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Integrated Phosphorus Placement and Form for Improving Wheat Grain Yield

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ABSTRACT

Banding of P can increase P availability to crops. Our objective was to determine if banding two forms of P fertilizer at multiple distances from the seed can improve wheat (*Triticum aestivum* L.) growth and P uptake vs. broadcast P fertilizer application. Waters-soluble and Ca_2– P concentrations in soil was greater near the point of P placement when monocalcium phosphate was used compared to diammonium phosphate, while the opposite result was found when the P diffusion distance was greater than 2 cm from the P placement. Another field experiment with four application strategies (broadcasting P, banding P under the wheat row, and banding P 5 and 12 cm from the wheat row) and two P forms was conducted over 2 yr. Banding P under the wheat row increased wheat yield and P uptake regardless of the P form compared to broadcasting P. Banding 12 cm from the row resulted in a 6.0% reduction in wheat yield for monocalcium phosphate compared to broadcasting P. Banding diammonium phosphate 5 or 12 cm from the row provided yield compensations over monocalcium phosphate. Dry matter at regreening was significantly depressed for banding 5 or 12 cm from the row with monocalcium phosphate application relative to broadcasting P, while there was compensatory growth for banding 5 cm from the row after regreening. Root length proliferated with diammonium phosphate than with monocalcium phosphate regardless of band placement. Diammonium phosphate should not be placed more than 5 cm from the row to ensure maximum P uptake potential.

Core Ideas

- We assessed the movement capacity of different P.
- Banding P fertilizer in suboptimal placement reduced wheat yield with monocalcium phosphate.
- Diammonium phosphate compensated for the reduction in wheat yield due to suboptimal placement.

Phosphorous fertilizer use by plants is relatively inefficient because of the low bio-availability of P in soils with moderate to high P-sorbing capacity (Simpson et al., 2011; Schröder et al., 2011). The majority of broadcast P supplied with fertilizers reacts with the soil (sorption or fixation with Fe, Al, and Ca) and only a small proportion is taken up by crops in the year of application (Vance et al., 2003; Syers et al., 2008; McLaughlin et al., 2011). Improper placement of P fertilizers has also been linked to greater P loss and environmental consequences, such as the eutrophication of water bodies associated with P runoff (Chien et al., 2009).

Plant phenotypic and physiological plasticity develops in response to the heterogeneous nutrient supplies as observed in the proliferation of lateral roots (Drew, 1975; Campbell et al., 1991), rhizosphere acidification (Shen et al., 2012), and increased nutrient uptake in nutrient-rich soil zones (Jackson and Caldwell, 1993; Fransen et al., 1999). Based on the well-documented foraging mechanisms, banding or point application of fertilizers can produce significant increase in crop yield, nutrient use efficiency, and decreased nutrient loss (McLaughlin et al., 2011; Farmaha et al., 2012; Nkebiwe et al., 2016). The beneficial effect of banding varies greatly with specific placement or position. Singh et al. (2005) reported that significant responses of grain yield in wheat occurred when placing P fertilizer in the soil at a depth of 10 to 15 cm compared with a depth of 5 to 7 cm in the semiarid cropping regions of northern Australia. Su et al. (2015) found banding N–P–K fertilizer at soil depths of 10 and 15 cm produced a greater dry weight of canola (*Brassica napus* L.) than at 5 cm, and the yield difference was greater when precipitation was less than normal.

Several studies have found little or no grain yield increase from deep placement of P fertilizer. Ma et al. (2009) found that deep-banding P may cause P deficiency during the seedling stage before seedling roots could reach the P-rich zone, and thus reduce grain yield. Hu (2016) found that placing P 12 cm from rice (*Oryza sativa* L.) seeding resulted in a significant reduction in rice yield and P uptake compared with broadcast P. Optimal P management should be considered when determining fertilizer placement. Many previous studies regarding crop response to regulation

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Abbreviations: AE_P, agronomic phosphorus efficiency; DAP, diammonium phosphate; DMr, dry matter accumulation at regreening stage; DMr-m, dry matter accumulation during the period from stem elongation to maturity; MAP, monoammonium phosphate; MCP, monocalcium phosphate; RE_P, recovery phosphorus efficiency; SSP, single superphosphate.

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of placement have focused on placement at different soil depth within the soil profile. Little information is available regarding crop responses to differences in horizontal P placement from crop seedlings at the same application depth. Understanding the effects of horizontal P banding from wheat row may be important for wheat production because subterranean branching of wheat roots in the horizontal direction is normally limited.

Previous studies have highlighted that P recovery efficiency may be improved by application of P fertilizers that either increase P solubility (Holloway et al., 2001; Rudresh et al., 2005; McLaughlin et al., 2011). The diammonium phosphate (DAP), monocalcium phosphate (MCP), monoammonium phosphate (MAP), and single superphosphate (SSP) are the commercial P products widely used for crop production. Even though all of these P fertilizers are water-soluble, the diffusion capacity of P fertilizer in soil varies considerably. Bell (1968) ranked the P movement capacity (the distance P diffuses from where it was placed) in the following order: DAP > MAP > MCP. There is no consensus on agronomic efficiencies (AEs) when using different form of P fertilizers (Chien et al., 2011). Inconsistent response of grain yield to P form may be attributed to the complex interaction between P forms and placement locations. Hence, we hypothesized that applying a P form with higher P movement capacity would achieve greater crop yields compared to P forms with lower P movement capacity when both forms are placed farther away from the seeds with equal nutrient input.

The Yangtze Plain is the second most intensive agricultural region in China, and farms on the plain mainly follow a rice–wheat cropping system. Since most farms on the Yangtze Plain are poorly mechanized, broadcasting and incorporation of fertilizer into the soil surface is still the main fertilization technique for cereal crops in the region. The specific objectives were to determine if P forms broadcast or banded at various distances from the seed row impact wheat yield, root growth, P use efficiency, and soil available P.

MATERIALS AND METHODS

Field experiments were established in 2015 and 2016 in Jiangyan (32.5° N, 120.2° E), Jiangsu province, China. A winter wheat–summer rice rotation was in place at the time, and winter wheat was normally sown in early November and harvested in late May. Rice was transplanted in late July and harvested in early October. The region is characterized by a humid subtropical and monsoon climate. The annual mean temperature in the experiment site ranges from 13 to 15°C, with mean annual rainfall of 900 to 1000 mm. No irrigation was provided during the wheat growing season in the experiment site. The monthly mean temperature and total rainfall for the two wheat growing seasons are shown in Table 1. The soil is sandy loam with a pH of 7.8 (1:2.5, soil/water suspension), organic matter of 13.1 g kg^{-1}, total N of 1.6 g kg^{-1}, Olsen P of 16.8 mg kg^{-1}, and NH_4OAc-extractable K of 85.5 mg kg^{-1} in the topsoil layer (0–30 cm).

Table 1. Monthly mean temperature (T) and rainfall amounts during two wheat growing seasons.

	2015		2016	
Month	$T_{average}$	Rainfall	$T_{average}$	Rainfall
	°C	mm	°C	mm
Nov.	11.8	101	11.5	52
Dec.	5.5	25	4.5	6
Jan.	2.4	47	4	11
Feb.	3.3	18	5.4	31
Mar.	6.9	24	9.7	67
Apr.	16.3	100	14.9	74
May	19.6	212	21.5	91

Field Experiment 1

Two P forms were tested in the field using P fertilizer point application incubation in four replicates arranged in a random pattern. The two P forms used were commercially ground $(NH_4)_2HPO_4$ [DAP, 21% P content and 18% N content] and $Ca(H_2PO_4)_2$ [MCP, 20% P content]. Each P form was point applied in the center of a bare plot (54 by 50 cm) at a depth of 5 cm and left for 35 d before analysis. A hole for P placement was made in each plot using an auger (5 cm i.d.). An equivalent P rate of 65.5 kg P ha^{-1} (1.77 g P $plot^{-1}$) was applied for each P form. The field situ incubation experiment is adjacent to the P placements × P-form field experiments.

Soil samples in the direction of and perpendicular to the row were destructively collected in the same soil profile from one placement in each pot after a 35-d incubation period. In the direction of P placement, a 12-cm-high rectangular soil block was collected from the surface soil in each plot using custom-made rectangular iron cuboids (length 6 cm by width 4.5 cm by height 12 cm).The 12-cm rectangular soil blocks were divided into 10 sections 1 cm long using a blade. In the direction of perpendicular to the P placement, there were six soil sections 1.5 cm long from the same P placement point using the same sampling device. All soil samples were air-dried, ground to pass through a 2-mm sieve, extracted using distilled water (1:20, soil/water suspension) for 30 min. After centrifugation (3500 r min^{-1}, 8 min), the supernatant was used to determine water-soluble P using the molybdo vanado phosphate method (Westerman, 1991). The soil was extracted with 0.25 mol L^{-1} $NaHCO_3$ and shaken for 30 min. The supernatant was used to determine Olsen-P (Olsen et al., 1954). The Ca_2-P was calculated by $NaHCO_3$–extracable P minus water soluble P.

Field Experiment 2

A field experiment was established consisting of nine P fertilizer treatments (four placements × two P forms plus a no-P treatment). The four placements included broadcasting P and banding P 0, 5, and 12 cm to the side of the wheat row at a depth of 10 cm. Wheat seeds were sown at a depth of 5 cm from the soil surface by hand. The two P forms were commercially ground $(NH_4)_2HPO_4$ (21% P content and 18% N content) and $Ca(H_2PO_4)_2$ (20% P content). The P-fertilizer band was placed by hand approximately 30 mm in width for the band treatments after rotary tillage. Nitrogen and K fertilizers for each treatment were broadcast into the field by hand and incorporated to a depth of 20 cm by rotary tillage prior to sowing. The application rates of the nutrients in each plot were as follows: 225 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1} (as KCl). To ensure the equal N input rate between MCP and DAP, the application rate of urea in DAP plots was reduced by the amount of N in DAP. 90 kg N ha^{-1} of the N fertilizer and all of the P and K fertilizer were applied prior to sowing. 67.5 kg N ha^{-1} of the remaining N fertilizer was top-dressed at growth stage (GS) 21 (Zadoks et al., 1974), while the final 67.5 kg N ha^{-1} was used at GS 30. Each plot was 24 m^2

Table 2. Results of ANOVA on the effects of P form, placement and their interactions on yield, yield components, total P uptake, recovery phosphorus efficiency (RE_P), agronomic phosphorus efficiency (AE_P), dry matter at pre-regreening (DMr), dry matter during the period from regreening to maturity (DMr-m), and soil Olsen-P content.

Effect	Grain yield	Spike number	Kernels spike^{-1}	Kernel weight	Total P uptake	AE_P	DMr	DMr-m	Olsen-P
P form	**	*	ns†	ns	*	ns	ns	*	***
Placement	***	***	ns	ns	*	**	**	**	***
P form × placement	*	*	ns	ns	*	*	*	*	**

* Significant level at $p < 0.05$.
** Significant level at $p < 0.01$.
*** Significant level at $p < 0.001$.
† ns means significant level at $p > 0.05$).

(2.4 by 10 m) consisting of 10 rows. Wheat (variety Yangmai 13) was sown on 6 Nov. 2014 and 4 Nov. 2015. The harvest date was on 26 May 2015 and 25 May 2016. Plant population density was 360 plants m^{-2}. Row spacing was 24 cm. The experiment had a randomized block design with four replications.

Root samples were collected in each plot from an area 30 by 24 cm to a depth of 20 cm at tillering stage. All roots in the soil block were collected by washing away the soil with water over a 2-mm sieve. The roots were scanned at 400 dpi. Root images were analyzed with WinRHIZO software (Regent Instruments, Quebec, QC, Canada) to calculate the root length. Soil samples from a soil cube (10 by 10 by 10 cm), in which the P band was centrally traversed, were collected in each plot after the wheat was harvested. Each soil sample was air-dried, ground, and passed through a 2-mm sieve to determine the Olsen-P concentration, extracted using 0.5 M $NaHCO_3$ with the molybdo vanado phosphate method (Westerman, 1991).

Aboveground biomass samples were collected at regreening stage (GS23) after sowing from a 1 m^2 area in the middle of each plot. Samples were oven dried at 65°C for 48 h and weighed to determine the dry matter accumulation at regreening stage (DMr). At maturity (GS100), wheat aboveground plants from a 6-m^2 area from each plot was harvested and separated into grains and straws. Wheat grain was oven dried at 65°C for 48 h and weighed to determine grain yield, standardized at 14% of water content. Wheat plant subsamples at the regreening and maturity stages (grain and straw samples) were ground to determine plant P concentrations using the molybdo vanado phosphate method.

Recovery phosphorus efficiency (RE_P) is the efficiency of P recovery from applied P fertilizer, and agronomic phosphorus efficiency (AE_P) is the yield increase per unit of P applied, defined as follows:

$$RE_P = \frac{(U_P - U_0)}{F_P} \quad [1]$$

where U_P and U_0 are aboveground crop P uptake (P concentration multiply dry matter accumulation) in applied P plots and 0P plots, respectively, F_P is the P amount from the applied P fertilizer.

$$AE_P = \frac{(Y_P - Y_0)}{F_P} \quad [2]$$

where Y_P and Y_0 are grain yield of P application plots and 0P plots, respectively; and F_P is the P amount from the applied P fertilizer.

Statistical Analysis

Prior to the statistical analysis, the spike number data were log10 transformed to satisfy the normal distribution. Three-way analysis of variance was performed to compare the effects of placement, P form, and their interactions on wheat grain yield, total P uptake, P use efficiency (RE_P and AE_P), root length, and the soil Olsen-P concentration without considering 0P treatment (Table 2). In the analyses, P form and placement were entered as fixed effects, and year and replicates were entered as random effects.The 0P treatment was used to estimate the P use efficiency (RE and AE). Significant pairwise differences among means were determined using one-way ANOVA based on the least significant difference (LSD) test at the 0.05 probability level. All statistical analyses were performed using SPSS ver. 16 (SPSS, Chicago, IL).

RESULTS

Phosphorus Movement Patterns

Water-soluble and Ca_2–P increased and were greatest near the depth of band placement (Fig. 1a and 1b). At 0 to 3.5 cm, there was no significant difference in water-soluble P and Ca_2–P concentration between MCP and DAP. At soil depths of 3.5 to 4.5 cm and 4.5 to 5.5 cm, close to P placement, the water-soluble P and Ca_2–P concentrations from MCP treatments were 50 and 32% greater than those of DAP for Ca_2–P and water-soluble P, respectively (Fig. 1a and 1b). In contrast, DAP treatments had significantly greater water-soluble P and Ca_2–P concentrations than those of MCP at a soil depth of 7.5–10.5 cm below P band, indicating greater downward movement of DAP than MCP. Water-soluble and Ca_2–P was greater with MCP than DAP at 0.5 to 1.5 cm horizontally from the P fertilizer band. Water-soluble and Ca_2–P was greater for DAP at 2.5 to 5.5 cm compared to MCP, indicating that DAP had greater P movement capacity horizontally from the point of P placement in the sandy loam soil. Combining the vertical and horizontal results as this indicates MCP mostly stays within 2 cm of the point of P injection vs. DAP which has greater overall movement.

Wheat Yield and Yield Components

Banding MCP under the row significantly increased wheat yield by 9.0 and 7.0% over broadcasting P and banding 5 cm from the row (Table 3). There was no significant difference in wheat grain yield when P was broadcasting or banded 5 cm from the row. Banding 12 cm from the row significantly reduced wheat grain yield by 6.0 and 5.6% over broadcasting treatment (Table 3). Banding DAP under the row achieved the greatest grain yield, and there was no difference from banding 5 cm from the row. Banding DAP under the row and banding 5 cm from the row significantly increased wheat grain yield by 12.6 and 9.5% over broadcasting treatment (Table 3). The two P forms produced similar wheat yields when P was broadcasting or

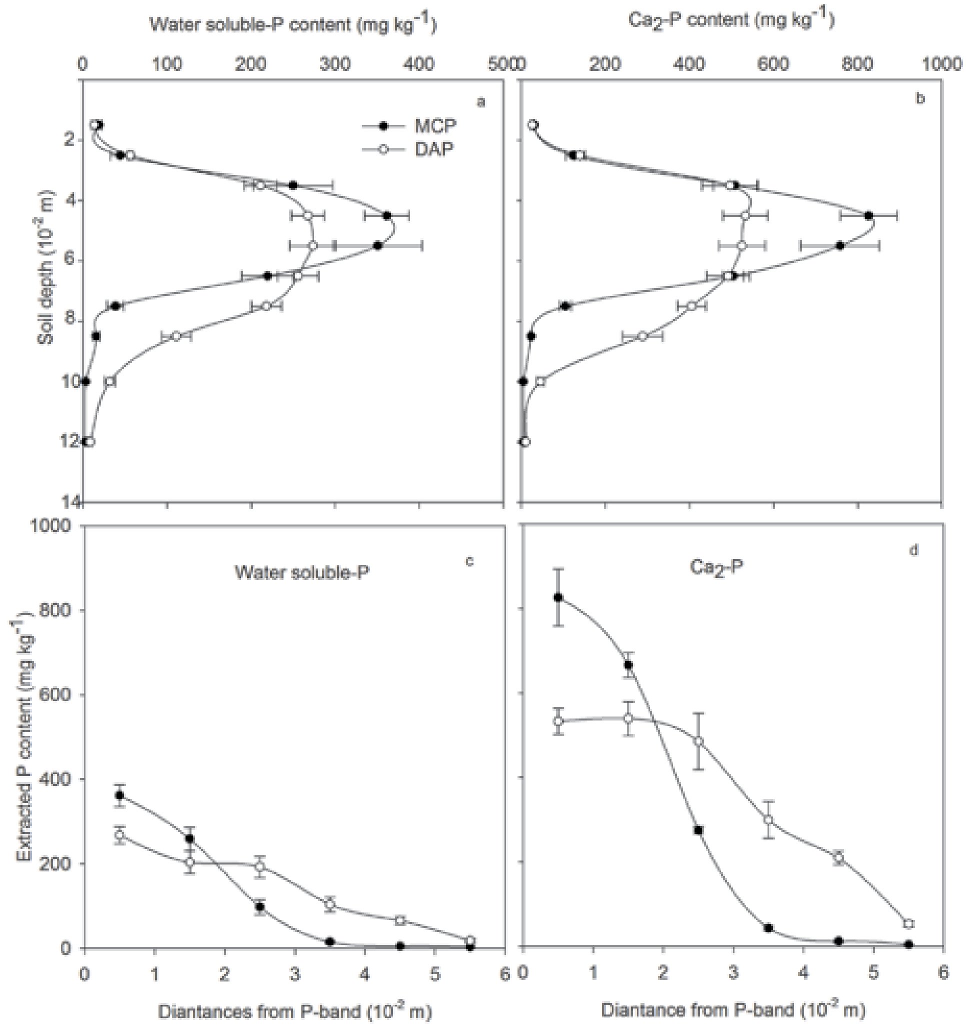

Fig. 1. Water-soluble P and Ca_2–P contents in the direction of- and perpendicular to the row of the two P forms in a field-situated incubation experiment (35-d incubation period). The two P forms used were diammonium phosphate (DAP) and monocalcium phosphate (MCP). Each P form was point-applied in the center of a micro-pot (0.54 by 0.50 m) at a depth of 5 cm for 35 d. Soil samples in the direction of and perpendicular to the row were destructively collected in the same soil profile from one placement in each pot after incubation. Horizontal bar represents ± SE of the mean.

banded under the row. However, grain yield for banding 5 and 12 cm from the row were significantly greater using DAP than those using MCP in both years.

In both seasons, spike number was significantly affected by band placement, P form, and their interactions, which was similar as the trend of wheat yield (Table 2). There was no interaction of the effects of band placement and P form for grains per spike and grain weight (Table 4). As a result, variations of wheat yield due to band placement and P form was closely correlated with spike number (Table 3).

Table 3. Wheat grain yield and spike number as affected by P placements and forms in 2015 and 2016. The four placements included broadcasting P and banding P under and 5 and 12 cm from the row at the same depth (10 cm). The two P forms used were diammonium phosphate(DAP) and monocalcium phosphate (MCP).

	Grain yield		Spike number	
Treatment	MCP	DAP	MCP	DAP
	—— Mg ha^{-1} ——		—— m^{-2} ——	
Broadcasting	6.62b†	6.57c	655b	650b
Banding under the row	7.22a	7.39a	703a	701a
Banding 5 cm from the row	6.75b	7.19b‡	660b	691a‡
Banding 12 cm from the row	6.23c	6.66c‡	604c	632c‡

† Means with different lowercase letters are significantly different among P placement locations within P sources are significantly different at $p < 0.05$.

‡ Indicates significant differences between MCP and DAP for the same placement.

Aboveground Phosphorus Uptake and Phosphorus Use Efficiency

Aboveground P uptake was significantly greater for banding P under the row than broadcasting and banding 12 cm from the row, regardless of the P form (Table 5). For MCP treatments, aboveground P uptake decreased significantly for banding 12 cm from the row compared with broadcasting treatment, whereas there were similar P uptakes between banding 12 cm from the row and broadcasting treatments using DAP. Phosphorus uptake for DAP was significantly greater than with MCP for the banding 5 and 12 cm from the row.

Recovery P efficiency and AE of banding under the row increased by 110 and 64.3% for MCP, and 100 and 85.7% for DAP than broadcasting, respectively (Table 5). Applying DAP instead of MCP increased RE from 13 to 22% for banding 5 cm from the row across both years, and from 7 to 14% in banding

12 cm form the row, respectively. For AE, DAP increased AE by 43.8% for banding 5 cm from the row than MCP, and by 87.5% for banding 12 cm from the row.

Dry Matter Accumulation and Root Length

The amount of DMr for the broadcasting treatment with both P forms was significantly less than banding P under the row. Banding the two P forms from the row had significant less DMr than broadcasting treatment (Table 6). Banding the two P forms from the row increased DMr-m than the broadcasting treatment. Banding MCP 12 cm from the row showed the same DMr-m as the broadcasting treatment. The DMr-m for banding DAP 12 cm from the row was greater than broadcasting. Banding DAP 12 cm from the row had greater DMr and DMr-m than that using MCP (Table 6).

At the tillering stage, root length was lower for broadcasting than banding under the row or banding 5 cm from the row for both P forms (Table 6). Root length for banding P under the row was the greatest, followed by banding 5 and 12 cm from the row for both P forms. There was no significant difference in root length between MCP and DAP in the broadcasting treatment. However, root lengths for banding DAP near or from the row (5 or 12 cm) were greater compared to those in treatments using MCP (Table 6).

Fertilizer Placement Effects on Olsen Soil Test Phosphorus

Soil Olsen P concentration for the broadcasting treatment at maturity was similar between the two P forms averaging 15.6 mg kg^{-1} across forms and years (Table 6). Band placement near and from the row (5 or 12 cm) using MCP increased Olsen-P concentration near the P band than DAP. There was no significant difference in soil Olsen-P concentration among the three band placements for either P form. The MCP produced grater soil Olsen-P concentration around the P band than did DAP in the three band placements (Table 6).

DISCUSSION

Band placement of P fertilizer under the wheat row provided a significant advantage in wheat grain yield, P uptake, and economic profits over P broadcasting, regardless of the P form (Table 3). Banding P fertilizer under wheat row also increased spike number (Table 3), the aboveground P uptake of wheat (Table 5) and stimulated root proliferation (Table 6). Many studies have attributed the positive effect of band placement to increasing P availability in a concentrated zone in close proximity to the seed row (Wijesinghe et al., 2004; Hodge, 2005; Kume et al., 2006) (Table 6). Other studies have reported that P must be placed deeper than 10 cm to increase wheat yield and P uptake compared to broadcast P application (Singh et al., 2005; Ma et al., 2009). A positive response of crops to banding P using deep placement has generally been observed in arid or water-limited environments (Jarvis and Bolland, 1991; McLaughlin et al., 2011). Deep placement provides ample water to facilitate P uptake. In addition, lower P concentration is observed in subsoil due to heterogeneous P distribution in soil profile due to surface application of P fertilizer and other practice such as reduced or no tillage. Deep placement compensated P fertilizer in subsoil to increase P uptake for crop roots (Ma et al., 2009; McLaughlin et al., 2011). In the Yangtze Plain, rainfall was adequate and the arable soil generally maintained favorable water content which was beneficial to increase availability of P fertilizer in topsoil. As a result, banding P 10 cm under the row showed significant improvements in wheat yield over P broadcasting.

Banding P 12 cm from the row had negative effects on wheat yield compared with broadcasting P. Hu (2016) also reported similar decreases in crop grain yield due to distant placement of P fertilizer 12 cm to wheat row. The negative response of crop grain yield to distant P placement further proved poor mobility of P in the soil. To address the poor mobility of P, placing P fertilizer near the root zone is an effective approach for improving spatial P acquisition. Increased root density or root colonization by arbuscular mycorrhizal fungi can increase the spatial acquisition of immobile P in soils (von Tucher et al., 2017). Yao and Barber (1986) found that the critical soil volume for P supply was from 10 to 20% of soil volume fraction to benefit crop yield, depending on crop species and soil types.

In our study, phosphorus deficiency has already occurred in the early growing stages when banding MCP 5 or 12 cm from the row compared with broadcast P (Table 6). The P deficiency in the early

Table 4. Grains spike^{-1} and grain weight as affected by P placement and form in 2015 and 2016.

Treatment	Kernels per spike	1000-Kernel weight
	no.spike^{-1}	g
Broadcasting	31.5	38.5
Banding under the row	31.5	38.0
Banding 5 cm from the row	31.8	37.5
Banding 12 cm from the row	32.0	40.0
LSD 0.05	ns†	0.8
MCP‡	31.6	38.5
DAP	31.9	38.1
LSD 0.05	ns	ns

† ns, not significant.

‡ MCP, monocalcium phosphate; DAP, diammonium phosphate.

Table 5. Aboveground total P uptake at maturity, recovery phosphorus efficiency (RE$_P$), and agronomic phosphorus efficiency (AE$_P$) as affected by P placement and form.

Treatment	Total P uptake		RE$_P$		AE$_P$	
	MCP†	DAP	MCP	DAP	MCP	DAP
	kg ha^{-1}		%		kg kg^{-1}	
Broadcasting	24.8b‡	25.0c	10.6c	10.9c	14.4b	13.6c
Banding under the row	31.6a	32.0a	21.1a	21.7a	23.5a	26.1a
Banding 5 cm from the row	26.1b	31.8a§	12.6b	21.3a§	16.4b	23.1b§
Banding 12 cm from the row	22.2c	27.1b§	6.7c	14.2b§	8.4c	14.9c§

† MCP, monocalcium phosphate; DAP, diammonium phosphate.

‡ Means with different lowercase letters are significantly different among P placement locations within P sources are significantly different at $p < 0.05$.

§ Indicates significant differences between MCP and DAP for the same placement.

Table 6. Dry matter at regreening stage (DMr), dry matter during the period from regreening to maturity (DMr-m), root length at tillering (GS21), and soil Olsen-P close to P placement at maturity as affected by P placement and form.

Treatment	DMr		DMr-m		Root length		Soil Olsen-P close to P placement	
	MCP†	DAP	MCP	DAP	MCP	DAP	MCP	DAP
	$Mg\ ha^{-1}$		$Mg\ ha^{-1}$		$m\ plant^{-1}$		$mg\ kg^{-1}$	
Broadcasting	2.89b‡	3.03c	10.7b	10.9c	1.11c	1.16c	15.8b	15.7b
Banding under the row	3.26a	3.40a	11.9a	12.3a	2.07a	2.40a§	47.7a	28.6a§
Banding 5 cm from the row	2.69b	2.90b	11.7a	12.2a§	1.58b	1.90b§	45.6a	29.1a§
Banding 12 cm from the row	2.20c	2.67b§	11.0b	11.6b	1.13c	1.51b§	48.3a	32.3a§

† MCP, monocalcium phosphate; DAP, diammonium phosphate.

‡ Means with different lowercase letters are significantly different among P placement locations within P sources are significantly different at $p < 0.05$.

§ Indicates significant differences between MCP and DAP for the same placement.

growing stages further highlighted the risk of P management when it comes to placement selection. The probable reason may be that limited root distribution or length before tillering could not reach the limited diffusion region of the P band for banding 12 cm from the row. Coinciding with the development of root branching and the proliferation of lateral roots, there was compensatory growth for banding 5 cm from the row after regreening due to the well-documented advantage of the local "high P concentration" effect (Lu et al., 2018). Similar results were also found by Su et al. (2015), who reported that oil-rape (*Brassica napus* L.) showed significant lag in dry matter accumulation at 36 d after sowing when fertilized with deeply placed N–P–K fertilizer at 15 cm. Compensatory growth during later growing stages of the oil-rape was also observed when roots had reached the fertilizer depot (Su et al., 2015).

Improved P mobility is desirable to increase the chance of root interception of P. Suitable selection of P may be an alternative way to increase P movement distance in soil. We found that there was a significant difference in movement capacity between MCP and DAP in soil. Water-soluble and Ca_2–P concentrations with DAP were greater as the distance from the point of application increased (Fig. 1). The difference in P movement capacity between MCP and DAP may be associated with the mobility of accompanying ions. Monovalent NH_4^+ can move farther than divalent Ca^{2+}, which is analogous to the fact that Cl^- move more freely than $H_2PO_4^-$, resulting in lower amounts of K leachate using KH_2PO_4 than regular KCl (Dong et al., 2014). Increased P mobility of DAP may be the underlying mechanism responsible for DAP reducing wheat yield and P uptake due to placement of P fertilizer greater distance away from the seed row.

The coordinated effect of N and P may contribute to DAP's better performance at suboptimal placements. Some studies have reported that the co-application of ammonium salts with P fertilizer can increase crop yield and P uptake in alkaline and neutral pH soils by stimulating root development and increasing P effectiveness, which is associated with lowering the rhizosphere pH (Miller and Ohlrogge, 1958; Duncan and Ohlrogge, 1959; Weligama et al., 2008). Field studies by Leikam et al. (1983) have found positive effects of simultaneously applying N (especially NH_4^+) and P rather than focusing on single P-band placement. In our study, part of the effect of DAP was attributed to improved root development (Table 6). Hence, N stimulates root growth in the band and attracts root growth toward the P depot to capture more P away from the plant. Jing et al. (2012) also found that dual placement of P and ammonium improves the growth of maize (*Zea mays* L.) seedlings by stimulating root proliferation and rhizosphere acidification than the band application of P fertilizer alone.

Providing a nutrient supply in the root zone is the best strategy for high-efficiency use of fertilizer. The selection of P fertilizer placement based on the movement capacity of nutrients for specific fertilizer forms in different soils is critical to attain these goals. Equipment is necessary to effectively band fertilizer in soil in the right place. Apart from the benefits of high crop yields, greater nutrient use efficiency, and environmentally friendly practices, high nutrient supplies in the root zone may realize one-time fertilization and reduce the time of dressing fertilizer and associated labor costs.

CONCLUSIONS

The extracted P concentration of DAP is consistently lower than that of MCP close to the site of P placement, while the opposite trend is observed with a P diffusion distance exceeding about 2 cm from the P placement, indicating that DAP has higher P moment capacity than MCP. Banding of P fertilizer under the seed row significantly increases wheat yield and P use efficiency than broadcasting P with recommendation rate of fertilizer at the sandy loam soil, regardless of the P form. However, increasing the distance of the band horizontally from the row results in P deficits in early growth stages of wheat seedlings and a significant reduction in wheat grain yield and P uptake when using P form with lower P movement capacity, such as MCP. Application of DAP with greater P movement capacity compensates the reductions in wheat grain yield by increasing root length. In conclusion, MCP should be placed closer to the seed row than DAP. However, while DAP has greater potential for movement the yield data indicated that DAP should not be placed more than 5 cm from the seed row to ensure maximum P uptake potential.

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