Benefits of increased soil exploration by wheat roots

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Abstract

Access to deep soil water during grain filling has the potential to increase wheat yield but benefits depend on the seasonal pattern of water supply to the crop. We used a crop simulation model to assess the yield benefits of 20% faster root descent and/or greater root proliferation in the subsoil (> 1m) under different management scenarios. The analysis was conducted in Mediterranean, temperate equi-seasonal and subtropical environments, on deep sand, loam and deep clay soils, respectively. In general, time of sowing and seasonal water supply dominated the effect of root modification on yield. On high water holding capacity soils in equi-seasonal zones, the benefit of root modification was variable (0 to 1.4 t/ha) but generally small (median 0.1 t/ha). Elsewhere, combining faster and more efficient roots produced yield benefits in more than 75% of years (median 0.2 to 0.6 t/ha) and rarely reduced yield. Increased extraction efficiency was generally more advantageous to crop production than more rapid root descent alone. On the light-textured soils (Harden and Wongan Hills), benefits increased for late-sown crops as modified roots explored more soil in these time-limited crops.

Key Words

Yield, root penetration rate, root depth, extraction efficiency, drought, APSIM

Introduction

Recent experiments have shown that the use of subsoil water by wheat (*Triticum aestivum* L.) crops can increase yield (Kirkegaard et al. 2007; Christopher et al. 2008), confirming predictions from related simulation studies (Manschadi et al. 2006; Lilley and Kirkegaard 2007). As a consequence there is interest in increasing capture of deep water using wheat genotypes with greater root vigour (Richards 2008). Genotypic variation exists in wheat root systems where desirable traits include root elongation rate, depth of rooting and root proliferation at depth. Richards et al. (2007) reported genotypic differences in root penetration rate of up to 14% in a soil with physical restrictions in the subsoil (high bulk density). Root length density typically declines with depth, and in clay subsoils, roots are clumped in soil pores and channels with poor root-soil contact, and slower water extraction (White and Kirkegaard 2010). In experimental studies, cultivars which differ in root traits also differ in shoot and phenological traits, which can confound evidence for the benefits of modified root systems. Moreover, the usefulness of individual root traits will be largely determined by the pattern of water stress development, which varies significantly across sites and with agronomic management. Well-validated simulation models can assist in exploring these interactions.

The simulation model APSIM-Wheat uses a maximum root penetration rate (RPR) of 1.2 mm/^{o}C.day, which is sensitive to temperature and soil-water constraints (Wang and Smith 2004). In the model, the capacity of the wheat root system to extract water decreases with soil depth, according to the parameter (KL) which captures the effects of reduced root density, increased clumping, reduced root-soil contact and changes in soil diffusivity in the subsoil. Several simulation studies of modified wheat roots have reported yield benefits associated with greater water capture (Manschadi et al. 2006; Asseng and Turner 2007; Semenov et al. 2009) although they did not investigate interactions with agronomic management such as sowing time and paddock history which strongly influence the pattern of root penetration and water extraction.

Our simulation study investigated the benefits of increased root penetration and subsoil proliferation to wheat yield in the absence of shoot variation, across a range of diverse sites and crop-management scenarios in the Australian wheat-belt.

Materials and Methods

Simulation setup

Wheat crops were simulated with APSIM v 6.1 (Keating et al. 2003; http://www.apsim.info) at four sites representing three contrasting climatic zones of the Australian wheat belt (Table 1). APSIM Wheat accurately simulates wheat yields across a broad range of environments in Australia and has been previously validated on the soil types used in this study (Hochman et al. 2007; Lawes et al. 2009; Lilley et al. 2004; Lilley and Kirkegaard 2007). At Harden, maximum root depth was limited to 1.6 m by a rock layer in the soil and at Dalby, downward root growth was slowed below 1.6 m by subsoil salinity. There were no subsoil constraints at the other locations and maximum rooting depths matched measured values.

Table 1. Key climatic variables and soil characteristics for the four locations in the simulation study.

Location	Latitude, Longitude	Mean annual rainfall (range) mm	Mean in-crop rainfall (range) mm	Soil type (Isbell 2002)	PAWC* (mm)
		Equi-seasonal/Temperate			
Harden, NSW	-34.56, 148.37	604 (197-1137)	365 (110-675)	Red Chromosol	171
Cootamundra, NSW	-34.64, 148.02	618 (202-1176)	382 (120-765)	Red Kandosol	247
		Winter-dominant/ Mediterranean			
Wongan Hills,WA	-30.84, 116.73	369 (153-664)	302 (112-518)	Deep yellow sand	132
		Summer dominant / Sub-tropical			
Dalby, Qld	-27.18, 151.26	665 (319-1033)	267 (73-610)	Black Vertosol	374

*PAWC (Plant available water content = drained upper limit – 15 bar lower limit) 0 to 2.2 m (1.6 m at Harden).

Wheat was sown in an optimal and a late window for each location when the rainfall over 10 days was >15 mm, or was sown dry at the end of the window, except at Dalby where the accumulation period was 5 days. For each sowing window and site combination an appropriate, locally adapted cultivar was simulated, so that anthesis and maturity dates predicted at the four sites were in the expected range.

Root characteristics were modified in three ways; 1) a 20% increase in the rate of root penetration of the soil, 2) efficiency of water extraction below 0.6 m was maintained at the value derived for the 0.6 m depth, so that extraction efficiency in the subsoil was up to 4-fold that of standard roots, and 3) both fast and more efficient roots.

Single-year simulations were run for 109 years (1900-2008) of the climatic record, for each sowing date and site combination and for standard and the 3 root modifications. Simulations commenced on Dec 15 of the previous year, and soil water content and surface residues set assuming an annual crop was harvested on that date. Subsequent fallow management assumed complete weed control, and in this way seasonal variation in pre-sowing climatic conditions was captured in the simulation and determined plant available water content at sowing. Nitrogen fertility was managed to be non-limiting.

Results

Root Depth

Maximum rooting depth occurs shortly after anthesis when simulation of downward root growth ceases. Median root depths increased by 0.08 to 0.24 m for optimal sowing compared to late sowings (Table 2). For optimal sowing, faster roots were 0, 0.20, 0.41 and 0.13 m deeper at Harden, Cootamundra, Wongan Hills and Dalby, respectively, and 0.08, 0.28, 0.37, and 0.20 m deeper, respectively, in the late sowing. Seasonal variability in root depth was low at Harden and Cootamundra, and greater at Wongan Hills and Dalby, since the soil profile did not wet fully to depth in some years (data not shown). At Wongan Hills, variability was less for late than early sown crops, indicating more reliable soil wetting for the later sowing window.

Water uptake during crop growth

Median total water uptake ranged from 115 mm at Wongan Hills to 249 mm at Dalby (Table 2). There was little effect of sowing time on uptake at Dalby, but sowing later reduced uptake by 21 to 39 mm at the other sites. Faster roots produced only a small increase in median water uptake (up to 11 mm) with the effect generally greater for late sown crops. Increasing extraction efficiency had a greater impact on water uptake (up to 24 mm increase), most noticeably in early sown crops. The combination of faster and more efficient roots increased water uptake by 21 to 39 mm (median).

Yield

Median yields at Harden, Cootamundra, Wongan Hills and Dalby were 5.2, 5.7, 3.8 and 3.6 t/ha, respectively for the optimal sowing, in line with expected potential yields in these regions. Later sowing reduced median yield by around 1 t/ha for the two NSW sites, 0.6 t/ha at Wongan Hills and made little difference at Dalby. In the optimal sowing window, the increased rate of downward root growth had a median yield benefit of 0.1 t/ha or less. Benefits were larger for late sowing dates; the median benefit was around 0.1 t/ha at Dalby and Harden, 0.2 t/ha at Wongan Hills but negligible at Cootamundra. The median benefit of increased extraction efficiency exceeded that for fast roots at Harden and Dalby (0.2 to 0.4 t/ha) but was similar at Wongan Hills and Cootamundra (Fig. 1). The effect on yield of combining faster downward root growth and higher extraction efficiency (the likely scenario achieved by genetic manipulation) was generally additive. Benefits were greater for late than optimal sowings at Harden and Wongan Hills, but not Cootamundra or Dalby (Fig. 1). At all sites, small yield reductions (<0.2 t/ha) were simulated in some years, while maximum yield benefits from root modification across the 109 years of simulation were 1.0, 1.2, 1.4 and 0.9 t/ha, for Harden, Cootamundra, Wongan Hills and Dalby, respectively, and were similar for optimal and late sowing windows.

Table 2. Median root depth (m) at maturity, and water uptake by wheat crops sown in the optimal (Opt) or late sowing window at four locations.

Location	Harden		Cootamundra		Wongan Hills		Dalby	
Sowing window Date range (Day/month)	Opt 6/5- 30/5	Late 1/6- 15/6	Opt 6/5-30/5	Late 1/6- 15/6	Opt 1/5- 30/5	Late 1/6- 30/6	Opt 24/5- 21/6	Late 22/6-21/7
Median depth at maturity (m) of:								
Standard roots	1.60	1.52	1.81	1.57	2.15	1.92	1.81	1.68
Faster roots	1.60	1.60	2.01	1.85	2.56	2.29	1.94	1.88
Median water uptake (mm)								
Standard roots	213	186	241	202	137	115	246	249
Increased median uptake (mm) for:								
Faster roots	2	4	5	6	10	10	9	11
More efficient roots	22	20	13	6	18	14	24	15
Faster, more efficient roots	24	27	23	21	31	32	39	35

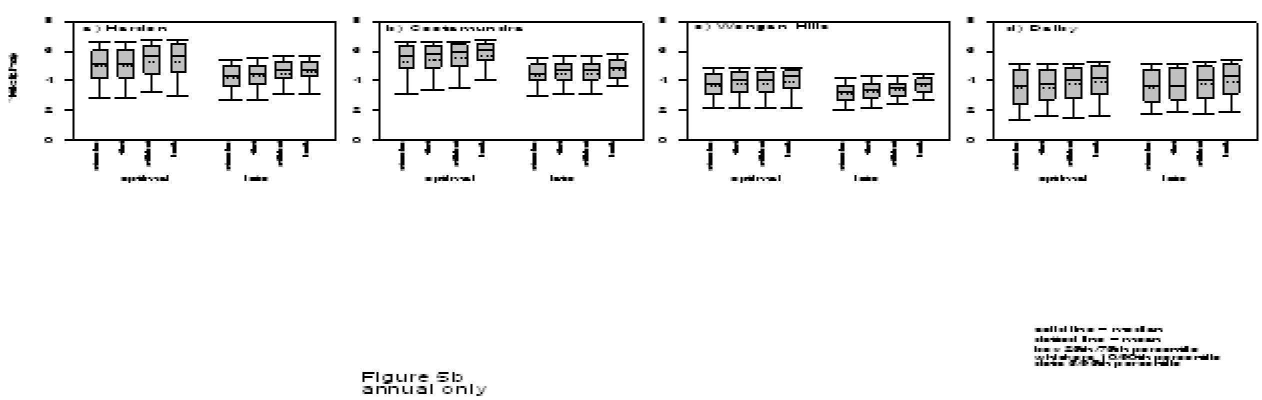

Figure 1. Range in simulated yield of wheat crops sown at four locations (a-d), in two sowing windows (optimal and late) with standard roots and 3 root modifications. Results are presented as a box plot. Median (solid line), mean (dotted line), 25th and 75th percentile (box), 10th and 90th percentile (whisker).

Discussion

Increasing the rate of root penetration by 20% resulted in a small increase in rooting depth (median 0.13 to 0.34 m) where root depth was not limited by subsoil constraints (Table 2). The consequence was an increase in water uptake of only 2 to 11 mm (median), and median yield benefits were 0.1 t/ha or less for crops sown in the optimal sowing window, but generally greater than 0.1 t/ha for late sown crops. Asseng and Turner (2007) also predicted minimal yield benefit of faster roots, (mean benefit of 0.2 t/ha on a sandy soil, and less with adequate N supply as was the case in our study). The increase in RPR of 20% used in this study may be achievable through breeding given the 14% differences reported by Richards et al. (2007) in the field. Deeper roots can also be achieved in other ways such as sowing long-season cultivars, which have a longer vegetative period and hence duration of downward growth, provided flowering and grain-filling periods do not coincide with periods with a high risk of frost or heat stress. Rooting depth is limited by subsoil constraints in many soils and unless the increased potential in rooting depth involves or includes tolerance of the subsoil constraint, faster downward root growth would make little difference, as seen at Harden where physical constraints prevented root penetration below 1.6 m. The depth of soil wetting, determined by rainfall and preceding management is often the overriding determinant of rooting depth (Lilley and Kirkegaard 2007). Increasing root exploration and extraction efficiency could be achieved using genotypes with greater root vigour, more seminal roots and increased branching, resistance to root disease, tolerance of soil acidity or salinity (Richards 2008). Agronomic practices which ameliorate disease and chemical constraints will also permit greater soil exploration by roots. In our study, modification of extraction efficiency resulted in an increased water uptake (median 6 to 24 mm) and a greater yield benefit (median up to 0.4 t/ha) than was produced by faster roots. Maximum benefits of around 1 t/ha are similar to those reported by Manschadi et al. (2006) in a simulation study where extraction efficiency was increased. The combination of faster and more efficient roots is the most likely outcome of any agronomic or genetic modification of root penetration rate, as more time in a given layer of soil will increase exploration, and the two components were largely additive with respect to water uptake and yield (Table 2, Fig. 1).

In reality, increased root vigour may be associated with changes in shoot characteristics not accounted for in this study, or possible carbon trade-offs caused by diverting assimilate to the roots. Crop sequence and fallow management also influence antecedent water content which can override the effects of improved genetics in some seasons (Lilley and Kirkegaard 2007). Consideration of these interactions provide further opportunities to identify sites and farming systems that best capture benefits from modified roots..

Conclusion

Our simulations predict that varieties with more rapidly descending and efficient roots will provide yield benefits at all of the sites tested and rarely result in reduced yields. Agronomic management (sowing date) had a greater effect on yield than root system modification, and increased extraction efficiency was generally more advantageous to crop production than more rapid root descent alone, especially for early-sown crops.

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