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Water deficit effects on root distribution of soybean, field pea and chickpea

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Abstract

Cropping diversity in the central Great Plains of the United States could be increased by including suitable legumes in crop rotations. Water is limiting to all crops grown in this region and agronomic crops frequently experience water deficit stress during their life cycle. The ability of a plant to change its root distribution to exploit deeper stored soil water may be an important mechanism to avoid drought stress.

An experiment was conducted to examine legume root system response to water deficit stress. Chickpea (*Cicer arietinum* L.), field pea (*Pisum sativum* L.), and soybean (*Glycine max* L. Merr.) were grown at two water regimes: under natural rainfall conditions and irrigated to minimize water deficit stress. Root distributions for each species were measured at 0.23 m depth intervals to a depth of 1.12 m directly beneath the plants at the late bloom and mid pod fill growth stages. Roots were washed free of soil and were separated from soil debris by hand. Root surface area measurements were made and root weights were recorded for each depth interval.

Water deficit did not affect the relative soybean root distribution. Approximately 97% of the total soybean roots were in the surface 0.23 m at both sampling times and under both water regimes. In contrast, water deficit stress resulted in a greater proportion of chickpea and field pea roots to grow deeper in the soil. Under irrigated conditions, about 80% of the chickpea and field pea roots were in the surface 0.23 m. Under dry conditions, about 66% of the total chickpea and field pea roots were in the surface 0.23 m and the remainder of the roots was deeper in the soil profile. Field pea had a root surface area to weight ratio (AWR) of 35–40 $m^2 kg^{-1}$, chickpea had a AWR of 40–80 $m^2 kg^{-1}$, whereas soybean had a AWR of 3–7 $m^2 kg^{-1}$, depending on plant growth stage. The greater AWR indicates a finer root system for the field pea and chickpea compared with soybean. From a rooting perspective, chickpea may be the best suited of these species for dryland crop production in semi-arid climates due to an adaptive root distribution based on water availability and large root surface area per unit root weight.
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Keywords: Chickpea; Dryland agriculture; Field pea; Root surface area; Soybean; Water deficit stress

1. Introduction

No-till soil management and chemical weed control have helped increase cropping intensity in the central Great Plains of the United States (Anderson et al., 1999). The amount of land devoted to the traditional wheat (*Triticum aestivum* L.)–fallow cropping system has steadily decreased while the amount of land with more intensive rotations has increased. Crops grown in rotation with wheat in this region include corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), proso millet (*Panicum miliaceum* L.), and sunflower (*Helianthus annuus* L.). Cropping diversity would be improved if legumes were found that could be included in rotation with cereals. Chickpea (*Cicer arietinum* L.), field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.) have shown promise for inclusion in dryland cropping systems, either as grain or as forage (Nielsen, 2001). There has been increasing interest in soybean (*Glycine max* L. Merr.) for this region because of the high value and ready market for this crop. Chickpea and field pea have a relatively short growing season and use less water than many other broadleaf crops such as sunflower or safflower (Johnson et al., 2002). They may fit better in rotation with grasses than other broadleaf crops because they use less water and thereby leave more water available for succeeding crops.

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Table 1
Planting dates, row spacings, sampling dates, plant growth stage at sampling, total precipitation, and total precipitation plus irrigation data for each crop in the legume rooting study

Crop	Planting date	Row spacing (mm)	Sampling date	Growth stage	Total precipitation and irrigation (mm)		
					Dryland	Irrigated	30-Year average
Profi pea	10 April	190	15 June	Late bloom	64	350	148
			6 July	Mid pod fill	86	452	195
Chickpea	12 April	250	20 June	Late bloom	79	318	160
			10 July	Mid pod fill	89	376	204
Soybean	15 May	250	1 August	Late bloom	165	320	254
			21 August	Mid pod fill	262	602	289

Rain-fed crops grown in this region experience water deficits during their life cycle. Several researchers (Pandey et al., 1984; Sponchiado et al., 1980) have hypothesized that the ability of a plant to change its root distribution in the soil is an important mechanism for drought avoidance. Pandey et al. (1984) determined that peanut and cowpea were able to change root distribution in the soil because of dry conditions and, therefore, extract water to deeper depths than soybean or mung bean. Sponchiado et al. (1980) showed that the ability of a plant to change root distribution to avoid drought stress could vary by cultivar within a species. Soybean (Hoogenboom et al., 1987) and sorghum (Merrill and Rawlins, 1979) appeared to grow deeper root systems as available water decreased. Spring wheat (Merrill and Rawlins, 1979) appeared to have a shallower root system as available water decreased. Merrill et al. (2002) showed that soybean and dry bean had the greatest root growth in the driest year of their study and the least root growth in the wettest year. Field pea in the Merrill et al. (2002) study had the greatest root growth in an average year followed by lesser root growth in the dry year and the least root growth in the wettest year.

Selection of plant species by their ability to alter root distribution in the soil due to drought stress may help find suitable species for a semi-arid environment. The objective of this study was to determine water deficit stress effects on root distributions of field pea, chickpea and soybean, which have potential for dryland crop production in the central Great Plains.

2. Materials and methods

Field pea (‘‘Profi’’), chickpea (‘‘Myles’’) and soybean (‘‘Pioneer[1] 9294’’) were grown on a Weld silt loam (fine, smectitic, mesic Aridic Paleustolls) at the Central Great Plains Research Station near Akron, Colorado in 2000. The station lies at 40.15°N latitude and 103.15°W longitude. The elevation of the station is 1384 m above mean sea level. Pea was planted at 200 kg ha^{-1} and chickpea was planted at 94 kg ha^{-1} in early spring (Table 1). Soybean was planted at 408,000 seeds ha^{-1} in late spring. Each crop was grown under both natural rainfall conditions and with supplemental irrigation in a completely randomized design with three replications. Variable water availability conditions were created via a line source solid-set irrigation system. The plot area for each crop was 24.4 m × 61.0 m. The center section of this area (12.2 m × 24.4 m) was bordered by the irrigation lines. This section was uniformly irrigated when the irrigation system was operating. On the outside edges of the gradient irrigation areas were the rain-fed plots (each 12.2 m × 24.4 m), which received no irrigation. Four soil water measurement sites and irrigation catch gauges were established in each of these areas. Approximately 37 mm of irrigation water was applied each week. Irrigations were generally applied in the evening when wind speeds were low to minimize water application variability. Further description of the field plot layout and cultural practices can be found in Nielsen (2001).

Soil samples for root measurements were taken from three plants in adjacent rows at late bloom growth stage and mid pod set growth stage for each species. A hydraulic probe with a sampling tube 75 mm in diameter and 1.12 m long was used for sampling. The plant material was clipped level with the soil surface and removed before sampling. Any loose plant residue on the soil surface was also brushed away from the sampling site. The sampling tube was centered over the plant and a sample was taken to a 1.12-m depth. The core was sectioned into 0.225-m lengths. The sample was then placed in a plastic, sealable bag and the bags placed in a Styrofoam cooler for transport from the field. After each half day's sample collecting, the samples were placed in refrigerated storage until washing the next day. Roots were washed from the soil cores and measurements were made using digital image analysis techniques as described in Benjamin and Nielsen (2004). Roots and debris were separated manually by placing the sample in a tray and examining the sample with the aid of a 3× lighted magnifier. All roots including taproot and large primary roots were included in the sample. Scans were made with an Agfa[2] Snapscan™ E40 flatbed scanner at 118 pixels/cm (300 dpi). A grid overlay technique was used to determine root surface

[1] Variety and product names are included for information purposes only and do not endorse this variety over similar varieties.

[2] Agfa-Gevaert N.V., Mortsel, Belgium.

area (Benjamin and Nielsen, 2004). After scanning, the roots were removed from the sample tray, dried and weighed.

An analysis of variance was conducted by species on the total root weight and root surface area within the soil volume and also for each soil layer. A protected LSD test was used to determine treatment differences. The LSD was used to distinguish treatment effects only if the F-test was significant at the 0.05 probability level.

3. Results

Rainfall for field pea and chickpea was less than half of the average cumulative precipitation at each growth stage during the growing season (Table 1) indicating severe drought stress during the growth period. Cumulative rainfall for soybean was about 2/3 of the 30-year average at the late bloom growth stage but, because of rainfall that occurred later in the season, the total precipitation at the mid pod fill growth stage was near the 30-year average. The irrigated plots received water equivalent to about 200% of the 30-year average.

Total pea root weight at the late bloom growth stage was similar for both water regimes (Table 2). By mid pod fill growth stage, the irrigated treatment had about 150% of the root weight as the dryland treatment. Root surface area was similar between dryland and irrigated treatments at both growth stages. The changes in pea root weight and root surface area occurred primarily in the surface 0.23 m of soil (Fig. 1). Root weight density for both sampling times under non-irrigated conditions and for the late bloom sampling time under irrigation were about 0.25 kg m^{-3}. Root weight increased with time under irrigated conditions so that the root weight density for irrigated conditions at the mid pod fill sampling time was nearly double the other treatments at 0.47 kg m^{-3}. Root weight density in deeper soil layers was similar regardless of treatment or time. Field pea had greater root surface area density under irrigated conditions than non-irrigated conditions (Fig. 2). There was a shift in the root distribution between the irrigated and non-irrigated conditions. Under irrigation, about 80% of the root mass was in the 0–0.23 m soil layer. With non-irrigated conditions, less than 70% of the total root weight was in the topmost layer. A greater proportion of the roots was found in deeper soil layers for pea grown under non-irrigated conditions than for irrigated conditions. About 20% of the roots were in the 0.23–0.46 soil layer under non-irrigated conditions compared with about 12% of the total roots in this layer under irrigation.

Total chickpea root weights were similar at the late bloom growth stage between irrigation treatments and total root weight increased by the mid pod fill growth stage (Table 2). Neither irrigation treatment nor growth stage had a significant effect on chickpea root surface area. Total root surface area was similar at about 50 m^2 m^{-2} for each sampling time and irrigation treatment. Significant root weight increases between growth stages occurred in almost every soil depth (Fig. 1). The greatest change in root weight density was at the soil surface, with the irrigated treatment increasing from 0.63 kg m^{-3} at late bloom to 1.24 kg m^{-3} at mid pod fill. Root weight density for the non-irrigated treatment changed from 0.48 kg m^{-3} at late bloom to 0.72 kg m^{-3} at mid pod fill. Irrigation increased root surface area density for chickpea in the topmost layer of soil (Fig. 2). The greater root surface area in the surface layer of the soil

Table 2
Total root weight (kg roots/m^2 soil surface area) and root surface area (m^2 roots/m^2 soil surface area) in a 1.12 m soil profile for field pea, chickpea, and soybean under dryland and irrigated growing conditions

Crop	Irrigation (I)	Growth stage (GS)					
		Root weight (kg)		LSD (0.05)	Root surface area (m^2)		LSD (0.05)
		Late bloom	Mid pod fill		Late bloom	Mid pod fill	
Field pea	Dryland	0.38 a	0.46 a	0.11	14.0 a	15.7 a	7.3
	Irrigated	0.28 a	0.67 b		13.7 a	22.4 a	
				$P > F$			$P > F$
			GS	0.0009		GS	0.14
			I	0.26		I	0.34
			GS × I	0.0099		GS × I	0.30
Chickpea	Dryland	0.74 a	1.21 a	0.62	53.1 a	47.5 a	11.7
	Irrigated	0.78 a	1.72 b		52.5 a	54.5 a	
				$P > F$			$P > F$
			GS	0.03		GS	0.55
			I	0.34		I	0.73
			GS × I	0.40		GS × I	0.48
Soybean	Dryland	3.4 a	4.5 a	1.6	12.2 a	23.9 b	5.7
	Irrigated	5.0 a	5.0 a		13.4 a	35.9 c	
				$P > F$			$P > F$
			GS	0.46		GS	0.0001
			I	0.18		I	0.027
			GS × I	0.48		GS × I	0.058

Within each species, values followed by the same letter are not significantly different at the 0.05 probability level.

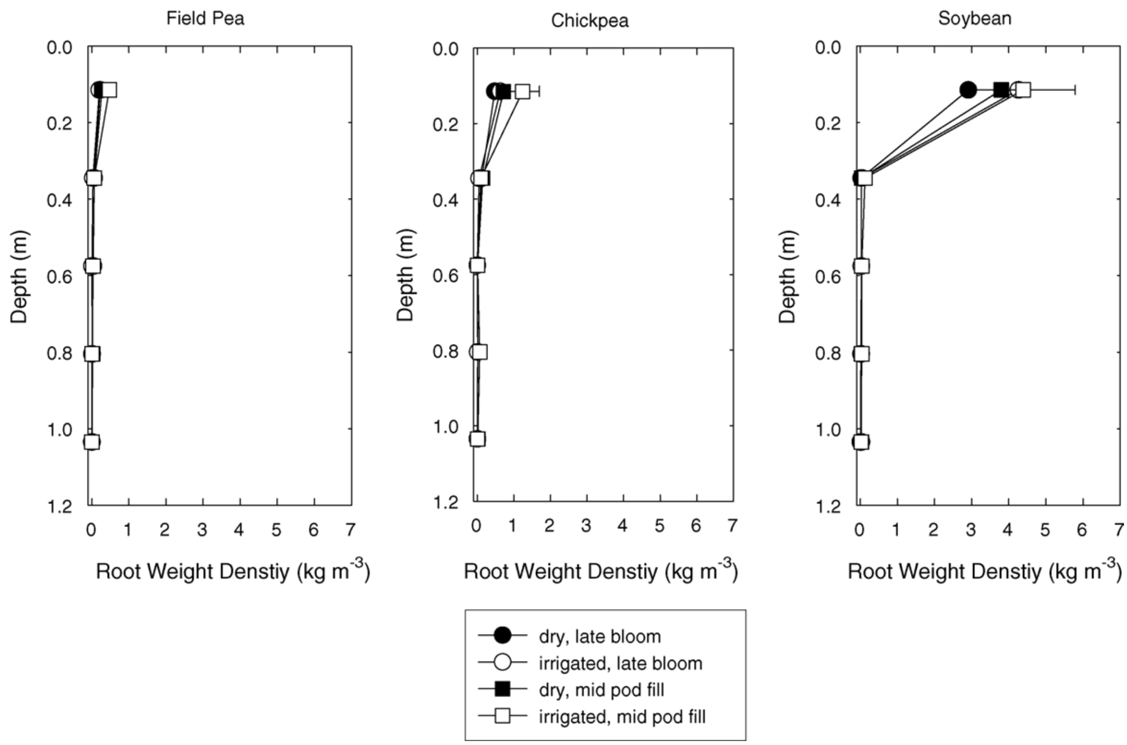

Fig. 1. Root weight density distribution with depth for field pea, chickpea, and soybean grown under natural rainfall and with supplemental irrigation. The error bar indicates ±1 S.D. from the mean for each crop and depth. If error bar is not evident, it is smaller than the symbol used.

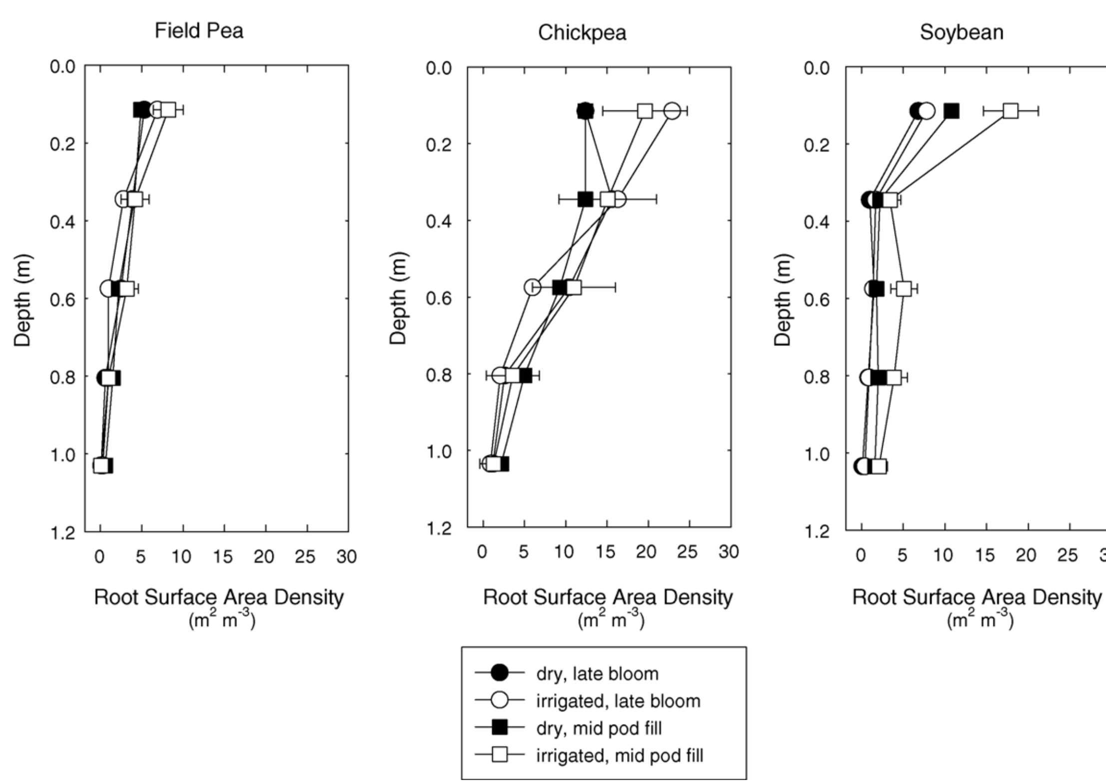

Fig. 2. Root surface area density distribution with depth for field pea, chickpea, and soybean grown under natural rainfall and with supplemental irrigation. The error bar indicates ±1 S.D. from the mean for each crop and depth. If error bar is not evident, it is smaller than the symbol used.

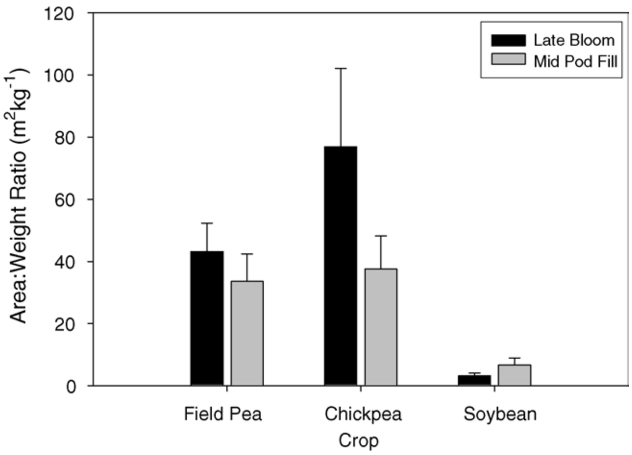

Fig. 3. Root surface area to root weight ratio for roots in the 0–1.12 m depth at the late bloom and mid pod fill growth stages. The error bar indicates 1 S.D. from the mean for each crop and time.

was offset by decreased root surface area in deeper soil layers.

There was no significant change in total soybean root weight caused by either growth stage or irrigation treatment (Table 2). There was, however, an increase in total root surface area in the top 1.12 m of soil with both irrigation treatment and growth stage (Table 2). The root surface area doubled between the late bloom and mid pod fill growth stages for the non-irrigated treatments and the root surface area almost tripled between the late bloom and mid pod fill growth stages for the irrigated treatments. The same total root weight at each growth stage and the large increase of root surface area between growth stages indicates a finer root system at the mid pod fill growth stage compared with the late bloom growth stage.

Although direct comparison of root weight and surface area measurements among species is not possible due to differences in row spacing and planting density, a few observations about the root characteristics should be noted. Chickpea had the greatest root surface area to weight ratio (AWR) and soybean had the lowest (Fig. 3). A high surface area to weight ratio indicates either a finer root system or roots with lower specific density. AWR remained about the same at 35–40 $m^2 kg^{-1}$ for field pea from the late bloom to mid pod fill growth stage. Chickpea AWR decreased from about 80 to 40 $m^2 kg^{-1}$ from the late bloom to mid pod fill growth stages indicating a thickening or densification of the root material. Soybean AWR increased from about 3 to 7 $m^2 kg^{-1}$ between the late bloom to mid pod fill growth stages indicating an increase in fine roots or lower root specific density. Irrigation had no statistically significant effect on the AWR for any species at any time.

4. Discussion

There were distinct differences among the species of how they responded to water deficit stress. Field pea and chickpea had a greater proportion of their root systems deeper in the soil profile than soybean, which could lead to better use of stored soil water. Field pea and chickpea responded to drier soil conditions by increasing the proportion of roots deeper in the soil whereas soybean maintained the majority of the roots near the soil surface regardless of water deficit stress. Field pea and chickpea had a greater root surface area to weight ratio than soybean, indicating more fine roots in the root system, which could lead to better soil exploration and water extraction.

There is little information in the literature for comparing root distribution response to water deficit stress for chickpea or field pea. The changes in root distribution for field pea observed by Merrill et al. (2002) occurred in different years so their results may also be affected by differences in temperature or ET demand between years. For soybean, we found 95–97% of the total root weight and 58–70% of the total root surface area in the surface 0.23 m of soil. This agrees with Mitchell and Russell (1970) who found 90–97% of the soybean root weight in the top 0.23 m. Mitchell and Russell (1970) found that the soybean root system continued to grow after initiation of pod fill. This contrasts with our findings that, under irrigation, we measured the same root weight at late bloom as at mid pod fill growth stages. We found that root surface area increased from the late bloom to mid pod fill growth stages under dryland conditions and that root surface area increased with addition of irrigation water.

Soybean had the same percentage root weight distribution whether grown under dryland or irrigated conditions or at either growth stage. Soybean root surface area distribution decreased in the surface layer and increased in deeper soil layers from the late bloom growth stage to the mid pod fill growth stage. Negligible irrigation effect for soybean root weight is similar to the findings of Mayaki et al. (1976) who found no increase of root mass with irrigation of soybean in Kansas. However, this is in contrast to Robertson et al. (1980) who found greater root mass for irrigated soybean than non-irrigated soybean grown in Florida. It would seem likely that the response of soybean roots to water deficit stress would be variety and climate dependent as was found by Sponchiado et al. (1980) for dry bean. Better variety selection of soybean, with particular attention given to root response to dry conditions, may be needed for soybean to be a viable crop in the semi-arid Great Plains.

5. Conclusions

Based on rooting characteristics, chickpea and field pea are better suited to dryland cropping systems in the semi-arid western United States than soybean. Both species are planted early in the spring and are harvested in mid-summer. A longer period of time exists for the soil to capture summer rainfall for use by the subsequent crop. Both species also have a greater portion of their root systems deeper in the soil than soybean and respond to water stress by shifting roots to deeper soil layers. Chickpea may be the best suited of these species for dryland crop production in Colorado. The chickpea root system responded to water deficit stress by increasing roots deeper in the soil profile. Greater root density deeper in the soil profile and the larger proportion of fine roots compared with field pea or soybean could lead to better exploitation of water stored at lower soil depths.

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