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The effect of deficit irrigation on the grain yield of dry bean (*Phaseolus vulgaris* L.) in semiarid regions

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Abstract

The aim of this study was to determine the optimum water use of the dry bean (*Phaseolus vulgaris* L.). Such information is needed by planners and producers for the design of irrigation schemes to minimise yield reductions under water deficit conditions. Under the present experimental conditions, high grain yields were obtained by meeting the full water needs of the crop (1.94-2.43 Mg ha^{-1}), by meeting 75% of their needs (1.92-2.40 Mg ha^{-1}), or by irrigation throughout the growing season except during ripening (1.93-2.23 Mg ha^{-1}). Grain yields were reduced when irrigation water was not provided during the flowering and yield formation periods, and did not increase significantly in such cases even if water had been supplied during the establishment, vegetative, and ripening periods. The yield response factors for the entire growing season, and for the vegetative, flowering, yield formation and ripening periods, were 1.28, 0.36, 0.84, 0.80, and 0.08 respectively. Thus, to achieve effective vegetative production in semiarid regions such as Isparta, irrigation is absolutely necessary. Under limited water conditions, a water deficit of 25-50% is tolerable throughout the growing season, or during the vegetative and ripening periods.

Additional key words: evapotranspiration, irrigation water use efficiency, water use efficiency, yield response factor.

Resumen

Efecto de un riego deficitario sobre la producción de judía de grano (*Phaseolus vulgaris* L.) en regiones semiáridas

El objetivo de este trabajo fue optimizar el uso de agua para la judía de grano (*Phaseolus vulgaris* L.), lo que es necesario para que productores y gestores puedan diseñar esquemas de riego en condiciones deficitarias de agua. En las condiciones experimentales de este trabajo se obtuvo una alta productividad (1,94-2,43 Mg ha^{-1}) cuando las necesidades de agua estaban completamente cubiertas. Cuando las necesidades de agua estaban cubiertas en un 75% y cuando se regaba toda la campaña excepto en la época de maduración, la productividad fue 1,92-2,40 y 1.93-2.23 Mg ha^{-1}, respectivamente. El rendimiento de grano se redujo cuando no se suministró agua de riego durante los periodos de floración y maduración de granos, y este rendimiento no aumentó significativamente en tales casos aunque el agua se suministrara durante los periodos de establecimiento, vegetativo y maduración. Los factores de respuesta del rendimiento para el periodo de crecimiento completo, y para los periodos vegetativo, de floración, de formación de granos y de maduración fueron de 1,28, 0,36, 0,84, 0,80 y 0,08 respectivamente. Por tanto, para conseguir una producción efectiva en regiones semiáridas como Isparta, el riego es absolutamente necesario. En condiciones restringidas de agua, un déficit del 25-50% es tolerable a lo largo de toda la campaña, o durante los periodos vegetativo y de maduración.

Palabras clave adicionales: eficiencia en el uso de agua, eficiencia en el uso de agua de riego, evapotranspiración, factores de producción, producción de granos.

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Abbreviations used: ET (evapotranspiration), I (irrigation water), IWUE (irrigation water use efficiency), k_y (yield response factor), PE (polyetilene), WUE (water use efficiency).

Introduction

The dry bean (*Phaseolus vulgaris* L.) is planted over large areas and is very important as a source of human food. In 2003, nearly 19 million tonnes of dry beans were produced on 27 million hectares of land around the world; in Turkey, 250,000 tonnes were produced on some 155,000 ha (FAOSTAT, 2004). Dry bean is grown over most of Turkey, but especially in the Black Sea and East Anatolia Regions (Anonymous, 2001). The province of Isparta, situated between the Aegean, Mediterranean and Central Anatolia, lies in one of the most important climatic transition regions of Turkey. Intensive agricultural activity take place outside the city where the climate is semiarid with an annual average precipitation of 524 mm. Nearly 30% of this rainfall falls between May and October (Anonymous, 2003).

Effective vegetative production in such semiarid regions demands the possible reductions in yield due to water deficit during the growing season be known. In addition, the increasing demand for irrigation water and high water costs demand the development of water-production functions that reflect the relationship between yield and irrigation; only then can optimal irrigation regimes be designed (Russo and Bakker, 1987).

The yield response of different crops to water deficit is of major importance in production planning. Water deficit in crops and the resulting water stress have an effect on both crop evapotranspiration (ET) and crop yield. When water supply does not meet crop water requirements, the ET falls below the maximum level. Under such conditions, water stress develops, adversely affecting crop growth and ultimately crop yield. The effect on crop yield of seasonal limitations to water supply might be examined as a preliminary evaluation, but ultimately the effect of limiting the water supply during each of the different growth periods of the crop needs to be known. The response of yield to water supply is quantified through the yield response factor, which relates relative yield reductions to relative ET deficits (Doorenbos and Kassam, 1979).

The aim of the present work was to determine the water use characteristics of dry bean in deficit irrigation water conditions during the vegetative, flowering, yield formation and ripening periods. In either dual or triple combinations of these periods, plant water requirements were met fully or deficiently in such a way that crop water consumption deficit emerged. Under these conditions the water-yield relationships were determined from grain yield and ET values. The results of this work may be of help to planners and producers, providing the information necessary for them to devise irrigation regimes that minimise yield reductions under water deficit conditions.

Material and methods

Field experiments involving drip-irrigated dry bean crops were conducted during the 2001 and 2002 seasons in a research field belonging to the Agricultural Faculty of the Süleyman Demirel University, Isparta, Turkey (37° 52´N, 30° 40´E, altitude 930 m). The study area has a semi-arid climate; the average annual temperature, relative humidity, wind speed, sunshine duration per day, and total annual precipitation are 12.4ºC, 55%, 2.4 m s^{-1}, 7.6 h and 524.4 mm respectively (Anonymous, 2003). Table 1 records the climatic features of the 2001 and 2002 growing seasons.

The soil type in the research field is generally deep, heavy textured and well drained. The water holding capacities at depths of 0.90 m and 1.20 m are 141.2 mm and 189.5 mm respectively. There are no salinity and alkalinity problems (Akgül *et al.*, 2002). Table 2 shows some of the physical characteristics of the soil. The field capacity and wilting point for each 0.30 m soil layer up to a soil depth of 1.20 m were determined using the pressure plate apparatus (Richards, 1949). Underground water with an electrical conductivity (EC) of 0.65 dS m^{-1}, a sodium adsorption ratio (SAR) of 6, and a pH of 7.5 was used for all irrigation purposes.

Beans were sown on May 23rd 2001 and June 8th 2002 and harvested on September 18th and October 8th of those years respectively. A randomised block design with three replications was used for the experiments. Each experimental plot had an area of 16.20 m^2 (5.40 m x 3.00 m) and included 160 plants with 0.60 m x 0.15 m spacing (Fig. 1). Gaps of 2 m were left between the plots. Irrigation was provided by the drip irrigation method; groundwater was taken from near the experimental site using a pump. The control unit consisted of a 20 L s^{-1} screen filter, a pressure regulator, and manometers mounted on the inlet and outlet ports. The irrigation system used was based on a main, 63 mm-nominal diameter polyethylene (PE) tube with 20 mm manifolds. The diameters of the lateral PE tubes were 16 mm; each lateral tube irrigated one plant row. Pressure-compensating drippers were used to supply a uniform water distribution. The dripper discharge rate was

Table 1. Climate data for the experimental area in 2001-2002[a]

	T max (⁰C)	Tmin (⁰C)	RH max (%)	RH min (%)	W (m s^{-1})	E pan (mm)	R (mm)	S (h)
2001								
May [b]	26.3	11.8	66.4	41.0	1.5	39	-	9.6
June	29.1	13.1	60.6	38.2	1.6	279	-	12.8
July	33.0	17.0	62.7	37.7	1.3	321	17	12.1
August	32.3	17.0	68.9	38.1	1.3	280	-	11.0
September [c]	27.7	11.4	78.7	39.2	1.5	104	-	10.1
2002								
June [d]	27.7	14.5	62.9	42.4	1.3	249	-	11.1
July	30.7	15.6	70.1	40.1	1.3	288	12	10.7
August	29.6	14.8	72.9	41.0	1.3	242	31	11.2
September	24.0	9.7	90.5	48.1	0.9	117	116	8.2
October [e]	20.0	7.9	86.3	48.5	1.5	83	46	7.4

[a] T_{max}: maximum temperature. T_{min}: minimum temperature. RH_{max}: maximum relative humidity. RH_{min}: minimum relative humidity. W: average wind speed at a height of 2 m. E_{pan}: class A pan evaporation. R: rainfall. S: sunshine per day. [b] Calculated from the data for May 23rd-31st. [c] Calculated from the data for September 1st-18th. [d] Calculated from the data for June 8th-30th. [e] Calculated from the data for October 1st-8th.

4 L h^{-1} at the operating pressure of 1 atm. Both the dripper and lateral tube spacings were 0.60 m. According to the principles of Keller and Karmeli (1975), the percentage of the area wetted was 100%. The experiment involved 19 treatments (with three replications) in such a way that plant water consumption deficits could be induced in different combinations, *i.e.,* involving the total growing season of the plants, or combinations of the vegetative, flowering, yield formation and ripening periods. Table 3 shows the treatments and the growing periods in which crop water demand was fully (+) or deficiently (-) met.

The amount of irrigation water (I, mm) supplied in each regime was determined using Class A pan evaporation values recorded at the middle of the experimental field and employing Equation [1]:

$$I = A \cdot E_{pan} \cdot K_{cp} \qquad [1]$$

where A is the plot area (m^2), E_{pan} is the amount of cumulative evaporation from a class A pan over 10 days (mm), and K_{cp} is the crop pan coefficient (Table 3).

The irrigation interval adopted was 10 days. Irrigation water was applied to cover up to 100% of the evaporation losses measured using the evaporation pan. Soil water deficits were created by delaying irrigation during different combinations of growth periods, i.e., the establishment, vegetative, flowering, yield formation, and ripening periods (Doorenbos and Kassam, 1979). During the establishment period, all treatments were irrigated in such a way that plant water requirements were met fully; uniform establishment was therefore achieved. Irrigation water was supplied in treatment I_1 (K_{cp}=1.0) in all the growing periods, i.e., the irrigation water supplied covered all evapotranspiration needs as determined by the class A pan evaporation technique. No irrigation water was supplied in treatments I_2, I_3, I_4 and I_5 during the pe-

Table 2. Physical characteristics of the soil at the experimental site

Soil depth (cm)	Soil texture	Volume weight (g cm^{-3})	Field capacity		Wilting point		Available water content	
			(%)	(mm)	(%)	(mm)	(%)	(mm)
0-30	Clay	1.16	27.91	97.13	15.10	52.55	12.81	44.58
30-60	Clay	1.18	30.65	108.50	16.60	58.76	14.05	49.74
60-90	Clay	1.09	31.24	102.15	16.90	55.26	14.34	46.89
90-120	Clay	1.10	31.95	105.44	17.30	57.09	14.65	48.35

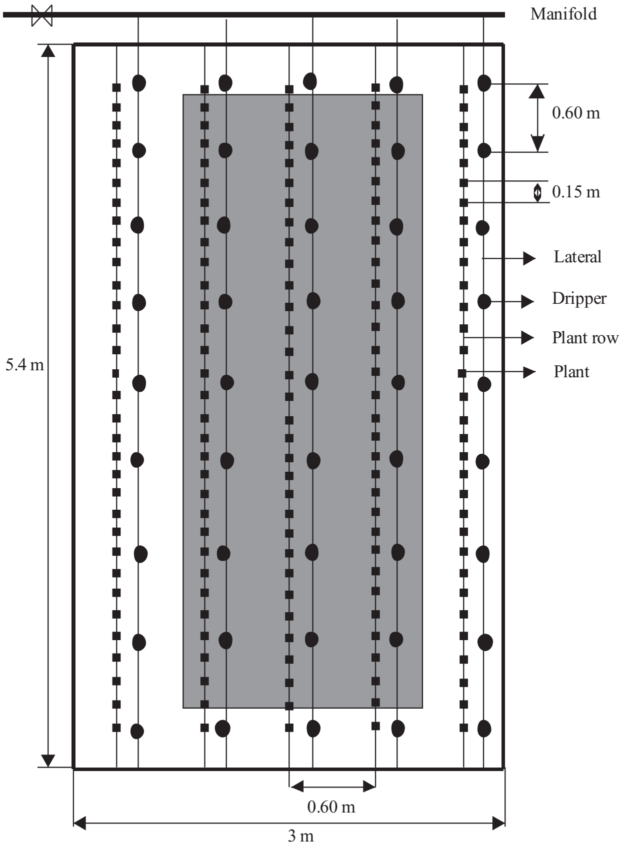


Figure 1. Design of an experimental plot. Harvest area shaded.

riods of vegetative growth, flowering, yield formation, and ripening respectively. The irrigation water was not supplied to treatments I_6, I_7, I_8, I_9, I_{10} and I_{11} in dual combinations of growth periods, and to treatments I_{12}, I_{13}, I_{14} and I_{15} in triple combinations. No irrigation water was supplied to treatment I_{16} during any period except the establishment period. For all the treatments mentioned above, irrigation at the beginning of each period was applied in sufficient quantity to raise the existing moisture at the depth of 90 cm to field capacity; subsequent applications were made as in treatment I_1. In treatments I_{17} (K_{cp}=0.25), I_{18} (K_{cp}=0.50) and I_{19} (K_{cp}=0.75), irrigation water was applied as 25%, 50% and 75% of the amount supplied in treatment I_1 respectively. Table 3 summarizes the design of each treatment.

The dates of the beginning and end of the plant growth periods were determined by phenological observation. When the plants had a few leaves they were rarefactioned to leave a 15 cm space between them. When the plants reached a height of 10-15 cm, hoeing was performed; this was repeated when weeds appeared.

Since there were no indications of diseases or harmful insects during either trial year, no insecticide was applied.

The change in soil water content at depths of 0-30, 30-60, 60-90 and 90-120 cm in each treatment plot was determined gravimetrically. Soil water contents were determined over 10 days, starting from the establishment date of the plants in both years. The ET (mm) for each treatment was calculated using Equation 2 (Garrity *et al.*, 1982; James, 1988):

$$ET = I + P + C_p - D_p \pm R_f \pm \Delta S \qquad [2]$$

where P is the precipitation (mm), C_p is the capillarity rise (mm), D_p the deep percolation (soil water content variation at the 90-120 cm soil depth [mm]), R_f the amount of surface runoff, (mm), and ΔS the change in soil water content at 0-90 cm (mm). The irrigation water supplied, precipitation and soil moisture contents were all measured. Runoff was assumed to be zero since the amount of irrigation water was controlled. Monitoring the soil water content in the plots showed that deep percolation and capillarity rise below the depth of 90 cm were negligible.

The total weight of bean grain obtained in each plot was adopted as the yield variable. The bean pods picked from plots were shelled by hand, weighed, and their moisture content determined and adjusted on a 90% dry matter basis. The yields obtained in different treatments were statistically compared (Steel and Torrie, 1980; Yurtsever, 1982).

The yield response factor, k_y, was determined according to the Stewart model (Doorenbos and Kassam, 1979):

$$k_y = [1-(Y_a/Y_m)] / [1-(ET_a/ET_m)] \qquad [3]$$

where Y_a is the actual crop yield (Mg ha^{-1}), Y_m the maximum crop yield without water stress (Mg ha^{-1}), ET_a the actual ET (mm/period), ET_m the maximum ET without water stress (mm/period) corresponding to Y_m, 1-(Y_d/Y_m) is the relative yield reduction, and 1-(Et_d/ET_m) is the relative *ET* deficit.

The acquired data were examined by ANOVA and the relationship between water use and bean grain yield examined by regression analysis.

To assess the productivity of irrigation in the treatments, water use efficiency (WUE, Mg mm^{-1} ha^{-1}) and irrigation water use efficiency (IWUE, Mg mm^{-1} ha^{-1}) were determined as below:

Table 3. Plant growth periods in which the crop water demand was fully (+) or deficiently (-) met in treatments I_1-I_{19}

Treatments	Growth periods				
	Establishment (0)	Vegetative (1)	Flowering (2)	Yield formation (3)	Ripening (4)
I_1	+	+	+	+	+
I_2	+	-	+	+	+
I_3	+	+	-	+	+
I_4	+	+	+	-	+
I_5	+	+	+	+	-
I_6	+	-	-	+	+
I_7	+	-	+	-	+
I_8	+	-	+	+	-
I_9	+	+	-	-	+
I_{10}	+	+	-	+	-
I_{11}	+	+	+	-	-
I_{12}	+	+	-	-	-
I_{13}	+	-	+	-	-
I_{14}	+	-	-	+	-
I_{15}	+	-	-	-	+
I_{16}	+	-	-	-	-
I_{17}	+	0.25+	0.25+	0.25+	0.25+
I_{18}	+	0.50+	0.50+	0.50+	0.50+
I_{19}	+	0.75+	0.75+	0.75+	0.75+

I_1: all irrigation needs supplied at all times, as determined by evaporation from a class A evaporation pan. I_2-I_5: irrigation water not supplied in one period. I_6-I_{11}: irrigation water not supplied in dual combinations of growing periods. I_{12}-I_{15}: irrigation water not supplied in triple combinations of growing periods. I_{16}: no irrigation supplied except in the establishment period. I_{17} (K_{cp}=0.25+), I_{18} (K_{cp}=0.50+) and I_{19} (K_{cp}=0.75+) irrigation water applied in ratios of 25%, 50% and 75% that supplied in I_1 respectively.

$$WUE = Y/ET \quad [4]$$

$$IWUE = Y_I - Y_{NI}/I \quad [5]$$

where Y is the grain yield (Mg ha^{-1}), Y_I is the grain yield obtained from the irrigated treatment (Mg ha^{-1}), Y_{NI} is the grain yield obtained in the rain-fed treatment (Mg ha^{-1}), and I is the irrigation depth (mm) (Hillel and Guron, 1975).

Results

Table 4 shows the beginning and end dates of the growing periods in 2001 and 2002, determined by phenological observations. The duration of the total growing season was 118 days in 2001 and 123 days in 2002.

Table 5 shows the amount of irrigation water supplied to the treatments in the individual growth periods over both years, as well as the precipitation and ET values measured. The greatest amount of irrigation water (1011.3 mm and 928.0 mm) was supplied to treatment I_1 in both years. The precipitation during the growing season was 16.6 mm and 159.4 mm for 2001 and 2002 respectively. The highest ET values (1109.2 mm and 1089.5 mm) were obtained in treatment I_1 in both years. Reductions in the ET values were observed in the other treatments depending on the reduction in the amount of irrigation water supplied. The lowest seasonal ET values (311.3 mm and 414.8 mm) were recorded for treatment I_{16}, in which no irrigation water was supplied except during the establishment period.

Table 6 shows the grain yield per unit area (adjusted for a dry matter basis of 90%) in 2001 and 2002. The

Table 4. Individual growth periods in 2001 and 2002

Growth periods	Starting date	Ending date	Length of period (days)
Establishment	23rd May 2001	20th June 2001	28
	08th June 2002	30th June 2002	23
Vegetative	20th June 2001	10th July 2001	20
	30th June 2002	31st July 2002	31
Flowering	10th July 2001	31st July 2001	21
	31st July 2002	20th August 2002	20
Yield formation	31st July 2002	31st August 2001	31
	20th August 2002	20th September 2002	31
Ripening	31st August 2001	18th September 2001	18
	20th September 2002	08th December 2002	18
Total 2001	23rd May 2001	18th September 2001	118
Total 2002	08th June 2002	08th December 2002	123

highest grain yield was obtained in treatment I_1 in both trial years (2001, 1.94 Mg ha^{-1}; 2002, 2.43 Mg ha^{-1}). No grain yield could was obtained for treatments I_{15} and I_{16}, in which no irrigation water was supplied except during establishment and ripening. The lowest grain yield in both years was obtained in treatment I_{12}, in which irrigation water was supplied during the establishment and vegetative periods (2001 = 0.17 Mg ha^{-1}; 2002 = 0.27 Mg ha^{-1}).

Figure 2 plots the Y_m, Y_a, ET_m and ET_a values used in determinations of the relative yield reduction [1--(Y_a/Y_m)] and relative ET deficit [1-(ET_a/ET_m)] for the whole growing season and the individual growth periods. The yield response factor, k_y, was 1.20 for 2001, 1.37 for 2002, and 1.28 for the average of both years (Fig. 2a).

Figure 2b shows that k_y was 0.24-0.49 (average 0.37) for the vegetative period, 0.67-1.01 (average 0.84) for the flowering period, 0.66-0.93 (average 0.80) for the yield formation period, and 0.01-0.15 (average 0.08) for the ripening period. Its value was 0.95-1.16 (average 1.05) for the vegetative and flowering periods, 0.89-0.94 (average 0.92) for the vegetative and yield formation periods, 0.50-0.89 (average 0.70) for the vegetative and ripening periods, 0.99-1.25 (average 1.12) for the flowering and yield formation periods, 0.46-1.02 (average 0.74) for the flowering and ripening periods, and 0.63-0.89 (average 0.76) for the yield formation and ripening periods (Fig. 2c, d). The value of k_y was 1.05-1.30 (average 1.17) for the flowering, yield formation and ripening periods, 0.91-1.12 (average 1.02) for the vegetative, yield formation and ripening periods, and 0.95-1.11 (average 1.03) for the vegetative, flowering and ripening periods. Since no yield could be obtained for I_{15} (in which no irrigation water was supplied during the vegetative, flowering and yield formation periods), nor for I_{16} (in which no irrigation water was supplied except during the establishment period), no k_y values were calculated.

The WUE and IWUE values were calculated for all treatments and both years (Table 7). Figure 3 also shows the relationships between irrigation water supply and grain yield, and between ET and grain yield. The highest WUE (average 0.024 Mg ha^{-1} mm^{-1}) and IWUE (average 0.028 Mg ha^{-1} mm^{-1}) values were recorded for treatment I_{19} in both years; in this treatment 75% of the evaporation value indicated by the Class A pan technique was supplied as irrigation water. These values were followed by those for treatment I_{18} (0.21 and 0.025 Mg ha^{-1} mm^{-1} respectively).

Discussion

Differences in ET were seen in the different treatments. These variations depended on the water deficits induced in the different growing periods. In both years, the highest seasonal ET was seen in treatment I_1, in

Table 5. Irrigation water (I), rainfall (R) and evapotranspiration (ET) values in 2001 and 2002 (mm) according to growth periods

Treatments		2001 Growth Periods						2002 Growth Periods					
		0	1	2	3	4	Total	0	1	2	3	4	Total
I_1	I	178.6	194.8	185.9	318.9	133.1	1011.3	235.5	285.6	191.0	178.9	37.0	928.0
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	215.8	319.0	145.8	1109.2	203.6	309.8	177.6	278.6	119.9	1089.5
I_2	I	178.6	–	185.3	318.9	133.1	815.9	235.5	–	181.5	178.9	37	632.9
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	211.6	302.1	136.8	908.7	203.6	71.8	126.7	285.6	68.9	756.6
I_3	I	178.6	194.8	–	315.4	133.1	821.9	235.5	285.6	–	221.8	37.0	779.9
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	64.1	287.6	140.0	920.3	203.6	309.8	38.3	235.9	95.0	882.6
I_4	I	178.6	194.8	185.9	–	183.6	742.9	235.5	285.6	191.0	–	126.0	838.1
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	215.8	44.0	95.9	784.3	203.6	309.8	177.6	159.8	75.7	926.5
I_5	I	178.6	194.8	185.9	318.9	–	778.2	235.5	285.6	191.0	178.6	–	891.0
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	215.8	319.0	50.7	1014.1	203.6	309.8	177.6	278.6	56.1	1025.7
I_6	I	178.6	–	–	311.6	133.1	623.3	235.5	–	–	241.0	37.0	513.5
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	36.7	290.3	139.9	725.1	203.6	71.8	23.6	249.0	77.1	625.1
I_7	I	178.6	–	185.3	–	193.9	557.8	235.5	–	181.5	–	80.9	497.9
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	211.6	36.9	90.6	597.3	203.6	71.8	126.7	103.9	124.6	630.6
I_8	I	178.6	–	185.3	318.9	–	682.8	235.5	–	181.5	178.9	–	595.9
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	211.3	302.1	27.6	799.5	203.6	71.8	126.7	285.6	44.9	732.6
I_9	I	178.6	194.8	–	–	186.0	559.4	235.5	285.6	–	–	148.4	669.5
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	64.1	12.2	105.9	610.8	203.6	309.8	38.3	138.1	107.9	797.7
I_{10}	I	178.6	194.8	–	315.4	–	688.8	235.5	285.6	–	221.8	–	742.9
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	64.1	287.6	34.6	814.9	203.6	309.8	38.3	235.9	75.0	862.6
I_{11}	I	178.6	194.8	185.9	–	–	559.3	235.5	285.6	191.0	–	–	712.1
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	215.8	44.0	8.0	696.4	203.6	309.8	177.6	159.8	42.6	893.4
I_{12}	I	178.6	194.8	–	–	–	373.4	235.5	185.6	–	–	–	521.1
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	211.4	64.1	12.2	10.2	515.1	203.6	309.8	38.3	138.1	24.4	714.2
I_{13}	I	178.6	–	185.3	–	–	363.9	235.5	–	181.5	–	–	417.0
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	211.6	36.9	2.6	509.3	203.6	71.8	126.7	103.9	99.3	605.3
I_{14}	I	178.6	–	–	311.6	–	490.2	235.5	–	–	241.0	–	476.5
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	36.7	290.3	22.9	608.1	203.6	71.8	23.6	249.0	49.6	597.6
I_{15}	I	178.6	–	–	–	180.5	359.1	235.5	–	–	–	145.0	380.5
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	36.7	6.4	60.6	361.9	203.6	71.8	23.6	103.1	87.9	490.0
I_{16}	I	178.6	–	–	–	–	178.6	235.5	–	–	–	–	235.5
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	41.0	36.7	6.4	10.0	311.3	203.6	71.8	23.6	103.1	12.7	414.8
I_{17}	I	178.6	48.8	46.5	79.8	33.3	387.0	235.5	71.4	47.8	44.8	9.3	408.8
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	80.6	96.8	84.7	42.2	521.5	203.6	100.3	62.5	164.2	34.0	564.6
I_{18}	I	178.6	97.4	93.0	159.5	66.6	595.1	235.5	142.9	95.6	89.5	18.5	582.0
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	121.6	117.2	178.6	57.4	692.0	203.6	164.9	113.6	159.2	69.7	711.3
I_{19}	I	178.6	146.2	139.4	239.2	99.8	803.2	235.5	214.3	143.2	134.3	27.8	755.1
	R	–	16.6	–	–	–	16.6	–	12.4	9.1	137.9	–	159.4
	ET	217.2	149.9	184.9	250.6	103.7	906.3	203.6	238.9	133.2	241.9	84.8	902.4

Growth periods: 0 = establishment, 1 = vegetative, 2 = flowering, 3 = yield formation, 4 = ripening

Table 6. Grain yields of bean per unit area (Mg ha^{-1})

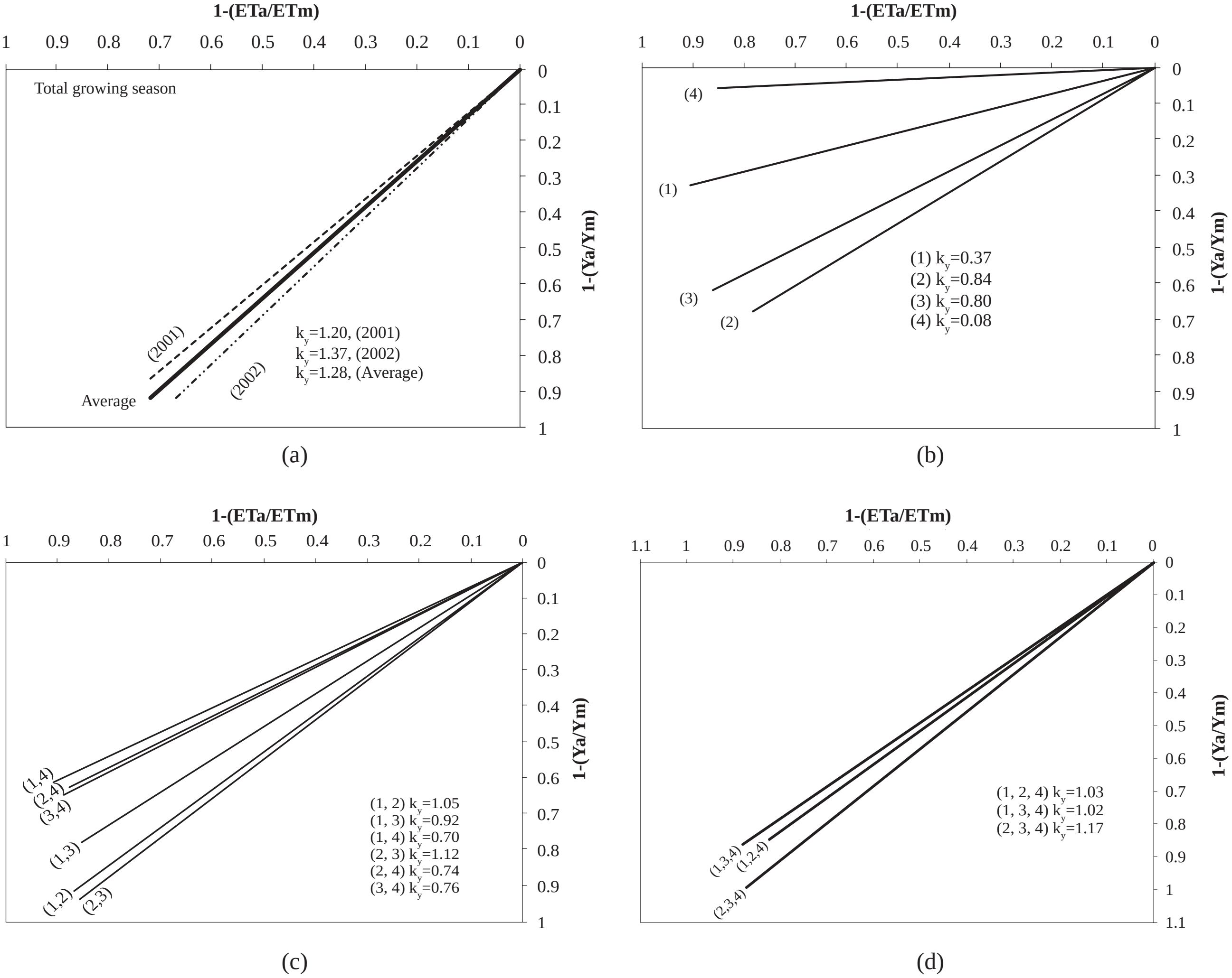
Treatments	2001 Replicates				2002 Replicates				Average for the two years
	I	II	III	Average	I	II	III	Average	
I_1	2.08	1.91	1.84	1.94 a	2.54	2.31	2.43	2.43 a	2.18 a*
I_2	1.59	1.66	1.46	1.57 b	1.36	1.61	1.56	1.51 bc	1.54 b
I_3	0.96	0.99	1.12	1.02 de	0.46	0.48	0.53	0.50 f	0.76 de
I_4	0.86	0.84	0.78	0.83 ef	1.61	1.57	1.23	1.47 bc	1.15 c
I_5	2.02	1.93	1.83	1.93 a	2.11	2.20	2.38	2.23 a	2.08 a
I_6	0.42	0.41	0.46	0.43 h	0.18	0.17	0.16	0.17 gh	0.30 ghi
I_7	0.49	0.48	0.43	0.46 gh	0.89	0.87	0.72	0.83 d	0.64 efg
I_8	1.13	1.22	1.14	1.16 cd	0.93	0.81	0.83	0.85 d	1.01 cd
I_9	0.37	0.29	0.23	0.30 hi	0.75	0.48	0.44	0.56 ef	0.43 efgh
I_{10}	1.45	1.38	1.04	1.29 c	0.96	0.91	0.83	0.90 d	1.10 c
I_{11}	0.94	0.81	0.78	0.85 ef	1.44	1.36	1.29	1.36 c	1.11 c
I_{12}	0.16	0.18	0.17	0.17 ij	0.36	0.41	0.34	0.37 fg	0.27 hi
I_{13}	0.37	0.40	0.39	0.39 h	0.68	0.74	0.86	0.76 de	0.57 efgh
I_{14}	0.38	0.41	0.45	0.42 h	0.43	0.35	0.35	0.37 fg	0.39 fgh
I_{15}	0.00	0.00	0.00	0.00 j	0.00	0.00	0.00	0.00 h	0.00 i
I_{16}	0.00	0.00	0.00	0.00 j	0.00	0.00	0.00	0.00 h	0.00 i
I_{17}	0.57	0.70	0.68	0.65 fg	0.79	0.85	0.83	0.82 d	0.74 def
I_{18}	1.54	1.16	1.24	1.31 c	1.72	1.60	1.63	1.65 b	1.48 b
I_{19}	1.93	1.96	1.87	1.92 a	2.50	2.29	2.42	2.40 a	2.16 a

*Significant difference at $p<0.01$ (Duncan's multiple range test). Figures in the same column with the same letters are not statistically significant ($p>0.01$).

which no water deficit was induced (2001 = 1109.2 mm; and 2002 = 1089.5 mm). Throughout the total growing season, 25%, 50%, and 75% of the water evaporated from the Class A pan was supplied to treatments I_{17}, I_{18}, I_{19} and respectively. In these experiments, the ET decreased as the water deficit ratio increased. The ET in I_{19} ranged from 906.3 to 902.3 mm in 2001 and 2002, whereas in treatments I_{18} and I_{17} these values were 692.0-711.3 mm and 521.5-564.6 mm respectively. These figures were 18%-17% (I_{19}), 38%-35% (I_{18}) and 53%-48% (I_{17}) lower than those recorded for treatment I_1 (in which the highest ET was obtained).

Differences in ET values were also observed depending upon whether the induced water deficit lasted the total growing season or not. In both years, the lowest seasonal ET was seen in treatment I_{16}, in which no irrigation water was supplied except during the establishment period (2001 = 311.3 mm, 2002 = 414.8 mm). Yildirim *et al.* (1994) and Şehirali *et al.* (2005) reported seasonal ETs of 696 mm, and 732 mm respectively in similar studies performed in Turkey. Some differences were observed between the same treatments with respect to the irrigation water applied and seasonal ET values over the two year experimental period. These differences may have been caused by the variations in climatic conditions in the two years of the trial. Similarly, the seasonal ET was higher in the present study compared to those reported in the other studies mentioned above. The reason for this may be once again attributed to climatic differences between the research areas.

The highest grain yield per unit area was obtained in treatment I_1 (2.18 Mg ha^{-1}), in which no water deficit was induced at any time. No grain yield was obtained in treatments I_{15} and I_{16}, in which no irrigation water was supplied except during the ripening and establishment periods, and the establishment period, respectively. The



(a) (b) (c) (d)

Figure 2. Yield response factors, k_y. (a) Values of k_y for the total growing period. (b) Values of k_y for an individual growing period. (c) Values of k_y for dual combinations of growing periods. (d) Values of k_y for triple combinations of growing periods. 1; vegetative, 2; flowering 3; yield formation and 4; ripening.

grain yields obtained in other treatments depended on the water deficit induced during the different growing periods. Grain yield reductions were generally more severe in treatments in which no irrigation water was supplied during the early part of the growth period (*e.g.*, in I_6, I_7, I_{13} and I_{14}). Not supplying irrigation water in the latter part of the growth period did not cause a significant reduction in grain yield. For example, no significant differences in grain yields were seen between treatment I_1 (in which irrigation water was supplied over the entire growing season) and treatment I_5 (in which water deficiency was supplied only during the ripening period). The non-supply of irrigation water during the flowering and yield formation periods caused water stress in the plants due to the water deficiency of the soil; the grain yield therefore became reduced. Even if irrigation water was supplied during the establishment, vegetative, and ripening periods, grain yield did not significantly increase in these plants. In similar experiments also performed in Turkey, Güngör (1981) and Günbatili (1991) reported the largest grain yields to be obtained when no water limitations were applied over the entire growing season. Miranda and Belmar (1977) also reported large grain yield reductions when the crop water demand was not fully met during the vegetative, flowering, and yield formation periods. Although in the present work the irrigation water supplied in treatment I_{19} was 25% lower than in treatment I_1, the grain yield was not significant-

Table 7. Water use efficiency (WUE) and irrigation water use efficiency (IWUE) (Mg ha^{-1} mm^{-1})

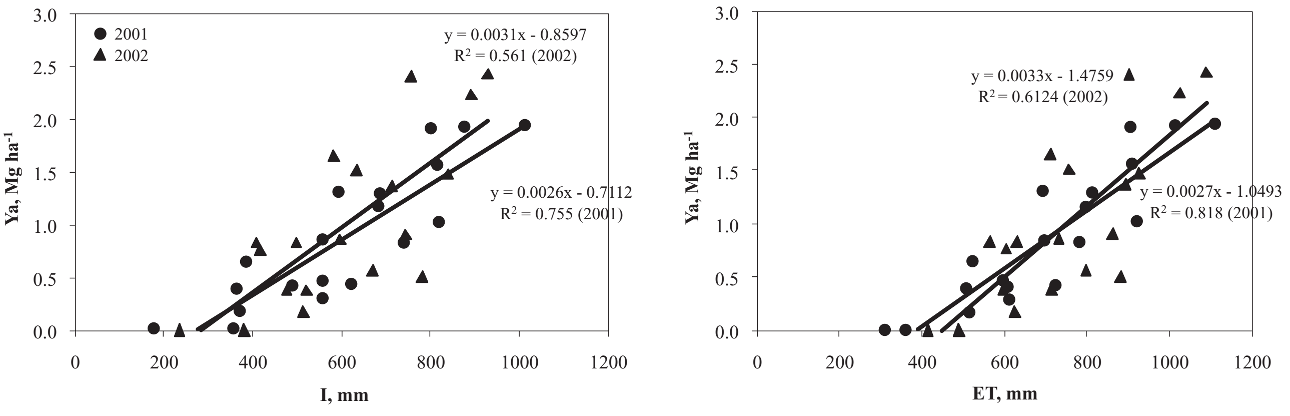
Treatments	2001		2002		Average	
	WUE	IWUE	WUE	IWUE	WUE	IWUE
I_1	0.018	0.019	0.022	0.026	0.020	0.023
I_2	0.017	0.019	0.020	0.024	0.019	0.022
I_3	0.011	0.012	0.006	0.006	0.009	0.009
I_4	0.011	0.011	0.016	0.018	0.014	0.015
I_5	0.019	0.022	0.022	0.025	0.021	0.024
I_6	0.006	0.007	0.003	0.003	0.005	0.005
I_7	0.008	0.008	0.013	0.017	0.011	0.013
I_8	0.015	0.002	0.012	0.014	0.014	0.008
I_9	0.005	0.005	0.007	0.008	0.006	0.007
I_{10}	0.016	0.019	0.010	0.012	0.013	0.016
I_{11}	0.012	0.015	0.015	0.019	0.014	0.017
I_{12}	0.003	0.005	0.005	0.007	0.004	0.006
I_{13}	0.008	0.011	0.013	0.018	0.011	0.015
I_{14}	0.007	0.009	0.006	0.008	0.007	0.009
I_{15}	0.0	0.0	0.0	0.0	0.0	0.0
I_{16}	0.0	0.0	0.0	0.0	0.0	0.0
I_{17}	0.012	0.017	0.015	0.020	0.014	0.019
I_{18}	0.019	0.022	0.023	0.028	0.021	0.025
I_{19}	0.021	0.024	0.027	0.032	0.024	0.028

ly reduced. The irrigation water supplied in treatment I_{18} was 50% that supplied in treatment I_1, and the yield reduction was 32%. Further reduction in grain yield was seen in treatment I_{17}, in which the plants received 75% less irrigation water than in treatment I_1.

The seasonal yield response factor (k_y), which is an important variable in irrigation and water deficit planning, was found to be 1.28 on average (Fig. 2a). This value differs from the values reported by Doorenbos and Kassam (1979) (k_y=1.15), Sezen *et al.* (2005) (k_y=1.23), Yildirim *et al.* (1994) (k_y=1.57) and Şehirali *et al.* (2005) (k_y=1.04). If the value of k_y is greater than 1, this generally means that the crop is sensitive to water deficit in the soil. The fact that k_y was 1.28 may be regarded as an indicator of these plants' sensitivity to water deficit. A number of other authors also report dry beans to be sensitive to water deficit (Miller and Burke, 1983; Nielsen and Nelson, 1998; Boutraa and Sanders, 2001).

With respect to treatments I_2, I_3, I_4 and I_5, in which water deficiency was induced only over a single period, the highest k_y value was seen in I_2 (average k_y=0.84), in which no water was supplied during the flowering period. This was followed by I_3 (average k_y=0.80), in which no water was supplied during the yield formation period, I_4 (average k_y=0.37), in which no water was supplied during the vegetative formation period, and I_5 (average k_y=0.08), in which no water was supplied during the ripening period. The bean plants can therefore be said to be sensitive to water deficiency in the flowering and yield formation periods, and highly resistant to water deficiency in the vegetative and ripening periods. Doorenbos and Kassam (1979) found k_y values of 0.20, 1.10, 0.75, and 0.20 for the vegetative, flowering, yield formation and ripening periods respectively. Yildirim *et al.* (1994) reported dry bean plants to be most sensitive to water in the yield formation period (k_y=0.69). The differences between the present k_y values and those reported by Doorenbos and Kassam (1979) and other authors may be attributed to the differences in climates, soil and plant conditions.

The average k_y value was 1.17 in treatment I_{12}, in which water deficiency was induced during the flowering + yield formation + ripening periods, while the average was 1.03 for I_{14}, in which water deficiency was



(a) (b)

Figure 3. The relationship between grain yield (Ya, Mg ha^{-1}) and (a) irrigation water quantity (I, mm) and (b) ET (mm).

induced during the vegetative + flowering + ripening periods, and 1.02 in treatment I_{13}, in which water deficiency was induced in the vegetative + yield formation + ripening periods. Since k_y was highest in I_{12} among these treatments, the bean plants appear to be sensitive to water deficiency during the flowering, yield formation, and ripening periods. Similarly, when the treatments in which no water was supplied in dual period combinations are studied, the highest k_y value obtained (1.12) is that of I_9, in which no irrigation water was supplied during the flowering and yield formation periods. The lowest k_y value, however, was that of treatment I_9, in which no irrigation water was applied in the vegetative and ripening periods. It can be concluded from these values that dry bean plants are more resistant to water deficiency in the vegetative and ripening periods than during the flowering and yield formation periods.

The WUE and IWUE values recorded also showed differences among treatments. The WUE ranged from 0 to 0.024 Mg ha^{-1} mm^{-1}, and IWUE from 0 to 0.028 Mg ha^{-1} mm^{-1}. Both the WUE and IWUE values for the trial conditions were lower in the treatments in which irrigation water was least supplied and the ET was higher.

In conclusion, the highest grain yield was achieved by meeting 75%-100% of the crop's water requirement, or by excluding irrigation only during the ripening period. The crop goes into stress due to soil water deficit when no irrigation is supplied in the flowering and yield formation periods. This stress leads to a reduction in the grain yield. The grain yield does not then increase significantly even if irrigation water has been made available during the establishment, vegetative and ripening periods. Consequently, dry bean can be said to be generally sensitive to water deficit, especially during the flowering and yield formation periods. However, it is highly resistant to water deficit during the vegetative and ripening periods. For effective vegetative production in semiarid regions such as Isparta, irrigation is therefore absolutely necessary. Under limited water conditions, the tolerable water deficiency is some 25-50% throughout the growing season or during the vegetative or ripening periods.

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