Assessment of foliar-applied phosphorus fertiliser formulations to enhance phosphorus nutrition and grain production in wheat

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Abstract.   The ability to utilise foliar-applied phosphorus (P) as a strategy to increase the P status and yield of grain crops grown in dryland regions with variable climates is attractive. Several P formulations with varying pH, accompanying cations and adjuvants were tested for their effectiveness as foliar fertilisers for wheat (*Triticum aestivum* L.) plants, first under controlled and then under field conditions. Experiments under controlled conditions suggested that several formulations with specific chemistries offered promise with respect to wheat fertiliser-P recovery and biomass responses. These formulations were then evaluated in two field experiments, and although wheat grown at the sites showed substantive responses to soil-applied P, there was no significant grain-yield response to foliar-applied P. Following the limited responses to foliar-applied fertiliser in the field, we used an isotopic dilution technique to test the hypothesis that the variation in responses of wheat to foliar addition of P could be explained by a mechanism of substitution, whereby root P uptake is downregulated when P is taken up through the leaves, but this was proven not to be the case. We conclude that foliar P application cannot be used as a tactical fertiliser application to boost grain yield of wheat in dryland regions.

Introduction

A large proportion of soil-applied fertiliser phosphorus (P) will undergo chemical reactions that remove it from the plant-available pool (Hedley and McLaughlin 2005). Owing to the low recovery of soil-based P fertiliser in the season of application, a high application rate is often required on soils where soil P reserves are low. For soils where P has been managed such that P levels are at a maintenance phase (Weaver and Wong 2011), the fertiliser requirement is often marginal and dependent on in-season rainfall (McBeath *et al.* 2012). In Mediterranean systems such as southern Australia, application of P to soils occurs at sowing. This does not allow the subsequent climatic conditions to be taken into consideration, unlike management of nitrogen (N). Furthermore, the immobility of P in dryland cropping soils means that soil topdressing with P fertiliser later in the season is not effective (McLaughlin *et al.* 2011). Hence, management of crop P supply in synchrony with variation of in-season demand for P in response to growth conditions is difficult.

With increasing costs of fertiliser P, this fertiliser input represents a large capital investment that could be managed more effectively. It is attractive to consider whether it is possible to develop more tactical P-application strategies, using foliar fertilisation to top up nutrients in-season as the crop requirements and climatic conditions dictate (Noack *et al.* 2010). However, consistent responses of wheat to foliar P applications in controlled and field conditions have been elusive (Noack *et al.* 2010).

Although wheat requirements for P are higher early in the growing season when most of the determinants of yield are set (Römer and Schilling 1986; Elliott *et al.* 1997; Grant *et al.* 2001), top-ups with foliar P have been found effective from first node visible to after anthesis in controlled conditions and/ or field experiments (Sherchand and Paulsen 1985; Benbella and Paulsen 1998; Mosali *et al.* 2006; McBeath *et al.* 2011; Peirce *et al.* 2019). In pot experiments in controlled conditions, applications of foliar P were found effective between wheat flag-leaf emergence and booting, with different degrees of

responsiveness in P uptake, biomass or grain yield (McBeath *et al.* 2011; Peirce *et al.* 2019), but earlier applications (at tillering, Zadoks growth stage GS22; Zadoks *et al.* 1974) were not effective (Peirce *et al.* 2019). However, there is a lack of consistency in responses, likely due to the interaction of factors that include physiological age of the crop, degree of crop P deficiency and leaf area of the crop available for spray interception (Noack *et al.* 2010).

In a previous study, we measured a 25% grain-yield response of wheat to foliar-applied phosphoric acid under controlled conditions in one of the two soils evaluated (McBeath *et al.* 2011). Further work focused on the use of phosphoric acid as the P source owing to this initial yield response and the availability of the product to farmers. However, yield responses to phosphoric acid have been inconsistent. This is despite the foliar uptake of P from phosphoric acid being high (>90% of the applied P) (Peirce *et al.* 2016). There is scope to investigate the effectiveness of other P formulations as foliar fertilisers because the accompanying cation and formulation pH can affect foliar P uptake (Koontz and Biddulph 1957). Previous studies have investigated the influence of replacing hydrogen from phosphoric acid with ammonium, sodium or potassium (K) and altering the pH (Tukey *et al.* 1956), but more recent evaluations of formulations is considered a gap (Froese *et al.* 2020). It is generally accepted that a low formulation pH of 2–3 facilitates more rapid uptake of foliar P (Swanson and Whitney 1953; Tukey *et al.* 1961; Bouma 1969), although it is often associated with necrotic spots and high leaf burn. For this reason, it is difficult to distinguish between the effect of pH and the effect of the associated cation, with most studies looking at the combined effect (Koontz and Biddulph 1957). The results from that study suggest that it is not a simple process of a lower pH resulting in higher uptake and translocation, given that at a pH of 5, NaH_2PO_4 had the highest translocation of P away from the treated area whereas KH_2PO_4 had the lowest. Furthermore, most previous studies that investigated the effect of pH and accompanying cation on foliar P absorption were conducted at P concentrations well below those used in the field (Koontz and Biddulph 1957; Tukey *et al.* 1961; Bouma 1969).

In addition to the source of P used, foliar fertilisation often includes the use of an adjuvant. An adjuvant is defined as any chemical added to a foliar spray solution that modifies the spray characteristics of the solution or aids in increasing the penetration of the leaf by the active ingredient (Hazen 2000). The use of adjuvants is especially important for wheat crops, because the hydrophobic nature of the wheat leaves render them difficult to wet with hydrophilic foliar sprays (Holloway 1969; Netting and von Wettstein-Knowles 1973; Peirce *et al.* 2016). The use of adjuvants can initially influence the deposition of the foliar fertiliser (through altering the spray characteristics including the droplet size) on the plant foliage (Spanoghe *et al.* 2007; Zabkiewicz 2007). Adjuvants also play a large role in increasing the retention of the sprays (particularly in the case of surfactants, which lower the surface tension of the formulation) and aiding the uptake of the foliar-applied P by increasing the diffusion of the active ingredient or increasing the hydration of the cuticle and hence its water permeability (Hess and Foy 2000). The role of

adjuvants in the translocation of foliar P once it enters the plant cells is still relatively unknown, although Stolzenberg *et al.* (1982) showed that there was little movement of a labelled surfactant and its metabolites away from the initial application site. Although the type of adjuvant was not important for either uptake or translocation of foliar-applied P when used in combination with phosphoric acid as the P source (Peirce *et al.* 2016; Peirce *et al.* 2019), it is not known what interactions may occur between adjuvants and other P sources.

In mycorrhizal plants, the direct P uptake via roots is reduced when plants take up P through the mycorrhizal pathway, resulting in no biomass gains despite increases in P uptake compared with artificially induced, non-mycorrhizal controls (Grace *et al.* 2009; Facelli *et al.* 2014). It is possible that wheat plants behave in a similar way when P uptake is increased through leaves (as foliar-applied P) by downregulating uptake from soil, hence showing lack of yield responses to foliar P. Furthermore, foliar P fertilisation (which potentially alters leaf P status) could influence the long-distance signalling (movement of molecules from shoot to roots or vice versa) that regulates the expression of transporters involved in nutrient uptake and mobilisation (Liu *et al.* 2009) as well as the partitioning of carbohydrates (Huang *et al.* 2011).

The first of this series of experiments screened combinations of source of P, adjuvant for P recovery and wheat-plant response in a controlled-environment experiment. The best treatments from the controlled environment were then tested in field conditions in combination with relevant application timing and P dose for wheat grain-yield response. Finally, a controlled-environment experiment was used to investigate the possible substitution of root P uptake by P uptake through the leaves in wheat plants as a reason for lack of in-field responsiveness to foliar formulations.

Methods

Formulation screening in a controlled environment

The experiment was set up to investigate the uptake and translocation of seven different foliar P sources in combination with three adjuvants belonging to different classes (Table 1). This gave a total of 21 formulations of P plus a non-foliar (soil) P-application control. The experimental design was completely randomised with four replicates of each foliar fertiliser treatment and 12 replicates of the nil foliar control, with a total of 96 pots.

Plants were grown in soil (1.5 kg) in pots of diameter 10 cm and depth 17 cm that were closed systems. Plants were grown in a P-responsive soil (diffusive gradient in thin film (DGT) P, 4 µg/L; Colwell P, 3 mg/kg; and total P, 48 mg/kg) from Black Point, South Australia (34°36.776′S, 137°48.599′E), with a surface soil pH of 8.5 and additional soil characteristics as described in Peirce *et al.* (2014). Before sowing, the soil was wetted to 5% (w/w) (field capacity (FC) was 22.2% (w/w) as measured according to the method of Klute 1986), with the following basal nutrients (per pot) mixed through the soil with a mixer: N as $CO(NH_2)_2$, 75 mg N; P as H_3PO_4, 4.8 mg P (equivalent to 6 kg P/ha based on pot surface area); K as K_2SO_4, 100 mg K; magnesium as $MgSO_4.7H_2O$, 25 mg Mg;

Table 1. Phosphorus products and adjuvants evaluated under controlled environment conditions as fully factorial combinations to create formulations

Product	N : P : K (w/w)	Manufacturer
Phosphoric acid[A]	0 : 26.9 : 0	Redox, Melbourne
PeKacid[A]	0 : 26.5 : 16.7	ICL Fertilisers, Sydney
Mono-ammonium phosphate[B]	12.2 : 27.0 : 0	BDH Merck, Darmstadt, Germany
Maxi Phos[A]	7.8 : 12.5 : 0	SprayGro Liquid Fertilisers, Adelaide
Potassium phosphate[B]	0 : 22.8 : 28.7	Merck, Sydney
Sodium phosphate[B]	0 : 22.5 : 0	BDH Merck, Darmstadt, Germany
Pick 15-42[A]	0 : 9.4 : 26.3	SprayGro Liquid Fertilisers
Adjuvant	Composition	
Hasten	Esterified and emulsified canola oil and non-ionic surfactants	Victorian Chemical Co., Melbourne
LI700	Soyal phospholipids and propionic acid	Nufarm Australia, Melbourne
SpreadWet 1000	Alcohol alkoxylate surfactant	SST Australia, Melbourne

[A]Commercially available fertiliser. [B]Analytical grade reagent.

zinc as $ZnSO_4.7H_2O$, 15 mg Zn; copper as $CuSO_4.5H_2O$, 12 mg Cu; manganese as $MnCl_2.4H_2O$, 2 mg Mn; and total sulfur (S) applied in these reagents, 81 mg S. Additional N and K were added to the basal nutrients (including control pots) to balance the N and K applied in the foliar fertilisers.

After a week of equilibration, the soil was added to the pots and wetted to 70% FC before sowing four pre-germinated seeds of wheat (*Triticum aestivum* var. Axe) per pot at a depth of 1 cm. Cv. Axe was selected because it has a short growth cycle and is well suited to radionuclide experiments where decay needs to be considered in terms of safety of total dose used and the maximum length of experiment that can be managed. Immediately after sowing, the surface of the pot was covered with 50 g polyethylene granules to minimise evaporation from the soil surface, and the soil was wetted to 80% FC. When the plants were at the two-leaf growth stage, they were thinned to the two most uniform seedlings per pot. Plants were watered by weight every 2 days to maintain 80% FC and grown in a controlled-environment room (12-h cycle of 20°C day, 15°C night for 41 days; 23°C day, 15°C night thereafter until harvest at 62–65 days after sowing (DAS)), with their positions randomised every few days. To ensure that N was not limiting, at 15 and 27 DAS, 25 mg N (as urea) was applied to the surface of each pot and watered in.

Foliar fertilisers were applied 34 or 35 DAS at GS37, flag leaf visible. Treatments were applied early in the morning within a 2-h window to avoid changing environmental conditions. Owing to the large number of treatments, application occurred over 2 days with two of four replicate blocks treated each day. Isotopically labelled P fertiliser was made by adding carrier-free ^{33}P (in the orthophosphate form) to give an activity of 144 kBq/pot at application. Fertilisers were applied with a Multipette M4 (Eppendorf, Hamburg), which controlled droplet size, delivering forty 2-µL drops to give an application rate of 1.6 mg P/pot, equivalent to 2 kg P/ha in a total volume 100 L/ha (0.65 M P). Fertiliser application was spread between the five leaves on the main stem excluding the flag leaf, provided they were healthy. If a leaf was not healthy, had been broken or had already senesced, it was excluded from the foliar application.

Aboveground plant material was harvested at the end of anthesis and separated into heads, treated leaves, tillers, and the main stem with the remaining leaves attached. All plant parts, including those of controls, were washed according to the method outlined in Fernández *et al*. (2014) to remove fertiliser P not taken up by the leaves. Plant parts were dried in an oven at 60°C for 72 h before being weighed, ground and digested in boiling nitric acid, then analysed for total P by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) (Zarcinas *et al*. 1987). A 2-mL sample of the digest was added to a vial with 10 mL scintillation fluid (Ultima Gold AB; PerkinElmer, Waltham, MA, USA), and ^{33}P activity was determined by using a Quanta Smart liquid scintillation analyser (Model Tri-Carb B3110TR; PerkinElmer). Washing solutions were also retained to analyse both total and radioactive P by both ICP-AES and liquid scintillation counting. All counts were corrected for decay.

Total P in the plant was calculated as the sum of P (mg/pot) in all harvested plant parts after washing. The total P was then divided as P derived from the soil and seed and P derived from the labelled foliar fertiliser. Phosphorus derived from the foliar fertiliser was calculated according to Eqn 1:

$$P_{\text{in plant part from foliar fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right) = \frac{P_{\text{in washed plant part}} \left(\frac{\text{Bq}}{\text{pot}}\right)}{\text{specific activity}_{\text{foliar fertiliser}} \left(\frac{\text{Bq}}{\text{mg P}}\right)} \quad (1)$$

By using the washing solution, the amount of P that was not absorbed by the plant was estimated by dividing the activity of the washing solution by the specific activity of the foliar fertiliser. Absolute recovery of the foliar fertiliser was then calculated as the sum of that recovered in the plant parts and in the washing solution as a percentage of the applied fertiliser (Eqn 2):

$$\%\text{Fertiliser recovery} =$$
$$\frac{P_{\text{in all plant parts from fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right) + P_{\text{in washing solution}} \left(\frac{\text{mg P}}{\text{pot}}\right)}{P_{\text{added in foliar fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right)} \times 100 \quad (2)$$

Both foliar P uptake and foliar P translocation were expressed as a percentage of the applied foliar fertiliser recovered in the plant parts after they were washed (Eqns 3

and 4). Translocated P (fertiliser P applied to leaves and translocated to other plant parts) was calculated as the percentage of foliar-applied P recovered in all plant parts at harvest excluding the treated leaves (Eqn 4):

$$\%\text{Foliar uptake} = \frac{P_{\text{in all plant parts from fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right)}{P_{\text{added in foliar fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right)} \times 100 \quad (3)$$

$$\%\text{Foliar translocation} =$$

$$\frac{P_{\text{in all plant parts from fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right) - P_{\text{in treated leaves}} \left(\frac{\text{mg P}}{\text{pot}}\right)}{P_{\text{added in foliar fertiliser}} \left(\frac{\text{mg P}}{\text{pot}}\right)} \times 100 \quad (4)$$

Field experiments: testing formulations, timing and rates

Replicated field experiments were established in 2015 at two locations in South Australian dryland cropping areas. Sites were selected at Sherwood in the Upper South East (36°04′S, 140°35′E) and Pinery in the Mid North (34°17′S, 138°28′E). Soil samples (0–10 cm) were taken from the sites before sowing to confirm soil P status. The soils were analysed, and the soil-test prediction was that the sites would produce wheat grain responsive to inputs of P fertiliser (Mason *et al.* 2010; Table 2). Rainfall was average for the growing season at Pinery, but below average for the months June and October.

Rainfall throughout the growing season was well below average at Sherwood (Fig. 1).

Each experiment comprised two levels of soil starter-P and 10 foliar fertiliser formulations applied at two timings. The formulations resulted from the combination of five sources of P and two adjuvants (Table 2) and were compared with nil foliar-fertiliser controls. These formulations were chosen based on results from the first controlled-environment experiment. The rates for soil starter-P were selected to provide enough soil P to increase levels to a marginal P status. The rates were 12 kg P/ha for Pinery and 15 kg P/ha for Sherwood, added as mono-ammonium phosphate (MAP). Nitrogen was balanced across all plots by using urea. Balancing the small amounts of K and S added with the foliar fertiliser was considered unnecessary because soil tests at both sites showed test levels well in excess of sufficiency (data not shown). Following establishing rains in May, field plots of wheat (cv. Mace) were sown at 80 kg/ha to achieve establishment of at least 150 plants/m². Cv. Mace was selected because it was the best adapted cultivar at the time and location of the experiments. These plots were sown with plot-scale equipment, and there were four replicate plots (2 m by 7 m; six rows with 0.25-m row spacing) per foliar fertiliser treatment at both levels of soil starter-P, arranged in a randomised complete block design.

At Pinery, the two timings for foliar P sprays were stem elongation, second node visible (GS32) and boots swollen (GS45). At Sherwood, timings of application were at sixth

Table 2.   Field-site soil phosphorus (P) properties and experimental treatments

DGT, Diffusive gradient in thin film (Mason *et al.* 2010); PBI, P buffering index (Burkitt *et al.* 2002); PA, phosphoric acid; MAP, mono-ammonium phosphate; GS, Zadoks growth stage

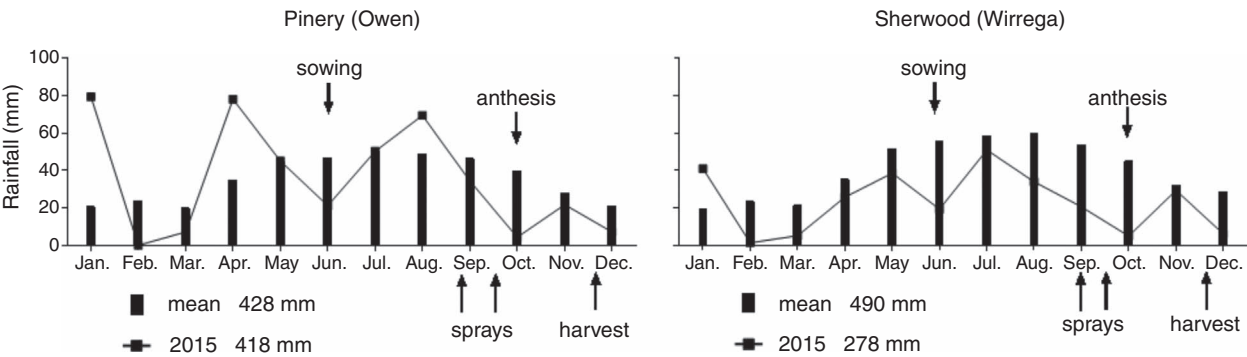|	Pinery	Sherwood
Soil type	Calcarosol	Sodosol
Colwell P (mg/kg)	42	18
DGT P (µg/L)	9	6
PBI	133	52
Sowing P rate (kg P/ha)	0, 12	0, 15
Foliar P rate (kg P/ha)	0, 2	0, 2
Foliar P sources	PA, Pick, PeKacid, MAP, sodium phosphate	PA, Pick, PeKacid, MAP, sodium phosphate
Adjuvant sources	0.4% Hasten, 0.5% SpreadWet®	0.4% Hasten, 0.5% SpreadWet
Foliar P Timing	GS32, GS45	GS36, GS45–55

Fig. 1.   Field experimental site monthly mean (based on ~100-year records) and 2015 rainfall data from the nearest Bureau of Meteorology weather station (in parentheses).

node visible (GS36) and boots swollen to half of inflorescence emerged (GS45–55). On the application date at Sherwood, plants growing in P0 plots were at GS45 whereas some of the plants in P15 plots were already at GS55. The application rate was equivalent to 2 kg P/ha in a total volume 100 L/ha. Sprays were applied with a 6-L handheld sprayer with two nozzles, each fitted with a constant pressure (100 kPa) valve at ~0.5 m above the crop. In-season plant nutrient concentrations were measured before the application of foliar treatments. Fifty plants were randomly sampled for youngest emerged blades from each control plot at GS36 and analysed for nutrient concentrations. Plant P concentration was measured according to the procedure outlined for the controlled-environment experiment. Plants from two 0.5-m sections of internal rows were randomly selected and cut at 2.5 cm above the ground, dried at 60°C and their dry weights were recorded.

At maturity, plots in all experiments were machine-harvested using a plot-scale harvester, and aboveground biomass was sampled by hand-cutting plants from four 0.5-m sections from each plot at ~2.5 cm above the ground.

Controlled environment experiment: substitution hypothesis

Wheat plants (cv. Axe) were grown in the same soil and conditions as the first controlled-environment experiment except that soil was treated to achieve two levels of basal soil P that mimicked deficient and marginal soil P levels for wheat growth. After a week of equilibration with basal nutrients, the soil was thoroughly mixed with labelled (^{33}P, 3 MBq/kg) H_3PO_4 solutions to provide 3.2 or 8.5 mg P/kg (equal to 6 or 16 kg P/ha) and allowed to equilibrate for a further 10 days. Soil was then added to pots and wetted to 80% FC before sowing four pre-germinated seeds per pot. When the plants were at the two-leaf growth stage, they were thinned to the two most uniform seedlings per pot. Plants were watered by weight to 80% FC every 2 days and were grown in a controlled environment room (12-h cycle of 20°C day, 15°C night; average irradiance 230 μmol/m^2.s) with their positions randomised at watering. To ensure N was not limiting, 25 mg N/pot as urea was applied to the surface at 15, 27 and 34 DAS and watered in.

The foliar fertiliser formulations Pick 15-42 and Maxi Phos in combination with SpreadWet 1000 were selected because they had contrasting effects on wheat dry mass and P uptake in the first controlled-environment experiment. Foliar fertilisers were applied as described for the first controlled-environment experiment at 35 DAS (GS 37, flag leaf visible). For each plant, fertiliser application was spread between three healthy leaves on the main stem and tillers (excluding flag leaf). The extra N and K applied in the foliar fertilisers was balanced in the corresponding treatments by addition of N (as urea) and K (as K_2SO_4) to the surface of the soil (watered in) the day before foliar fertilisation. Plants were harvested at early anthesis (GS63) and processed and analysed according to the procedures used in the first controlled-environment experiment.

Statistical analyses

For both controlled-environment experiments, analysis of variance (ANOVA) was used to test for treatment effects. For field experiments, ANOVA or *t*-tests were used to analyse the data. GENSTAT Release 16.1 (VSN International, Hemel Hempstead, UK) was used for analysis. Assumptions of distribution normality and constant variance error were tested for all data analysed. Least significant difference (l.s.d.) between treatments was calculated using Fisher's protected l.s.d. at $P = 0.05$.

Results

Growth room formulation evaluation

There were differences in aboveground dry weight between treated plants and the controls (Fig. 2*a*). Three treatments resulted in an increase in tiller biomass and total aboveground biomass compared with the control: PeKacid + SpreadWet, sodium phosphate + Hasten, and Pick + SpreadWet. Five treatments resulted in greater head biomass than the controls: MAP + Hasten, sodium phosphate + SpreadWet, and Pick with all three adjuvants.

The uptake of foliar P by plants was >80% of that applied for 15 of the 21 treatments (Fig. 2*b*). In most cases, nearly all of the recovered foliar fertiliser was located within the plant parts; only a small proportion (0–3%) of the fertiliser did not adhere to the leaves. Most of the products also had a large proportion of the foliar P translocated out of the treated leaves (Fig. 2*b*). The treatments that had lower foliar uptake (<80% of applied P) were MAP + Hasten, Maxi Phos + Hasten, potassium phosphate with all three adjuvants, and sodium phosphate + Hasten. These treatments represented the range from ammonium phosphate, potassium phosphate and sodium phosphate products. The pH of the first five of these formulations was ~4.3, whereas the pH of sodium phosphate + Hasten was 6.5.

Of the products that were commercially sourced (phosphoric acid, PeKacid, Maxi Phos, Pick), which varied in pH and associated cations, the uptake of foliar P was high (76–100% of applied amount) regardless of which adjuvant was utilised (Fig. 2*b*). The products that were analytical grade reagents (MAP, potassium phosphate, sodium phosphate) had variable uptake results. Phosphoric acid differed from all other products in the amount of foliar P that was translocated to other plant parts; for phosphoric acid, only 22–26% of the applied P was translocated, with the remainder (72–75%) located in the treated leaves at harvest (Fig. 2*b*). By comparison, all other products had a significantly higher proportion of their P translocated out of the treated leaves (38–82% of the foliar P recovered in the plant parts).

Field experiment: testing formulations, timing and rates

The results from the soil analyses were complemented by tissue analyses (Table 3) indicating that plant P concentrations at the first timing of foliar P application were close to the range given for diagnosis of P deficiency (0.21–0.25% total P for youngest emerged blades, GS31; Reuter and Robinson 1997). The concentrations of soil N, K and S (elements present in the foliar formulations tested at Pinery and Sherwood) were above adequate ranges (data not shown), suggesting that plants would not be responsive to further addition of these nutrients.
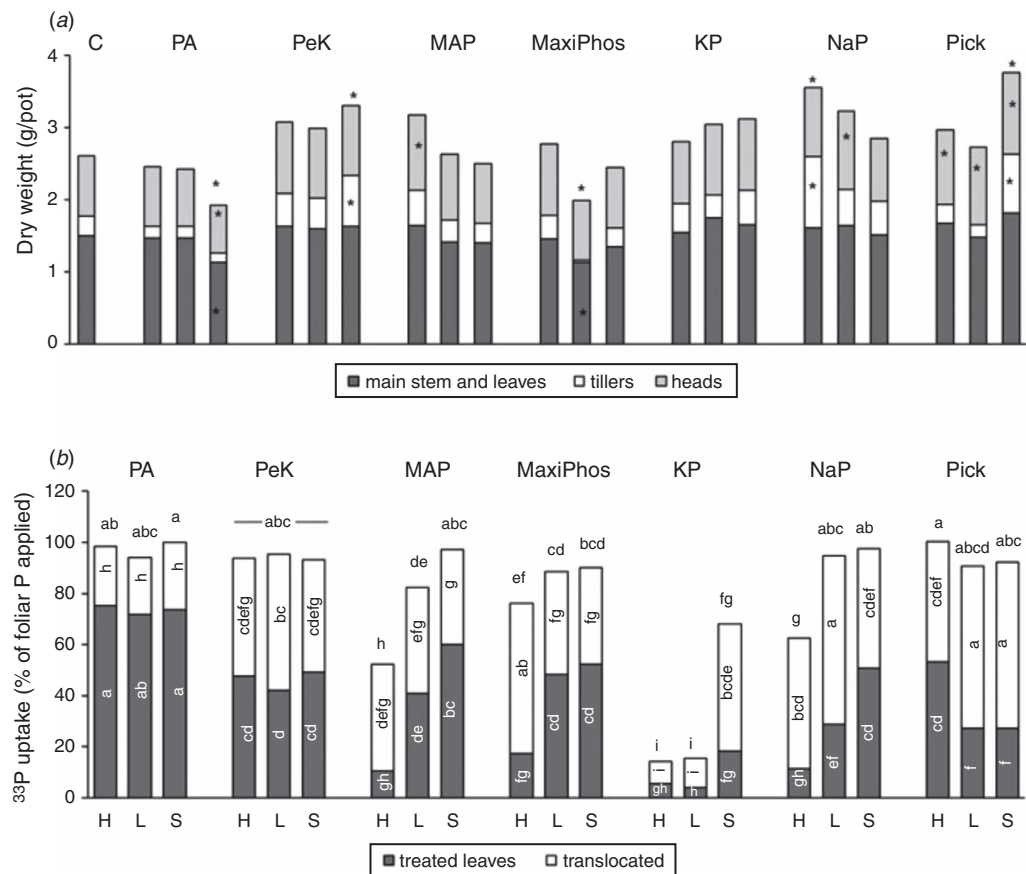
Fig. 2. (*a*) Total dry weight and (*b*) plant foliar P uptake of the seven foliar products (PA, phosphoric acid; PeK, PeKacid; MAP, mono-ammonium phosphate; Maxi Phos; KP, potassium phosphate; NaP, sodium phosphate; Pick) in combination with three adjuvants (H, Hasten; L, LI700; S, SpreadWet). Wheat plants were harvested at the end of anthesis and fertilised or not (C, control) at GS37. For biomass, significant (*P* < 0.05) differences compared with the control are indicated by an asterisk (*) for total (above bars), and for tiller, head, or main stem and leaves (on bars). In (*b*), among treatments for each plant part, means with the same letter are not significantly different (*P* > 0.05).

Table 3.   In-season soil and plant measurements

DGT, Diffusive gradient in thin film; PBI, P buffering index. Post-foliar plant phosphorus (P) was determined on samples taken at flag leaf emergence (GS39) from the youngest emerged blade. Harvest index, grain protein and grain P concentration and uptake were taken at maturity. Values are mean ± standard error of the mean. Only main effects for soil fertiliser P are presented because there were no significant effects of any foliar treatment. For each site, parameter means that differ between soil fertiliser P levels (*P* < 0.05) are followed by different letters

| Site:	Pinery		Sherwood	
Sowing fertiliser P (kg P/ha):	0	12	0	15
Pre-foliar soil Colwell P (mg/kg)	30 ± 1.8b	65 ± 7.6a	14 ± 0.9b	36 ± 5.4a
Pre-foliar soil DGT P (µg/L)	12 ± 3.7b	73 ± 19.0a	5 ± 0.6b	71 ± 17.3a
Pre-foliar soil PBI	100 ± 1.5	98 ± 1.8	33 ± 1.5a	30 ± 0.6b
Post-foliar plant P (% w/w)	0.26 ± 0.01	0.27 ± 0.01	0.21 ± 0.01	0.23 ± 0.01
Anthesis biomass (t/ha)	1.00 ± 0.02a	1.14 ± 0.01b	0.37 ± 0.01a	0.67 ± 0.01b
Maturity biomass (t/ha)	6.7 ± 0.11a	7.4 ± 0.10b	2.0 ± 0.05a	3.0 ± 0.05b
Grain yield (t/ha)	2.8 ± 0.4a	3.0 ± 0.4b	0.63 ± 0.2a	1.04 ± 0.2b
Harvest index	0.43 ± 0.03	0.42 ± 0.03	0.37 ± 0.03	0.37 ± 0.03
Grain protein (% w/w)	14.1 ± 1.3	12.7 ± 1.0	14.9 ± 0.8	14.2 ± 0.9
Grain P concentration (% w/w)	0.33 ± 0.05	0.29 ± 0.02	0.26 ± 0.01	0.27 ± 0.03
Grain P uptake (kg P/ha)	10.1 ± 1.07	8.9 ± 0.92	1.4 ± 0.15a	3.0 ± 0.10b
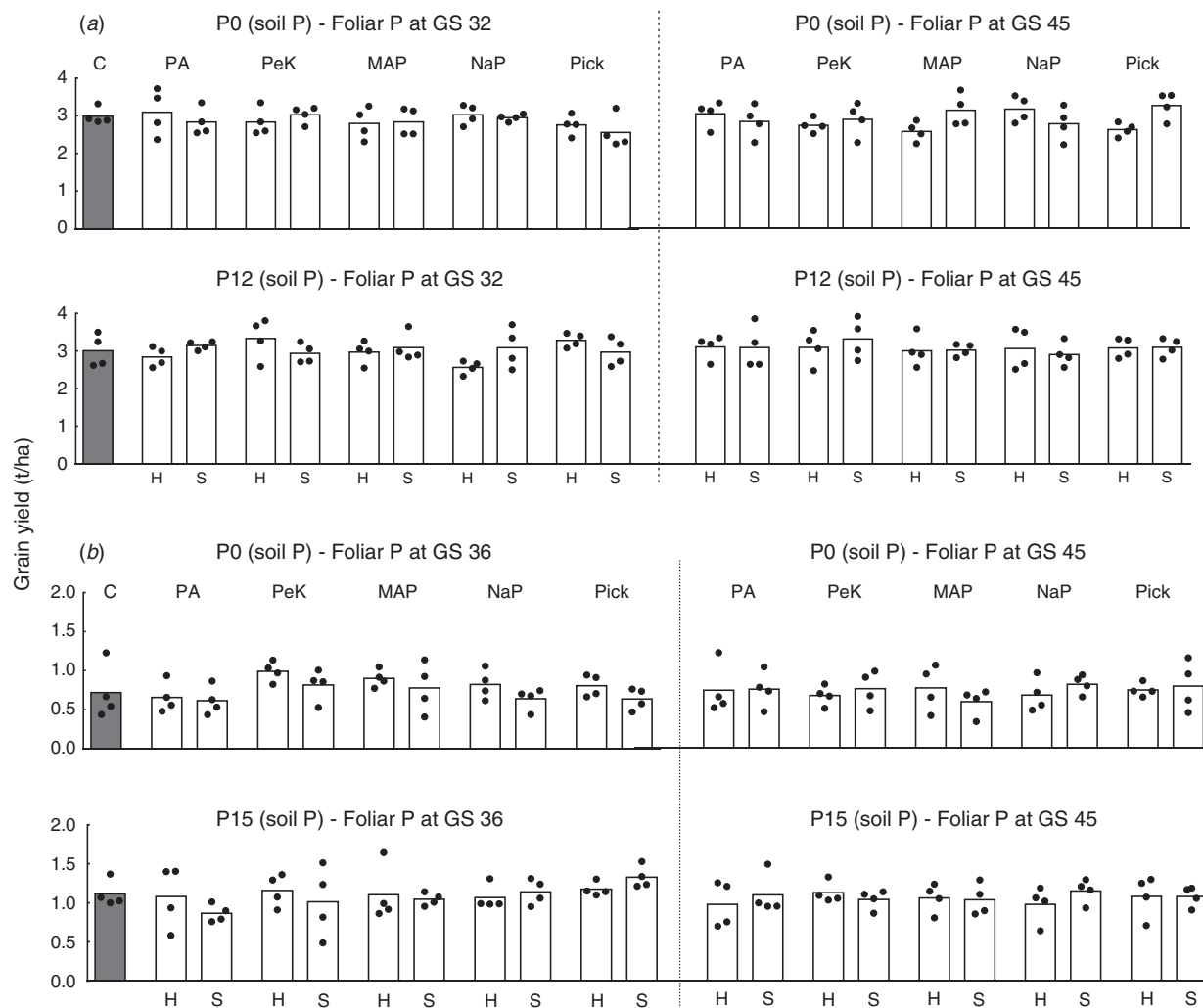
Fig. 3. Grain yield of wheat (cv. Mace) plants grown at two rates of soil starter-P, and fertilised or not (C, control) with foliar P formulations in combination with adjuvants at two timings (GS 32–36 or GS 45–55). Soil starter-P applied as MAP at sowing at (*a*) Pinery (at 0 (P0) and 12 (P12) kg P/ha); and (*b*) Sherwood (at (P0) and 15 (P15) 15 kg P/ha). Foliar formulations: PA, phosphoric acid; PeK, PeKacid; MAP, mono-ammonium phosphate; NaP, sodium phosphate; Pick. Adjuvants: H, Hasten; L, LI700; S, SpreadWet. Bars represent treatment means and dots the individual replicates.

There was no effect of foliar P on grain yield (Fig. 3). However, there were increases in shoot P concentration and biomass due to applications of soil fertiliser P at both sites; the positive biomass response of the crops to soil starter-P was evident at anthesis, as it was in grain yield response at maturity at both sites (Table 3). From anthesis to maturity, the differences in biomass between nil P and added soil P decreased at both sites but there were still significant benefits of up to 38% higher grain yield with soil-applied P (Table 3). There was no effect of soil starter-P on grain protein, grain P concentration or harvest index at either site, although there was an increase in grain P uptake in line with the grain yield response at Sherwood (Table 3).

Controlled environment experiment: substitution hypothesis

Aboveground and head biomass values were higher in pots with higher soil P, but there was no effect of foliar P application (Fig. 4*a*, *b*). However, the effects of foliar P application were significant for plant P uptake, and at each level of soil P there was an overall increase in plant P due to foliar P application (Fig. 4*c*). Similarly, there was an increase in head P due to foliar treatments in plants grown at high soil P, but in plants grown at low soil P, there was no difference in head P between foliar P treatments and the controls (Fig. 4*d*). The ^{33}P activity per g plant was not different between foliar treatments and the controls within each level of soil fertility (Fig. 4*e*), indicating no effect of foliar P on uptake of P from soil (i.e. substitution).

Discussion

Growth room formulation evaluation

The responses measured in the controlled environment do not seem highly dependent on source of P (pH, accompanying
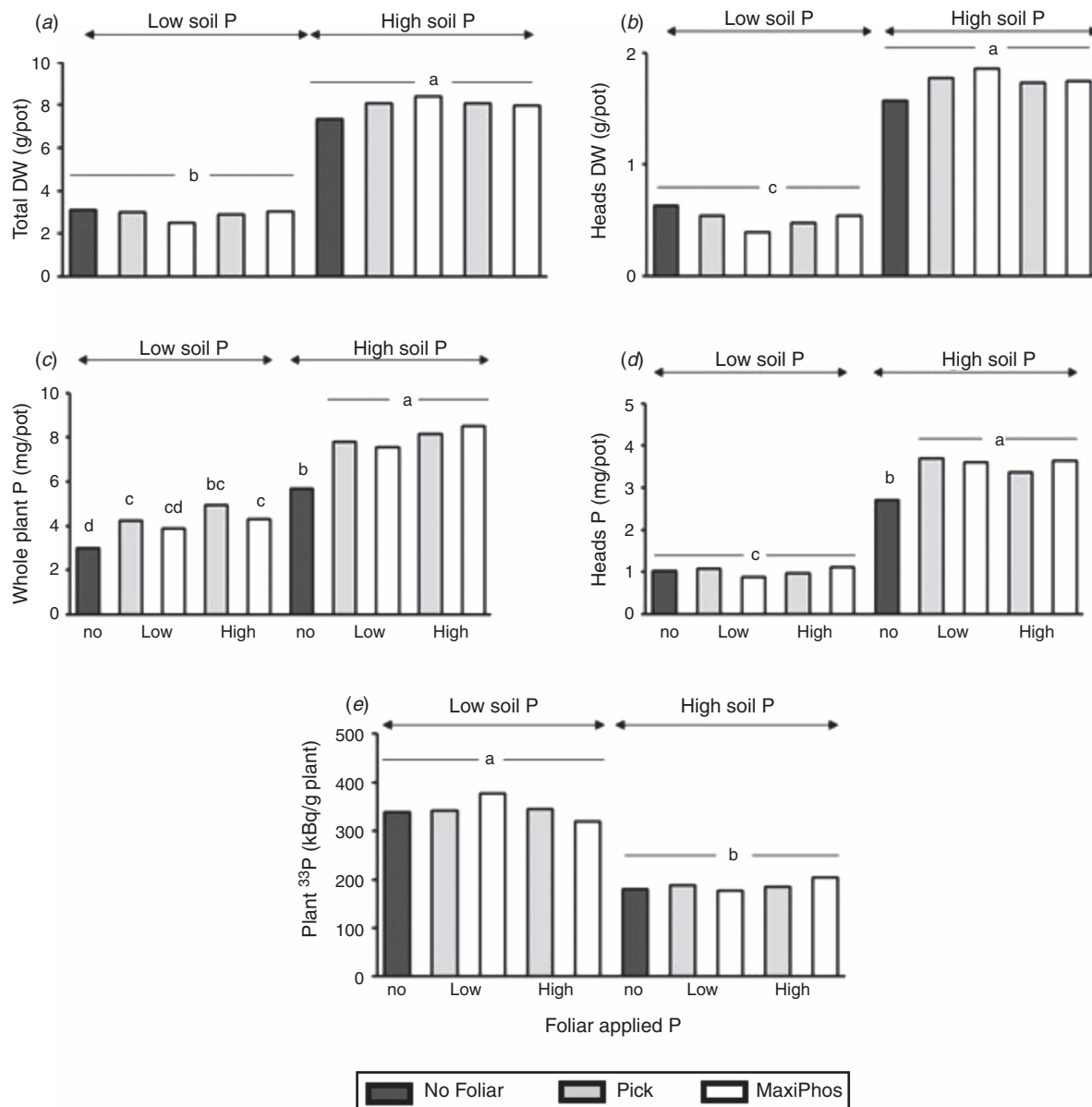
Fig. 4. (*a*, *b*) Total and head dry weight (DW); (*c*, *d*) total and head P uptake; and (*e*) activity of ^{33}P in wheat plants grown in soil with P added at sowing as radiolabelled (~3 MBq/pot) H_3PO_4 solutions at two rates (6 (Low) or 16 (High) kg P/ha equivalent) and fertilised or not (no foliar controls) with foliar applications of P as Pick or Maxi Phos plus SpreadWet at two application rates (2 (Low) or 3 (High) kg P/ha equivalent). Within a graph, means with the same letter are not significantly different (*P* > 0.05).

cations) or adjuvant type. The products Pick and PeKacid in combination with SpreadWet produced the most consistent biomass increase over the control. An increase in biomass due to increased uptake of P from foliar application has previously been reported (Sherchand and Paulsen 1985; Mosali *et al*. 2006; McBeath *et al*. 2011). The high recovery (>60% in most cases) of the foliar pathway found in this study is consistent with findings from other studies that used foliar P at rates relevant for field applications (McBeath *et al*. 2011; Peirce *et al*. 2014, 2016). The efficiency of foliar P uptake was not affected by formulation, with only potassium phosphate having lower efficiency, owing to crystallisation of the

fertiliser on the leaf surface, which was subsequently washed off the leaves. It is expected that higher P uptake from foliar fertiliser, and therefore more P resources for the plant to grow, would lead to aboveground biomass increases compared with the control, particularly if the tissue P concentration was low.

For a foliar application to be effective, once it is absorbed by the leaf, it must be able to move to the growing plant parts and be utilised for growth. Phosphorus is a nutrient that has been shown to be very effectively translocated from senescing plant parts to the grain when grown through to maturity (Batten *et al*. 1986). Phosphoric acid had high overall

uptake across all formulations with the three different adjuvants. However, only 22–26% was translocated out of the treated leaves. It is likely that the small amount of foliar P that was translocated, regardless of the high uptake, is responsible for the lack of biomass response for this product. This low translocation is consistent with previous work at similar foliar P rates (Peirce *et al.* 2014, 2016).

There were three products that contained P in combination with potassium: PeKacid, potassium phosphate and Pick. The best performing of these three products was Pick, which consistently increased plant biomass across the three adjuvants. It also had high foliar P uptake (>90%) and translocation (47–65%). This product is a commercial potassium phosphate and potassium citrate solution that had an average pH of 8.7 when applied to the plants in combination with the adjuvants. By contrast, the analytical reagent potassium phosphate had very low uptake and translocation with Hasten and LI700, both of which formed a crystalline deposit on the leaf as the fertiliser dried. Reed and Tukey (1978) also observed decreased absorption for foliar fertilisers that dried as salt deposits on the leaf. They observed that for potassium phosphates, the highest absorption by chrysanthemum leaves was at a pH of 2, with absorption decreasing as the pH increased to 7, after which absorption increased again (Tukey *et al.* 1956). Those absorption trends with pH are consistent with our study. Interestingly, several field studies have documented wheat yield increases with application of potassium phosphate (Sherchand and Paulsen 1985; Benbella and Paulsen 1998; Mosali *et al.* 2006). However, those studies did not indicate the pH of the foliar fertilisers applied, but it would be expected to be similar to the potassium phosphate in our study if prepared with high-quality water. It is not known whether those yield responses were to the P or K in the fertilisers because the K applied in the foliar fertilisers was not balanced in the soil as was done in our study, and little information was provided on the K status of the plants. Yield responses in the study by Mosali *et al.* (2006) were documented in a field site with low soil K levels.

For the products that contained P in combination with N (MAP and Maxi Phos), only MAP + Hasten produced a positive head-biomass response, despite both products having the same pH. The only difference between the products was the N : P ratio. When applied at the same P rate of 1.6 mg/pot, MAP added 0.7 mg N/pot to the leaves and Maxi Phos added 1 mg N/pot to the leaves. It is therefore difficult to say why the products did not produce the same biomass response. Foliar uptake was variable for the products, ranging from 52% to 97%, but in all cases the translocation of foliar P was high (37–59%). In a study on the foliar uptake of P by bean leaves, comparing treatments across the pH range 2–7 and the accompanying cations of K, Na and ammonium, ammonium phosphate solutions at a pH of 2–3 performed best (Tukey *et al.* 1956). Likewise, Reed and Tukey (1978) found that ammonium phosphate absorption was highest at pH 2 and was much lower (only 5–8%) at all other pH values. Despite those results, we found high uptake of P from ammonium phosphates suggesting that at higher concentrations of P, total foliar absorption increases.

Sodium phosphate was the second-best performing product and produced some positive biomass responses when it was applied in combination with Hasten or LI700. Foliar uptake ranged from 62% to 98%, with high translocation particularly for sodium phosphate +LI700 (66%). Our results are comparable to those of Thorne (1957) who found 79–87% of foliar-applied P from sodium phosphate was recovered in the plant parts of swede and sugar beet plants. Tukey *et al.* (1956) showed that sodium phosphate absorption and translocation to the roots of bean plants was highest at a pH of 2–3 and second highest at a pH of 5 when the foliar fertilisers were applied at pH values ranging from 2 to 7, although the amount of P absorbed as a percentage of P applied was not discussed. Reed and Tukey (1978) also found that P absorption when using sodium phosphate reduced as the pH increased (from 22% at pH 2 to 5% at pH 6). However, our results did not indicate a relationship between P uptake from sodium phosphate and solution pH.

The inconsistent results regarding the use of adjuvants and their effect on foliar uptake and yield make generalisations difficult. Given that the three adjuvants were chosen across different classes, they might be expected to influence the uptake by different mechanisms. Hasten is an esterified oil with non-ionic surfactants, whereas LI700 is an emulsion of soyal phospholipids and propionic acid with some surfactants that the manufacturer claims to acidify the formulation. Given the low concentration of LI700 in the fertiliser formulation and the high pH-buffering capacity of phosphate in solution, we saw negligible pH differences among formulations as a result of the adjuvants (data not shown). SpreadWet is a pure non-ionic surfactant. The action of the adjuvant to increase the retention of the fertilisers on the leaves was performed equally well by all three adjuvants. In all cases, <3% of the foliar fertiliser volume for each treatment was not retained by the leaves. We have shown in previous work that uptake of foliar-applied P was high regardless of the adjuvant used, provided the adjuvant reduced the surface tension of the fertiliser to allow it to be retained on the leaf surface (Peirce *et al.* 2016, 2019).

Field experiments: testing formulations, timing and rates

Although foliar-applied P appears to be effectively taken up by wheat leaves and can increase biomass for some treatments in a controlled environment, a translation to increased grain yield was not measured in the field. Lack of grain-yield response to foliar-applied P in wheat in the field has been reported before (Sherchand and Paulsen 1985; Mosali *et al.* 2006; Froese *et al.* 2020) and is in line with the inconclusive results reviewed by Noack *et al.* (2010), and with more recent investigations where grain P concentrations (Ali *et al.* 2014) or P-use efficiency (Froese *et al.* 2020) were increased as a result of foliar applications but no benefits in yield were found. Overall, ~50% of the experiments reported in the literature (including both controlled environment and field experiments) have been non-responsive (Noack *et al.* 2010). The failure to achieve grain yield increases has been attributed mainly to the use of non-responsive soils. However, we selected soils that were deficient to marginal for P supply to

wheat, and plants were evidently responsive to soil-applied P through to maturity.

In controlled conditions, the recovery of foliar fertiliser has been mostly >80% (McBeath *et al.* 2011; Peirce *et al.* 2016), but in field conditions where the fertiliser is sprayed instead of applied in small drops, a much lower recovery is expected. Our target rate of 2 kg P/ha has been effective in our experiments in controlled conditions (although responses were small) and it is within the recommended range for P applied as foliar sprays in the field (Noack *et al.* 2010). Increasing the rate in one application may lead to leaf damage via scorch, but not all damage precludes benefits of foliar P (Peirce *et al.* 2016). In the field experiments, only phosphoric acid produced scorch (but without biomass or grain yield penalty); thus, there is scope for rate increases. An increase in rate could also be achieved through multiple applications but they may not be economically feasible for dryland cropping.

The application times were within the time 'window' where wheat plants, after the early responses to soil-applied P (Rodríguez *et al.* 1999), may require a small amount of P to complete grain filling without P stress. By the end of stem elongation, wheat takes up most of the required P for maximum production of biomass, but it may need a small amount during grain filling to achieve maximum yield. However, the efficiency of utilisation of P in production of grain is directly proportional to water availability (Clarke *et al.* 1990), and overall growth conditions around flowering are associated with variation in wheat yield (French and Schultz 1984; Fischer 2015). Phosphorus added in foliar sprays at later stages could be used to boost plant growth and grain filling in cases where soil-available P is limiting or dry soils prevent soil P uptake, but this will be productive only if the stress induced by lack of water has not affected leaf P metabolism (Sutton *et al.* 1983; Grant *et al.* 2001). One of the promises for using foliar P as a 'top-up' is to be able to complement the soil starter-P in seasons with adequate yield potential. Overall, we were not able to detect significant yield responses to inputs of P applied in-season as foliar fertiliser.

The field experiments showed a wheat yield increase in response to soil starter-P but a response to foliar-applied P was lacking. At Sherwood the annual rainfall in the year of the experiments (2015) was markedly below the historical mean (Fig. 1), and at Pinery there were critical points in the growing season (e.g. June and October) with rainfall below the historical mean (Fig. 1). Although there was an increase of ~45% in grain yield in response to starter P, the maximum yield achieved in the experiment was still half of the 5-year regional yield average (1 t/ha vs 2 t/ha, PIRSA 2016). Importantly, rainfall was particularly low (Fig. 1) and temperatures unseasonably high around anthesis (October) at Sherwood and Pinery. The October mean temperatures were 20% and 30% above the long-term average at Pinery and Sherwood, respectively, with both sites having [3]3 days with temperatures >35°C. Thus, the utilisation of P in the foliar 'top-up' could have been thwarted by unfavourable climatic conditions at the time when grain-yield components such as spikelet and floret numbers, which depend on growth conditions just before anthesis, were determined (French and Schultz 1984; Calderini *et al.* 2001; Fischer 2015).

Controlled environment experiment- Substitution hypothesis

The lack of any foliar P effect on anthesis biomass despite the increase in P uptake is in line with results reviewed in the literature (Noack *et al.* 2010) and reported from more recent greenhouse and field experiments (Ali *et al.* 2014; Peirce *et al.* 2016). It is surprising, though, that Pick did not increase anthesis biomass and Maxi Phos increased P uptake, because these results contrast with findings in the first controlled-environment experiment. These results highlight the complexity of predicting the efficacy of foliar-applied P. These plants may have had their physiology compromised despite the soil-P levels being only marginally limiting for wheat plant growth, because leaf P status and function are determinants of the capacity of plants to be able to uptake and translocate P (Fernández *et al.* 2014; Peirce *et al.* 2016). The lack of treatment effect on the plant ^{33}P activity indicates that there was not a reduction in the uptake of P by roots in foliar-fertilised plants compared with plants that were not foliar-fertilised. Given there was no effect of foliar P addition on root P uptake from soil, it is not possible to use the concept of substitution to explain why foliar P uptake had an effect on plant P uptake but not on biomass.

Conclusions

Under controlled environment conditions, plant uptake of P from foliar-applied solutions was high. Except for potassium phosphate, plant uptake of P was 80–95% of the amount applied to the leaves for most formulations. The foliar route is therefore an effective pathway for P acquisition by crops. Biomass responses, and the efficiency of foliar P uptake and translocation were not consistently related to fertiliser pH, adjuvant type or accompanying cation. However, P applied as phosphoric acid appears to be poorly translocated from treated leaves, perhaps because of serious scorch damage to leaves. Responses to foliar P application are therefore possible, but dependent on product formulation.

Our results show that despite foliar P increasing P uptake by wheat in soils with concentrations of available P considered marginal for wheat production under controlled conditions, there were no significant effects observed under field conditions. Furthermore, wheat plants did not downregulate uptake of P by roots in response to foliar P fertilisation, suggesting that the plant was not substituting foliar P uptake for root P uptake. Why the increase in P uptake from foliar fertilisation is not translated into increases in biomass or grain yield remains unclear. Other mechanisms need to be investigated to explain the variation in responses of wheat to foliar addition of P. There remains insufficient evidence to recommend foliar-applied P as a management option for dryland wheat P nutrition.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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