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Experimental and modelling studies of drought-adaptive root architectural traits in wheat

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ABSTRACT

Yield improvement in drought-prone environments based on selection for yield per se has been slow due to large genotype by environment interactions (G x E). In this paper, we present an interdisciplinary approach to crop improvement that links physiology with plant breeding and simulation modelling to enhance the selection of high yielding, drought-tolerant varieties for the water-scarce environments.

In a series of field experiments in Queensland, Australia, we found that the yield of CIMMYT wheat line SeriM82 ranged from 6 to 28% greater than the current adapted cultivar Hartog. Physiological studies on the adaptive traits underpinning this advantage revealed that SeriM82 and Hartog differ in root architectural traits. In large soil-filled chambers, SeriM82 had a narrower root system architecture and extracted more soil moisture per soil volume, particularly deep in the profile, late in the growing season when marginal water use efficiency (WUE) is high. To quantify the value of these adaptive root traits, we conducted a simulation analysis with the cropping systems model APSIM for a range of rain-fed environments contrasting in soil water-holding capacity in southern Queensland using long-term historical weather data. The analysis indicated a mean relative yield benefit of 14.5% in water-deficit seasons and that each additional millimetre of water extracted during grain filling generated an extra 55 kg ha^{-1} of grain yield. Further root studies of a large number of current Australian and CIMMYT wheat genotypes in small gel-filled chambers revealed that wheat root system architecture is closely linked to the angle of seminal root axes at the seedling stage - a trait which is suitable for large-scale and cost-effective screening programmes.

Overall, our results suggest that an interdisciplinary approach to crop improvement based on identification of root traits conferring tolerance to drought stress, evaluation of drought-adaptive traits in the target population of environments using simulation modelling, and development of simple and efficient screening methods is likely to enhance the rate of yield improvement in rain-fed crops in a changing climate.

1. INTRODUCTION

Improving crop yield in rain-fed environments based on selection for yield *per se* has been slow due to large genotype by environment interactions (G×E). Enhancing the selection of high yielding, drought-tolerant varieties requires an interdisciplinary approach that links physiology with plant breeding and simulation modelling. In this approach, traits conferring tolerance to water stress are dissected, and secondary physiological traits associated with improved yield are identified. The expression of physiological and morphological traits linked with high yield in the target population of environments (TPE) may be less susceptible to environmental influences than yield *per se*. To demonstrate the validity of this approach we examined wheat genotype SeriM82 which is known to have superior drought adaptation in northern Australia.

SeriM82 exhibits a stay-green phenotype by maintaining green leaf area longer during the grain filling period than the current, widely-grown cultivar Hartog. The subtropical northern cereal belt of Australia is characterised by summer dominant rainfall and deep clay soils with high water holding capacity. Winter cereals are often reliant on stored soil moisture from the previous summer for much of the growing season and suffer some degree of terminal drought stress in the majority of seasons. The reliance of winter cereals in the Australian northern region on stored soil moisture suggests that access to soil moisture and the timing of soil moisture extraction could be important factors contributing to the high yielding, stay-green phenotype of SeriM82.

In this paper, we present the shoot- and root-related traits that underlie the adaptive advantage of SeriM82 using a variety of experimental systems. These included field experiments and a range of root observation chambers that allowed roots to be examined at developmental stages from seedling to maturity.

2. MATERIALS AND METHODS

Detailed field measurements were made in a number of seasons at a single site with a well characterised, common soil type and used a single conventional management strategy (Christopher et al. 2008). Water availability was varied by use of natural rainfall variation, rain excluding shelters and irrigation. Flag leaf greenness was measured using a Minolta SPAD 502 which expresses leaf greenness in arbitrary units. Values of 55 to 65 units are typical of new leaves while those with values below 10 are fully senesced.
Soil-filled chambers with glass observation panels were used to characterise root systems of wheat plants at various stages from tillering to maturity using digital imaging of roots and destructive sampling. Small gel-filled chambers were used to characterise the number and angle of seedling roots of 8 day old wheat seedlings. Methods for root chamber experiments are described in detail elsewhere (Manschadi et al. 2006, 2008).

3. RESULTS AND DISCUSSION

Yield of SeriM82 ranged from 6 to 28% greater than Hartog in 6 environments with differing moisture availability in the field (Table 1). The yield difference was greatest in the irrigated treatment of 2003 and was lower where rain was excluded using rainout shelters post anthesis. Significant differences were also observed in rain-fed environments in 2004 with a severe terminal drought and in 2005 where terminal drought was alleviated by natural rainfall events during the mid and late grain filling period.

Table 1. Wheat yield in field trials conducted in Kingsthorpe, QLD, Australia

Year	Treatment	Yield (g/m^2)		
		Hartog	Seri	Diff. (%)
2003	Irrigated	610	780	28*
	Rain excluded post anthesis	260	320	14*
2004	Rain-fed	390	460	18*
2005	Rain-fed	280	340	20*
2006	Profile moisture depleted at sowing	207	219	6

*Values significantly different ($P < 0.05$)

The yield difference was lowest in 2006 when soil moisture prior to sowing had been depleted by a previous summer crop (Table 1). SeriM82 exhibited a stay-green phenotype in each environment where yield was significantly greater than Hartog as indicated by its ability to maintain leaf greenness in the flag leaf for longer after anthesis. However, where the availability of deep soil moisture was limited in 2006, SeriM82 failed to exhibit significantly greater yield or to express the stay-green phenotype. SeriM82 also failed to exhibit stay-green or a yield advantage in some root observation chamber experiments where soil moisture was fully extracted shortly after anthesis (data not shown). Thus, the availability of deep soil moisture late in the season was important for expression of the high-yielding, stay-green phenotype.

SeriM82 and Hartog differed in root architectural traits. In large soil-filled chambers where single plants were grown to maturity, SeriM82 had a narrower root system architecture and extracted more soil moisture per soil volume, particularly deep in the profile, late in the growing season when marginal water use efficiency (WUE) is high (Manschadi et al. 2006). To quantify the value of these adaptive root traits, we conducted a simulation analysis with the cropping systems model APSIM for a range of rainfed environments contrasting in soil water-holding capacity in southern Queensland using 100 years of long-term historical weather data. The analysis indicated a mean relative yield benefit of 14.5% in water-deficit seasons and that each additional millimetre of water extracted during grain filling generated an extra 55 kg ha^{-1} of grain yield (Figure 1). Thus, the marginal water use efficiency of extra soil moisture that becomes available post anthesis is nearly three times higher than that calculated over the whole growing season. This means that small amounts of additional moisture extracted post anthesis can lead to relatively large differences in grain yield.

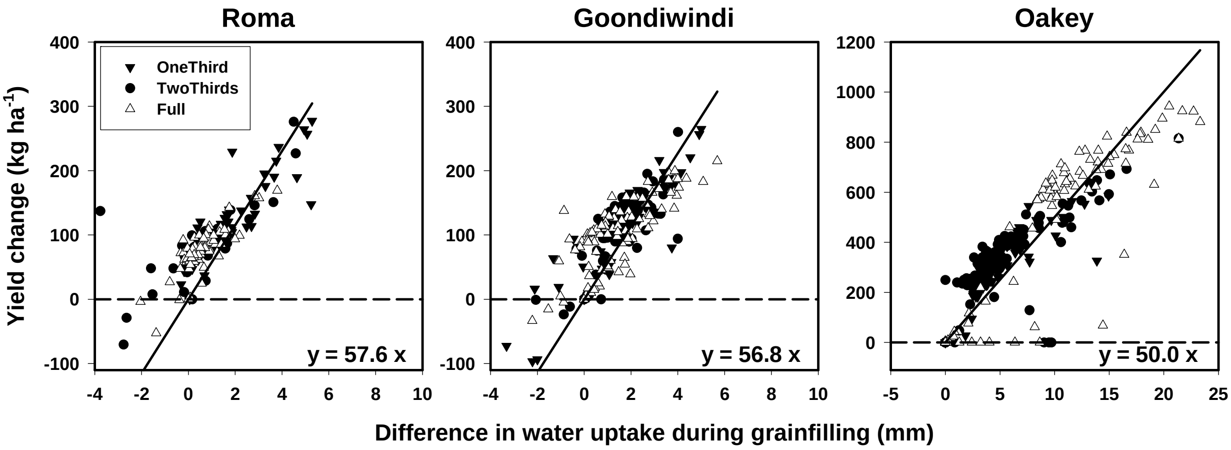

Figure 1. Simulated yield difference between the standard wheat cultivar Hartog and the root-modified (RM) genotype plotted against difference in water uptake during the grain filling phase. OneThird, TwoThirds, and Full indicate the initial soil water content at sowing as the fraction of total plant available soil water in the profile (Manschadi et al. 2006).

In small gel-filled chambers, SeriM82 exhibited a more vertical seedling seminal root angle indicating that seminal root angle is closely related to the vertical root distribution of mature plants. SeriM82 had narrower seminal root angle and narrower maximum lateral root distribution than Hartog. In a population of doubled haploid lines developed from a cross between SeriM82 and Hartog, certain genotypes with field performance similar to Hartog had similar seminal root angle. Other genotypes with field performance more like SeriM82 had seminal root angle more similar to SeriM82. Studies of 29 current Australian and CIMMYT wheat genotypes in small gel-filled chambers revealed considerable variation within existing elite germplasm (Figure 2).

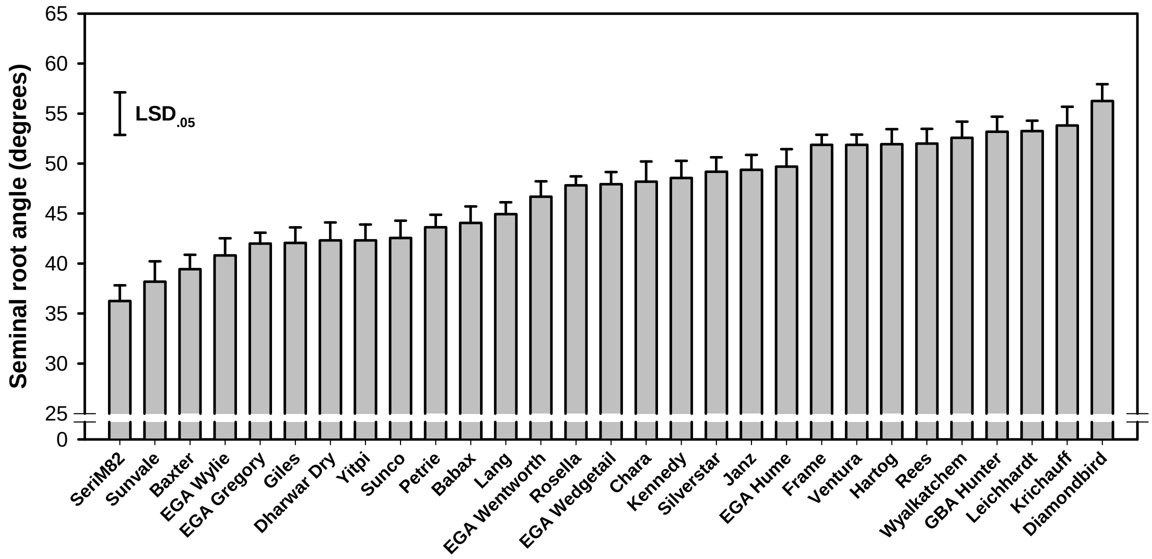

Figure 2. Growth angle (degrees) of wheat seminal roots in a set of CIMMYT and widely grown Australian genotypes. The bars indicate standard error of the mean; the vertical bar represents LSD ($p = 0.05$) for comparing the mean values (Manschadi et al. 2008).

These studies suggest that narrow seminal root angle is advantageous in the northern Australian grains region where crops often rely heavily on stored soil moisture. However, it is likely that where crops rely on smaller in season rainfall events a wider root angle would be advantageous. Gel-filled chambers provided a rapid and effective method of screening for seminal root angle. This screening technique is suitable for screening large numbers of genotypes in genetic mapping studies aimed at identifying the genetic regions controlling root angle.

4. RESULTS AND DISCUSSION

Overall, our results suggest that an interdisciplinary approach to crop improvement based on identification of physiological traits conferring tolerance to drought stress, evaluation of drought-adaptive traits in the target population of environments using simulation modelling, and development of efficient screening methods is likely to enhance the rate of yield improvement in rain-fed crops in a changing climate.

REFERENCES

List references in the last section of your paper in alphabetical order by the first author's last name. References must be cited in the text form of (author's last name, year of publication).

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