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Quantifying the potential yield benefit of root traits in a target population of environments

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Highlights: Despite their importance, roots characteristics and their influence on crop growth remain poorly understood. A modelling approach was used to evaluate the potential impact of different root traits in targeted environments. Increased root extractable water at depth gave some substantial advantage to crops in all regions of the Australian wheatbelt, while increased root growth rate was only advantageous in the West of the belt.

Keywords: root, drought, water deficit, wheat, APSIM model, genotype-environment interaction.

INTRODUCTION

In rain-fed agriculture, crop yield greatly varies depending on the timing and intensity of water-deficit. While shoot traits have been extensively studied in such environments, root traits remain poorly understood, mainly due to technical difficulty associated with their assessment. Historical yield improvement is nevertheless thought to be substantially related to improvement of the root system architecture and water capture in crops like maize (Hammer et al., 2009). Understanding genotype-environment interactions of root characteristics and their impact on yield is thus an active area of research (e.g. Richards et al., 2010). Root traits with potential yield benefit in water-limited environments include increased root depth and root elongation rate (Hurd, 1974; Lopes and Reynolds, 2010), higher root distribution at depth (Hurd, 1974; Manschadi et al., 2006; Fig. 1), narrow seminal-root angle (Nakamoto and Oyanagi, 1994; Manschadi et al., 2008), decreased root:shoot biomass ratio (Siddique et al., 1990) and decreased xylem vessel diameter to increase hydraulic resistance, thus allowing some water saving for later more crucial stages (Richard and Passioura, 1989). The value of these traits, however, depends on the environment.

A modelling approach was used to quantify the impact of root-related traits in a broad range of environments that reflects the variability of soil and climates of the Australian wheatbelt ('target population of environments'; Chenu et al., 2011 and 2013). The considered traits included (1) root-front growth rate, water extraction rate in (2) shallow and (3) deep soil layers, as well as (4) water extractability at depth.

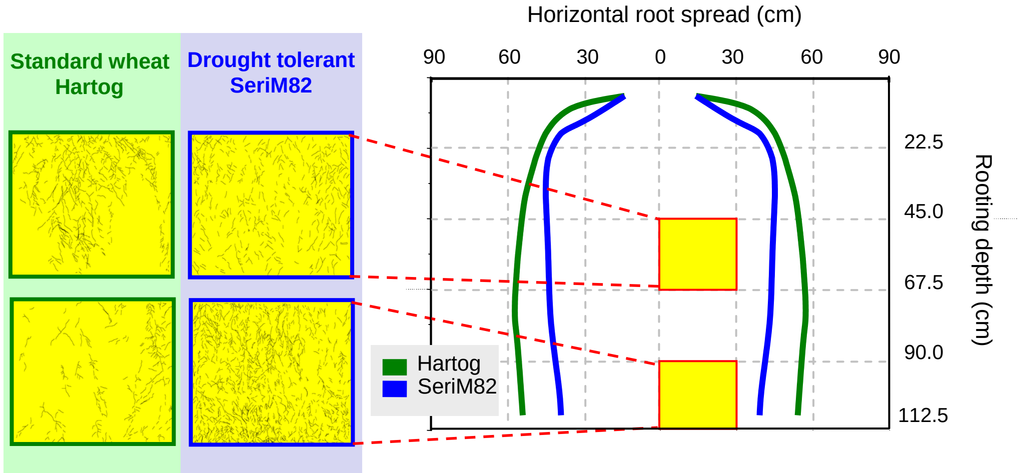

Fig. 1. Spatial root occupancy of the drought-tolerant cultivar SeriM82, and the check cultivar Hartog in a root chamber experiment at crop maturity. On the right, zone occupied by the roots of the two cultivars (green, Hartog; blue, SeriM82) within the root chamber. On the left, distribution of roots in the some sections of the root chamber. Figure adapted from Manschadi et al. (2006).

SIMULATIONS

The impact of root traits was simulated across the Australian wheatbelt over 123 years, using the APSIM-wheat crop model (e.g. Wang et al., 2002). The complete APSIM cropping system simulation platform is documented at www.apsim.info, and a detailed description of the wheat crop model and the soil modules is given at http://www.apsim.info/Wiki/APSIM-Documentation.ashx.

To represent the Australian wheat cropping system, simulations were performed in 60 locations, each representing between ~130,000 and 230,000 hectares of planted wheat (averaged data from 1975-2000, 2005 and 2006; source: Australian Bureau of Statistics). The simulations used a standard management system representing current grower practice from the region, and weather records for 1889-2011 (SILO Patched Point Dataset; http://www.longpaddock.qld.gov.au/silo/).

The simulations were conducted for the check wheat cultivar 'Hartog' with the following traits modified singly or in combination to produce 'virtual genotypes':

- Rate of downward root growth ('root-front growth rate') that ranged from 22.5 to 45 mm day^{-1} (Hartog: 30 mm day^{-1}) to capture the genetic variability reported in wheat root growth rate (from 0.84 to 1.8 mm °Cd^{-1}; Kirkegaard and Lilley, 2007),
- Water extraction rate ('*kl*' parameter in APSIM) in the top 50-cm soil layers, ranging from -20% to +20% compared to the reference cultivar (*kl* values typically decrease with depth, and vary among soil types),
- Water extraction rate (*kl*) in soil layers below 50-cm deep, ranging from -20% to +20% compared to the reference cultivar,
- Water extractability below 50 cm of depth (defined as the lowest soil water content to which the crop can extract water; '*lower limit*'), which varied from -20% to +20% from the value of reference cultivar.

All possible combinations of these root-related traits were considered, and their simulated yield and water extraction were compared to the reference genotype. Overall, 500 virtual genotypes (4 root-front growth rates x 5 shallow water extraction rate x 5 deep water extraction rate x 5 deep water extractability) were generated and these crops were simulated in 7380 environments (60 locations x 123 years), which resulted in a total of over 3.5 million simulations.

In each location, the yield advantage resulting from extra water uptake after flowering was calculated as the slope between (1) the extra grain yield produced by the virtual genotype compared to the reference genotype, and (2) the extra water uptake of the virtual genotype between flowering and maturity. Unstressed crops (<5% of the simulations) were removed from the analysis, as in these conditions, any extra water uptake had little impact on yield.

Results are presented as the average per region for yield advantage compared to the reference genotype, and for yield advantage per extra water uptake (Fig. 2).

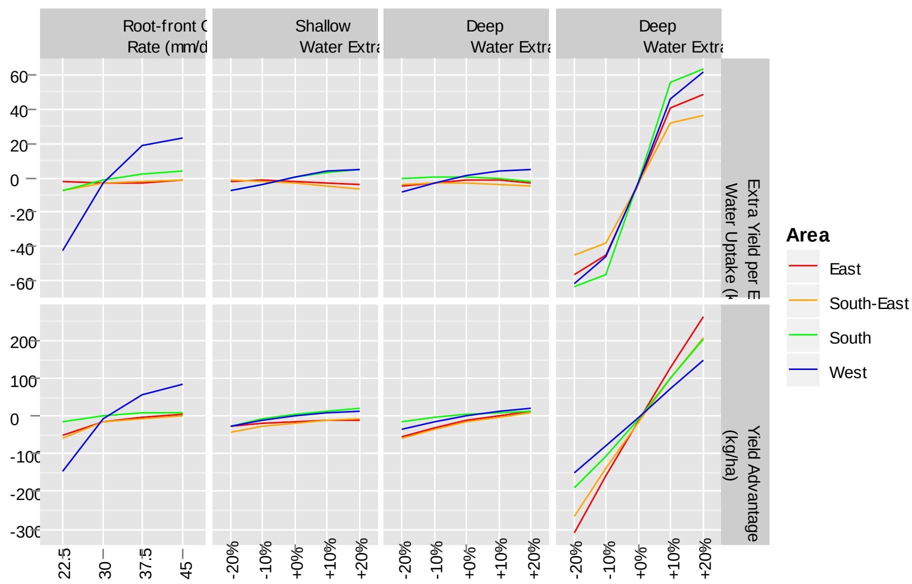

Fig. 2. Average impact of four root-related traits across the main areas of the Australian wheatbelt. The impact is presented in terms of (1) yield advantage per extra mm of post-flowering water uptake; (2) yield advantage compared to the reference genotype (Hartog).

RESULTS AND DISCUSSION

Out of the four integrated root-related traits studied, only increased water extractability below 50 cm conferred a substantial yield advantage in all regions (Fig. 2). Increasing the water extraction rate by up to 20% in either shallow or deeper soil layers (or both) did not change yield average greatly, irrespectively of whether crops were subjected to high or low in-season rainfall patterns, or whether they were grown in light or heavy soils. The rate of penetration of the deepest roots ('root-front growth rate') only substantially impacted yield in the West where wheat crops are produced on sandy-loamy soils with a relatively low water holding capacity, so that crops rely on the in-season rainfall. Thus, greater root penetration rate may increase the plant ability to chase water as it drains rapidly down the soil profile.

Importantly, the yield advantage conferred by all 'beneficial' traits was related to an increase in water uptake after flowering (Fig. 2), when water is required to maintain a green canopy (stay-green phenotype) and sustain carbon assimilation to fill the grains. Some research in this area has revealed that the stay-green drought-tolerant genotype 'SeriM82' has an adaptive root architecture (Manschadi et al., 2006; Christopher et al., 2008). The SeriM82 root system is more compact, and more uniformly distributed than the reference genotype Hartog, with greater root length at depth (Fig. 1; Manschadi et al., 2006). The greater root-length density at depth allows SeriM82 to have a greater water-extraction rate, while the better root 'occupancy' (more even root-branching) gives the crop a ~10% increase in water extractability below 50 cm (Manschadi et al., 2006). In accordance with experimental observations, simulations for this 'adapted' genotype showed a net yield advantage in the East area. When extended to a wider range of traits and to the entire wheatbelt, this modelling approach revealed that water extractability below 50 cm was beneficial in all areas, and that this trait had a greater impact than the rate of water extraction (at least for increase up to a 20%). Such results can help focus research on root traits with greatest potential to improve adaptation in the target population of environments. This study indicates that increased root occupancy at depth is one such trait.

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