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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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A B S T R A C T

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