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Dry bean water use/yield production function to estimate dryland yields in the U.S. Central High Plains

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ABSTRACT

Dry edible bean (*Phaseolus vulgaris* L.) could be used to diversify dryland rotational cropping systems in the U.S. Central High Plains. Dryland production potential of dry bean is undocumented in this region. The objectives of this study were to determine dry bean yield and water use under a range of water availability conditions in order to produce a water use-yield production function and to use that production function in conjunction with long-term precipitation records to estimate average yields and probabilities of attaining given yields. Dry bean was grown over a six-yr period at Akron, CO under a line-source gradient irrigation system to impose a range of water availability conditions. Seed yield was linearly correlated with water use resulting in a production function defined as seed yield (kg ha^{-1}) = 8.24 X (water use [mm] - 104). The slope was similar to another seed legume, field pea (*Pisum sativum* L.). This production function was used with the long-term precipitation record to determine an average dry bean yield of 1192 kg ha^{-1} (range 359–2514 kg ha^{-1}). These yield estimates were used to create a cumulative probability exceedance graph of yield that can be used to assess production risk as farmers consider the possibility of including dry bean as a component of a dryland crop rotation.

1. Introduction

Dryland farmers in the U.S. Central High Plains region of the United States could diversify the traditional winter wheat (*Triticum aestivum* L.)-fallow cropping system if they had information about the productivity of potential crops. One such crop is dry bean. It is traditionally grown in this region as an irrigated crop. A water use-yield production function would be a useful tool to help farmers assess the potential productivity of dry bean grown under dryland conditions and to assess risk involved in using dry bean as a rotation crop.

Yonts (2006) reported that irrigated dry bean uses 381 to 405 mm of water during the growing season in western Nebraska, but he did not present any corresponding yield data. Yonts et al. (2018) reported a 6-yr average Great Northern dry bean crop water use value (as estimated by the High Plains Regional Climate Center; https://hprcc.unl.edu/) of 379 mm (ranging from 362 to 432 mm) under non-water-stressed conditions in western Nebraska. Non-water-stressed dry bean yield from their study averaged 3555 kg ha^{-1}, while rainfed yields averaged 1013 kg ha^{-1} over the six years of the study. However, they did not present water use data that could be used to construct a water use-yield production function. The yield, irrigation, and precipitation data they presented did allow us to estimate that the average response of dry bean yield to water availability in their western Nebraska environment was approximately 10.7 kg ha^{-1} for each additional mm of water availability. Miller and Burke (1983) presented dry bean yield and irrigation amount data from two years on a sandy soil in south-central Washington from which yield responses of 16.2 and 17.4 kg ha^{-1} per mm of applied irrigation were calculated.

Muñoz-Perea et al. (2007) provided two years (2003, 2004) of water use and yield data for six dry bean varieties grown in south-central Idaho. A production function constructed from these data varied between the two years, but in both years seed yield increased at a rate of 5.4 kg ha^{-1} per mm of water use. However, for any given water use, yields in 2004 were approximately double what they were in 2003 due to the more stressful environmental conditions in 2003 (much greater evaporative demand and warmer temperatures). They cited Masaya and White (1991) who showed that temperatures greater than 28 °C caused excessive flower drop, a reduction in pollen viability, and abortion of fertilized ovules. Likewise, Prasad et al. (2002), Laing et al. (1984), and Gross and Kigel (1994) demonstrated that maximum air temperatures greater than 31 °C could reduce pollen production per flower, seed size, pollen viability, anther dehiscence, and pollen tube growth. Omae et al. (2012) reviewed a number of previously conducted studies that demonstrated that dry bean yields were greatly reduced when daily maximum temperatures were 32–35 °C during the reproductive growth stage. A field bean production guide from Manitoba, Canada, states that temperatures greater than 30 °C can cause flower blasting (dropping of buds and flowers, https://www.gov.mb.ca/agriculture/crops/production/print,field-beans.html)

Nielsen and Nelson (1998) showed that black bean seed yield was most sensitive to water stress during the reproductive growth stage and concluded that high temperatures and high evaporative demand during

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the growing season could lower seed yields. In that two-yr controlled rainout shelter study, where water availability from available soil water and applied irrigation were the same in both years, seed yields were 28% lower in the year with 33 days of maximum temperature greater than 35 °C than in the year with only 4 days of maximum temperature greater than 35 °C. Also in that study, water use efficiency ranged from 2.3 to 8.7 kg ha^{-1} mm^{-1}, with the lowest value occurring when irrigation was withheld during the reproductive growth stage.

Lyon et al. (1995) presented dry bean (pinto) water use and yield data for two years from western Nebraska, but did not calculate a water use/yield production function. They did however show that dry bean seed yield was strongly correlated with soil water at planting. The responses differed between years, with one year having seed yield increase at a rate of 10.3 kg ha^{-1} per mm of additional soil water at planting and the other year having a response of 17.9 kg ha^{-1} mm^{-1}. Water use/yield production functions constructed from the tabulated data in their paper resulted in two very different production function slopes (3.7 kg ha^{-1} per mm of water use in the first year of the study and 24.4 kg ha^{-1} per mm of water use in the second year of the study).

In the classic water requirement study of Briggs and Shantz (1914), they measured the water requirement of two species of *Phaseolus vulgaris* L. based on one year of water use and seed yield data from a study at Akron, CO in which plants were grown in above-ground lysimeters with a soil volume of about 85 L. The average water requirement of the two species was 1767 g of water to produce one g of seed. This value converts to a water use efficiency of 5.72 kg ha^{-1} per mm of water use. In the evaluation of dry bean water use efficiency under fully irrigated and limited irrigation conditions in Idaho that was cited earlier, Muñoz-Perea et al. (2007) reported water use ranging from 318 to 548 mm under non-water-stressed conditions and from 248 to 338 mm under intermittent drought stressed conditions. The water use efficiencies in that study ranged from 3.4 to 10.9 kg ha^{-1} mm^{-1} (average 6.84 kg ha^{-1} mm^{-1}) under non-water-stressed conditions and from 1.1 to 10.4 kg ha^{-1} mm^{-1} (average 6.03 kg ha^{-1} mm^{-1}) under the intermittent drought stressed conditions. Soil water extraction was reported to be generally from the 0–100 cm soil profile.

Al-Kaisi et al. (1999) reported dry bean water extraction in southwestern Colorado occurred in the 0–30 cm soil profile under non-water-stress conditions and in the 0–60 cm layer under drought stressed conditions. However, Nielsen and Nelson reported black bean water use on a silt loam soil in northeast Colorado occurring from the entire 0–180 cm measured soil profile when available soil water at planting was about 80% of field capacity and growing season conditions were above average in temperature and evaporative demand. Actual root observations of dry bean in North Dakota (Merrill et al., 2002) indicated a median root length of 50 cm and a maximum rooting depth of 100 cm.

While water use/yield production functions for dry bean have not been previously published, such a production function suitable to the climate conditions of the U.S. Central High Plains should be close to the function previously published for field pea by Nielsen (2001) with a slope of 8.00 kg ha^{-1} per mm of water use and with a water use offset of 22 mm since both field pea and dry bean are non-oilseed legumes. Previously published water use/yield production functions provided by Nielsen et al. (2011) showed slopes of oilseeds < seed legumes < C3 grains < C4 grains due to the greater photosynthetic costs of producing oil compared with protein and starch (Nielsen et al., 2005) and the more efficient photosynthetic pathway of C4 plants compared with C3 plants (Kellogg, 2013). The objectives of this study were to determine dry bean yield and water use under a range of water availability conditions in order to produce a water use-yield production function, and to use that production function in conjunction with long-term precipitation records to estimate average yields and probabilities of attaining given yields.

Table 1
Dry bean varieties planting dates, seeding rates, harvest dates and harvest areas at Akron, CO (1993–1998).

Year	Variety	Planting Date	Seeding Rate Seeds/ha	Harvest Date	Harvest Area m^2
1993	‘Midnight’	14 June	215,200	16 Sep	6.10
1994	‘Midnight’	6 June	215,200	2, 6 Sep	6.20
1995	‘Midnight’	28 June[a]	195,600	28 Sep	3.41
1995	‘Othello’	28 June	195,600	28 Sep	3.41
1996	‘Othello’	5 June	84,700	26 Aug	13.94
1997	‘Othello’	6 June	84,700	4 Sep	13.94
1998	‘Fisher’	28 May	84,700	4-10 Sep	13.94

[a] The delayed planting date in 1995 was due to frequent precipitation events totaling 176 mm from 15 May to 21 June.

2. Materials and methods

This study was conducted during the 1993–1998 growing seasons at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO (40°09′ N, 103°09′ W, 1384 m). The soil type was a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll). Dry bean varieties, planting dates, seeding rates, harvest dates, and harvest areas for the seven data sets are shown in Table 1. Dry bean varieties ‘Othello’ and ‘Fisher’ were pinto beans (race Durango; Type 3; Burke et al., 1995; Fisher et al., 1995) and ‘Midnight’ was a black bean (race Mesoamerican; Type 2; Sutton and Coyne, 2007). Higher seeding rates were used for black bean production in 1993–1996 than for pinto beans in subsequent years because of lower germination percentage. Seeds were inoculated with an appropriate strain of rhizobium prior to planting. Additionally, the experimental area was fertilized with 56–87 kg N ha^{-1} to ensure no nitrogen deficiency was present. The experimental area was treated for weed control with recommended rates of either Sonalan (ethalfluralin:N-ethyl-N-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)benzenamine) or Treflan (trifluralin: a,a,a-trifluoro-2,6-dinitro-N, N-dipropyl-p-toluidine), lightly tilled for incorporation prior to planting.

Plots were established under a line-source gradient irrigation system (diagrammed and described in Nielsen, 2004) in which water application amount declined linearly with distance from the irrigation line. The experimental layout provided for four replications of four water treatments. Individual plot size was 6.1 m by 12.2 m. Row spacing was 51 cm in 1993 and 1994, 56 cm in 1995, and 76 cm in 1996–1998. Row direction was north-south. Irrigations were generally applied at approximately weekly intervals in the evening when wind speeds were low to minimize differences in water application due to shifts in the spray patterns. Water application amounts were aimed at maintaining the plot area between the two irrigation lines (highest water treatment) at nearly a non-water-stressed condition.

Water use was calculated for each plot by the water balance method using soil water measurements at planting and physiological maturity, and assuming runoff and deep percolation were negligible (a reasonable assumption as plot area slope was less than 0.5% and amounts of growing season precipitation were generally small). Irrigation amounts were recorded with catch gauges located in the center of each plot. Soil water measurements were made at planting and harvest in the center of each plot. The measurements were made at 30-cm intervals down the soil profile using a neutron probe (Model 503 Hydroprobe, CPN International, Martinez, CA). The depth intervals were 30–60 cm, 60–90 cm, 90–120 cm, 120–150 cm, and 150–180 cm, with the neutron probe source centered on each interval. Volumetric soil water in the 0–30 cm surface layer was determined using time-domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, CA) with 30 − cm waveguides installed vertically approximately 40 cm from the neutron probe measurement site to average the water content over the entire 30 − cm layer. The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Bulk density was determined from the dry weight of the soil cores (38 mm diameter by 300 mm length) taken from each depth at the time of neutron probe access tube installation.

Harvesting was done by hand-sampling areas surrounding the soil water measurement sites. These areas varied in size from year to year (6.2 m^2 to 18.6 m^2). Harvest samples were oven-dried for 72 h at 58 °C and were then threshed with a plot combine. Seed yields are reported at 0.14 kg kg^{-1} moisture content.

Hourly average and daily maximum air temperatures and daily average vapor pressure deficit were recorded by an automated weather station located about 300 m from the plot area. At this same weather station location, daily Class A pan evaporation was recorded. Daily precipitation amounts were measured in the plot area.

Averages of water use and seed yield were computed from the four replicate measurements at each of the four water gradient positions in each year. Seed yield was only available for the two lowest water use treatments for 1995 black bean due to stand establishment problems. Linear regressions of yield vs. water use were determined with Statistix 10 software (Analytical Software, Tallahassee, FL).

3. Results

3.1. Weather

The weather during the six years of the study varied in precipitation amount and timing, maximum air temperatures, and evaporative demand (Table 2). June, July, and August precipitation ranged from 105 mm (1994) to 215 mm (1996). The driest July/August period, the time of flowering and pod and seed development, occurred in 1995 (57 mm) and the wettest July/August period occurred in 1998 (160 mm). Evaporative demand ranged from 823 mm of pan evaporation (1993) to 1043 mm (1994). The coolest growing season occurred in 1993 with a mean 3-month maximum temperature of 28.2 °C and the warmest growing season occurred in 1994 with a mean 3-month maximum temperature of 32.1 °C. The year with the least number of days with a maximum temperature greater than 32 °C was 1993 (24 days) and the year with the most number of days with a maximum temperature greater than 32 °C was 1994 (50 days).

3.2. Water use/yield production function

Dry bean seed yield was linearly related to water use (Fig. 1, Table 3). The regression slopes ranged from −21.04 kg ha^{-1} per mm of water use (1996 ‘Othello’) to 10.97 kg ha^{-1} per mm of water use. Although the 1996 data set is anomalous because of the negative slope of the relationship over a fairly small water use range (294–313 mm), the four data points are in the same general region of the water use/yield data distribution as the points from the other six data sets. The four points from the 1997 ‘Othello’ data set define a relationship somewhat different from the other six data sets (greater yield for a given water use). These higher yields can be attributed to precipitation timing. August rainfall was greatest in 1997 (87 mm) with 55 mm coming during the August 4–6 period (corresponding to late flowering and early pod filling), a critical period for water stress effects on seed yield (Nielsen and Nelson, 1998). No other year had August precipitation comprising such a high percentage of June, July, and August precipitation (44%).

The three data sets for the ‘Midnight’ black bean collected in 1993–1995 provide a very uniform response of yield to water use, with a slope of 8.86 kg ha^{-1} per mm of water use and a water use offset of 151 mm. The coefficient of determination for this regression was 0.98. A regression using all seven of the data sets produced a production function with a slope of 6.99 kg ha^{-1} per mm of water use with an offset of 41 mm of water use. However, because the 1997 ‘Othello’ yields were higher for any given water use value than seen with the other data sets due to the fortuitous timing of August precipitation, it seems prudent to ignore this data set when choosing data for the determination of a production function that will conservatively estimate yields. The production function defined by all of the data collected excluding the 1997 ‘Othello’ data had a slope of 8.24 kg ha^{-1} per mm of

Table 2

Monthly (June, July, August) maximum temperature, number of days with maximum temperature greater than 32 C, vapor pressure deficit, precipitation, and pan evaporation at Akron, CO.1993–1998.

Year	Month	Maximum Temperature C	Number of Days with Tmax > 32 C	Vapor Pressure Deficit kPa	Precipitation mm	Pan Evaporation mm
1993	June	26.8	8	1.116	44	269
	July	29.4	9	1.098	122	311
	August	28.4	7	1.022	23	243
	Average or sum	28.2	24	1.078	189	823
1994	June	32.3	18	1.955	6	371
	July	31.6	15	1.417	69	341
	August	32.3	17	1.552	30	331
	Average or sum	32.1	50	1.634	105	1043
1995	June	25.2	4	0.779	125	239
	July	31.6	16	1.620	39	317
	August	34.3	26	1.969	18	318
	Average or sum	30.4	46	1.456	182	874
1996	June	28.2	4	1.002	63	284
	July	29.9	13	1.383	79	294
	August	29.4	8	0.949	73	284
	Average or sum	29.2	25	1.113	215	862
1997	June	28.1	8	1.044	79	291
	July	32.5	16	1.689	29	365
	August	29.3	12	1.116	87	249
	Average or sum	30.0	36	1.286	196	905
1998	June	27.1	9	1.319	9	369
	July	31.3	15	1.367	98	313
	August	30.9	13	1.397	62	290
	Average or sum	29.8	37	1.362	169	972

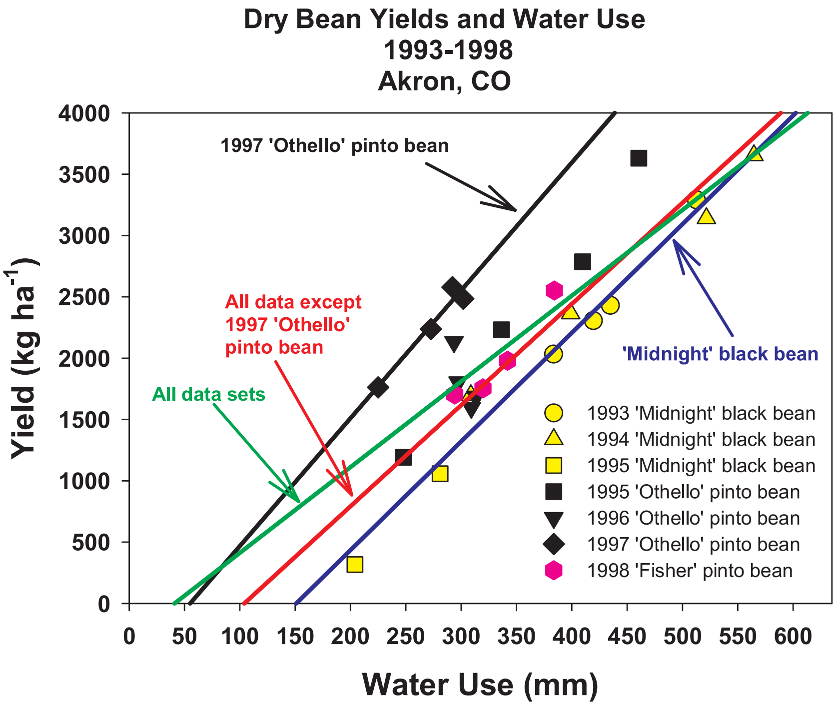


Fig. 1. Water use vs. seed yield for dry bean grown at Akron, CO (1993–1998). Yields reported at 0.014 kg kg^{-1} moisture content. Linear regression coefficients for the lines shown and other regressions are reported in Table 3.

Table 3
Linear regression slope, water use offset, and coefficient of determination values for dry bean water use and yield data collected at Akron, CO from 1993 to 1998. The linear regression has the form of Yield (kg ha^{-1}) = slope X (Water use [mm] - offset).

Data Set	Slope kgha^{-1}per mm	Offset mm	R^2
1993 ‘Midnight’ black bean	9.94	185	0.99
1994 ‘Midnight’ black bean	7.35	79	0.99
1995 ‘Midnight’ black bean	9.62	171	1.00
1995 ‘Othello’ pinto bean	10.97	139	0.98
1996 ‘Othello’ pinto bean	−21.04	389	0.71
1997 ‘Othello’ pinto bean	10.42	55	0.95
1998 ‘Fisher’ pinto bean	9.82	132	0.93
‘Midnight’ black bean 1993-1995	8.86	151	0.98
All sets except 1997 ‘Othello’ pinto bean	8.24	104	0.87
All data sets	6.99	41	0.71

water use with a water use offset of 104 mm and a coefficient of determination of 0.87 (Table 3).

Tanner and Sinclair (1983) pointed out that water use efficiency (basically the slope of the water use/yield production function) was influenced by vapor pressure deficit, with water use efficiency declining as vapor pressure deficit increased. Even though a single production function was determined the fit most of the data collected in this study, the data do show that the conclusion of Tanner and Sinclair (1983) is correct (Fig. 2). In general, production function slopes decreased as the average June, July, and August vapor pressure deficit increased.

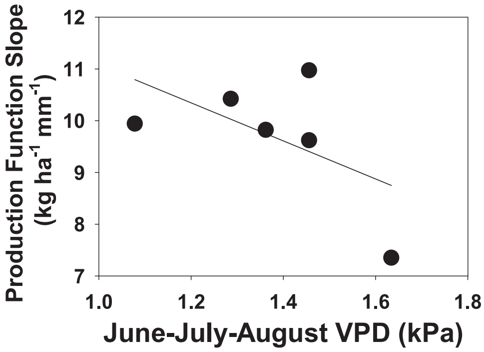


Fig. 2. Relationship between dry bean production function slope and average June, July, and August vapor pressure deficit at Akron, CO.

3.3. Estimated yields from precipitation record

The production function defined in this study (using all of the data sets except 1997) was used with the historical precipitation record at Akron (1908–2017) to estimate the distribution of estimated dry been seed yields. In order to do so, an estimate of soil water extraction by dry bean is needed. The average soil water extracted by dry bean varied by gradient position in the plot area, with water extraction of 108 mm for the rainfed plots (gradient position 1), 87 mm for gradient position 2, 59 mm for gradient position 3, and 40 mm for gradient position 4 (the wettest treatment). These soil water extraction results are in agreement with root observations reported by Benjamin and Nielsen (2006) that greater proportions of chickpea (*Cicer arietinum* L.) and field pea roots were found in deeper soil layers under non-irrigated conditions than under irrigated conditions. The growing season (9 June to 8 September) precipitation over the 1908–2017 period ranged from 40 mm to 369 mm (Supplemental Fig. 1). Since the soil water extraction appears to vary with growing season precipitation, the following soil water extraction values were arbitrarily chosen when estimating yields with the production function. For the 7.3% of the driest years (growing season precipitation less than 102 mm), 108 mm of soil water was assumed to be extracted. For years with growing season precipitation between 102 and 178 mm (53.6% of the 110 years), 87 mm of soil water was assumed to be extracted. For years with growing season precipitation between 178 and 254 mm (30.9% of the 110 years), 59 mm of soil water was assumed to be extracted, and for the wettest years (greater than 254 mm of growing season precipitation, 8.7% of the 110 years), 40 mm of soil water was assumed to be extracted. Using these values of soil water extraction with the 110 years of growing

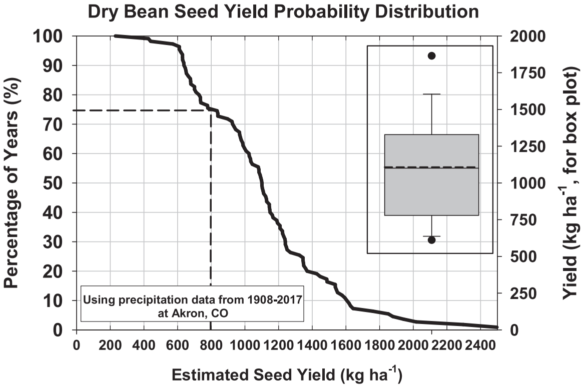


Fig. 3. Cumulative probability exceedance graph of dry bean yield at Akron, CO (1908–2017) using the production function, seed yield (kg ha^{-1}) = 8.24 X (water use [mm] - 104), where water use is the sum of growing season precipitation and average soil water extraction. Inset is a box plot of estimated seed yield where the solid line is the median yield, the dashed line is the mean yield, the bottom and top of the box are the 25th and 75th percentile yields, the bottom and top whiskers are the 10th and 90th percentile yields, and the bottom and top dots are the 5th and 95th percentile yields, respectively.

season precipitation data as estimates of water use in the production function, estimated seed yields ranged from 359 kg ha^{-1} to 2514 kg ha^{-1}, and averaged 1192 kg ha^{-1} (Fig. 3, inset box plot, dashed line). This average is about 18% greater than the six-yr average rainfed dry bean yield reported by Yonts et al. (2018) at Scottsbluff, NE (193 km northwest of Akron) of 1013 kg ha^{-1}. Fifty percent of the estimated seed yields fell between 878 (25th percentile) and 1402 kg ha^{-1} (75th percentile). The whiskers of the box plot indicate the 10th and 90th percentiles (747 and 1662 kg ha^{-1}).The dots indicate the 5th and 95th percentiles (723 and 1914 kg ha^{-1}).

Because of the close agreement between the estimated average yield in this study (1192 kg ha^{-1}) and the field-measured average yield of Yonts et al. (2018) (1013 kg ha^{-1}), these estimated yields can be confidently used in a cumulative probability exceedance graph of dry bean yield for Akron (Fig. 3). This figure can be used by farmers to assess the risk in producing dry bean in this region due to variability in growing season precipitation. For example, if a farmer had a yield goal of 800 kg ha^{-1}, Fig. 3 indicates that there is an 83% chance of obtaining at least that yield. As another example, there is a 50% chance of obtaining at least a yield of 1187 kg ha^{-1}. Of course, these yield expectations are based on yield response to water availability and assuming that to be the only factor that is affecting yield, whereas in reality timing of precipitation (Nielsen and Nelson, 1998), high temperature stress (Omae et al., 2012), plant stand, fertility, insects, diseases, weeds, shattering losses at harvest, etc. (Kandel, 2013) can potentially affect yield. In any case, Fig. 3 provides a good first estimate of the risk involved in producing acceptable yields of dry bean at Akron, CO based on growing season precipitation variability.

4. Discussion

In recent publications, Nielsen et al. (2017a,b) showed that there were numerous production functions for grain sorghum (*Sorghum bicolor* L. Moench) and proso millet (*Panicum miliaceum* L.), even for data that came from the same location. They acknowledged that the variability could arise from differences in growing season conditions, such as timing of precipitation, evaporative demand, extreme temperatures, seed shattering, etc. The 1997 'Othello' data set that produced greater yields for given water use amounts than the other data sets in this experiment appears to be such a case. The different production function for this data set compared with the other six data sets is likely attributable to very favorable timing of precipitation in early August.

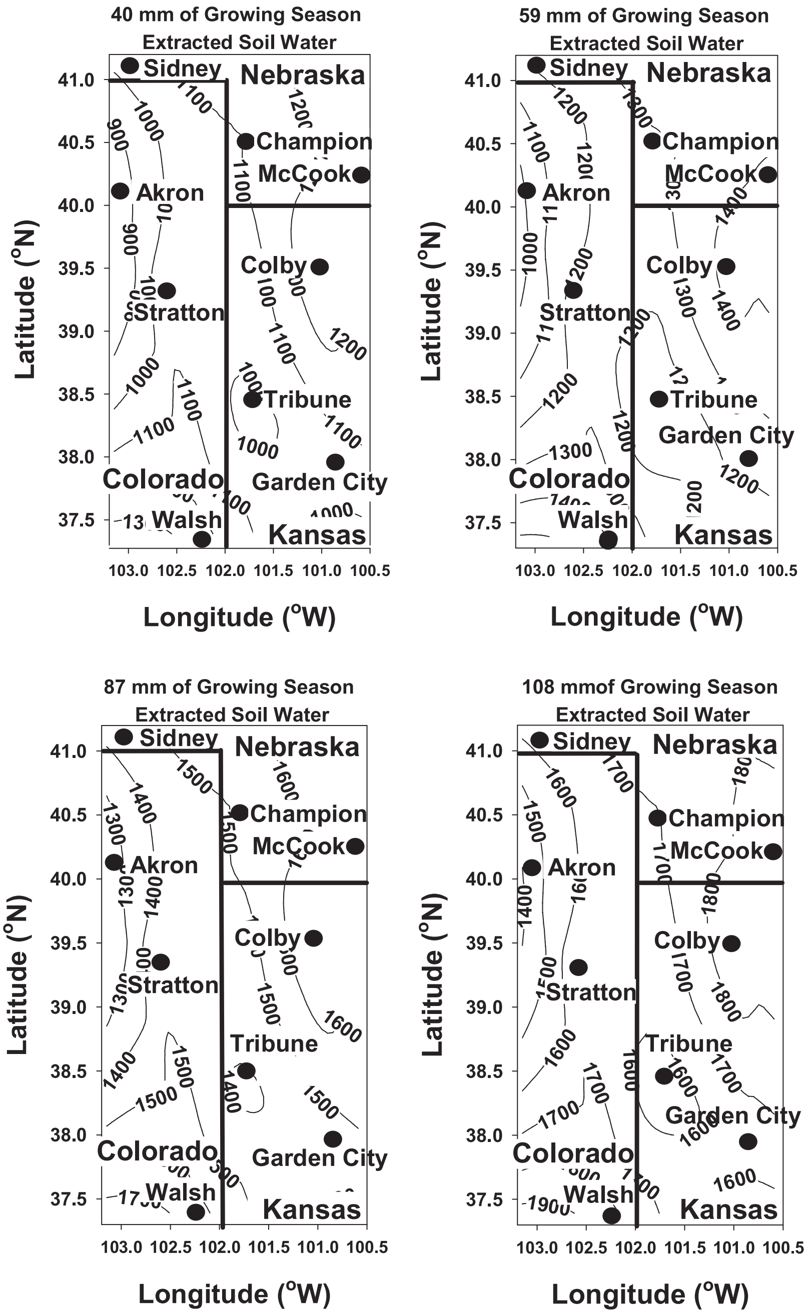
It appears that 1993 might be considered a low stress year because of low evaporative demand, moderate precipitation and relatively cooler temperatures, while 1994 was a much more stressful year because of high evaporative demand, very low growing season precipitation, and the warmest growing season temperatures (Table 2). The conditions in 1995 were intermediate to those two years. Yet the data points of yield vs water use for all three years appear to fall on nearly the same production function line (Fig. 1, Table 3). It is also interesting to note that, aside from the 1997 'Othello' data set, all of the other data sets are adequately represented by one production function, even though 'Othello' and 'Fisher' are Durango race dry beans and 'Midnight' is a Mesoamerican race dry bean with very different origins (Singh et al., 1991).

The slope of the production function defined in the current study for dry bean (8.24 kg ha^{-1} mm^{-1}) compares well with a previously defined production function for another seed legume (field pea) at Akron, CO (slope = 8.00 kg ha^{-1} mm^{-1}; Nielsen, 2001). The magnitude of the production function slope for dry bean also fits the expected order of slopes compared with previously published slopes obtained at Akron, where oilseeds < seed legumes < C3 grains < C4 grains. For example, previously published production function slopes for oilseeds were 7.73 kg ha^{-1} mm^{-1} for canola (*Brassica napus* L., Nielsen, 1998); 6.64 kg ha^{-1} mm^{-1} for sunflower (*Helianthus annuus* L., Nielsen, 1999); and 6.53 kg ha^{-1} mm^{-1} for soybean [*Glycine max* (L.) Merrill, Nielsen, 1990]. A previously published production function for a C3 grain (winter wheat) had a slope of 12.49 kg ha^{-1} mm^{-1} (Nielsen et al., 2011), while production function slopes for C4 grains were reported as 26.57, 30.2. and 32.57 kg ha^{-1} mm^{-1} for corn (*Zea mays* L., Nielsen et al., 2011), grain sorghum (Nielsen and Vigil, 2017a), and proso millet (Nielsen and Vigil, 2017b)

As stated earlier, there appear to be no other published production functions for dry bean. However, relationships constructed from previously published yield and water use, irrigation, or soil water data (as noted in the introduction of this paper) showed dry bean yields responding to available water at a rate varying from 3.7 to 24.4 kg ha^{-1} mm^{-1}. Such a large range in the reported response of dry bean yield to water availability would appear to argue against the productive use of a single water use/yield production function for dry bean, Yet this current study did find that such a single production function was applicable to data collected over several years varying in climatic conditions and over dry bean cultivars varying in origin, type, and market class.

Lyon et al. (1995) found that there was a strong correlation between dry bean yield in western Nebraska and soil water in the 0–120 cm profile at planting, arguing for using soil water contents at planting to estimate growing season yields and for making crop choice decisions. Contrary to the finding of Lyon et al. (1995), the data in the current study (Supplemental Fig. 2) did not strongly define a useable relationship between dry bean yield and available soil water at planting (calculated as amounts of available soil water in the 0–120 cm, 0–150 cm, and 0–180 cm soil profiles). It is not clear why different results were obtained at these two locations separated by only 112 km.

While there might be some uncertainty regarding the geographic transferability of the production function defined in this study, it is probably not too dangerous to assume its applicability to a restricted area of the U.S. Central High Plains in order to get an idea of the potential average dry bean yield grown under dryland conditions. Average growing season precipitation values (1981–2010, usclimatedata.com) for Akron, CO and eight other locations within 320 km of Akron were combined with four levels of extracted soil water to estimate dry bean water use across the region and used with the production function to estimate dry bean yields (Fig. 4). As expected, yields increased from west to east in response to the east-west precipitation gradient that is primarily due to the effect of the rain shadow of the Rocky Mountains (Nielsen, 2018). Assuming 40 mm of growing season soil water extraction leads to an estimated average dryland yield ranging from 915 kg ha^{-1} at Akron, CO to 1327 kg ha^{-1} at McCook, NE and Colby,


40 mm of Growing Season Extracted Soil Water

59 mm of Growing Season Extracted Soil Water

87 mm of Growing Season Extracted Soil Water

108 mmof Growing Season Extracted Soil Water

Fig. 4. Estimated average dry bean yield for Central High Plains locations in Colorado, Nebraska, and Kansas using the production function, seed yield (kg ha^{-1}) = 8.24 X (water use [mm] - 104), where water use is the sum of average (1981–2010) growing season precipitation and four levels of soil water extraction.

KS (Fig. 4, upper left panel). Assuming 108 mm of growing season soil water extraction leads to an estimated average dryland yield ranging from 1475 kg ha^{-1} at Akron, CO to 1887 kg ha^{-1} at McCook, NE and Colby, KS (Fig. 4, lower right panel).

A potential problem with these regional yield estimates that are based only upon the water use/yield relationships reported here is that they probably do not account for the increased heat stress effects on yield that are likely to reduce yields for the southern locations (Tribune, Walsh, Garden City). Yet, as noted earlier, evidence of that detrimental temperature effect was not observed in the data collected in this study in 1993, 1994, and 1995.

The production function could be useful for farmers who wish to estimate dry bean yields in order to make crop choice decisions prior to planting in flexible fallow or opportunity cropping systems (as described by Nielsen et al., 2011). A farmer could estimate growing season water use as the sum of an estimate of growing season precipitation and measured or estimated available soil water at planting and then use that value in the production function to get an estimate of the expected dry bean yield. For example, if the famer estimated that growing season precipitation at Akron would be 80% of normal (140 mm) and that there was 70 mm of available soil water at planting, then the estimated growing season water use would be 210 mm. The production function would predict a dry bean yield of 873 kg ha^{-1}. Then the farmer could decide if that yield would be profitable enough to justify the expense and risk of planting dry bean that year.

The production function could also be potentially useful in quantifying the effects of future climate change or increased climate variability on dry bean yield. Simulated precipitation records from future decades would be used to calculate likely future water use values to be used with the production function. As an example, if average growing season precipitation at Akron were to increase by 3% by 2050 (as reported by Kennedy, 2014), the production function would predict an expected increase in dry bean yield of 3 to 5%, depending on the soil water extracted. However, use of this technique fails to incorporate the detrimental effects on yield of the predicted greater temperatures that climate models generally predict for 2050. Hence, use of cropping systems models would be a better approach to use for determining effects of climate change on dry bean yield.

The production function defined in this study could be transferrable to other semi-arid environments around the world that have similar vapor pressure deficit conditions and similar timing of precipitation during the growing season. However, even for those semi-arid environments which differ in vapor pressure deficit and precipitation timing and amount, the production function defined in this study serves as a benchmark for comparison of other production functions locally determined at other locations around the world.

As stated earlier, Briggs and Shantz (1914) reported one year of seed yield and water use data for two dry bean species grown in 85 L lysimeters at Akron, CO. These values produced an average water use efficiency of 5.72 kg ha^{-1} mm^{-1}. Water use efficiency calculated for each data point shown in Fig. 1 resulted in an average value of 6.11 kg ha^{-1} mm^{-1} (range of 1.55 to 8.83 kg ha^{-1} mm^{-1}, Supplemental Table 1). This result would seem to support the conclusion of Tanner and Sinclair (1983) that it is unlikely that major improvements to WUE can be made through plant breeding. Therefore, even though the water use and yield data sets used in the current study to define a production function for dry bean are 20–25 years old, they are still likely valid for such a purpose today. However, readers should be aware that some authors disagree with Tanner and Sinclair (1983) and report that improvements in water use efficiency have occurred through plant breeding changes that better match phenology to prevailing climate, increase harvest index, and support increased plant populations (Richards et al., 1993; Basso and Ritchie, 2018). Yet even in 1993, Richards et al. (1993) stated that further major improvements to harvest index were not likely as that value approached its theoretical limit. Readers are cautioned to not extrapolate the use of the production function defined in this study to water use values greater than the data used to generate the production function (about 550 mm) as other factors may become limiting factors to yield.

5. Conclusions

As with many crops, dry bean exhibits a well-defined linear response of seed yield to water use with the magnitude of the slope of the response being similar to a previously reported slope for another seed legume, field pea. This linear relationship can be used as a production function to estimate dry bean seed yields. While there are many caveats associated with the use of production functions to estimate dry bean yields based on precipitation records, this method does provide a first approximation of the average dry bean yields, range of yields, and probabilities of achieving minimum specified yields in the U.S. Central High Plains, and can be used to assess risk in dryland dry bean production in this region.

Ultimately, whether dry bean is used successfully as an alternative dryland rotational crop in the U.S. Central High Plains depends upon the economic return produced for the farmer. The average yields estimated by the production function determined in this study can be used with costs of production to further quantify production risk.

Disclaimer

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2018.08.016.

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