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Comparing rooting characteristics and soil water withdrawal patterns of wheat with alternative oilseed and pulse crops grown in the semi-arid Canadian prairie

The climate of the Canadian Prairies is very diverse, including highly variable and unpredictable precipitation, large diurnal ranges in temperature, long, cold winters, short, warm summers and frequent strong winds (Padbury et al. 2002). The climatic uncertainties associated with precipitation and temperatures are serious risks to agriculture, especially in the semi-arid regions of the Prairies.

Water stress is the most important factor limiting crop production in the semi-arid prairie (Campbell et al. 1992; Angadi et al. 2008), a region with large temporal (Cutforth 2000) and spatial (McConkey et al. 1990; Akinremi et al. 2000) variations in rainfall patterns. Increasing cropping intensity in the region has reduced fallow frequency (Zentner et al. 2002), leading to less frequent recharge of the soil moisture profile (Tanaka et al. 2010). Thus, reliance on low and erratically distributed rainfall for crop production is increasing (Akinremi et al. 2000; Cutforth 2000). Therefore, the ability of a crop or cropping system to extract water from the soil and use that water more efficiently is of increasing importance for sustainable production under water-limited conditions. Also, a greater understanding of the drought response of alternate crops under a range of water availabilities would contribute significantly to the planning and development of sustainable cropping systems suitable for the semi-arid prairie.

There are at least two opposing views regarding root growth and functioning in stressful environments where wide fluctuations in temperature and water availability are the rule rather than the exception. First, a crop with a deeper, exploratory root system is considered ideal for yield stabilization in a semi-arid climate (Hurd 1973; Gregory and Brown 1989). The efficiency of water extraction depends on the size and activity of the root system (Gregory 1994). Alternatively, because maintaining a unit of root costs more than maintaining an equal unit of shoot, a root system just large enough to tap all the available moisture reserves rather than an unnecessarily large root system is considered ideal for maximizing crop production (Passioura 1994). Further, a well-distributed smaller root system with fewer roots at shallower depth and more roots in deeper soil horizons is more efficient in using soil moisture (O'Toole and Bland 1987).

Our goal was to monitor root growth and water withdrawal patterns for the unrestricted growth of roots of Brassica and pulse crops in comparison to spring wheat grown on the semi-arid Canadian prairie.

MATERIALS AND METHODS

The field experiments were conducted at the Semiarid Prairie Agricultural Research Centre, Swift Current (50.26 N, 107.473 W) in the semi-arid environment of the Brown soil zone of southwestern Saskatchewan (Padbury et al. 2002). The 1971-2000 mean annual temperature was 4 C with a mean annual precipitation of 351 mm. Three levels of available water included in the study were well-watered, rainfed, and drought regimes.

Crops grown included three oilseeds [two canola cultivars, Cyclone (*B. napus*) and Tobin (*B. rapa*) and Oriental mustard cultivar Cutlass (*B. juncea*), three pulses [Cheston desi chickpea, Grande field pea, Laird lentil] and Katepwa spring wheat. Due to space limitations, Laird lentil and Tobin canola were not included in the drought treatment.

Variables Measured

Daily values of minimum and maximum air temperatures and rainfall between April to August were obtained from a meteorological recording station located within 400 metres of the research plots. In each well-watered, rainfed and drought plot, one or two access tubes were installed shortly after seeding and soil water contents from a 10 to 120-cm depth or from a 10 to 180-cm depth were measured in 10-cm increments about every two weeks from seeding to harvest using a neutron probe.

Water Regimes

To augment water availability under rainfed conditions, we irrigated and imposed drought to obtain the full range of available water for crop growth that can

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occur under rainfed (dryland) crop production on the semi-arid Canadian prairie. Treatments were replicated four times in a randomized complete design, except in the drought regime, where only two replications were possible.

Well-watered

Well-watered treatments were established on fallow. Precipitation and periodic irrigation maintained soil moisture levels above 70 per cent of the amount of available water between field capacity and the wilting point. Thus, well-watered treatments received 120, 127, and 71 mm of additional water during 1996, 1997, and 1998, respectively.

Rainfed (Dryland)

Rainfed treatments were also established on summer fallow managed similarly to the well-watered treatment. Soil moisture conserved during the fallow phase (up to 200 mm) and the growing season precipitation were available for crop production.

Drought

To establish and maintain drought, an automated rainout shelter was used to limit water use to approximately 150 mm by covering the plots during precipitation events. For each year, no precipitation/irrigation was allowed on the plots after the second week of June. However, prior to mid-June, irrigation water was added and/or precipitation was excluded to keep the plants under stress but still allow proper crop establishment.

Trench

In another trial, to directly measure the root system, Argentine canola (cv. Cyclone), field pea (cv. Grande), and spring wheat (cv. Katepwa) were seeded April 22, 1998 on a small block of land next to the drought study. On July 8, 1998 a vertical trench across crop rows was dug to a depth of 150 cm and the root systems of at least three plants of each crop were exposed using the profile wall method (Bohm 1979). The root length density (RLD) was measured to a depth of 120 cm at 20-cm increments by using the modified line intersect method (Tennant 1975).

RESULTS AND DISCUSSION

Weather

The distribution of rainfall and seasonal temperatures during the April-August growing season varied considerably among the four years (data not shown).

Root Length Density

We found root length density (RLD) to the 120-cm depth totaled 1,253 mm^{-2} for spring wheat, 798 mm^{-2} for canola, and 661 mm^{-2} for field pea (Fig. 1). The largest amount of roots for each crop were found in the surface 0-20 cm soil layer. Consequently, assuming RLD is a good indicator of root activity, canola and wheat would be much more active than field pea in water and nutrient uptake at rooting depths below 60 cm, whereas the majority of water/nutrient uptake by field pea would occur above 60 cm.

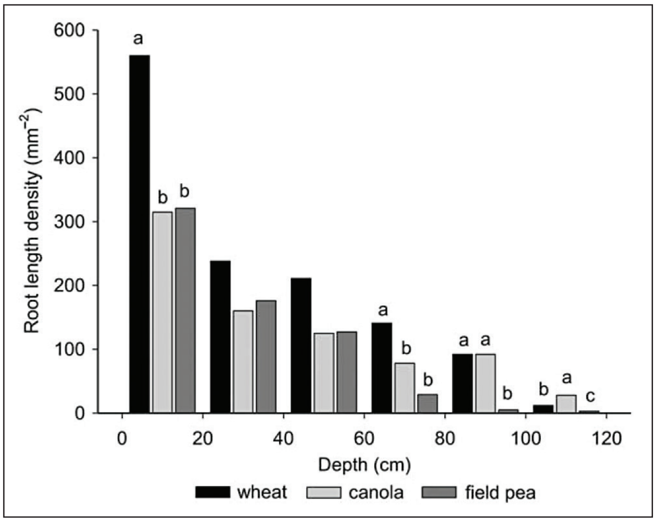

Fig. 1. *Root length density (mm $^{-2}$) of wheat, canola and field pea grown in a Swinton Clay loam soil at Swift Current during 1998. Letters are $LSD_{0.05}$ comparisons at each depth. The F test for root length density comparison for the 0-20 cm layer was significant at P=0.051. (For the 0-60 cm layer, RLD for wheat was greater than RLD for canola and field pea, which had similar RLD (F test significant at P=0.063).)*

SOIL WATER WITHDRAWAL

Soil Water Use

Soil water use for oilseed and pulse crops was compared to those for spring wheat (data not shown). Prior to anthesis, wheat and oilseeds used similar amounts of soil water whereas the pulses used the least (Table 1). After anthesis, wheat used the most and oilseeds the least amount of soil water, while soil water use by pulses was intermediate to the others. Further, from seeding to maturity, wheat withdrew the most water from the soil profile and withdrew about 48 per cent of that water after anthesis. Pulses withdrew the least amount of soil water and withdrew about 52 per cent of that water after anthesis. The oilseeds withdrew intermediate amounts of soil water and withdrew only about 42 per cent of that water after anthesis. Generally, the oilseeds withdrew a larger portion of their water requirements earlier in the growing season whereas pulses withdrew a larger proportion of their water requirements later in the growing season

Table 1. *Soil water used to the 130-cm depth by cereal, oilseed, and pulse crops during the indicated growth periods for wheat*

	Soil water use (mm)				
Species	*Start date to early boot*	*Early boot to anthesis*	*Start date to anthesis*	*Anthesis to ripe*	*Start date to ripe*
Wheat	28.3	52.7	81.9	75.8	158.5
Oilseed	29.9	52.2	82.9	61.6	145.4
Pulse	20.7	39.8	61.5	67.1	129.0
$LSD_{0.05}$	6.0	9.6	10.5	9.7	9.9

Soil Water Depletion

When averaged across water regimes, water withdrawal patterns were species-dependent (Fig. 2). Further, Gan et al. (2009) found water withdrawal patterns were similar under rainfed (dryland) and irrigation conditions, i.e., for a given species, water withdrawal patterns were independent of water availability. Prior to the early boot stage of wheat, cereal and oilseed crops withdrew similar amounts of soil water, and more soil water than pulses from depths above 70 cm (Fig. 2a), an observation also noted by Gan et al. (2009). From early boot to anthesis of wheat, cereal and oilseed crops withdrew similar amounts of soil water (Table 1), and more soil water than pulses from depths between 60 and 110 cm (Fig. 2b). Post-anthesis, above the 80-cm depth, oilseeds withdrew the least amount of soil water whereas pulses tended to withdraw more water than the cereal (wheat) crop (Fig. 2c). From 90 to 120 cm deep, the cereal withdrew the most, whereas the pulses withdrew the least amount of soil water. As the depth increased below 90 cm, the amount of soil water withdrawn by the oilseeds increased relative to the cereal so that below 110 cm the cereal and oilseeds withdrew similar amounts of soil water. From seeding to harvest, the total amount of soil water withdrawn throughout the effective rooting depth (approximately 0 to 130 cm) was highest for the cereal (Table 1, Fig. 2d). After harvest, more water was stored in the soil below the 60-70 cm depth under pulses than under oilseeds or cereals. This stored water would be available for the following year's crop.

There were differences in water withdrawal patterns between the Brassicas included in the oilseed species group (data not shown). Comparing water withdrawal patterns across the whole growing season, *B. rapa* withdrew the least amount of water, whereas *B. napus* and *B. juncea* withdrew similar amounts of water from the layers within the rooting zone (0-130 cm). Generally, *B. rapa* has a shorter growing season than *B. napus* or *B. juncea* (data not shown), contributing to the lower water withdrawal amounts by *B. rapa* compared to the others.

Due to space constraints, lentils were not grown in the drought water regime. The water withdrawal patterns of desi chickpea and field pea when averaged across drought, dryland and well-watered conditions were very similar to those averaged across dryland and well-watered conditions only. Therefore, the water withdrawal patterns for lentil, chickpea and field pea were compared and presented when averaged across dryland and well-watered conditions (data not shown). We found that there were differences between the pulses in the rate of water withdrawal for different growth periods, but over the whole growing season there was essentially no significant difference between the pulses in water withdrawal with depth. Similar to Gan et al. (2009), we suggest that more research into effective rooting depth and water withdrawal patterns for pulses is needed.

Maximum Depth of Water Withdrawal

When averaged across water regimes and years and comparing between species, we found the maximum depth of water withdrawal for wheat and oilseeds was between 120 and 130 cm deep, and 100-110 cm deep for pulses (data not shown).

Merrill et al. (2002) suggested that maximum rooting depth is dependent upon subsoil moisture (wetter subsoil, deeper roots). Similarly, our data suggested there might be a relationship for pulses and especially oilseeds between the maximum depth of water withdrawal and water regime, but further study is required

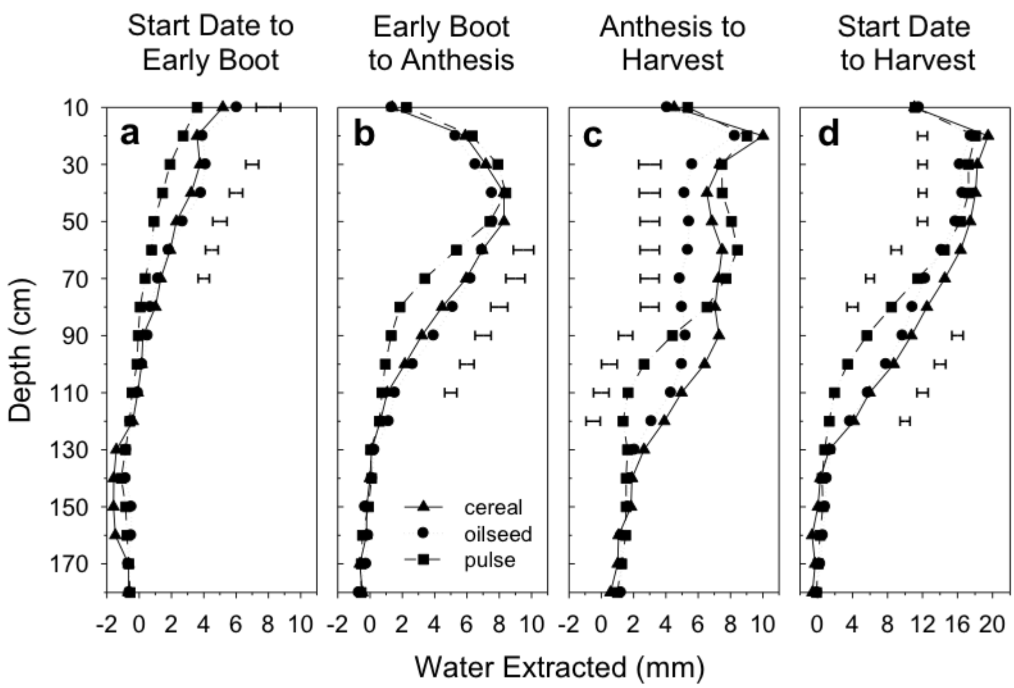

Fig. 2. *Water withdrawal patterns by cereal, oilseed and pulse species. Growth periods were determined for spring wheat and were sequential from near seeding to early boot, early boot to anthesis, anthesis to ripe (near harvest), as well as the whole growing season from near seeding to ripe. The growth periods were averaged over 1996-98. LSD bars (P<0.05) indicate significant differences in water content with depth.*

to determine the extent of these relationships. Although not significant, the Brassicas showed a tendency to root deeper as water availability at depth increased (data not shown).

Generally, the maximum depth of water extraction is achieved by the beginning of grain-filling (Dardanelli et al. 1997). Evidence suggests that maximum rooting depths for wheat and canola can reach 150 cm and deeper (Dharmasri et al. 1993; Nielsen 1997; Merrill et al. 2004; Kirkegaard and Lilley 2007). However, the maximum rooting depth may be substantially deeper than the maximum depth of water withdrawal (referred to by Dharmasri et al. (1993) as the 'effective rooting depth').

Some Australian wheat varieties can withdraw soil water from as deep as 180 cm. Lilley and Kirkegaard (2007) studied the effect of water stored deep in the soil profile (between 120-180 cm, the bottom third of the root zone) on wheat yield. (Comparatively, in the semi-arid Canadian Prairies, the effective root zone for wheat is 0-130 cm and the bottom third would be the 86-130 cm layer. Therefore, we define water stored below 80-85 cm as deep soil water.) They found the value of this deep water to crop yield depended on preceding management and seasonal rainfall distribution. Water stored deep in the profile is most often used later in the growing season during grain filling (i.e., post-anthesis), especially when higher water deficits occur (Kirkegaard et al. 2007; Passioura 1983, 2006). The water use efficiency of this deep soil water can be as much as three times greater than the WUE for water use calculated across the whole growing season (French and Schultz 1984). Thus, depending upon the environmental conditions, water used from deeper in the soil profile can make a greater contribution to grain yield than water withdrawn from shallower depths (Passioura 2006).

Gan et al. (2003) and Kirkegaard et al. (2008) suggested wheat and Brassica yields following pulses are often increased above those following wheat for several reasons, including increased amounts of deep soil water accumulating during a pulse crop year, especially for field pea and lentil. In the semi-arid prairie of southwest Saskatchewan, Gan et al. (2007) found the amount of available water left below the 60 cm depth at harvest was about 33 mm by field pea and about 20 mm by desi chickpea, for an overall average for pulses of about 27 mm. Similarly, in a Montana study, Miller and Holmes (2012) found that lentil averaged 20 mm less water used than spring wheat over 4 years in the 60-120 cm soil depth, while pea used 29 mm less water averaged over 3 years for the same soil depth. Although these increased water reserves at first glance appear small, soil water below 60 cm can make a significant contribution to meeting total crop water requirements, especially in dry years (French and Schultz 1984; Gan et al. 2007). For example, Merrill et al. (2004) found canola withdrew about 45 per cent of the water it used from depths below 60 cm, while wheat withdrew 33 per cent and dry pea 27 per cent from below 60 cm in a year with low precipitation. During an above-average precipitation year, they found there was little difference in the depth distribution in soil water withdrawal between crops. Further, wheat and Brassica oilseeds withdrew similar amounts of deep soil water from 90 cm deep to the effective rooting depth of 130 cm. However, above 90 cm the Brassicas withdrew less water from the profile than wheat, leaving more water in the upper regions of the soil profile available to the following crop. Gan and Goddard (2008) found wheat following *B. juncea* yielded substantially more grain than wheat following wheat and slightly less than wheat following pulses.

SUMMARY

Wheat and Brassica oilseeds withdrew water to an effective rooting depth of 120-130 cm, whereas pulses had an effective rooting depth of 100-110 cm. On average, pulses withdrew substantially less water than oilseeds and wheat below about the 80 cm depth, increasing deep soil water reserves potentially accessible by deeper-rooting crops planted in subsequent growing seasons. As well, the oilseeds withdrew less water from the upper regions of the soil profile than wheat. Thus, compared to wheat, the oilseeds left a larger amount of water available to the following crop, especially if the following crop is wheat. Deep soil water is most often used later in the growing season (i.e., during grain filling) and the water use efficiency (WUE) of this deep water can be up to three times greater than the WUE for water used across the whole growing season. Consequently, water used from deeper in the soil profile can make a greater contribution to grain yield than water withdrawn from shallower depths. Therefore, on the Canadian semi-arid prairie, producers can increase the overall yield and water use efficiency of a crop rotation by growing deeper-rooted crops such as wheat and canola one or two years following a shallower-rooted pulse crop, and by growing wheat following a Brassica oilseed.

Compared to wheat and pulse, canola would probably benefit more than the others from irrigation in the latter half of the growing season relative to the first half. Canola uses substantially less water from pod filling to maturity than during the vegetative period, especially from the surface to 90-cm depth. With a limited water supply, it would probably be more beneficial to irrigate in the latter half of the growing season to replenish the deficit by increasing the water supply and increasing the duration of pod filling (i.e., increasing the time from anthesis to maturity). However, this is speculative and further research is needed on irrigation scheduling to optimize yields of wheat, pulse and especially canola by increasing water use efficiency and/or increasing the time to maturity under water-limited conditions.

Because pulses withdraw water from the soil profile to a depth of 100-110 cm and wheat and canola to a depth of 120-130 cm, for water use studies (especially by researchers) we recommend sampling to at least 120 cm for pulses and 140-150 cm for wheat and canola.