Improving yield on sodic soil: assessing the value of genetic improvement

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Abstract
Soils with alkaline sodic (dispersive) subsoils are widespread in the Australian grains belt. Improving the tolerance of wheat to the range of stresses encountered in these soils has the potential to improve yield and water use efficiency. Wheat varieties were tested at sites on alkaline soils with varying degrees of sodicity in all mainland States. The lines were also screened for tolerance to high boron, pH and aluminium. Genetic correlations among sites from the southern and western regions were high but were markedly different from the Queensland sites. The benefit of tolerance to multiple stresses was expressed at sodic sites with yields less than about 3 t/ha and tolerance to soil constraints was estimated to improve yields by up to 10% when yields were less than 2 t/ha.

Key Words
breeding, abiotic stress, subsoil constraints, dispersive soils

Introduction

Alkaline, sodic (dispersive) subsoils are widespread in the cropping zone of Australia. These soils have a number of chemical and physical properties that can restrict root growth and limit the growth and yields of crops (Rengasamy 2016). The major constraints of these soils are high pH leading to a range of nutrient deficiencies and toxicities, high concentrations of exchangeable Na resulting in poor soil structure, high soil strength and poor aeration, and high concentrations of dissolved ions causing osmotic stress in a drying profile (Adcock et al. 2007, Dang et al. 2010).

The importance of sodicity as a constraint to wheat yields in Australia is highlighted by the observation that many of the most successful and widely-adapted wheat varieties developed for the southern and western grain belt are tolerant to one or more of the constraints associated with sodic soils (McDonald et al. 2012). Some management practices can alleviate the problems of subsoil sodicity, but their use is limited for a range of financial and technical reasons. The best long-term strategy is a ‘belts and braces’ approach that combines improved management practices with better varieties, and in this respect the development of tolerant germplasm is an important strategy to improve productivity on sodic soils. Here, we describe a project that addresses this issue and present some preliminary results of field trials using a range of current wheat varieties.

Methods

Field trials

Between 2015 and 2017 field trials were conducted at sites throughout the Australian grains belt with varying degrees of sodicity (Table 1). A core set of varieties was grown at each site and these were supplemented by local check varieties. The varieties tested had known tolerance to one or more of the subsoil constraints of interest, were parents of existing doubled haploid populations and included a selection of current high-yielding varieties. Management of the trials reflected best practice for the environment in which the trials were grown. Plant establishment ranged from 100-150 plants/m^2, nutrients (N, P and Zn) were added as fertiliser at recommended rates appropriate to the site and season and weeds were controlled with pre- and post-sowing herbicides. All trials contained 4 replicates and were optimally designed in a spatial row-column arrangement using the DiGGeR software (Coombes 2009) available in the R statistical computing environment (R Core Team 2017). The multi-site trial grain yield data was analysed using the linear mixed modelling software package ASReml-R (Butler et al. 2009)) also available in R. From the fitted model, the Best Linear Unbiased Predictors (BLUPs) were extracted and used to calculate the predicted means for each variety at each site. Genetic correlations among the trials were also extracted and summarized. The flag leaf from a subset of varieties was sampled at anthesis, oven dried and digested in nitric acid. The digest was analysed for elemental concentrations by Inductively Coupled Plasma (ICP) spectrometry.

Table 1. The median and range in soil properties among the sites used to evaluate varieties. The soil profile has nominally been divided into the topsoil (0-30 cm) and the subsoil (30-100 cm)

Depth (cm)	Soil property		
	pH_{water}	$EC_{1:5}$ (dS/m)	ESP (%)
0-30			
Median	7.9	0.17	6.1
Range	4.7-8.8	0.003-0.40	0.8-14.8
30-100			
Median	9.1	0.60	19.1
Range	6.7-10.0	0.01-1.85	1.6-31.7

Screening for individual traits and assessment of overall tolerance

The lines that have been used in the field trials were screened for tolerance to high boron (B), high pH (McDonald et al 2012) and high aluminium (Al) at high pH. The method of Osborne and Rengel (2002) was used to classify varieties as either tolerant, intermediate or sensitive to each stress. Varieties were then classified as Tolerant if they were tolerant to at least two of the three stresses and intermediate for the third, as Sensitive if they were sensitive to at least two of the stresses and intermediate to the third and Intermediate if they showed intermediate tolerance to at least two of the stresses and either sensitive or tolerant to the third.

Among the varieties screened, 19 adapted varieties were selected to examine the genotype x environment (G×E) interaction, based on the level of tolerance to the three stresses (Table 2). The varieties were also selected so they had similar mean predicted yields. Varieties were allocated to one of the three categories – Tolerant, Intermediate and Sensitive – and the effect of the level of tolerance was tested by regressing the predicted mean variety yield within each group against the site mean using 'Simple Linear Regression within Groups' in Genstat Version 18.2 (VSN International; www.vsni.co.uk).

Table 2. The list of varieties in each category of overall tolerance to three soil constraints and their mean predicted yields based on the analysis of all sites between 2015 and 2017.

Category	Variety	Mean yield (t/ha)
Tolerant	Emu Rock, Gladius, Mace, Spitfire, Zen	3.34
Intermediate	Corack, Scout, Tammarin Rock, Ventura, Westonia, Wyalkatchem, Yitpi	3.34
Sensitive	Axe, Cobra, Gregory, Hydra, Janz, Magenta, Trojan	3.38

Results and discussion

Using a critical ESP of 6% to indicate sodicity, most of the trial sites were sodic in the topsoil with sodicity increasing with depth (Table 1). The majority of the soils were alkaline and pH increased with depth. EC also increased with depth, but most soils were not saline ($EC_{1:5}$ <0.8 dS/m).

Table 3. The mean concentrations of elements in the flag leaves of wheat at anthesis, the standard deviation and the range in concentrations among trial sites. Values are based on data from 15 sites between 2015 and 2017

	P	K	Ca	Mg	S	Na	Cl	Zn	B	Mn
				(%)					(mg/kg)	
Mean	0.24	2.04	0.36	0.16	0.29	0.04	0.72	20	22	84
Std Dev.	0.047	0.359	0.137	0.031	0.056	0.032	0.343	5.2	20.0	34.1
Minimum	0.16	1.65	0.15	0.11	0.23	0.01	0.07	11	6	30
Maximum	0.33	2.78	0.63	0.22	0.45	0.11	1.84	30	68	139

Flag leaf elemental concentrations varied widely among the sites, with a two- to three-fold variation in concentrations being typical (Table 3). Comparing the minimum values with published values (Reuter et al. 1997) suggested deficiencies in P, Ca, Mg and Zn occurred at some sites, but overall, there were no severe nutrient deficiencies or toxicities among the sites.

Genetic correlations were consistently strongest among sites in WA and SA (Figure 1). The correlations with the Victorian and NSW sites were less consistent: two of the six sites from Victoria (VIC.PBC.2016, VIC.Rethus.2017) and one of the three sites in NSW (Rand 2017) were poorly correlated with the SA and WA sites. Interestingly, the correlations among the Queensland sites was poor: the strongest correlations occurred between sites within a year rather than across years, suggesting a large G×E effect among the three years. Negative or weak correlations occurred between the Queensland sites and sites from the southern and western regions. These probably reflect the major regional differences in rainfall distribution, reliance on stored soil moisture and soil properties that distinguishes the Queensland sites from the other trials. The implication is that attributes and germplasm for improved adaptation to the sodic soils in Queensland will be different to those at the remaining sites, but a similar suite of traits will be suitable on sodic soils in WA and SA. The Victorian and NSW sites show some relationship between both the northern and southern regions which may vary from year to year.

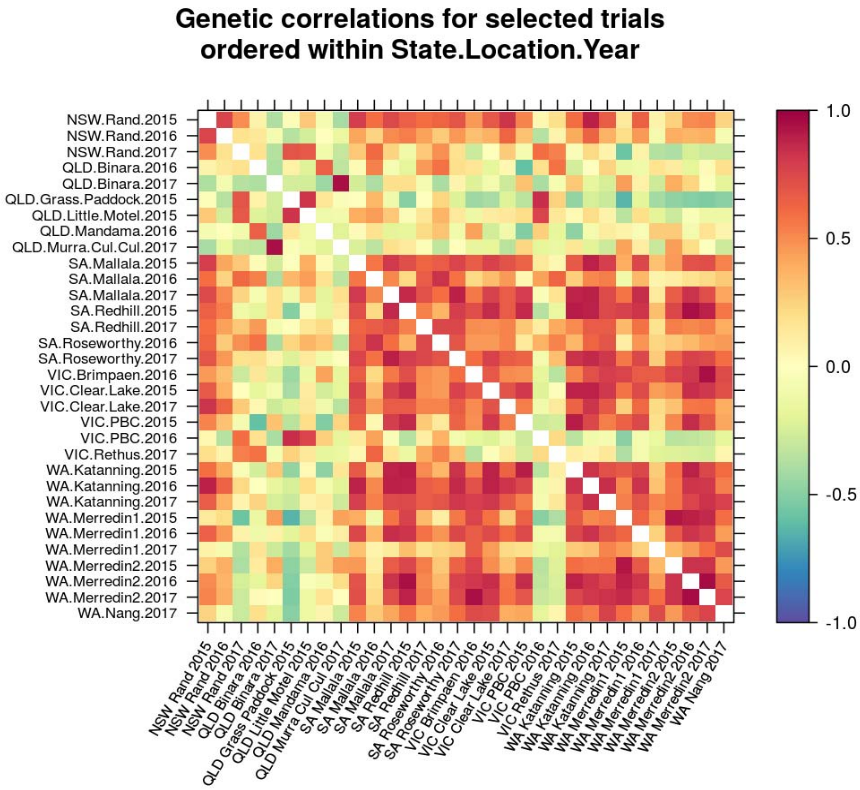

Figure 1. A heat map showing the genetic correlations among sites between 2015 and 2017. The genetic correlations are based on the core set of varieties grown at each site. The correlations are ordered by State and Year.

The comparison of regressions among the three groups indicated that there were significant differences in the slopes of the lines (Table 4). The Sensitive group of varieties were lower yielding than the Tolerant and Intermediate groups in low yielding environments but were more responsive to high-yielding environments. There was a cross over in the lines for the Sensitive and Tolerant groups, which intersected at a Site mean yield of 3.2 t/ha.

Table 4. The slope and intercepts of the regressions of predicted variety mean yield on site mean yield among varieties with different degrees of tolerance to three soil constraints. The analysis had an $r^2 = 0.94$

Category	Number of varieties	Intercept	Slope
Sensitive	7	-0.0003 ± 0.067	1.047 ± 0.0184
Intermediate	7	0.192 ± 0.065	0.962 ± 0.0174
Tolerant	5	0.154 ± 0.082	0.999 ± 0.0822

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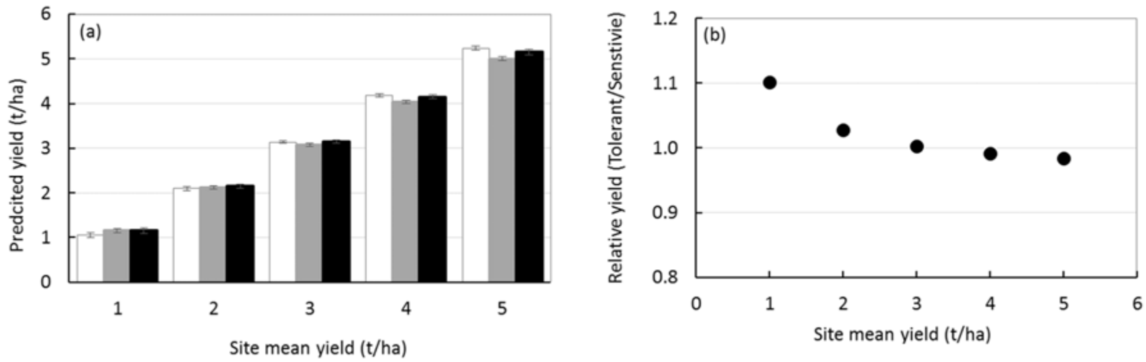

Figure 2. (a) The predicted yields of the three groups of varieties over different environments based on the regressions in Table 3. The error bars are the standard error of the predicted mean. The groups of varieties are: Sensitive □, Intermediate ■ and Tolerant ■; (b) The relative predicted yields of the varieties with multiple tolerance to soil constraints relative to the yield of varieties that are sensitive to the soil constraints assessed.

Tolerance to three soil constraints provided a yield advantage of up to 10% when yields were 3 t/ha or less (Figure 2), but at yields of greater than 3t/ha, there was little difference between the Tolerant and Sensitive groups of varieties. When yields were less than 2 t/ha there was no significant difference between the Tolerant and Intermediate groups, suggesting that tolerance to two of the stresses and an intermediate level of tolerance to the third was sufficient to provide a yield benefit. This analysis is consistent with an earlier analysis (McDonald et al. 2012) which suggested that the yield benefits from improved tolerance to a number of subsoil constraints was greatest when seasonal rainfall was low.

Conclusion

While alkaline sodic subsoils are widespread throughout the Australian grains belt, enhancing the tolerance of wheat to subsoil constraints for the northern Queensland region are likely to target different germplasm to the southern and western regions. This initial analysis suggests that the benefit from improved tolerance to constraints found in alkaline sodic soils becomes greater at sites where yields are less than 3.0 t/ha. At yields of approximately 1-2 t/ha, common in areas with multiple soil constraints, Tolerant genotypes may provide a yield advantage of up to 10%.

Acknowledgement

This work was funded by the GRDC (Project UA00159)

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