Reprinted from *Crop Science*
Vol. 38, No. 2

Black Bean Sensitivity to Water Stress at Various Growth Stages

David C. Nielsen* and Nathan O. Nelson

ABSTRACT

Producers relying on the traditional central Great Plains cropping system of winter wheat (*Triticum aestivum* L.)-fallow could increase crop yield and resource sustainability by changing to more diverse crop rotations. Crops suited to the variable timing and amount of precipitation characteristic of this region need to be identified so that rotations can be diversified. This study was conducted to determine the effects of water deficit at various growth stages on leaf area index, plant height, yield components, soil water extraction pattern, and seasonal water use of black bean (*Phaseolus vulgaris* L.). The study was conducted during the 1995 and 1996 growing seasons near Akron, CO, on a Rago silt loam (fine, montmorillonitic, mesic Pachic Argiustoll). An automated rainout shelter was used to eliminate precipitation. Irrigation treatments consisted of withholding water at vegetative, reproductive, or grain-filling growth stages. All treatments received 18.3 cm of water during the growing season. Water stress during the vegetative growth stage produced the shortest plants with the least leaf area. Soil water extraction and total water use were also least when water was withheld during the vegetative stage. Seed yield was reduced because of reductions in pods per plant and/or seeds per pod when water stress occurred during the reproductive stage. Black bean appears to have potential as a dryland rotation crop in the central Great Plains when soil water profiles are near field capacity at planting and normal to above normal precipitation is expected.

THE TRADITIONAL dryland cropping system of the central Great Plains is winter wheat-fallow, in which one wheat crop is grown every 2 yr. The fallow period covers approximately 15 mo. in which two summers occur: (i) the summer immediately following winter wheat harvest in early July and (ii) the summer prior to fall-seeding of winter wheat in the following year. The wheat-fallow system came into practice in order to stabilize production, which was variable due to wide variations in annual precipitation. However, very little increase in soil water occurs during the second summer fallow period (1 July–15 September) prior to planting winter wheat (Haas and Willis, 1962). Recent studies have shown that more intense cropping systems (two crops in 3 yr, three crops in 4 yr, annual cropping) are possible when reduced tillage systems are used. These systems increase precipitation storage efficiency during non-crop periods (Halvorson and Reule, 1994; Peterson et al., 1994; Halvorson et al., 1994). Peterson et al. (1996) suggested that a more efficient and profitable way of using summer precipitation was to use a spring-planted crop in rotation with winter wheat instead of a summer fallow period.

Crop rotations employing diversity in plant water use, rooting pattern, and crop type (broadleaf vs. grass) generally show a "rotation effect", i.e., increased crop yields compared with monoculture. The rotation effect may arise from beneficial effects on soil moisture, microbes, nutrients, and structure, and from decreases in diseases, insects, weeds, and phytotoxic compounds (Bezdicek and Granatstein, 1989; Crookston et al., 1991).

Dry bean could be grown as a seed legume in dryland rotations with winter wheat to increase production diversity. However, dry bean is reported to be sensitive to water stress. Singh (1995) reported that water stress during flowering and grain filling reduced seed yield and seed weight and accelerated maturity of dry bean. Robins and Domingo (1956) showed that dry bean yields were reduced most when water stress occurred during flowering. Reductions in yield during flowering were the result of both fewer pods and seeds per pod. Water stress during grain filling reduced the average weight per seed. They also found that vegetative-stage water stress delayed flowering, while water stress during reproductive and grain-filling stages hastened plant development. Water stress during vegetative stages retarded root development as well as vegetative growth. Total number of pods and pod fresh weight of bush bean were significantly reduced by water stress occurring at preflowering, flowering, or post flowering (Dubetz and Mahalle, 1969). Reductions were greatest when water stress occurred during flowering. Miller and Burke (1983) found strong linear relationships between water applied during flowering and grain filling and dry bean yields on a sandy soil. Stoker (1974) reported that dry bean yield reductions came mainly through abscission of flowers and young pods. Yield was not affected by water stress during pod development. Similar results were found for navy bean by Gunton and Evenson (1980), but they stated that water stress during the vegetative stage was not very detrimental to seed yield if the crop was not stressed during flowering.

Precipitation timing and amounts in the central Great Plains exhibit wide year-to-year variation, producing variability in timing and severity of crop water stress. It is not uncommon for there to be periods of 4 to 5 wk during the growing season with virtually no precipitation. Dry bean production potential under dryland agricultural production systems needs to be evaluated with regard to this variable water availability. Preliminary screenings of several dry bean market classes at Akron, CO, indicated that black bean appeared to yield more than other market classes of dry bean under rainfed conditions. Therefore, the objective of this study was to determine effects of water deficit at three growth stages on leaf area index, plant height, yield components, soil water extraction pattern, and seasonal water use of black bean.

David C. Nielsen, USDA-ARS, Central Great Plains Res. Stn, P.O. Box 400, Akron, CO 80720; and Nathan O. Nelson, Dep. of Agronomy, 2004 Throckmorton Hall, Kansas State Univ., Manhattan, KS. Received 19 May 1997. *Corresponding author (dnielsen@lamar.colostate.edu).

Published in Crop Sci. 38:422–427 (1998).

Abbreviations: V, vegetative period; R, reproductive period; GF, grain-filling period.

Table 1. Irrigation treatments to determine effect of water stress timing on black bean production for 1995 and 1996 at Akron, CO.

Treatment	Water withheld during†	Water applied during	Number of irrigations	Weekly irrigation amount	Total water applied
				cm	
1	–	V, R, GF	14	1.31	18.3
2	GF	V, R	9	2.03	18.3
3	R	V, GF	10	1.83	18.3
4	V	R, GF	9	2.03	18.3

† V = vegetative stage, R = reproductive stage, GF = grain-filling stage.

MATERIALS AND METHODS

The study was conducted during the 1995 and 1996 growing seasons at the USDA Central Great Plains Research Station, 6.4 kilometers east of Akron, CO, (45°09′N, 103°09′W, 1384 m). The soil type is a Rago silt loam (fine, montmorillonitic, mesic Pachic Argiustoll).

Black bean (cv. Midnight) was planted in rows 61 cm apart on 1 June 1995 and 31 May 1996 into 12 small plots (2.75 by 2.66 m), each bordered by corrugated metal lawn edging. Seeding rate was 215 000 seeds ha^{-1} in 1995 and 646 000 seeds ha^{-1} in 1996. Following emergence in 1996, plant stands were thinned to 215 000 plants ha^{-1}. An automated rainout shelter covered the plots during precipitation events. Three replications of four water treatments were arranged in a randomized complete block design (Table 1). Prior to planting, all plots received 67 kg N ha^{-1} as ammonium nitrate. Pendimethalin [*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrolbenzenamine] was applied at a rate of 1.1 kg ai ha^{-1} and incorporated by tilling with a small garden tiller. No crop residues remained on the soil surface after planting. The rainout shelter plot area had been in canola (*Brassica napus* L.) production in 1994. Plots were pre-irrigated to bring the beginning soil water to approximately 27 cm of available water in the 1.8 m profile. The 14-wk growing season was divided into a 5-wk vegetative period (V), a 4-wk reproductive period (R), and a 5-wk grain-filling period (GF), as determined by observations of black bean development at Akron from previous years (D.C. Nielsen, unpublished data). The reproductive period began with the appearance of floral buds and ended with full length pods at lower nodes. Long-term average precipitation during the 14-wk growing season is 18.3 cm. All plots received this amount of water (applied in equal weekly amounts) over the growing season, but at different times (Table 1). The distribution of weekly precipitation (averaged from 1964–1996) is shown in Fig. 1. Total average amounts of precipitation during the vegetative, reproductive, and grain-filling periods are 7.3, 6.4, and 4.6 cm, respectively.

Water use (evapotranspiration) was calculated by the water balance method using soil water content measurements, assuming runoff and deep percolation were negligible. Soil water content in the 0- to 30-cm layer was measured by time-domain reflectometry. Soil water content at 45, 75, 105, 135, and 165 cm was measured in the center row of each plot with a neutron probe. Soil water measurements were made at planting and at the end of the reproductive and grain-filling stages in 1995, and at the end of the vegetative, reproductive, and grain-filling stages in 1996.

Crop height and leaf area were measured periodically during the growing season with the LAI-2000 Plant Canopy Analyzer (LI-COR, Inc., Lincoln, NE)[1]. Plots were hand-weeded as needed throughout the experiment. A three-row by 2-m (3.66 m^2) area around each neutron-probe access tube was hand-harvested on 13 Sept. and 3 Oct. 1995 and on 10, 11, and 18 Sept. 1996. Two harvest dates in 1995 and three harvest dates in 1996 were needed because of differences in maturity associated with the stress-timing treatments. Number of plants from the sample areas were counted at harvest. Individual pods were removed from the sampled plants and counted. Pods were threshed with a plot combine. The seed sample was weighed for plot yield and weight of 100 seeds was measured to obtain seed weight. Water use efficiency was calculated as the total seed yield divided by the total water used during the growing season.

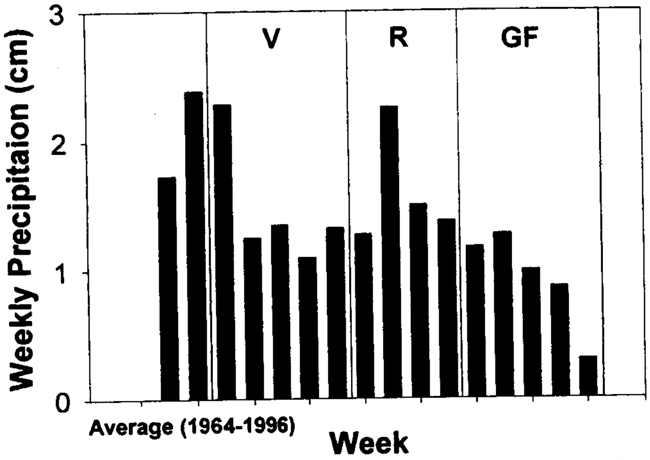

Fig. 1. Weekly precipitation at Akron, CO, during the bean growing season; averaged over 1964 to 1996. (V = vegetative, R = reproductive, GF = grain filling).

Analyses of variance were performed and analyzed as a randomized complete block design with the general AOV procedure of STATISTIX for Windows (Analytical Software, Tallahassee, FL). Treatment means and least significant differences (P = 0.05) are reported. The probability levels (P) of significant differences due to water stress treatments are reported. Where treatment differences in height and leaf area index were significant ($P \leq 0.05$), least significant difference bars are plotted on the figures.

Potential evapotranspiration was used to quantify differences in evaporative demand between the 2 yr of the study. We used the Penman-Monteith equation from the REF-ET computer program (Allen, 1990) to calculate potential evapotranspiration using daily maximum and minimum air temperature, daily average vapor pressure, daily total solar radiation, and daily average wind speed recorded by an automated weather station located next to the rainout shelter.

RESULTS AND DISCUSSION

Crop Height, Leaf Area Index, and Growth Stage

Water stress timing treatments produced statistically significant crop height differences (Fig. 2). In both years, Trt. 2 (water withheld during grain filling) produced the tallest plants, and Trt. 4 (water withheld during vegetative growth) produced the shortest plants.

Leaf area development during the growing season differed between years and with water stress treatment (Fig. 3). Leaf area development was less in 1995 than in 1996, with a maximum leaf area index of 1.92 m^2 m^{-2} for Trt. 2 in 1995 compared with 3.66 m^2 m^{-2} for Trt. 2

---

[1] Trade names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors, the USDA, or Kansas State University.

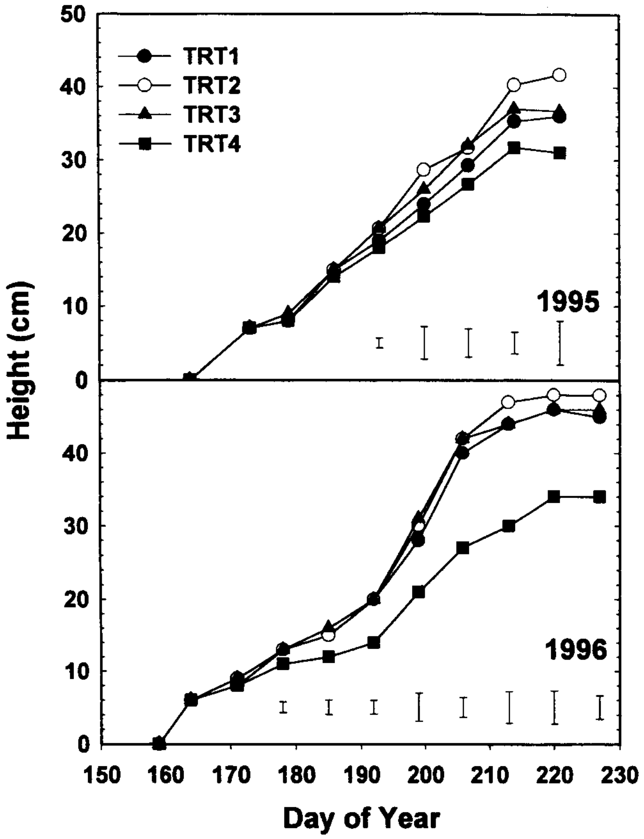

Fig. 2. Height of black bean plants as influenced by water stress timing [bars are LSD(0.05) where analysis of variance indicated significant treatment differences]. TRT1 = no single-period water stress; TRT2 = water withheld during grain-filling stage; TRT3 = water withheld during reproductive stage; TRT4 = water withheld during vegetative stage.

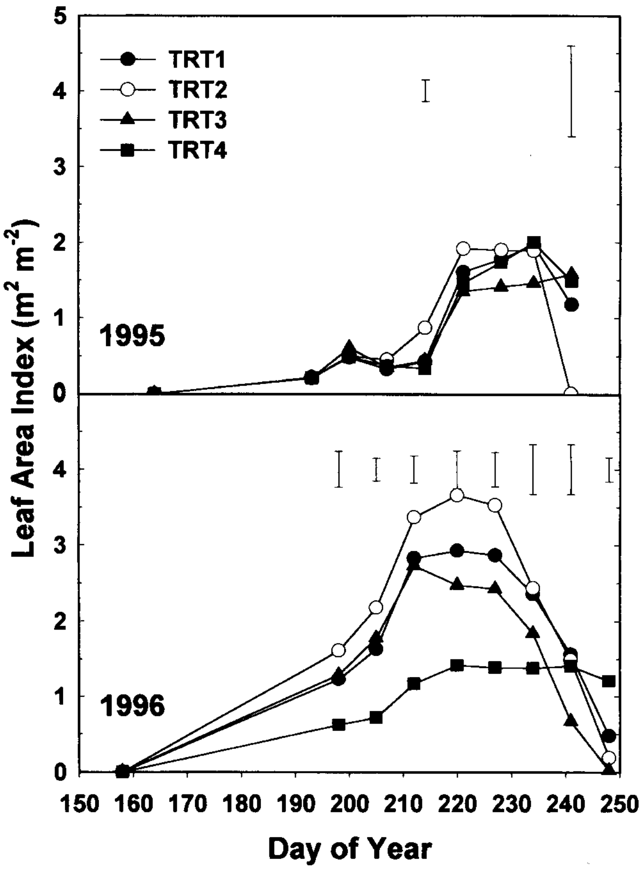

Fig. 3. Leaf area index of black bean plants as influenced by water stress timing [bars are LSD(0.05) where analysis of variance indicated significant treatment differences]. TRT1 = no single-period water stress; TRT2 = water withheld during grain-filling stage; TRT3 = water withheld during reproductive stage; TRT4 = water withheld during vegetative stage.

in 1996. This difference is probably a result of the greater water stress in 1995 due to the greater evaporative demand (Fig. 4). Potential evapotranspiration was nearly the same in both years during the vegetative stage, but 32% greater in 1995 than 1996 during the reproductive stage, and 24% greater in 1995 than 1996 during the grain-filling stage. Thirty-three days in 1995 had maximum temperatures greater than 35°C, compared with only 4 d in 1996 (average from 1987 to 1996 is 17 d).

Leaf area development during 1995 differed among treatments at only two dates. At Day of Year 214, Trt. 2 had greater leaf area than the other treatments due to the greater application of water during the vegetative and reproductive stages. At the end of 1995, Trt. 2, which received no water during the grain-filling stage and lost leaf area more rapidly than the other treatments, had significantly less leaf area than the other treatments. During 1996, water stress timing induced differences in leaf area index, with the largest differences appearing between Trt. 2 and Trt. 4. Treatment 4 had no water application during the vegetative stage, and leaf area index was reduced compared with the other treatments. Recovery of leaf area index did not occur later as watering resumed during the reproductive and grain-filling stages, but the three other treatments lost leaf area more quickly at the end of the growing season. Retention of leaf area index in Trt. 4 toward the end of the season relates to an observed delay in maturity. Treatments 1 and 3 had similar leaf area index for all of the growing season except the second to the last measurement, when Trt. 3 was losing leaf area faster than Trt. 1. Gunton and Evenson (1980) observed reductions in dry bean leaf area index with water stress imposed during vegetative growth. They noted some recovery of leaf area development when irrigations were subsequently applied during flowering and grain filling.

Crop development did not differ among water treatments. The main difference in both years was the continued flowering and podding of plants in Trt. 4 when plants in the other treatments were showing pods and seeds at full development. Consequently, at harvest, Trt. 4 had many more green, immature pods than the other treatments. The immature pods did not thresh, so there was no lowering of seed quality due to green seed.

Crop Water Use

Evapotranspiration (Table 2) was significantly affected by water stress treatments both years at each growth stage (vegetative and reproductive evapotranspiration combined in 1995 because of no soil water reading taken at end of vegetative stage). In both years, evapotranspiration during the vegetative and reproduc-

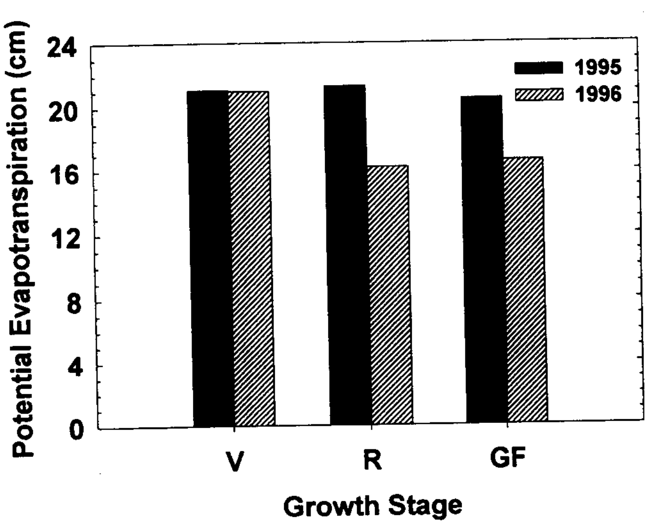

Fig. 4. Penman-Monteith potential evapotranspiration (a measure of evaporative demand) during black bean growing season at Akron, CO. (V = vegetative, R = reproductive, GF = grain filling).

tive growth stages was greatest for Trt. 2 and least for Trt. 4, following the pattern of water application. During the grain-filling stage, evapotranspiration was least for Trt. 2, which received no water during that growth stage. Total water use in both years was least for Trt. 4, possibly a result of the leaf area reduction (in 1996) or restricted root development and soil water extraction (in 1995 and 1996) due to water stress during the vegetative growth stage. Evapotranspiration was 41% greater in 1995 than in 1996 due to the higher evaporative demand, previously noted in Fig. 4.

Significant treatment differences in soil water extraction (differences between beginning and ending soil water content) were found in only the top soil layer (0–30 cm) in both 1995 ($P = 0.001$) and 1996 ($P = 0.004$) (Fig. 5). Treatment 2 showed greater extraction in the 0- to 30-cm layer because of withholding of water application during the last 5 wk of growth. Although water extraction did not differ at the other soil depths in either year, the total water extracted from the profile was least in Trt. 4 in both years (1995, $P = 0.013$; 1996, $P = 0.034$).

Yield, Yield Components, and Water Use Efficiency

Seed yield and all the yield components (except pods per plant in 1995 and seeds per pod in 1996) showed significant treatment effects (Table 3). In 1995, the greatest yield was obtained when water was withheld during the vegetative stage (Trt. 4) or when there was no long period of water stress (Trt. 1). Lowest yields were seen when water was withheld during the reproductive (Trt. 3) or grain-filling (Trt. 2) stages. Treatment 3 had the fewest pods per plant and seeds per pod. Water stress during grain filling (Trt. 2) reduced seed weight in 1995.

In 1996, not withholding water (Trt. 1) and withholding water during the grain-filling stage (Trt. 2) produced the greatest seed yield, while Trt. 3 again had the least seed yield and the fewest pods per plant. Number of

Table 2. Black bean evapotranspiration by development stages for 1995 and 1996 at Akron, CO.

Treatment	Water withheld during†	Evapotranspiration for Growth Stage Period		
		V + R	GF	Total
		cm		
1995				
1	–	30.7	14.8	45.5
2	GF	36.1	8.9	45.0
3	R	28.8	15.9	44.7
4	V	27.1	14.6	41.7
P‡		0.000	0.002	0.011
LSD(0.05)		1.7	2.5	2.0

		Evapotranspiration for Growth Stage Period			
		V	R	GF	Total
		cm			
1996					
1	–	9.7	14.4	7.6	31.7
2	GF	14.1	15.4	5.7	35.2
3	R	13.2	11.3	7.4	31.9
4	V	3.5	10.8	12.2	26.5
P		0.000	0.026	0.000	0.053
LSD(0.05)		3.9	3.1	1.1	5.7

† V = vegetative stage, R = reproductive stage, GF = grain-filling stage.
‡ *P* = probability level of significant differences due to water stress treatments.

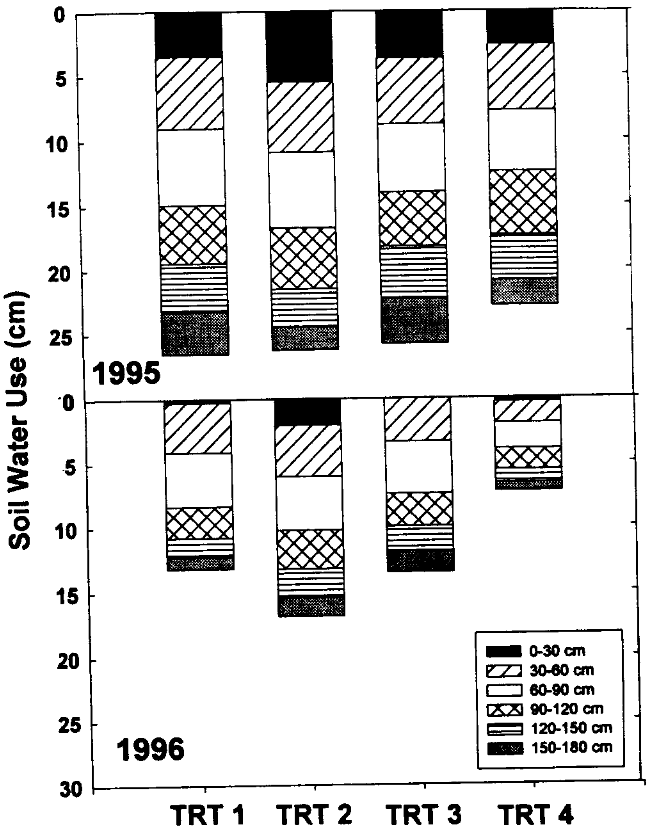

Fig. 5. Soil water use by depth for black bean as influenced by water stress timing. TRT1 = no single-period water stress; TRT2 = water withheld during grain-filling stage; TRT3 = water withheld during reproductive stage; TRT4 = water withheld during vegetative stage.

Table 3. Seed yield, yield components, water use, and water use efficiency for black bean for 1995 and 1996 at Akron, CO.

Treatment	Water withheld during†	Population	Pods plant^{-1}	Seeds pod^{-1}	Seed wt	Seed yield§	Water use	Water use efficiency
		plants ha^{-1}			mg	kg ha^{-1}	cm	kg ha^{-1} cm^{-1}
1997								
1	–	176 700	20.3	3.1	182.6	1 975	45.5	43.4
2	GF	160 300	15.4	3.1	156.1	1 280	45.0	28.4
3	R	158 500	12.5	2.4	219.2	1 035	44.7	23.2
4	V	154 800	19.4	3.4	188.3	2 511	41.7	60.2
P‡		0.5757	0.2190	0.0030	0.000	0.009	0.011	0.005
LSD(0.05)		39 500	8.9	0.4	13.9	719	2.00	16.2
1996								
1	–	196 700	14.6	4.2	203.9	2 758	31.7	87.2
2	GF	202 200	14.5	4.4	186.7	2 672	35.2	76.5
3	R	202 200	12.1	3.8	180.2	1 881	31.9	59.2
4	V	176 700	15.1	3.5	215.2	2 197	26.5	83.3
P		0.0494	0.0154	0.0763	0.0030	0.0012	0.053	0.0101
LSD(0.05)		19 200	1.6	0.7	13.9	303	5.74	13.7

† V = vegetative stage, R = reproductive stage, GF = grain-filling stage.
‡ *P* = probability level of significant differences due to water stress treatments.
§ Yield reported at moisture content of 0.14 kg H_2O/kg dry matter.

seeds per pod was not significantly affected by water stress timing. Water stress during grain filling (Trt. 2) and reproductive development (Trt. 3) reduced seed weight. The yield component with the highest correlation to seed yield was number of pods per plant in 1995 and number of seeds per pod in 1996 (Table 4). Lyon et al. (1995) found both seed number and seed weight of dry bean to be positively correlated with grain yield. Evapotranspiration during the reproductive stage in 1996 was significantly correlated with seed yield.

Seed yields averaged across all water stress timing treatments were much lower in 1995 than in 1996. This was probably a result of the much greater water stress in 1995 due to the higher temperatures and greater demand for water, as previously noted. Turk et al. (1980) similarly found seed yield of cowpea was negatively correlated with high temperatures during the 30 d after the appearance of floral buds.

Water use efficiency was significantly affected by water treatment, with water stress during reproductive development (Trt. 3) having the lowest water use efficiency. Water use efficiencies for Treatments 1, 2, and 4 were not significantly different from one another in 1996, with average values ranging from 70 to 90 kg ha^{-1} cm^{-1} water use. Withholding water during the reproductive stage (Trt. 3) significantly reduced water use efficiency. Water use efficiencies for the four treatments were much lower in 1995 due to the additional stress associated with the higher temperatures and evaporative demand.

CONCLUSIONS

The data in this study show black bean yields to be most sensitive to water stress during the reproductive growth stage, and plant height and leaf area to be most sensitive to water stress during the vegetative growth stage. High temperatures and high evaporative demand during the growing season may also lower seed yields. Black bean extracts water from soil depths down to 180 cm, with more water extracted when evaporative demand is high, and lower soil water use when vegetative period water stress limits leaf area development. Periods of limited rainfall during the flowering stage will significantly reduce yields. Analysis of the precipitation record for 1964 to 1996 for Akron, CO, indicates that reproductive stage precipitation (23 July–19 August) ranged from 1.2 to 14.8 cm. Fifty-five percent of the years of record had greater than 5.2 cm of precipitation (the amount received by Trt. 1) during the reproductive period. Twent-nine percent of the years of record had greater than 8.1 cm of precipitation (the amount received by Trt. 2 and Trt. 4) during the reproductive period. Moving the planting date ahead 2 wk would increase the average seasonal precipitation from 18.3 to 21.2 cm (Fig. 1), which could potentially increase yield. However, the increase in precipitation comes early in the season, which would likely result in more vegetative growth and greater depletion of stored soil water prior to the more critical reproductive growth stage. Earlier planting only slightly changes the average precipitation during the reproductive stage (from 6.4–5.9 cm). Conse-

Table 4. Correlation (and *P*† values) of yield components and water use with yield for black bean.

Year	Population	Pods plant^{-1}	Seeds pod^{-1}	Seed wt	Vegetative water use	Reproductive water use	Grain-filling water use	Total water use
1995 yield	0.28 (0.383)	0.85 (0.001)	0.78 (0.003)	−0.12 (0.710)	NA‡ (NA)	NA (NA)	0.20 (0.532)	−0.33 (0.299)
1996 yield	0.05 (0.888)	0.65 (0.023)	0.73 (0.008)	0.12 (0.707)	−0.16 (0.630)	0.79 (0.002)	−0.32 (0.309)	0.41 (0.191)

† *P* = probability level of significant differences due to water stress treatments.
‡ NA = not available.

quently, there may be little benefit to yield with earlier planting. Black bean appears to have potential as a dryland rotation crop in the central Great Plains when soil water profiles are near field capacity and normal to above normal precipitation is expected.

ACKNOWLEDGMENTS

The authors express their appreciation to A. Figueroa, K. Couch, M. Harms, C. Kuntz, K. Lindahl, A. Page, H. Lagae, D. Webb, and D. Scott for assistance with plot preparation and data collection.

REFERENCES

Allen, R.G. 1990. REF-ET. Reference evapotranspiration calculator, Ver. 2.0. Utah State University, Logan, UT.

Bezdicek, D.F., and D. Granatstein. 1989. Crop rotation efficiencies and biological diversity in farming systems. Am. J. Alt. Agric. 4:111–118.

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113.

Dubetz, S., and P.S. Mahalle. 1969. Effects of soil water stress on bush beans *Phaseolus vulgaris* L. at three growth stages. J. Am. Soc. Hort. Sci. 94:479–481.

Gunton, J.L., and J.P. Evenson. 1980. Moisture stress in navy beans. I. Effect of withholding irrigation at different phenological stages on growth and yield. Irrig. Sci. 2:49–58.

Haas, H.J., and W.O. Willis. 1962. Moisture storage and use by dryland spring wheat cropping systems. Soil Sci. Soc. Am. Proc. 26:506–509.

Halvorson, A.D., R.L. Anderson, S.E. Hinkle, D.C. Nielsen, R.A. Bowman, and M.F. Vigil. 1994. Alternative crop rotations to winter wheat-fallow. p. 6–11. *In* J. Havlin (ed.) Great plains fertility conference, Vol. 5, Denver. 7–8 March 1994. Kansas State Univ., Manhattan.

Halvorson, A.D., and C.A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. Agron. J. 86:315–318.

Lyon, D.J., F. Boa, and T.J. Arkebauer. 1995. Water-yield relations of several spring-planted dryland crops following winter wheat. J. Prod. Agric. 8:281–286.

Miller, D.E., and D.W. Burke. 1983. Response of dry beans to daily deficit sprinkler irrigation. Agron. J. 75:775–778.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180–186.

Peterson, G.A., D.G. Westfall, L. Sherrod, R. Kolberg, B. Rouppet. 1994. Sustainable dryland agroecosystem management. Colorado State University Agric. Exp. Stn. Bull. TB94-1.

Robins, J.S., and C.E. Domingo. 1956. Moisture deficit in relation to the growth and development of dry beans. Agron. J. 48:67–70.

Singh, S.P. 1995. Selection for water stress tolerance in interracial populations of common bean. Crop Sci. 35:118–124.

Stoker, R. 1974. Effect on dwarf bean of water stress at different phases of growth. N.Z.J. Exp. Agric. 2:13–15.

Turk, K.J., A.E. Hall, and C.W. Asbell. 1980. Drought adaptation of cowpea. I. Influence of drought on seed yield. Agron. J. 72:413–420.