Phosphorus use efficiency in wheat and barley

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Abstract

Genetic variation in responsiveness to P under field conditions was examined in up to 48 varieties of wheat or barley grown with 0 or 30 kg P/ha at Mallala and Halidon (SA) (sites with low available soil P). Early biomass production was assessed non-destructively using NDVI and significant responses to P and differences among the genotypes occurred but there was no significant Variety x P interaction. Grain yield responses to P were 5-10% at Mallala and 40-50% at Halidon. Neither grain yield nor the yield responses to P were associated with the P responses observed in NDVI. Yield at low P, one measure of PUE, showed strong genetic correlations between sites and with yield with P fertiliser. Genetic correlations for responsiveness to P across sites were much smaller. The ability to respond to P fertiliser and the yield under low P supply did not show strong genetic correlations suggesting that it may be possible to select for the two traits independently. Although there was a strong influence of site on P responsiveness, some genotypes of wheat and barley showed consistent efficiency across sites, and selection based on yield at low P supply as well as the ability to respond to P should be feasible.

Key Words

Nutrition, wheat, barley, fertiliser

Introduction

Sustainable agricultural production in Australia relies on an adequate supply of phosphorus (P), but the efficiency of P fertiliser use is low. Diminishing reserves of high-grade rock phosphate and the recent dramatic increases in fertiliser costs have renewed interest in the development of more P-efficient farming systems. There will not be a single pathway to improved efficiency: industry-wide improvements in P use efficiency (PUE) will be achieved through a number of strategies, including improvements in fertiliser formulation and application technology, the use of microbial inoculants to increase availability of P and improve P uptake and changes in fertiliser practices. However, an important aspect is also genetic improvement whereby varieties of wheat and barley have a greater capability to use available soil and fertiliser P. In 2009 a series of experiments was conducted to characterise the responses to P among a range of wheat and barley varieties as part of a larger program to improve PUE in winter cereals.

Methods

Forty-eight genotypes of wheat and 47 genotypes of barley were grown in separate trials at Mallala and Halidon in South Australia; these are sites with low available P (Table 1). The genotypes were selected from (i) a range of released varieties and breeding lines from different breeding programs in Australia, (ii) varieties that had been reported to have shown differences in responses to P, (iii) varieties that were key parents in breeding programs within Australia, and (iv) barley lines from ICARDA nurseries that had shown consistent yield in low-rainfall environments. Each variety was grown at two levels of P, 0 and 30 kg P/ha applied as triple superphosphate. Nitrogen was applied to wheat at Halidon (23 kg N/ha as urea at sowing) and at Mallala (two post-sowing applications of 20 kg N/ha as urea-ammonium nitrate) and Zn and Cu were applied at sowing at both sites. The experiments were sown on 11 June (Mallala) and 17 June (Halidon) at a rate of 180 seeds/m^2 (wheat) and 145 seeds/m^2 (barley) in plots 7 m x 6 rows, with a row spacing of 30 cm. A severe wind storm soon after sowing at Halidon reduced establishment in wheat which affected subsequent growth and yield and these data are not presented.

Vegetative responses to P were measured at both sites by normalised difference vegetation index (NDVI) using a Greenseeker™. Measurements were made during August at Mallala and between mid-August and early October at Halidon. Based on the initial readings of responses to P at Mallala, the five most responsive and five most non-responsive varieties of wheat and barley were selected to assess root distribution in the surface 10 cm of soil by measuring root DNA concentration of the soil (Riley et al. 2010), 6-8 weeks after sowing. The root DNA concentrations were standardised against a common variety (Krichauff wheat and Galleon barley) to correct for differences in the amount of DNA per g of root among the varieties. Shoot dry matter and shoot P concentration were measured on these varieties and grain P on all varieties.

Table 1. Soil chemical properties at Halidon and Mallala in 2009

Depth (cm)	Mallala			Halidon		
	pH(water)	EC (dSm^{-1})	Colwell P ($mg\ kg^{-1}$)	pH(water)	EC (dSm^{-1})	Colwell P ($mg\ kg^{-1}$)
0-20	8.13	0.20	18.0	8.10	0.07	6.7
20-40	8.70	0.28	7.3	8.30	0.14	2.3
40-60	9.23	0.41	4.7	8.80	0.21	3.0

Statistical design and analysis

The experiment was designed as a split-plot randomised complete block with three replicates, with variety as the main plot and P rate as the subplot. The data on the subset of 10 varieties were analysed by ANOVA and orthogonal contrasts were used to compare the differences between the responsive and non-responsive varieties. The grain-yield data for the 48 wheat varieties and 47 barley varieties were analysed using a mixed model analysis with Residual Maximum Likelihood (REML) used to partition the variance and the Best Linear Unbiased Predictors (BLUPs) to estimate differences among varieties (Smith et al. 2001, Stefanova et al. 2009). The data for barley from both sites were combined into a single multi-environment analysis. The yield at 0 kg P ha^{-1} was considered to be a measure of a variety's P efficiency because it indicates the ability to utilise native soil P. The responsiveness of a variety to P fertiliser was estimated as the deviation from the regression of the true genetic effects of the plus P treatment against the minus P treatment: a large positive deviation indicates a variety with above average response to P fertiliser.

Results

Early growth and P concentration in responsive and non-responsive genotypes

In each experiment there was a significant response to P in vegetative growth and in shoot P concentration. The largest response to P occurred in barley at Halidon (112% average increase in shoot dry matter) and the smallest occurred in barley at Mallala (39% average increase). The mean shoot P concentrations in the unfertilised treatment of barley were 2.01 g/kg at Halidon and 4.26 g/kg at Mallala and 3.90 g/kg for wheat at Mallala. There were significant increases in NDVI with the addition of P and also significant differences among the genotypes at both sites, but there was no Variety x P interaction.

Differences in NDVI diminished between successive times of measurement as leaf area and ground cover increased.

Applying P increased root DNA in the top 10 cm of soil. Significant differences occurred in root DNA between the responsive and the non-responsive varieties in all experiments (Table 2). A higher concentration of root DNA was detected in the non-responsive wheat varieties at Mallala, but in barley the non-responsive varieties at both sites had lower concentrations of root DNA in the surface soil.

Grain yield

Site mean yield of wheat was 2.33 t/ha at Mallala and the mean barley yields were 0.89 t/ha at Halidon and 2.89 t/ha at Mallala. The responses to P were much greater at Halidon (~ 40-50%) than at Mallala (<10%). There was no significant difference in yield between the responsive and non-responsive varieties (data not shown) and there was no consistent difference in the grain P concentration between the two groups of varieties (Table 2). The variation in yield among the varieties of wheat and barley was only weakly related to the variation in NDVI. Among the three experiments the maximum amount of phenotypic variation in yield explained by NDVI was 30%, which occurred in barley at Halidon.

Barley. There were strong genetic correlations (r_g) for yields at the two rates of P at each site (r_g = 0.88 at Halidon and r_g = 0.98 at Mallala) as well as for each rate of P across the two sites (r_g = 0.86 for 0 kg P/ha and r_g = 0.65 for 30 kg P/ha). The correlation for P responsiveness was small (r_g = 0.25). The outstanding variety was Fleet which yielded well and had a low response to P at both sites (Fig. 2). The line CM72 also showed little response to P but it had low yields at both sites, largely due to a high incidence of head loss. There was no genetic correlation between yield at 0 kg P/ha and response to P and at Halidon genetic variance for yield at low P was 3 times greater than that for P responsiveness.

Table 2. The mean concentrations of root DNA in the surface 10 cm of soil and whole shoot and grain P concentrations for varieties identified as responsive and non-responsive to P fertiliser, based on readings of NDVI approximately 6 weeks after sowing. Values are presented as averages of P rates as the interaction between Responsiveness and P treatment was not significant. Significant differences between the 5 responsive and 5 non-responsive varieties are indicated: * P<0.05, ** P<0.01, *** P<0.001, ns – not significant.

	Root DNA (10^{-3} ng/g)	Shoot dry matter (mg/plant)	P concentration (g/kg)	
			Shoot	Grain
		Mallala wheat		
Responsive	121.2	475	4.22	3.26
Non responsive	153.0**	435*	4.39*	3.28ns
		Mallala barley		
Responsive	89.1	684	4.47	3.11

Non responsive	72.3*	602*	4.57ns	3.36***
		Halidon barley		
Responsive	73.4	603	2.91	2.96
Non responsive	61.4**	532ns	3.06*	2.86*

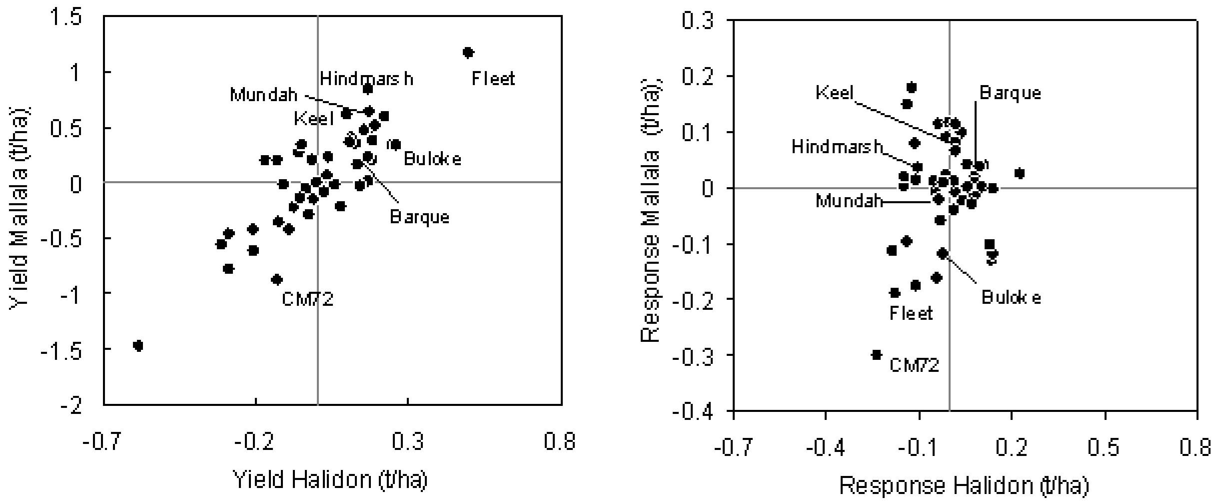

Figure 2. Analysis of barley yields at Mallala and Halidon for grain yield at 0 kg P ha^{-1} and responsiveness to applied P fertiliser. The data are presented as BLUPs where a positive value indicates an above-average yield and a negative value indicates a below-average value. The values of some barley varieties are shown

Wheat. As with barley, there was no genetic correlation between yield at 0 kg P/ha and responsiveness to P (Fig. 3) and the genetic variance for yield at low P was greater than the genetic variance for responsiveness. Yitpi and Correll produced above average yields and had low responses to applied P (Fig. 3). Gladius had the highest yield and showed above average responsiveness. Axe and Wyalkatchem also showed high responsiveness to P.

Discussion

A problem with the concept of PUE is that it can be interpreted in a number of ways. The often-cited definition of nutrient use efficiency is the relative yield of a variety when grown under limiting and non-limiting supplies of a nutrient (Graham 1984). However this fails to take account of the yield potential of a variety. Phosphorus-use efficiency can be associated with the ability to utilise native soil P, which is expressed as high yields under low supplies of P, a trait that can reduce dependence on fertiliser inputs. This may be useful in circumstances where the levels of soil P are low or in low-input farming systems. It can also be argued that improvements in PUE and recovery of fertiliser P can be achieved by increasing the responsiveness to P. An ability to respond to P may allow higher yields with the same amount of fertiliser inputs or allow varieties to respond to highly fertile soils. An ideal variety may be one that yields well under low supplies of P but also has the capacity to respond to P when availability is increased. This provides a high base level of yield as well as the flexibility to respond to high levels of soil fertility. Therefore in screening germplasm to develop more efficient varieties, both traits need to be considered.

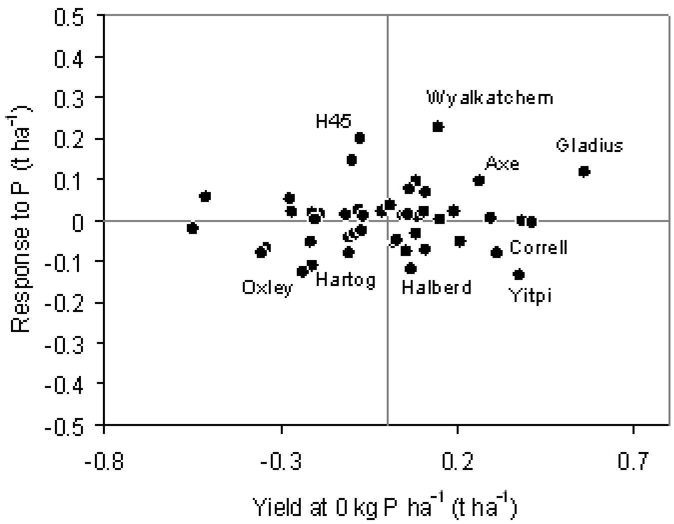

Figure 3. The plot of the BLUPs for responsiveness to applied P against yield at 0 kg P ha^{-1} for wheat al Mallala.

Grain yield at low P and P responsiveness showed low genetic correlation in both wheat and barley, indicating that selection for high yield at low P may not compromise the ability to select for responsiveness to P. Nevertheless, the weaker genetic correlation for responsiveness across sites and its smaller genetic variance compared to yield at low P, even at a very responsive site, suggest that environmental influences on the expression of the trait are greater and the potential genetic gains are likely to be smaller. More site x season combinations are required to more clearly define the relationship between these two traits.

The use of NDVI as a non-destructive method of assessing responses in vegetative growth and as a potential selection tool was explored, but with limited success. While significant effects of P and differences among the genotypes were found in each experiment, there were no Genotype x P interactions and the values of NDVI were only weakly related to yield.

The size of the root system has been suggested as a trait associated with P efficiency (Gahoonia and Nielsen 2004). Studies with a limited number of varieties have found a relationship between root size and P uptake, but there has been no work to demonstrate that this concept can be successfully developed into a selection criterion for germplasm development. Significant differences in the concentration of root DNA were found among varieties showing different vegetative responses to P, but these differences were not consistent between wheat and barley and did not influence variation in yield.

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