield responses to nutrient supply and placements: it was highest under treatment LNP with 3 cm placement and lowest under treatment LP with 10 cm placement (Table 2).

Grain N concentration was unaffected by local nutrient supply type with both 3 cm and 10 cm placements (Table 3). The straw N concentrations were greater under treatments LN and NP than under treatment UNP (Table 3). Hence, the total N uptake was greater under treatments LN and LNP than under treatments UNP and LP (Table 3).

Root length and mass density

With 3 cm placement, the root length densities around the fertiliser placement sites were highest under treatments LN and LNP, followed by treatments LP and UNP (Table 4). With 10 cm placement, the root length densities were greater under treatments LN and NP than under treatments LP and UNP (Table 4).

With 3 cm placement, the root mass density around the fertiliser placement site was greatest under treatment LN (Table 4). Root mass densities did not differ among treatments LNP, LP, and UNP (Table 4). With 10 cm placement, the trends in root mass density and root length density were similar.

Root/shoot dry weight ratio

Treatment LN with 3 cm placement enhanced root/shoot dry weight ratio by 33.6%, relative to treatment UNP (Fig. 2). The root/shoot dry weight ratios under treatments LN, LP, and NP with 10 cm placement, and under treatment LN with 3 cm placement, were not significantly different from ratios under treatment UNP (Fig. 2). With 3 cm placement under treatment LN, the root/shoot dry weight ratio was reduced by 33.8%, compared with the ratio under treatment UNP (Fig. 2).

Discussion

Rice responses to manipulation of localised nutrient supply and placement site

Differences in the responses of rice grain yield between point fertilisation and uniform nutrient supply (at the same application rate) varied among combinations of nutrient type and placements. Treatments LP, LN, and LNP with 3 cm placement produced rice grain yields similar to or greater than yields under treatment UNP (Fig. 1). However, treatment LP with placement at 10 cm reduced rice grain yields below those under treatment UNP, but there was no equivalent reduction under treatment LN with 10 cm placement (Fig. 1). Thus, this result suggested that P placement requires care and precision because this element has poor movement capacity in soils (Shen et al., 2011). The point application method used in this study was not optimal for immobile P because it produced nutrient pools with high P concentration and limited capacity for diffusion, thereby limiting P capture by plants (Yao and Barber 1986; Lu et al. 2018). An optimal method for P application for wheat production involves mixing the fertiliser with 10–20% of the soil volume (Yao and Barber, 1986; Lu et al., 2018). This protocol has a high wheat yield potential. Both increases and decreases in the soil volume mixed with P fertiliser (relative to the optimal mix) reduce wheat yield at the same P input rate (Yao and Barber 1986; Lu et al. 2018).

Using point application of P alone, the maximum vertical and horizontal movements of the element away from the placement site was 2–4 cm over 30 days in sandy loamy soil with a favourable moisture content (Lu et al. 2019). Movement significantly varied with soil type and P source type (Lu et al. 2019). There was a low-P soil space between the maximum diffusion distance of 4 cm from the placement site and the rice seedling roots. As a result, rice grain yield was reduced with P point placement at the 10×10cm placement in this study (Fig. 1). Similar reductions in wheat grain yield also occurred when monocalcium phosphate fertiliser was applied in bands located 10 cm from the wheat rows in field experiment (Lu et al. 2018). In contrast, the N diffusion distance of NH_4^+ fertiliser in soil under favourable water conditions was in the range of 7–10 cm over 30 days (Liu et al. 2016). Hence, the rice yield did not reduce with point application in this study because rice seedling roots readily captured N when the N fertiliser placement was located 10 cm distant from the seedlings (Fig. 1).

The root length density around the fertiliser site under treatment LN exceeded the density under treatment LP with both 3 cm and 10 cm placement locations (Table 4); this confirmed that local N supply had a greater root-stimulating effect than P. This can be attributed to greater N movement capacity than P from the fertilizer placement. The proliferation of fine roots and lateral roots resulting from induced effect of N fertiliser enabled earlier and better access to the P source in the fertiliser mix over an extended period of time. As a result, a 10 cm placement site location of treatment LNP offset the reductions in rice grain yield obtained in treatment LP with 10 cm placement (Fig. 1). Similar findings was also reported that the point placement of diammonium phosphate significantly improved rice root proliferation around the fertiliser placement site and increased rice yield in comparison with monocalcium phosphate fertilisation, regardless of specific placement location (Lu et al. 2019).

The synergistic effect of treatment LNP with local point supply was further enhanced with 3 cm placement (Fig. 1). With this placement location, the root length densities around the fertiliser site were

similar under treatments LN and LNP (Table 4). However, the root mass density around the fertiliser site under treatment LN was significantly greater (Table 4), indicating that treatment LNP stimulated finer root growth, thereby enlarging the root uptake area. Furthermore, the root/shoot dry weight ratio was greater under treatment LNP than under treatment LN (Fig. 2). In this situation, plants under treatment LNP were able to invest more assimilates into aboveground structures, thereby enhancing grain yield. Many studies have shown that the root/shoot dry weight ratio often increases when a crop is subjected to nutrient or water stress (Ciereszko et al. 1996; Mollier et al. 1999). Heterogeneous nutrient supply may be less satisfactory than homogeneous supply, presumably because of excessive root growth in certain parts of the soil volume under point application (Hutchings and John 2004). Hence, lower root/shoot dry root ratio under the LNP suggested the nutrient supply environment was better for LNP than LN, LP, and UNP with both 3 cm and 10 cm placement locations. In addition, previous studies have also shown that localised P alone or NP combined induced root proliferation and enhanced shoot growth in a short time, but a positive effect disappeared with longer time due to the suboptimal partition between the crop root and shoot (Li et al. 2014; Jing et al. 2012).

With 3 cm placement, treatment LN did not enhance rice yield, in comparison with that obtained under treatment UNP (Fig. 1). Nevertheless, the root length density was enhanced around the fertiliser placement site in treatment LN (Table 4). The main nutrient uptake area was concentrated around N placement location, where P was not rich in this active zone, leading to further P deficiency at the fertilisation site. This may explain why plant performance was not better under treatment LN than under treatment UNP.

High efficiency nutrient placement management

Diffusion of both N and P away from point sources was very limited (Lu et al. 2018). Hence, it is unsurprising that centimetre-scale differences in fertiliser placement may result in different crop responses to treatments LP and LNP. Identification of the correct match in space and time between the root zone and nutrient distributions is crucial for achievement of high crop yields (Cassman et al. 2002; Chen et al. 2011; Lu et al. 2018). This identification can only be done through fine manipulation of specific placement sites. Locating NP fertiliser sources <3 cm from rice seedlings may increase the risk of salt damage to the plants, if the vertical placement depth was also close to rice root. When the vertical placement depth is near rice roots, the fertiliser point source should be 10 cm from rice seedlings in the vertical plane. The placement depth of 10cm was a recommended depth for rice seedling (Yao et al. 2018), hence fertiliser placement distances in the horizontal plane <3 cm may be safe for rice growth. Early studies showed that placement of NP fertiliser directly under wheat rows at a depth of 10 cm did not result in salt damage to the crop (Lu et al., 2019).

Currently, major efforts aimed at improvements of fertiliser use focus on (i) application rate, (ii) application timing, and (iii) development of new fertiliser products under conventional broadcast fertilisation; notably, these three elements are readily manipulated. The lack of adequate mechanisation has hampered efforts to improve fertiliser placement methods, especially in developing countries. New

application devices are required for precise application of fertiliser close to the crop root zone, a procedure that will considerably reduce nutrient loss and maintain fertilisers in the soil (Fujii et al. 2015; Islam et al. 2016;Yao et al. 2018). Furthermore, reductions in nutrient losses that result from local application may reduce the frequency of fertiliser dressing for high-yield crops (Jiang et al. 2018). Single applications of fertiliser through precise point application will realise large benefits under current intensive agriculture protocols, as labour costs rise and the availability of manpower decreases in ageing populations.

Conclusion

Both treatments LN and LP stimulated root proliferation, in comparison with treatment UNP. This effect was greater under treatment LN, probably because N has a greater diffusion capacity than P. Treatment LNP offset the yield loss under treatment LP with 10 cm placement, presumably by enhancing root proliferation around the fertiliser placement site. Under treatment LNP with 3 cm placement, further enhancements in rice yield were realised through reductions in the root/shoot dry weight ratio and greater development of finer roots, in comparison with treatment LN. Thus, we showed that crop yield potential and fertiliser use efficiency can be enhanced by precise manipulation of both fertiliser placement and nutrient combinations.

Methods

The treatments

This experiment was conducted in a naturally lit greenhouse at the Institute of Soil Science, Chinese Academy of Sciences. The soil was a silt loam collected from a long-term experiment that had received no fertiliser for 6 years. The background soil contained 9.5 g kg^{-1} organic carbon, 10.6 mg kg^{-1} available N (NO^{3-} + NH_4^+, measured with a TRAACS 2000 continuous flow analyser [Bran+Luebbe, Norderstedt, Germany]), 2.8 mg kg^{-1} $NaHCO_3$-extractable P, and 86 mg kg^{-1} NH_4OAc-extractable K; the pH was 8.3. The soil was air-dried and passed through a 2-mm sieve. Fifteen kilograms of soil were transferred into individual PVC boxes, each measuring 30 × 15 × 35 cm (length × width × height). The boxes had no drainage holes.

Three nutrient supply types were tested using a localised point application: N-only (LN), P-only (LP), and combined N and P (LNP). In each condition, the nutrients were supplied at two placement sites: 3 cm and 10 cm distant from individual rice seedlings, both at a soil depth of 10 cm. The effects of localised and uniform NP (UNP) applications were compared. In total, seven treatments were performed (three nutrient supply types each were applied at two placement locations, plus a single uniform nutrient supply application); all treatments were replicated eight-fold in a completely randomised design. Four replicates were used to determine root growth at anthesis; four replicates were used for measurements of rice yield and nutrient uptake at maturity.

In treatment LN, 60 mg kg^{-1} N (as urea) was point applied at the two placement sites; 20 mg kg^{-1} P (as monocalcium phosphate) was evenly mixed with the entire soil. In the LP supply treatment, 20 mg kg^{-1} P was point applied and 60 mg kg^{-1} N was evenly mixed with the entire soil. In treatment LNP, 60 mg kg^{-1} N and 20 mg kg^{-1} P were point applied together. In treatment UNP, 60 mg kg^{-1} N and 20 mg kg^{-1} P were evenly mixed with the entire soil. Other nutrients (e.g., K, Ca, Mg, and trace elements) were evenly mixed with the entire soil at the recommended rate (Yoshida, 1976). All point placement fertilisation was performed after rice transplantation; fertilisers applied by mixing with the whole soil were incorporated prior to rice transplantation.

Rice seeds of similar weight were germinated in germination pans filled to a depth of 2 cm with clean moist pearlite. Two rice seedlings with 4 or 5 leaves each, which developed *ca*. 30 days after sowing, were transplanted on 2 June 2018 into the central one-third of the soil surface area within each PVC box. The transplanted rice was maintained under flooded conditions (4–5 cm water depth).

Harvest and measurements

The rice was harvested on 28 October 2018. Aboveground shoots in each treatment were harvested at the soil surface. All samples were oven-dried at 105°C for 30 min, followed by 72 h at 60°C. Plant samples in each treatment were separated into grain and straw parts, then weighed separately to determine grain yield. Subsamples of grain and straw were ground prior to analyses of (i) total N by the Kjeldahl method, and (ii) P concentration by the molybdovanadophosphate method (Johnson and Ulrich, 1959).

Ninety days after transplantation, root samples around the fertiliser placement sites in each treatment were collected by excision of a soil cube (10 × 10 × 10 cm). Each fertiliser placement site was in the centre of each soil cube.

All root samples in individual soil cubes were freed by carefully washing away the soil under running water; roots were collected in a 0.84-mm sieve. Root samples in the remaining soils in each box were collected in the same manner. Root images were captured with an optical scanner at a resolution of 400 dpi. Root lengths were estimated with WinRHIZO software (Regent Instruments, Quebec, Canada). All root samples in individual soil cubes, remaining soil in the box, and shoot samples in each treatment were oven-dried at 75°C to constant weight; they were then weighed to determine root dry matter. Root length density around each fertiliser placement site was calculated as the root length in the soil cube divided by the volume of the cube. Root mass density was calculated as the root dry weight in the soil cube divided by the volume of the cube. Root/shoot dry weight ratios were calculated as the total root dry weight in a box divided by the shoot dry weight.

Statistics

Significant effects of nutrient supply type on rice grain yield, grain and straw nutrient concentrations, total aboveground nutrient uptake, root length density, root mass density, and root/shoot dry weight ratio were identified by one-way analysis of variance. Two-way analysis of variance was used to identify significant

effects of nutrient supply type, placement location, and their interaction on all dependent parameters (treatment UNP was not included in this analysis) (Table 1). Significant pairwise differences among means were identified by the least significant difference test with $p < 0.05$. All statistical analyses were performed with SPSS ver. 16 software (SPSS Inc., Chicago, IL, USA).

Abbreviations

N: nitrogen; P: phosphorus; LN: localised N-only application; LP: localised P-only application; LNP: localised combined N and P application; UNP: uniform NP applications.

Declarations

Ethics Approval and Consent to Participate

No applicable.

Consent for Publication

No applicable.

Availability of supporting data

The datasets supporting the conclusions of this article are provided within the article and its additional files.

Competing Interests

The authors declare that they have no competing interests.

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Authors' Contributions

DJ L, H S conducted the experiments, performed data analysis and

wrote the manuscript. XQ C HY W and JM Z conceived the experiments, drafted proposals and corrected the manuscript. All authors read and approved the final

manuscript.

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Tables

Table 1

Two-way analysis of variance tests for significant effects of nutrient supply, nutrient placement, and their interaction on rice grain yield, grain and straw N and P concentrations (con), aboveground N and P uptake, root length, root mass density, and root/shoot dry weight ratio.

Parameters	Nutrient supply		Placement		Nutrient supply × placement	
	F-value	*P-value*	*F-value*	*P-value*	*F-value*	*P-value*
Grain yield	12.3	0.001	17.2	0.001	3.9	0.04
Grain Pcon	6.3	0.01	1.1	0.32	4.6	0.03
Straw Pcon	0.8	0.48	2	0.18	0.2	0.85
Grain Ncon	1.9	0.18	5.7	0.03	0.97	0.4
Straw Ncon	10.4	0.001	1.2	0.29	2.1	0.16
Total P uptake	10.6	0.001	14.9	0.002	4.3	0.03
Total N uptake	10.9	0.001	16	0.001	0.8	0.46
Root length density	46.3	<0.001	132.5	<0.001	1.7	0.22
Root mass density	12.9	0.001	221.1	0	1.7	0.21
Root/shoot ratio	17.4	0	0.6	0.44	5.4	0.02

Table 2

Grain and straw P concentrations (con) and total aboveground P uptake of rice at maturity under different nutrient supply combinations. Lower-case letters identify significant pairwise differences between means in columns (within placement distances). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.

Placement (cm)	Nutrient supply	Grain Pcon (mg g^{-1})	Straw Pcon (mg g^{-1})	Total P uptake (mg $plant^{-1}$)
3	LN	2.27 b	0.88 a	68 b
	LP	2.48 b	0.97 a	73 b
	LNP	2.95 a	0.92 a	103 a
	UNP	2.53 b	0.82 a	73 b
10	LN	2.52 a	0.70 a	69 ab
	LP	2.35 a	0.75 a	54 b
	LNP	2.78 a	0.92 a	77 a
	UNP	2.53 a	0.82 a	73 a

Table 3

Grain and straw N concentrations (con) and total aboveground N uptake of rice at maturity under different nutrient supply combinations. Lower-case letters identify significant pairwise differences between means in columns (within placement distances). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.

Placement (cm)	Nutrient supply	Grain Ncon (mg g^{-1})	Straw Ncon (mg g^{-1})	Total N uptake (g $plant^{-1}$)
3	LN	15.7 a	13.8 a	0.65 ab
	LP	16.0 a	10.5 bc	0.57 b
	LNP	16.9 a	11.2 b	0.72 a
	UNP	16.5 a	9.7 c	0.58 b
10	LN	16.5 a	11.9 a	0.58 a
	LP	17.8 a	10.2 bc	0.45 b
	LNP	16.9 ab	11.3 ab	0.60 a
	UNP	16.5 a	9.7 c	0.58 a

Table 4

Root length and mass density of rice at anthesis around fertiliser placement sites. Lower-case letters identify significant pairwise differences between means in columns (within placement distances). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.

Placement (cm)	Nutrient supply	Root length density ($cm\ cm^{-3}$)	Root mass density ($mg\ cm^{-3}$)
3	LN	17.6 a	1.3 a
	LP	9.5 b	0.9 b
	LNP	15.6 a	0.9 b
	UNP	6.6 c	0.8 b
10	LN	10.3 a	0.4 a
	LP	3.6 b	0.2 b
	LNP	8.7 a	0.3 a
	UNP	2.2 b	0.1 b

Figures

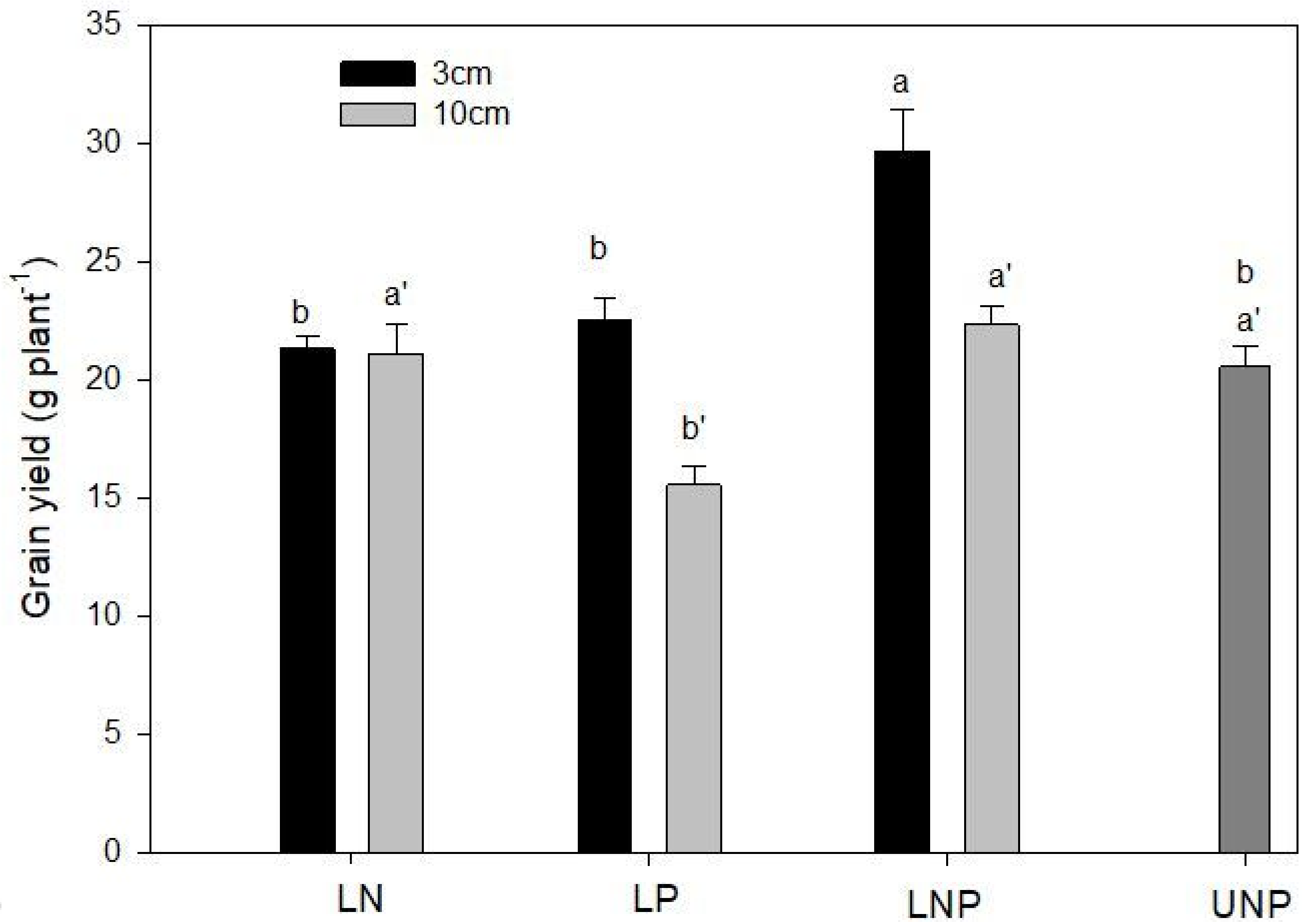
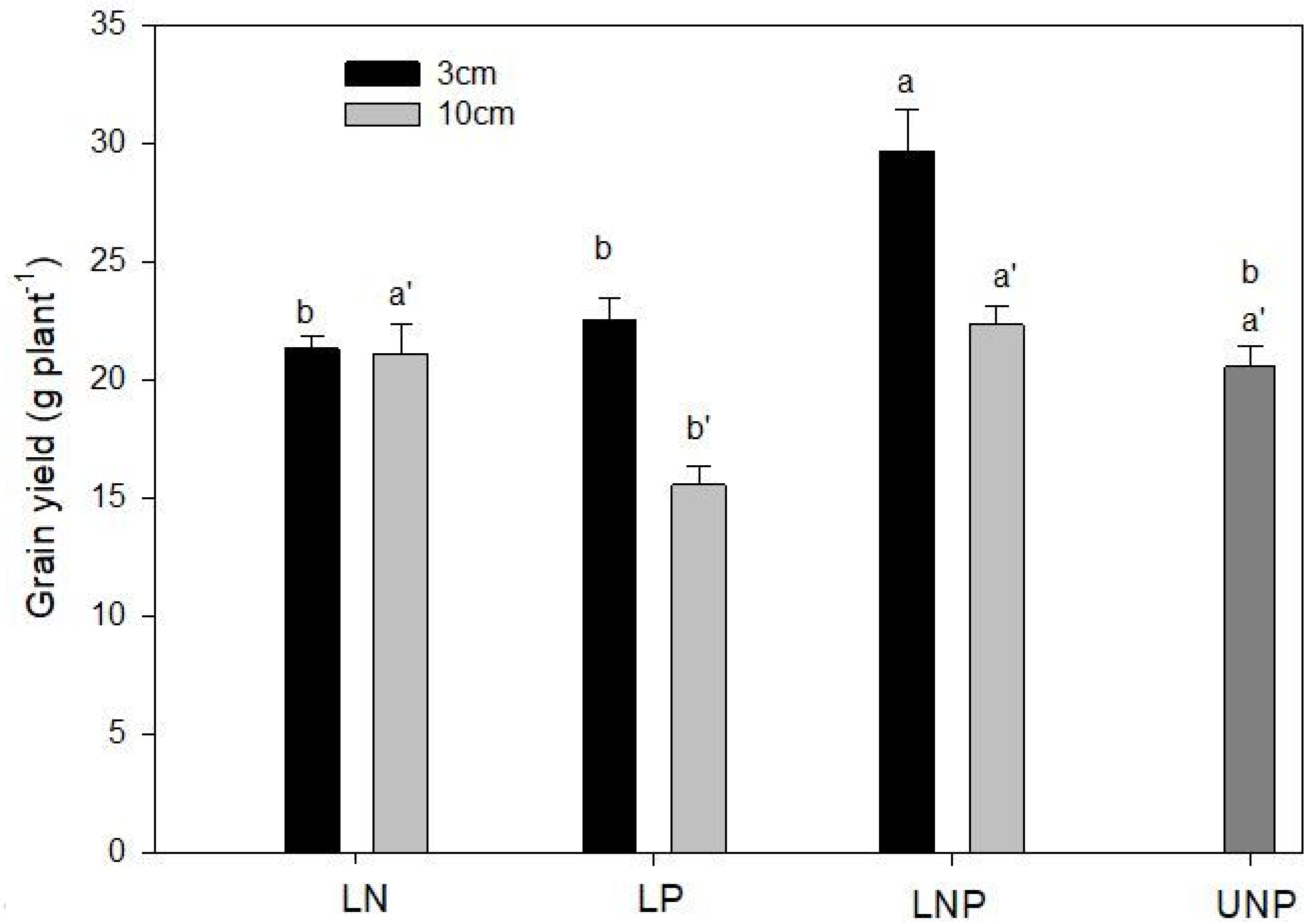


Figure 1

Rice grain yield responses at maturity to (i) different combinations of N and P, and (ii) placement location. Within nutrient placement levels (3 cm or 10 cm placement), lower-case letters identify significant differences between nutrient combinations ($P < 0.05$). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.



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Rice grain yield responses at maturity to (i) different combinations of N and P, and (ii) placement location. Within nutrient placement levels (3 cm or 10 cm placement), lower-case letters identify significant differences between nutrient combinations ($P < 0.05$). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.

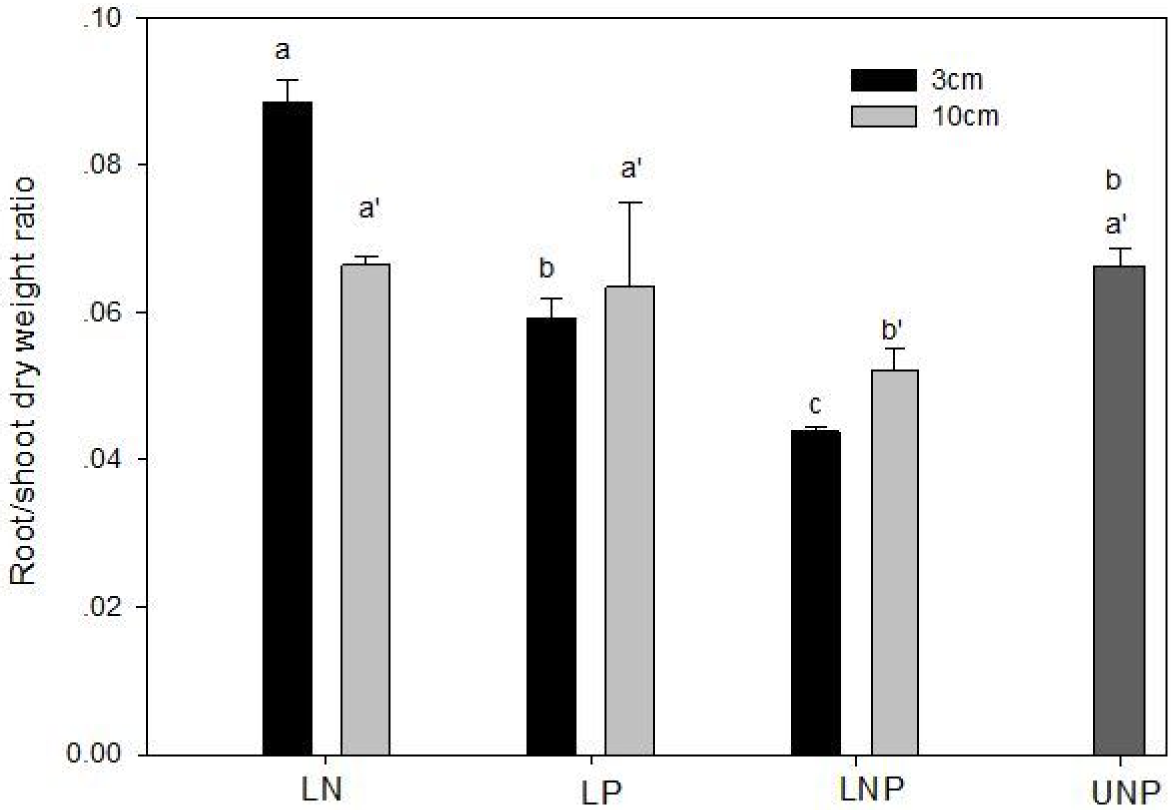
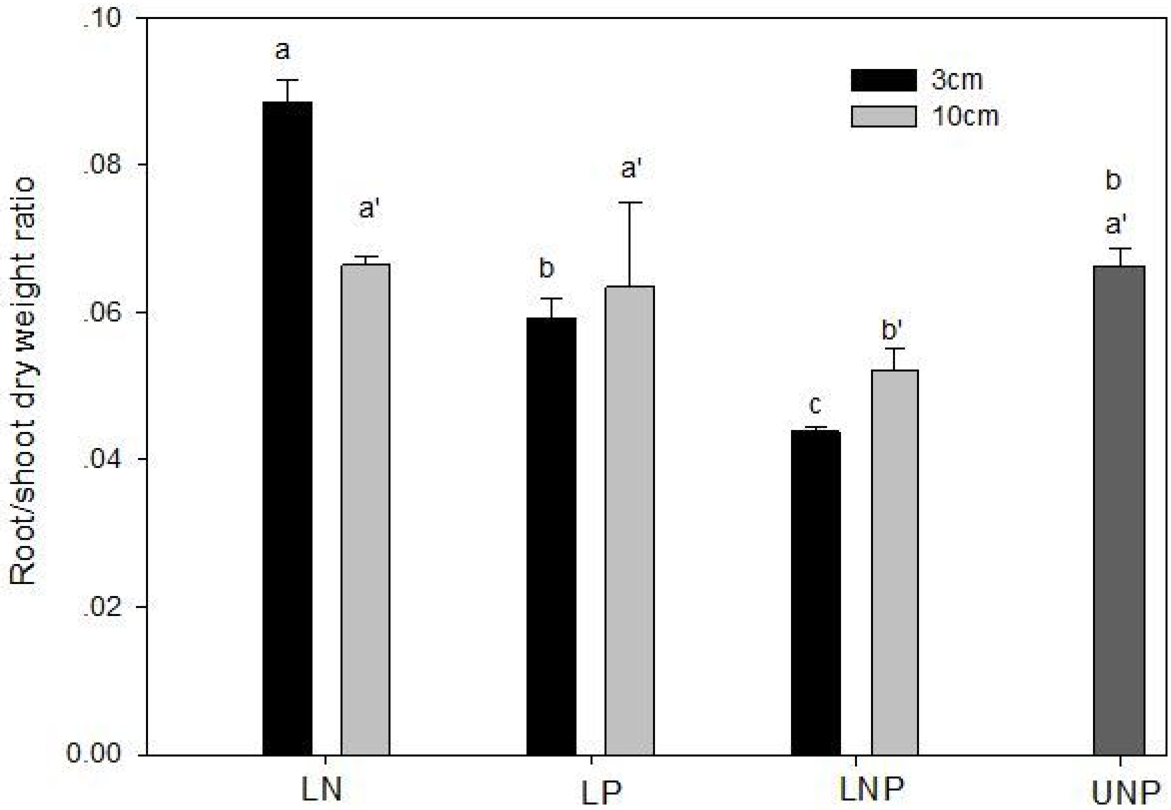


Figure 2

Root/shoot dry weight ratio responses at anthesis to (i) different combinations of N and P, and (ii) fertiliser placement location. Within nutrient placement levels (3 cm or 10 cm placement), lower-case letters identify significant differences between nutrient combinations ($P < 0.05$). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.



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Root/shoot dry weight ratio responses at anthesis to (i) different combinations of N and P, and (ii) fertiliser placement location. Within nutrient placement levels (3 cm or 10 cm placement), lower-case letters identify significant differences between nutrient combinations ($P < 0.05$). LN, localised N-only supply; LP, localised P-only supply; LNP, localised NP together supply; UNP, uniform NP supply.