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Production Functions for Chickpea, Field Pea, and Lentil in the Central Great Plains

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ABSTRACT

A short-season legume grown in rotation with winter wheat (*Triticum aestivum* L.) is needed to diversify and enhance dryland crop rotations in the central Great Plains. This study was conducted to determine the potential of chickpea (*Cicer arietinum* L.), field pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.) as such rotational legumes based on yield responses to water and soil water extraction patterns. The legumes were planted under a line-source gradient irrigation system to provide a range of available water conditions. Soil water content, crop water use, and seed yield were measured to determine relationships between water use and yield. Distributions of estimated yields were produced using these relationships and the local historical rainfall record. Chickpea exhibited the greatest rate of increase in yield with increases in water use (10.6 kg ha^{-1} mm^{-1}), followed by field pea (8.0 kg ha^{-1} mm^{-1}) and lentil (3.3 kg ha^{-1} mm^{-1}). Yields estimated from the historical rainfall record ranged from 951 to 3782 kg ha^{-1} (mean of 2092 kg ha^{-1}) for chickpea, 523 to 2718 kg ha^{-1} (mean of 1406 kg ha^{-1}) for field pea, and 286 to 1247 kg ha^{-1} (mean of 654 kg ha^{-1}) for lentil. All three legumes have agronomic potential to be used as dryland crops ahead of winter wheat in the central Great Plains.

Producers in the central Great Plains have traditionally used a winter wheat–fallow production system in which one crop is grown every 2 yr. Recent studies have shown the feasibility of intensifying and diversifying from this production system when reduced or no-tillage systems are used (Halvorson et al., 1994; Peterson et al., 1996; Anderson et al., 1999; Nielsen et al., 1999). Adding new crops to rotation sequences can complicate the system when a new crop's maturity and harvest period interfere with timely winter wheat establishment in mid to late September. A short-season legume that could be planted early would provide rotational benefits such as N fixation, increased soil organic matter, and increased surface soil stability; sufficient time for late summer rains to recharge the surface soil water for good winter wheat establishment; and alleviation of monoculture insect, disease, and weed problems (Power, 1987). Three legumes that have potential to fit into dryland rotations with winter wheat are chickpea, field pea, and lentil.

Chickpea

Chickpea is a drought-tolerant, cool-season legume used for human consumption. Most of the chickpea grown in the USA are the large-seeded kabuli type sold for canning purposes. The major USA production areas are the rainfed Palouse area of the Pacific Northwest and the irrigated production area of California's San Joaquin Valley. Dryland chickpea trials in Fort Collins, CO gave a 2-yr average yield of 1049 kg ha^{-1} (Brick et al., 1998). A number of studies have reported the yield response of chickpea to available water (Table 1). Gradient irrigation studies with chickpea in Yellowjacket, CO (elevation of 2128 m) showed a strong yield response to water applied, but the response was not consistent from year to year. Overall yields ranged from 4.8

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Table 1. Previous research on seed yield response of chickpea, field pea, and lentil to water use traits.

Crop	Reference	Location	Seed yield response†	r^2	Water use trait
Chickpea	Leach and Beech (1988)	Australia	kg ha^{-1} = 6.8X	NA‡	Cumulative evapotranspiration
	Singh and Bhushan (1980)	India	kg ha^{-1} = 13.1 (X $-$ 34.9)	NA	Soil water at planting and rainfall
	Sivakumar and Singh (1987)	India	kg ha^{-1} = 8.8 (X $-$ 34.4)	0.90	Cumulative evapotranspiration
	Siddique and Sedgley (1987)	Australia	kg ha^{-1} = 4.7 (X $-$ 172.6)	NA	Postflowering water use
	Grewal et al. (1984)	India	kg ha^{-1} = 3.5 (X $-$ 123.3)	0.98	Cumulative evapotranspiration
	Silim and Saxena (1993)	Syria	variable with variety; regression slopes avg. 6.0 kg ha^{-1} mm^{-1}	NA	Cumulative evapotranspiration
	Brick et al. (1998)	Colorado	variable, regression slopes range from 4.8 to 9.6 kg ha^{-1} mm^{-1}	NA	Irrigation amount
	Singh and Singh (1988)	India	kg ha^{-1} = 10.4 (X + 71.3)	0.62	Growing season rainfall
	Brown et al. (1989)	Syria	kg ha^{-1} = 3.6 (X + 40.3)	0.79	Cumulative evapotranspiration
Field pea	Borstlap and Entz (1994)	Canada	kg ha^{-1} = 10.9 (X $-$ 76.4)	0.55	Cumulative evapotranspiration
	PIRSA (2000)	Australia	kg ha^{-1} = 15.0 (X $-$ 130)	NA	Growing season rainfall
	McDonald (1995)	Australia	kg ha^{-1} = 4.3 (X $-$ 87.0)	0.89	Growing season rainfall
Lentil	Silim et al. (1993)	Syria	variable with variety; regression slopes average 6.1 kg ha^{-1} mm^{-1}	NA	Irrigation amount
	PIRSA (2000)	Australia	kg ha^{-1} = 15.0 (X $-$ 130)	NA	Growing season rainfall
	Yusuf et al. (1979)	India	kg ha^{-1} = 6.8 (X + 62.8)	0.99	Growing season rainfall + irrigation
	Sharma and Prasad (1984)	India	kg ha^{-1} = 8.4 (X $-$ 115.7)	0.99	Cumulative evapotranspiration

† X, water use trait (mm).
‡ NA, not available.

to 9.6 kg ha^{-1} for each additional millimeter of water applied (Brick et al., 1998). A production fact sheet for South Australia reports a chickpea yield increase of 15.0 kg ha^{-1} for each additional millimeter of growing season precipitation received. Other reports also indicate a significant relationship between chickpea yield and water availability (Table 1). However, Singh (1984) and Rahman et al. (1983) found no consistent relationship between water use and yield.

Thomas and Fukai (1995) reported that maximum soil water extraction by chickpea occurred in the 20- to 40-cm soil depth, but part of that was attributed to evaporation from the soil surface. Very little soil water extraction was noted below 130 cm. Measurements of root length density in this same experiment confirmed the presence of very few roots in the 130- to 170-cm soil profile. Brown et al. (1989) found chickpea roots in Syria penetrated to at least 120 cm (the limit of their sampling) but suggested that a rooting depth of 150 cm was probably reasonable. They did report significant reductions in soil water content in the 120- to 150-cm soil layer from 19 May to 15 June as evidence that roots were present in that soil layer. Leach and Beach (1988) reported that, in both wet and dry years of a 2-yr study, chickpea did not extract water from below the 100-cm depth in Australia. They also reported that soil water measurements showed chickpea to be an effective moisture scavenger during pod filling because the profile water contents were dried below -1.5 MPa of matric potential. Sivakumar and Singh (1987) found water depletion by both desi and kabuli chickpea cultivars to be confined mainly to the top 67 cm of the soil profile in India. Silim and Saxena (1993) reported somewhat deeper soil water extraction for both desi and kabuli types (120–150 cm). Siddique and Sedgley (1987) reported chickpea roots reaching a maximum depth of 100 cm in Australia with most of the roots in the top 40 cm. Grewal et al. (1984) measured water extraction by chickpea from all soil layers down to a depth of 150 cm and found fairly uniform extraction in each 30-cm layer. Singh et al. (1980) reported that soil water extraction in the top 60 cm contributed 74 to 83% of the total crop water use.

Harris (1979) stated that temperatures exceeding 30 to 32°C limit yield of chickpea by hastening maturity. Work in South Australia noted that chickpea will tolerate higher temperatures during flowering than field pea (Hawthorne et al., 1999). Sivakumar and Singh (1987) reported that high temperatures from flowering to maturity of late-sown chickpea led to reduced seed size and lower yield.

Field Pea

Field pea is typically grown in the USA for livestock feed although some varieties are grown for human consumption. Only a few literature citations exist describing the yield response of field pea to available water (Table 1). Borstlap and Entz (1994) found a linear relationship between seed yield and evapotranspiration using yield and water use data from a 2-yr study in two locations in Manitoba, Canada. These authors also quoted Wilson et al. (1985) as saying that seed yield in field pea was closely related to seasonal evapotranspiration. McDonald (1995) reported a strong response of seed yield to growing season rainfall (Table 1) with yield increasing by 4.3 kg ha^{-1} for each additional millimeter increase in rainfall. Martín et al. (1994) cited previous experiments that showed a positive linear correlation between yield and precipitation for 13 field pea cultivars.

Baigorri et al. (1999) stated that pea seed yield was strongly dependent on water availability, especially at flowering and pod filling. Similarly, Martín et al. (1994) reported that water stress during the last half of the growing season (pollination and pod and seed formation periods) was a major factor in reducing seed yields in temperate dry areas.

There is some disparity in reported rooting depth of field pea. Frick (1995) found roots at soil depths of 102 to 114 cm. Borstlap and Entz (1994) found roots in their deepest sampling depth of 70 to 90 cm. Martín et al. (1994) reported that soil water in the 45- to 75-cm layer was not completely used by field pea. Heath and Heb-

Table 2. Cultural operations and observed plant development dates for chickpea, pea, and lentil, 1996–1999, Akron, CO.

Crop	Year	Planting date	Emergence date	Flowering date	Harvest date	Row spacing	Seeding rate
						m	kg ha^{-1}
Chickpea							
	1996	09 Apr.	30 Apr.	11 June	30 July–06 Aug.	0.25	168
	1997	19 Apr.	06 May	23 June	22–24 July	0.25	168
	1999	12 Apr.	16 May	16 June	11 Aug.	0.25	190
Pea							
	1998	06 Apr.	24 Apr.	10 June	02 July	0.19	202
	1999	31 Mar.	23 Apr.	08 June	09 July	0.19	202
Lentil							
	1997	19 Apr.	06 May	16 June	30 July	0.25	168
	1999	13 Apr.	05 May	09 June	28 July	0.25	168

blethwaite (1985) showed that the maximum water extraction depth for spring pea was about 70 cm.

Lentil

Lentil is a cool-season crop with moderate resistance to drought and high temperature. It is grown mainly for human consumption. Major production areas in North America are found in Saskatchewan, Alberta, Manitoba, Washington, and Idaho.

Silim et al. (1993) found strong linear relationships ($r^2 > 0.90$) between yield and moisture supply for 25 diverse lentil lines grown in northern Syria. The seed yield response ranged from 3.0 to 8.6 (mean of 6.1) kg ha^{-1} mm^{-1} (Table 1). Information from South Australia (PIRSA, 2000) states that yield of red lentil increases by 15 kg ha^{-1} for each additional millimeter of growing season rainfall. Sharma and Prasad (1984) reported that lentil seed yield increased with irrigation frequency and total water use. Yusuf et al. (1979) also found that lentil yield increased with irrigation and reported that the seedling and flowering stages were most sensitive to water availability.

Erskine et al. (1994) stated that lentil had poor tolerance for high temperatures, especially at flowering and pod set. However, recent studies by Turner et al. (1996) indicate that lentil has considerable potential for drought resistance through osmotic adjustment.

Both Sharma and Prasad (1984) and Silim et al. (1993) reported the 0- to 30-cm soil layer as the site of most water extraction by lentil. Sharma and Prasad (1984) found deepest water extraction in the 90- to 120-cm layer while Silim et al. (1993) reported water extraction from the 135- to 165-cm depth.

The objective of this study was to identify soil water extraction patterns and determine the production functions (yield vs. water use) for chickpea, field pea, and lentil. Those production functions were used with amounts of soil water extraction and the historical rainfall record to estimate potential yield variability and use of these crops in dryland rotations with winter wheat.

MATERIALS AND METHODS

Studies were conducted with chickpea (‘UC5’), field pea (‘Profi’), and lentil (‘Brewer’) during the 1996–1999 growing seasons at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO (40°09′ N, 103°09′ W; elevation of 1384 m). The soil is a Weld silt loam (fine, smectitic, mesic Aridic Argiustolls). Planting and harvest dates, seeding rates, and row-spacing details are given in Table 2. A new plot area was used each year of the study, and winter wheat was always the preceding crop. Before planting, the plot area was tilled twice with a sweep plow equipped with an applicator to apply granules of ethalfluralin [*N*-ethyl-*N*-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)benzenamine] at a rate of 1.1 to 1.7 kg ha^{-1} (depending on year) for weed control. Additional control was performed by hand weeding as necessary. Seeds were not innoculated, and the plot area was fertilized with 56 kg ha^{-1} N [as ammonium nitrate (NH_4NO_3)] before planting to eliminate N fertility as a variable.

Variable water availability conditions were created using a gradient line source solid-set irrigation system. The plot area for each crop was 24.4 by 61.0 m (Fig. 1). The center section of this area (12.2 by 24.4 m) was bordered by the irrigation lines. This section was uniformly irrigated when the lines were turned on (fully irrigated site). The irrigation system applied water to this area at the rate of 3.3 mm h^{-1}. On either side of the center section were the two gradient irrigation areas (gradient levels 1 and 2, each 6.1 by 24.4 m) where the water applications decreased as distance from the irrigation line increased. On the outside edges of the gradient irrigation areas were the rainfed plots (each 12.2 by 24.4 m), which received no irrigation. Four soil water measurement sites and irrigation catch gauges were established in each of the areas (i.e., four rainfed sites, four gradient-1 sites, four gradient-2 sites, and four fully irrigated sites). Irrigations were generally applied in the evening when wind speeds were low to minimize differences in water application across the two gradient irrigation areas.

Water use (evapotranspiration) was calculated by the water balance method using soil water measurements and assuming runoff and deep percolation were negligible (plot area slope was <0.5%, and amounts of growing season precipitation were generally small). Soil water measurements were made at planting and at harvest at each of the 16 sample sites using a neutron probe at soil depths of 15, 45, 75, 105, 135, and 165 cm.

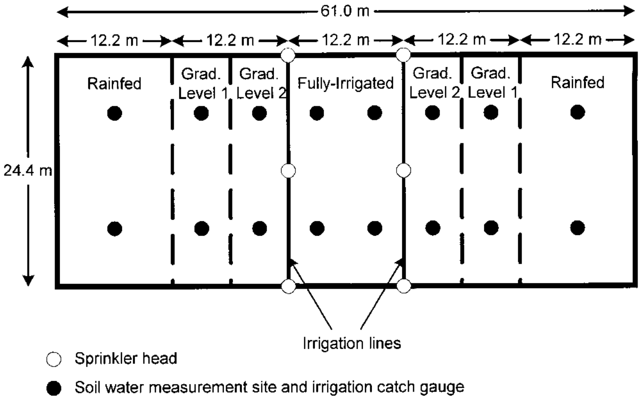

Fig. 1. Plot layout for water use–yield studies.

Table 3. Growing season precipitation and irrigation amounts (avg. by gradient position).

			Plot position				Growing season precipitation 1965–1999	
Crop	Year	Growing season precipitation	Rainfed	Gradient level 1	Gradient level 2	Fully irrigated	Avg.	Range
		mm						
Chickpea							253	146–412
	1996	270	0	–†	–	–		
	1997	143	0	36	62	93		
	1999	275	0	62	101	183		
Pea							193	82–358
	1998	31	0	59	95	148		
	1999	133	0	55	82	147		
Lentil							230	117–412
	1997	163	0	34	58	89		
	1999	175	0	66	102	175		

† Irrigation amounts not given for gradient levels 1 and 2 and fully irrigated in 1996 because crop was not harvested due to field difficulties.

At physiological maturity, samples were harvested and threshed with a small-plot combine. Sample area was 9.3 m^2, centered on each soil water measurement site.

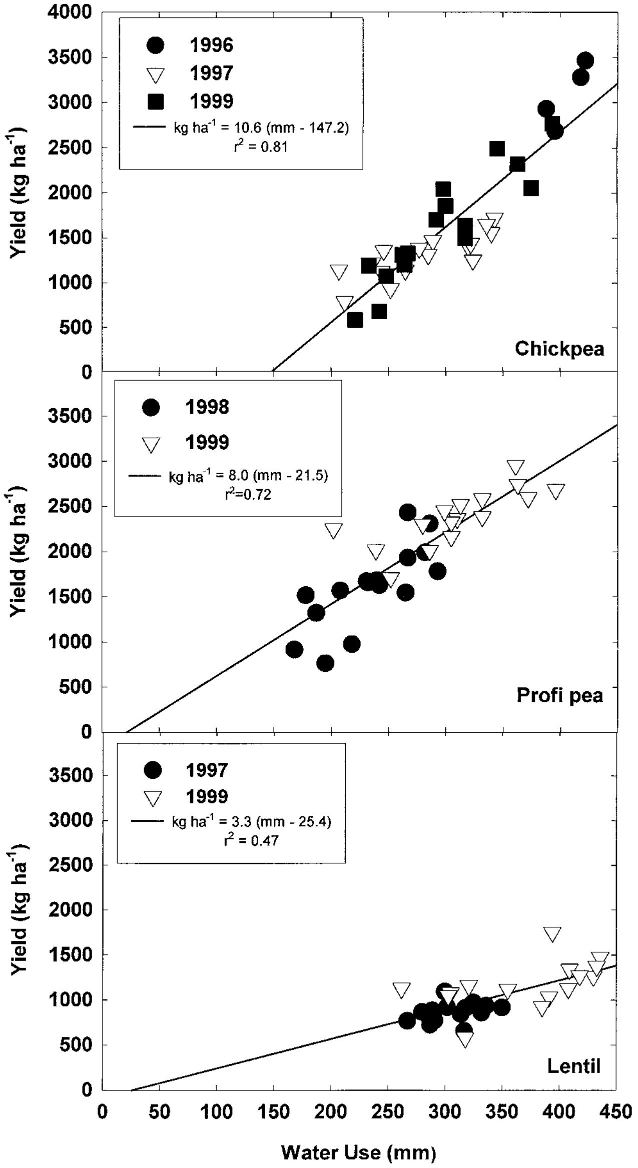

Fig. 2. Water use–yield production functions for chickpea, pea, and lentil.

Linear regressions were performed on all water use and yield data collected for each species to determine the production functions (yield vs. water use). These production functions were used with 35 yr of growing season precipitation data (1965–1999) from Akron and an assumed soil water extraction amount to obtain estimated yield histograms to evaluate yield variability due to precipitation variability. The assumed soil water extraction value was based on soil water extracted from the rainfed plots.

RESULTS AND DISCUSSION

Table 3 gives the growing season precipitation amounts and irrigation amounts (avg. across the four replicate sites at each irrigation level) for each crop by year. Also given are the mean and range of growing season precipitation for the 1965 to 1999 period. In 1997, only three irrigations were applied due to failure and delayed replacement of the irrigation controller. The large differences in growing season precipitation among the three species in 1999 were due to the differing harvest dates among the crops and rain at the end of July and during the first part of August.

All three crops showed linear increases in seed yield with increases in water use (Fig. 2). The strongest response ($r^2 = 0.81$) was noted for the chickpea relationship, whereas the weakest response ($r^2 = 0.47$) was seen for lentil. Only four data points were available for the 1996 chickpea (the rainfed plots) because of harvest problems in the other 12 plots. The combination of high growing season rainfall and lack of excessively high temperatures during the flowering and grain-filling periods resulted in these very high rainfed yields in 1996. Chickpea yields ranged from 600 to 3500 kg ha^{-1} with 220 to 420 mm of water use. Field pea yields ranged from 750 to 2850 kg ha^{-1} with 170 to 380 mm of water use. Lentil yields ranged from 750 to 1300 kg ha^{-1} with 270 to 430 mm of water use.

Chickpea gave the greatest response to increased water use (10.6 kg ha^{-1} for each millimeter increase in water use), and lentil responded the least (3.3 kg ha^{-1} for each millimeter increase in water use). Previously reported research from South Australia (PIRSA, 2000) suggests that the production functions for lentil and chickpea should be similar (Table 1). In fact, all of the previous literature indicated that lentil yield is more

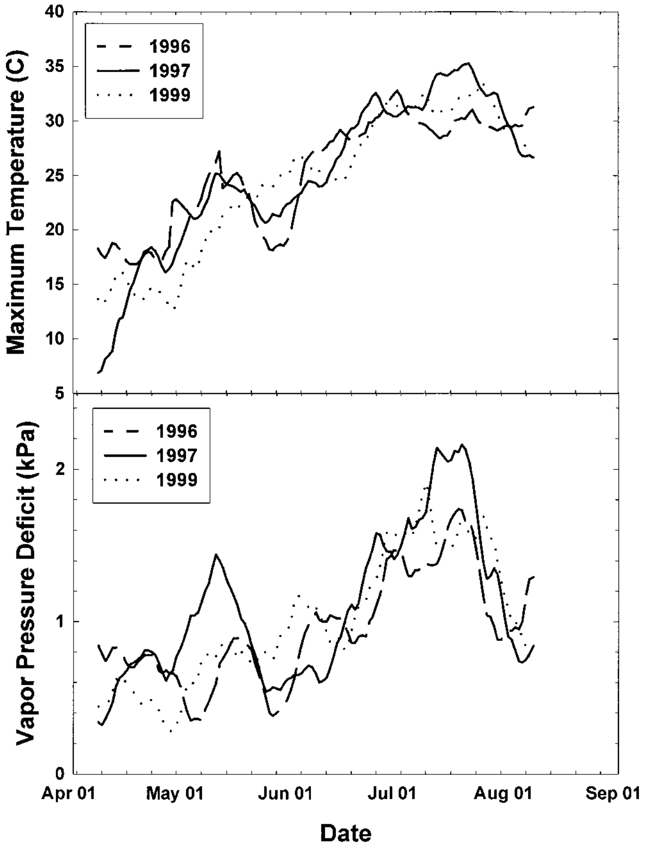

Fig. 3. Two-week running average daily maximum temperature and vapor pressure deficit at Akron, CO in 1996, 1997, and 1998.

responsive to water than was found in this study. The regression slopes for chickpea and pea were not significantly different, whereas the slopes of both chickpea and pea were significantly greater ($P < 0.05$) than lentil.

A deficiency with the data presented in Fig. 2 is the lack of data points at the lower end of the water use range. This is most noticeable for the lentil data where no values were recorded below 260 mm. Data points in the low yield–low water use range could greatly affect the regression slope and intercept when added to the data from 1997 and 1999.

The 1997 data for chickpea have a significantly different slope ($P < 0.001$) than the data from 1996 and 1999 although the 1997 data seem to be in a reasonable range of water use and yield to be consistent with the other years' data. A possible explanation for the apparent lower water use–yield response in 1997 may be higher temperatures and vapor pressure deficit during flowering, pod set, and seed development in that year (Fig. 3). Chickpea flowering began on 23 June 1999 (Table 2), much later than in the other 2 yr (11 June 1996 and 16 June 1999). During this critical period of flowering and pod and seed development, maximum daily temperatures and daily average vapor pressure deficits were noticeably higher in 1997 than in 1996 and 1999. In the 3-wk period following flowering, the number of days with maximum temperatures above 30°C was 9 in 1996, 14 in 1997, and 10 in 1999. This period of higher temperatures may have resulted in flower and pod abortion and shortening of the seed-filling period, resulting in lower yields in the 300- to 350-mm water use range in 1997.

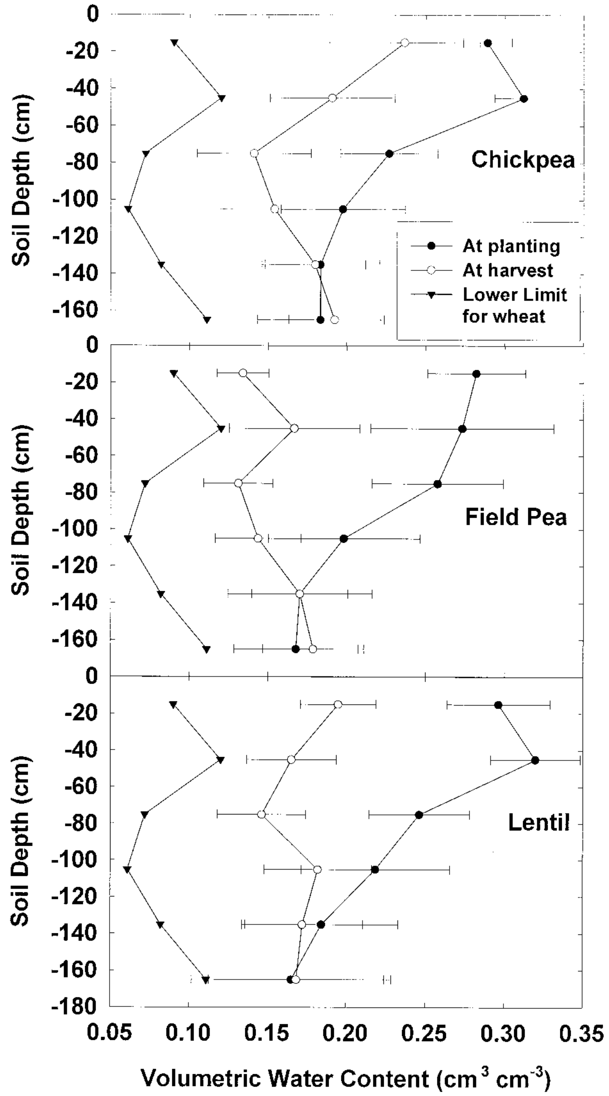

Fig. 4. Volumetric water content of rainfed plots (avg. across years) at planting and harvest for chickpea, field pea, and lentil; also, lower limit of volumetric water for winter wheat on Weld silt loam at Akron, CO. Bars are ± one standard deviation.

Beginning and ending volumetric soil water contents averaged over growing seasons are shown for the rainfed plots in Fig. 4. Significant differences between beginning and ending soil water contents were observed to a soil depth of 75 cm for all crops. All crops also showed water extraction at the 105-cm soil depth although the difference between beginning and ending water contents at this soil depth were not significant for any species (as determined by error bar overlap). The significantly higher ending water content for chickpea at the 15-cm depth compared with pea and lentil is probably the consequence of a large rainfall just before harvest in 1999, as opposed to any rooting differences among species. Ending water contents for pea and lentil in 1999 were taken before this heavy rainfall event. Ending water contents at lower depths did not differ significantly by species. Using the difference between begin-

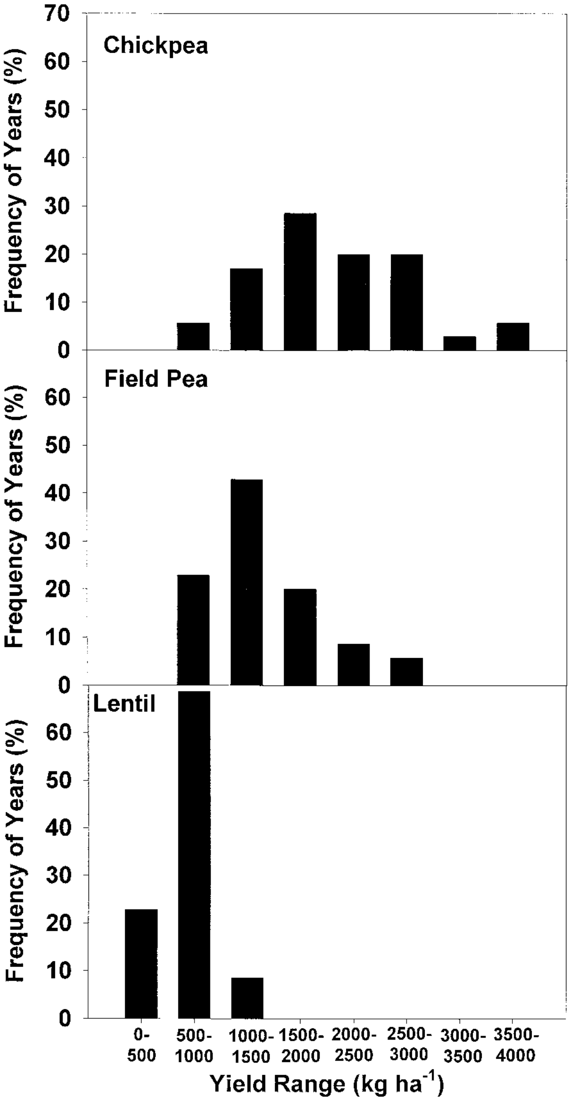

Fig. 5. Frequency distributions of chickpea, field pea, and lentil yields predicted from production functions, average soil water extraction, and historical precipitation records (1965–1999) from Akron, CO.

ning and ending soil water contents in the upper four soil depths gives average soil water use of 91 mm (SD = 15 mm) for chickpea, 131 mm (SD = 20 mm) for field pea, and 118 mm (SD = 13 mm) for lentil. The low value for chickpea is, in part, a consequence of the high rainfall before harvest in 1999.

The average soil water use values given above were used with the local precipitation record (1965–1999) to provide a range and distribution of water use values to use with the production functions shown in Fig. 2. These calculated water use values for chickpea and field pea all fall within the range of values used to establish the production function, except for the upper 9% of the chickpea values and upper 14% of the field pea values. Therefore, the yield histograms (Fig. 5) result from some linear extrapolation of the production functions slightly beyond the values used to generate them at the upper end. The data range for lentil water use and yield is smaller, and both the lower 9% and upper 14% of the water use values used to generate yield values lie outside of the data range used to establish the production function.

The distribution of predicted yields were somewhat different among the legumes due to differences in precipitation resulting from different lengths of growing seasons and from the slopes of the production functions. Chickpea, with the greatest slope, produced the greatest range in predicted yield (951 to 3782 kg ha^{-1}) with the highest frequency of occurrence (29%) in the 1500 to 2000 kg ha^{-1} category. The predicted mean chickpea yield was 2092 kg ha^{-1}. The yield range for field pea was narrower (523 to 2718 kg ha^{-1}) with the highest frequency of occurrence (43%) in the 1000 to 1500 kg ha^{-1} category. The predicted mean field pea yield was 1406 kg ha^{-1}. Lentil had the narrowest predicted yield range (286 to 1247 kg ha^{-1}) with the highest frequency of occurrence (67%) for the 500 to 1000 kg ha^{-1} category. The predicted mean lentil yield was 654 kg ha^{-1}. These yield distributions may be skewed somewhat towards higher frequency of high yields due to the use of a single value of soil water use for each legume and all precipitation conditions. Generally, as growing season precipitation increases, amount of existing soil water used declines.

One of the reasons for determining the potential productivity of these legumes was to assess their potential in rotations with winter wheat. While productivity of the legumes is an important consideration, equally important is successful establishment and productivity of the following winter wheat crop. Depending on the legume harvested, a period of 1 to 3 mo would elapse before planting winter wheat in mid to late September. An important consideration then is the amount of soil water remaining following the legume crop.

Using the lower limit of volumetric water content (Ritchie, 1981; Ratliff et al., 1983) as noted for winter wheat on this soil type (Nielsen et al., 1999) and shown in Fig. 4, the amount of available profile soil water remaining at legume harvest would be 144, 104, and 124 mm for chickpea, field pea, and lentil. These amounts of remaining soil water should allow the use of these legumes in rotation with winter wheat.

These legumes could be harvested successfully with a stripper header. The stripper header leaves greater amounts of standing residue than a conventional combine header equipped with a cutter bar. The additional standing residue would protect the soil surface from wind erosion, decrease soil surface evaporation, and increase the precipitation storage efficiency during the period between legume harvest and winter wheat planting (McMaster et al., 2000), thereby increasing the chances of successful stand establishment of winter wheat.

From an agronomic standpoint, considering the water use–yield relationships and soil water extraction patterns, all three legumes investigated in this study appear to have potential for use in dryland crop rotations ahead of winter wheat. Ultimately, the interaction of these agronomic findings with the economics of production and marketability of the crop produced will determine whether any of these three legumes find their way into dryland rotations of the central Great Plains.

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