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Full Length Research Paper

Quality and yield response of soybean (*Glycine max* L. Merrill) to drought stress in sub–humid environment

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The aim of the study was to determine the response of soybean [*Glycine max* (L.) Merr.] to drought at various stages of development in a sub-humid environment of Turkey. Drought-stress treatments was applied to plants in 2005 and 2006 by withholding irrigation at six critical stages: completely vegetative (fifth trifoliate) (T_2), flowering (T_3), podding (T_4), seed fill (T_5), full bloom + podding (T_6), and podding + seed fill (T_7). Growth and production was compared in each treatment to full irrigated (T_1) and non-irrigated (T_8) controls. Each drought treatment reduced shoot biomass and seed yield compared to well-watered plants, but only non-irrigated plants or plants droughted at vegetative or flowering stages produced fewer seed pods and seeds. Seed protein and oil content was highest among treatments when plants were droughted during the seed filling stage. Yield increased exponentially with crop water use and ranged from 2.1 - 2.5 tons ha^{-1} in non-irrigated plants to 3.5 - 4.0 tons ha^{-1} in the well-watered controls. However, plants droughted during the vegetative stage of development produced the highest yield per unit of irrigation water applied (that is, irrigation water use efficiency). This research results will be useful for maximizing soybean production and/or seed quality when irrigation water is limited.

Key words: *Glycine max*, flowering, irrigation, seed development, water use efficiency.

INTRODUCTION

Water stress is considered one of the most important factors limiting plant performance and yield worldwide (Boyer, 1982). Water stress during reproductive development often decreases the seed size in soybean (Kadhem et al., 1985; Momen et al., 1979; Sionet and Kramer, 1977).

Recent evidence indicates that the reduction in seed size is primarily due to a shortening of the seed filling period rather than an inhibition of seed growth rate (Meckel et al., 1984). Irrigation can significantly increase soybean seed yield (Heatherly, 1983) and can increase profits (Salassi et al., 1984). Stressful conditions such as high temperature or moisture deficiency reduce soybean yield in one or more of its components. Drought stress occurring during the flowering and early pod development periods significantly increases the rate of pod abortion thus decreasing final seed yield (Westgate and Peterson, 1993; Liu et al., 2003).

As the soybean plant ages from R1 (beginning bloom) through R5 (seed enlargement), its ability to compensate for stressful conditions decreases and the potential degree of yield reduction because of stress increases (Foroud et al., 1993). Previous studies related to soybean response to water deficit reported by Shaw and Laing (1966), Doss et al. (1974), Woods and Swearingen (1977), Sionet and Kramer (1977), Ashley and Ethridge (1978), Krote et al. (1983), Huck et al. (1983), and Foroud et al. (1993) showed that water deficit during flowering (R2 stage) had little effect on seed yield whereas during pod elongation (R3 stage) and seed enlargement (R5 stage) the effects were significant. Brown et al. (1985) showed that water deficit at either the R2 or R3 stages significantly reduced yields. They also reported that water stress at the flowering stage resulted in greater yield loss than the one at pod elongation stage. Drought stress occurring during the early reproductive growth may increase the flower and pod abortion (Krote

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Table 1. Drought treatments applied to soybean at four stages of development in 2005 and 2006. '+' = irrigation, '–' = no irrigation.

Treatment	Description of drought timing	V5 Vegetative DOY 174 23 June	R2 Flowering DOY 193 12 July	R4 Podding DOY 207 26 July	R6 Seed fill DOY 228 16 Aug
T_1	Full irrig (Non-stressed)	+	+	+	+
T_2	Early (V_5)	_	+	+	+
T_3	Mid early (R_2)	+	_	+	+
T_4	Mid late (R_4)	+	+	_	+
T_5	High mid (R_6)	+	_	_	+
T_6	Late (R_2+R_4)	+	+	+	_
T_7	Mid and Late (R_2+R_6)	+	_	+	_
T_8	Full drought (Non-irrigated)	_	_	_	_

V5: 5 nodes on the main stem beginning with the unifoliate node; R2: Full bloom; R4: Pod 2 cm long; R6: pod containing full-size green beans (From Fehr and Caviness, 1977). DOY: Day of year.

et al., 1983), thus decreasing the seed number and increasing the seed weight. Momen et al. (1979) and Cox and Jolliff (1986) demonstrated that soybean is most sensitive to water stress during the podfilling period (R6 stage).

The objective of the present study was to identify the stage or stages of development in which soybean is most sensitive to drought in the sub-humid environment of Turkey. The study was conducted for 2 years in a sub-humid climate with hot, dry summers and mild, rainy winters. The results will be used to determine the most critical stages of scheduling irrigation and for reducing water use when plants are most tolerant of drought.

MATERIALS AND METHODS

The study was conducted at the Agricultural Research and Application Center of Agriculture Faculty of Uludag University in western Turkey (40.3° N, 28.9° E, elev. 72 m). Mean (1975 - 2003) precipitation at the site is 697 mm, with 80% of it occurring during winter months from November to March (Demir et al., 2006).

The soil is very fine with 48% clay. At planting, the soil had 0.1% total N, 0.68 $kg \cdot ha^{-1}$ P, 3.65 $kg \cdot ha^{-1}$ exchangeable K, 6.9 pH, 0.47% organic matter, 0.08% total salt. It had a water holding capacity of 120 mm at 0 to 0.9 m depth and a bulk density of 1.34 - 1.36 $g \cdot cm^{-3}$. Soil water content ranged from 38.2 - 43.0% at field capacity to 23.2 - 27.2% at -1.5 MPa soil matric potential.

Soybean [*Glycine max* (L.) Merr. 'Nova' (MG IV)] seeds were obtained from Jacques Seed Company (Prescott, WI, USA) and planted on 21 April 2005 and 3 May 2006. Sunflower was planted the previous year. The seeds were planted 3 cm deep and 5 cm apart in 0.65-m wide rows (310,000 seeds/hectare). Granular fertilizer (10-10-10) was incorporated prior to planting at a rate of 50 $kg \cdot ha^{-1}$ of N, P, and K, and urea was applied at a rate 50 $kg \cdot ha^{-1}$ of N when plants reached 25 - 30 cm in height. Linuron [3(3.4 dichlorophenyl)-1-methoxyl-methylurea] was applied at a rate of 1.12 kg a.i. ha^{-1} for weed control immediately after planting. Precipitation was sufficient to germinate the seeds in 2005, but 15 mm of irrigation was applied by sprinklers for uniform germination in 2006.

Plants were irrigated by drip tape (SunStream) with 2.0 L h^{-1} emitters spaced every 0.20 m. Irrigation was scheduled at each critical stage of plant development. Water was applied to reach field capacity after each irrigation. Irrigation water was measured by water meter. Weather conditions were monitored daily using an automatic weather station (WatchDog Spec 7 Pro, Spectrum Technologies Inc.) installed near 150 m the field.

Eight drought treatments were applied to the field (Table 1). Drought treatments were applied to plants in 2005 and 2006 by deficit irrigation at six critical stages: completely vegetative (fifth trifoliate) ($T_2 = V_5$)), flowering ($T_3 = R_2$), podding ($T_4 = R_4$), seed fill ($T_5 = R_6$), full bloom + podding ($T_6 = R_2 + R_4$), and podding + seed fill ($T_7 = R_2 + R_6$). Growth and production was compared in each treatment to full irrigated (T_1) and non-irrigated (T_8) controls. Total growing period was 159 and 153 days for 2005 and 2006, respectively. The experiments were designed in a randomized complete block with three replications, with individual plot size of 23.4 m^2 (3.9 x 6.0 m). Each plot was 6.0 m long and consisted of 6 rows of plants.

Soil water content was measured weekly using a neutron probe (model 503 DR, Campbell Pacific Nuclear Intl., Inc., Martinez, CA, USA) and aluminum access tubes installed 1.8 m deep in the center of each plot. Neutron counts (16-s intervals) were collected at each 0.3 m depth increment between 0.15 and 1.5 m from the soil surface and converted to soil water content using a calibration curve developed for the site, following procedures outlined by Evett and Steiner (1995).

Crop evapotranspiration in each plot was estimated by a water balance approach (Allen et al., 1998), which accounted for precipitation, irrigation, and soil water depletion calculated from changes in water content in the top 0.9 m of the soil profile (estimated root zone). Deep percolation was also accounted for by measuring changes in soil water content below the root zone at 0.9 - 1.2 m.

Leaf area was measured at each critical stage of plant development using a LI300A leaf area meter (Li-Cor Inc., Lincoln, NE, USA).

Seed yield, harvest index, and 1000 seed weight were determined by hand-harvesting four 4-m-long sections of crop row from each plot at harvest maturity (R_8 growth stage) in both years. Ten plants were also randomly selected from each plot at maturity for measurement of plant height, number of branches per plant, number of pods per plant and number of seeds per plant. The plots were harvested on 26 September 2005 and 02 October 2006.

Table 2. Precipitation, irrigation, and crop evapotranspiration (ET_c) of well-watered soybean planted in 2005 and 2006.

Growth stage	Precip. (mm)		Irrigation (mm)[a]		ET_c (mm)	
	2005	2006	2005	2006	2005	2006
Vegetative(V5)			105	128		
Flowering(R2)			80	80		
Podding(R4)			106	141		
Seed fill(R6)			137	89		
Total	156	150	428	453	684	771

[a]An additional 15 mm of irrigation was applied at planting in April 2006 for seed zone wetting to obtain uniform emergence.

All data were analyzed by analysis of variance using MSTAT-C (ver. 2.1) and MINITAB software. When treatment effects were significant, means were compared at the 0.05 level using the least significant difference ($LSD_{0.05}$) (Note: this test is inappropriate when the total number of treatments is greater than five. Consult a statistician and use a more appropriate test).

RESULTS AND DISCUSSION

Applied irrigation water and evapotranspiration

Weather data recorded during the experiments were compared with the long-run averages recorded in Bursa Meteorological Station. In both years, monthly air temperature and relative humidity were the same as the long-run averages of the period between 1975 and 2003. Figure 1 shows the seasonal variation of some climatic parameters during the experiment years.

The first irrigation water was applied to DOY 174 and DOY 185 in 2005 and 2006 respectively. The amount of the applied irrigation water for each treatment is given in Table 2. The irrigation water applied to the treatments ranged between 80 and 137 mm in 2005, and between 80 and 141 mm in 2006. As it is seen in Table 2, the amounts of irrigation water showed differences from each other except for R2 period, and the highest level of irrigation water was applied in R6 period (137 mm) in the first experiment year and in R4 period (141 mm) in the second year. The total amounts of irrigation water applied to the control treatment (T_1) were 428 and 453 mm in 2005 and 2006, respectively. In both experimental years, almost equal amounts of irrigation water were applied in T_2 and T_4 treatments in the first year and in T_3 and T_6 treatments in the second year.

The seasonal amount of the applied irrigation water for each stages of development, seasonal ET and precipitation values during the experiment years are given in Table 2. The total amounts of irrigation water applied to the control treatment (T_1) were 428 and 453 mm in 2005 and 2006, respectively. The seasonal evapotranspiration 684 mm in the first year and 771 mm in the second year, respectively (Table 2). In the growing periods, the total amounts of rain were 156 mm in 2005 and 150 mm in 2006. The seasonal evapotranspiration variations between T_1 and T_8 treatments were 80% in the first year and 123% in the second year. These values are comparable with ET values pointed out by Doorenbos and Kassam (1979). The authors stated that the water requirements of soybean vary from 400 to 700 mm/season and the total growing period of soybean vary from 100 to 130 day depending on climate and length of total growing period. The main reason for differences was that the total growing period was 159 and 153 days for 2005 and 2006, respectively. In similar experiments elsewhere, average across years of crop evapotranspiration (ETc) was found totaled 762.5 mm for an average growing season of 139 days from planting till harvest (Karam et al., 2005). Cox and Jollift (1986) found that evapotranspiration of soybean plant for deficit-irrigated and non-irrigated treatments were 17 and 68% less than the one in well-irrigated treatment, respectively. These differences may be attributed to the environmental conditions and the different soybean cultivars used in the experiments. Carter and Hartwing (1963) indicated that seasonal water use for soybean can range between 508 and 762 mm. Whitt and van Bavel (1955) found that seasonal water requirements ranged from 330 to 584 m, with a maximum water use rate of 7.6 $mmday^{-1}$ in July and August. The period between July and August coincides with the pod initiation and seed enlargement stages, where higher levels of water requirements of soybean are recorded (Asley, 1983).

Table 3 presents the seasonal applied water, seasonal total evapotranspiration (ET), seed yield, water use efficiency (WUE), and irrigation water use efficiency (IWUE) for the drought stress treatments.

Seed yield increased significantly as irrigation amount increased (Table 3). The WUE and IWUE were different depending upon the drought stress treatments and little change when irrigation amount decreased. However, WUE and IWUE were different depending on the treatments. T2 treatment is the most efficient in WUE with the value of 0.59 and 0.54 $kg.m^{-3}$ for 2005 and 2006, respectively. WUE values of T_2 treatment were higher

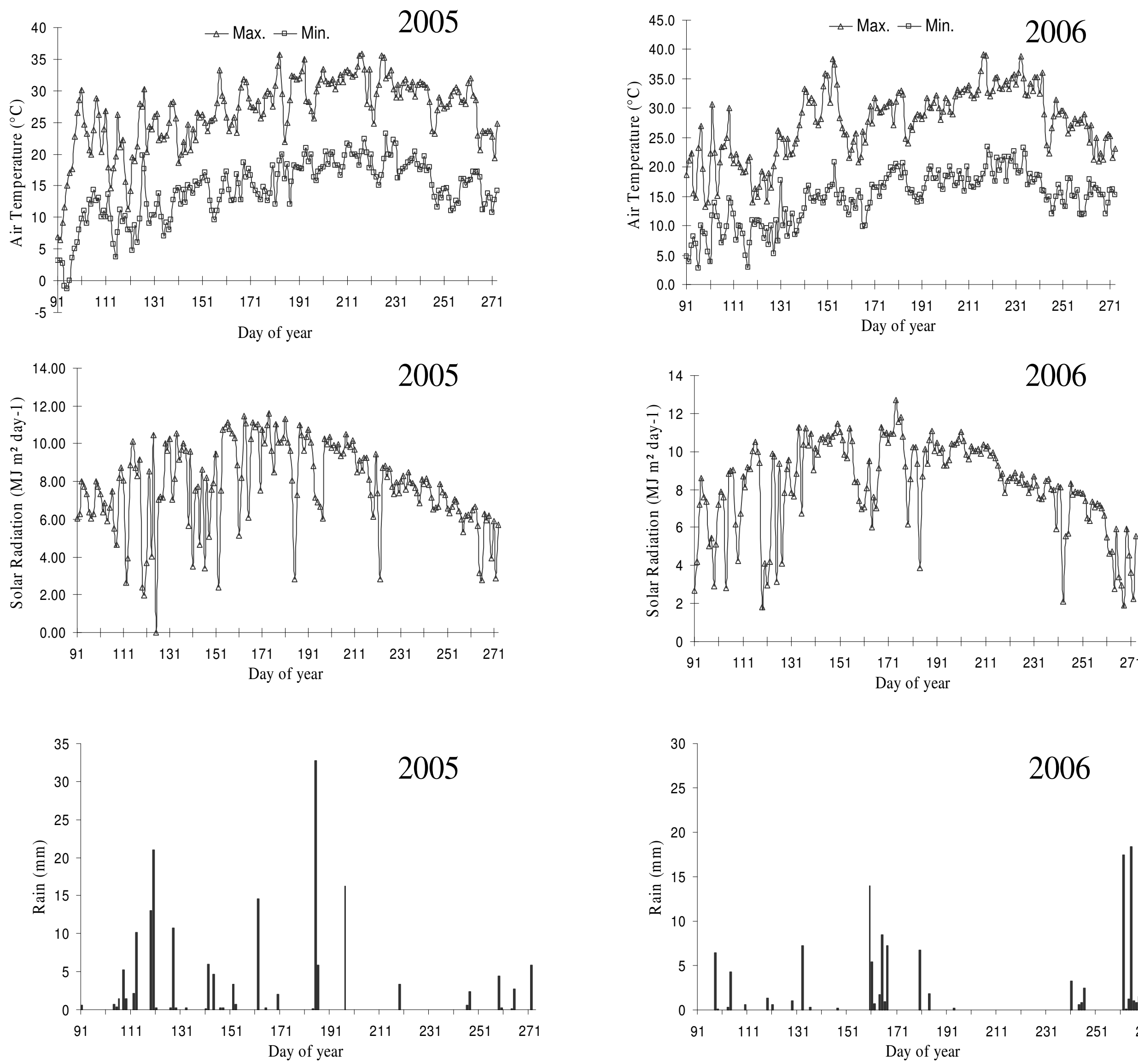

Figure 1. Daily climatic parameters for 2005 and 2006 of experimental area.

than the other treatments with the percentage of 1 - 18% and 16 - 30% for the same years, respectively. Karam et al. (2005) stated that average crop evapo-transpiration (ET_c), as measured by drainage lysimeters, totaled 800 mm for a total growing period of 140 days. When ET_c was measured by weighing lysimeters, it was 725 mm during a growing period of 138 days. Eck et al. (1987) reported that applying water stress did not increase WUE in soybean. On the other hand, Karam et al. (2005) found that WUE of the deficit irrigated treatments S_1 (Treatment irrigated at 100% FC with no irrigation at full bloom stage) and S_3 (Treatment irrigated at 100% FC with no irrigation at mature seed stage) were 13 and 4% higher than the well-irrigated (control) treatment, whereas the S_2 (Treatment irrigated at 100% FC with no irrigation at seed enlargement) had a WUE value 17% lower than the control. Scott et al. (1987) reported that the average water use efficiency of soybean was approximately 6.0 kg ha^{-1} mm^{-1}, while the water use efficiency increased 7.3 kg ha^{-1} for each millimeter of water used.

Yield-ET relations for soybean were obtained by plotting observed yield on the Y-axis and the ET on the X-axis, over the mean of 2-years (Figure 2). An exponential relationship was found between seasonal ET and seed yield at 99% level of confidence. Seed yield responded exponentially to increased ET, which can be attributed to applied water (Figure 2).

The correlation coefficients between seasonal evapo-transpiration and seed yield were found as r^2 = 0.98 and r^2 = 0.92 in 2005 and 2006, respectively (Figure 2). Payero et al. (2005) found that the correlation coefficient between seasonal evapotranspiration and seed yield as

Table 3. Effect of drought treatments on irrigation, crop evapotranspiration (ET_c), seed yield, water use efficiency (WUE), and irrigation water use efficiency (IWUE) of soybean in 2005 and 2006.

Treatment[a]	Irrigation (mm)[b]		ET_c (mm)		Yield (tons ha^{-1})		WUE (kg·m^{-3})[c]		IWUE (kg·m^{-3})[d]	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
T_1	428	453	684	771	4.00	3.57	0.58	0.46	0.37	0.34
T_2	323	310	616	638	3.66	3.46	0.59	0.54	0.38	0.45
T_3	348	358	654	759	3.64	3.41	0.56	0.45	0.35	0.37
T_4	322	297	642	711	3.51	3.27	0.55	0.46	0.34	0.40
T_5	242	217	578	646	2.91	2.67	0.50	0.41	0.20	0.28
T_6	291	349	632	689	3.35	2.93	0.53	0.43	0.32	0.25
T_7	211	269	571	603	3.01	2.60	0.53	0.43	0.28	0.20
T_8	0	0	381	346	2.42	2.07	0.64	0.60	--	--

[a]Treatments are summarized in Table 1.
[b]An additional 15 mm of irrigation was applied to each treatment at planting in April 2006.
[c]Calculated as the ratio of seed yield to total crop evapotranspiration.
[d]Calculated as the difference between treatment seed yield (T_{1-7}) and seed yield under rain-fed conditions (T_8) divided by the total amount if irrigation applied to the treatment (Howell, 2000).

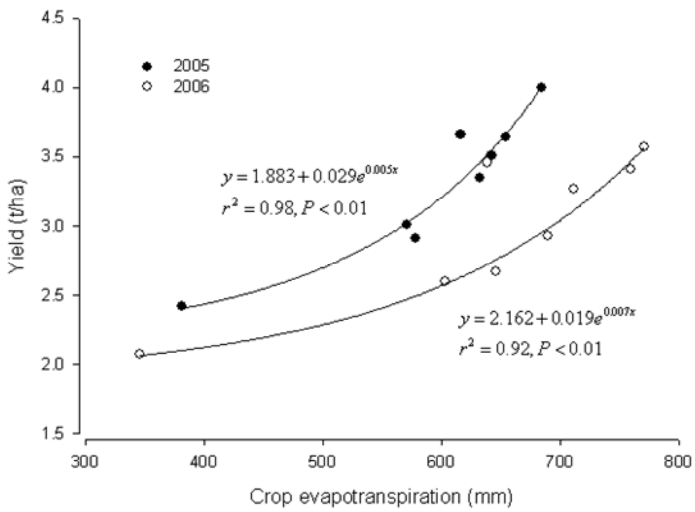

Figure 2. Relationship between seed yield and crop evapotranspiration of soybean in 2005 and 2006.

r^2 = 0.80 and r^2 = 074 in their two years study.

The impacts of drought stress on agronomic parameters

The drought stress significantly effected to the seed yield, biomass, and the number of seed per plant and the height of the plant in both experimental years (Table 4).

The results indicated that non-irrigated treatments at different growth stages significantly reduced plant height in soybean. In other studies, it was also reported that irrigation treatments significantly enhanced plant height compared to non-irrigated (Brady et al., 1974; Korte et al., 1983; Kadhem et al., 1985). Drought stress also significantly affected number of branches per plant.

The T_1 (Non-irrigated) and T_6 (R_2 + R_4) or T_7 (R_2 + R_6) drought stress treatments significantly decreased number of branches per plant compared with the non-stressed check and single T_2 (V_5) or T_3 (R_2) drought stress treatments. Our findings do not correspond to those of Ashley and Ethridge (1978) and Momen et al. (1979) who reported that irrigation treatments had no significant effect on the number of branches per plant. On the other hand, Frederick et al. (2001) stated that drought stress treatment had no effect on branch number per m^2 measured at flowering but had a large effect on the final number of branches formed. This disagreement may be due to the different environmental conditions and the different soybean cultivars used in the experiments.

The drought stress significantly effected height of the

Table 4. The effects of irrigation treatments on soybean yields and its components in 2005 and 2006.

Treatments	Year	Plant height (cm)	First pod height from the ground (cm)	Number of branches per plant	Number of pods per plant	Number of seeds per plant	Biomass (tons ha^{-1})	Seed yield (tons ha^{-1})	Harvest index (%)	1000-seed weigth (g)	Seeds per pod
T_1	2005	97.1 a	18.3 a	5.3 b	57.0 a	155.0 a	10.75 a	4.00 a	37.2	132.2	2.7
	2006	77.5 a	16.5 a	4.2	39.7 a	111.6 a	9.44 a	3.57 a	37.8	130.5 a	2.8
T_2	2005	94.0 a	16.4 a-c	5.0 b	49.9 ab	140.5 ab	9.90 b	3.66 ab	37.0	130.9	2.4
	2006	73.5 ab	15.4 ab	3.9	36.9 ab	107.5 a-c	8.95 ab	3.46 a	38.6	128.7 ab	2.9
T_3	2005	97.1 a	16.9 ab	6.7 a	50.7 ab	139.3 ab	9.30 bc	3.64 b	39.1	133.7	2.7
	2006	72.0 ab	16.1 a	3.7	37.8 ab	110.2 a	9.19 ab	3.41 a	37.2	127.6 a-c	2.9
T4	2005	86.8 ab	14.2 bc	5.1 b	48.1 bc	132.4 b	9.06 cd	3.51 b	38.7	133.0	2.8
	2006	69.5 b	14.5 a-c	3.7	35.2 ab	100.6 ab	8.55 bc	3.27 ab	38.3	126.4 a-c	2.8
T5	2005	89.8 ab	16.7 a-c	4.8 b	40.5 cd	95.1 cd	8.69 d	2.91 bc	38.5	131.3	2.7
	2006	72.2 ab	14.9 a-c	3.4	37.1 ab	102.7 a-c	8.16 c	2.67 bc	35.8	124.2 bc	2.8
T6	2005	77.5 b	14.4 bc	4.3 bc	37.3 de	104.5 c	7.81 e	3.35 d	37.2	127.1	2.8
	2006	69.5 b	13.5 bc	3.3	32.6 a-c	90.2 b-d	7.44 d	2.93 c	35.9	122.8 cd	2.7
T7	2005	76.3 b	14.2 bc	4.3 bc	33.9 de	97.0 cd	7.74 e	3.01 cd	39.0	128.0	2.8
	2006	68.3 b	13.1 c	3.2	30.5 bc	84.7 cd	7.26 d	2.60 c	35.8	123.6 cd	2.8
T8	2005	60.2 c	13.3 c	3.6 c	29.7 e	78.4 d	6.21 f	2.42 e	39.0	125.1	2.6
	2006	57.0 c	9.9 d	3.0	27.2 c	72.7 d	5.88 e	2.07 d	35.0	119.1 d	2.7
Block	2005	2.4	10.9	0.5	28.4	333.6	3239.0	236.8	3.6	6.0	0.02
	2006	73.1*	4.5	0.6	78.5*	421.3*	4350.0	892.7	3.4	7.2	0.03*
Treatment	2005	491.0**	9.2*	2.4**	268.5**	2250.4**	0215.0**	7644.4**	2.5	28.5	0.07
	2006	109.1**	13.5**	0.5	53.6*	568.9**	42828.0**	8252.0**	5.2	39.6**	0.01
Error	2005	68.0	3.9	0.4	20.1	141.1	1240.0	417.0	7.0	30.5	0.04
	2006	12.7	1.5	0.5	17.7	101.0	1555.0	467.1	3.9	8.3	0.01
LSD(0.05)	2005	14.4	3.4	1.1	7.8	20.8	61.6	35.7	ns	ns	ns
	2006	6.2	2.1	ns	7.3	17.6	69.1	37.8	ns	5.0	Ns
CV	2005	0.5	0.01	0.003	0.1	1.7	17.7	5.2	0.01	0.1	0.001
	2006	0.02	0.002	0.001	0.1	1.0	30.2	7.3	0.004	0.01	0.001

ns: Not significant.

plants in both years and the heights of the plants ranged between 60.2 and 97.1 cm in the first year and between 57.0 and 77.5 cm in the second year. While the highest values were obtained in T_1 treatment, the lowest values were in T_8 treatment. Kadhem et al. (1985), Korte et al. (1983) and Brady et al. (1974) also reported that irrigation treatments significantly increased the plant height more than the plant heights in the non-irrigated treatment.

The height of the first pod from the ground was significantly affected in both experimental years of the study and while the highest values were in T_1 treatment, the lowest values were obtained in T_8 treatment. However, all of the treatments except for T_1 and T_8 treatments were in the same group.

The drought stress treatments significantly effected number of the pods per plant in both experimental years and the values varied between 29.7 to 57.0 in the first year and 27.2 to 39.7 in the second year. The highest values were obtained in T_1, T_2, T_3 and T_4 treatments. This agrees with the results related to the number of the pods per plant in the study of Desclaux et al. (2000). They reported that each drought stress treatment decreased the number of pods per plant in different ways. Other researchers reported similar results (De Costa and Shanmugathasan, 2002; Kadhem et al., 1985).

Drought stress effected insignificantly on number of seeds per plant and it was varied 2.4 - 2.8 in the first year, and 2.7 - 2.8 in the second year. However, the number of the seeds in the plant was found significant in both experimental years.

In a similar study, Smiciklas et al. (1992) found that the R_2 + R_4 and R_2 + R_6 drought- stress treatments significantly decreased seed number per plant in comparison with the non-stressed and single R_2 or R_4 drought-stress treatments. Our findings were also in agreement with the results reported by Kadhem et al. (1985), Korte et al. (1983) and Karam et al. (2005).

The highest seed yield was obtained in T_1 and T_2

Table 5. The effects of irrigation treatments on leaf area (cm^2 per plant) and leaf area index (LAI) measured at four growth periods in 2005 and 2006.

Treatment	Growth periods															
	V_5				R_2				R_4				R_6			
	Leaf Area (cm^2)		LAI		Leaf Area (cm^2)		LAI		Leaf Area (cm^2)		LAI		Leaf Area (cm^2)		LAI	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
T_1	782.0 a	710.3	2.4 ab	2.2 ab	1113.5 ab	031.8 bc	3.4 bc	3.2 bc	2070.5 b	1956.4 b	6.4 b	6.1 b	1863.2 b	1788.6 b	5.8 b	5.5 b
T_2	771.8 ab	710.0	2.4 ab	2.2 ab	1056.5 bc	1011.8 c	3.3 c	3.1 c	1862.0 c	1764.0 c	5.8 c	5.5 c	1786.2 c	1701.5 c	5.5 c	5.2 c
T_3	727.2 b	700.5	2.3 b	2.1 b	1093.1 ab	042.3 bc	3.4 bc	3.2 bc	2045.8 b	1946.4 b	6.3 b	6.0 b	1758.4 c	1645.1 c	5.4 cd	5.1 c
T_4	726.3 b	732.2	2.3 b	2.2 ab	1120.0 a	1053.5 ab	3.5 ab	3.3 ab	2057.3 b	1985.8 b	6.4 b	6.1 b	1730.3 c	1629.3 c	5.3 d	5.0 c
T_5	764.2 ab	687.0	2.4 ab	2.1 b	1088.5 ab	1022.9 bc	3.4 bc	3.2 bc	1727.5 e	1663.9 d	5.3 e	5.1 e	1515.0 d	1427.0 d	4.7 e	4.4 d
T_6	725.9 b	692.7	2.3 b	2.1 b	1089.0 ab	037.4 bc	3.4 bc	3.2 bc	1799.1 d	1704.4 cd	5.6 d	5.3 d	1511.5 d	1428.2 d	4.7 e	4.4 d
T_7	782.5 a	734.6	2.5 a	2.3 a	1146.3 a	1089.9 a	3.6 a	3.4 a	2188.5 a	2104.4 a	6.8 a	6.5 a	2049.5 a	1935.4 a	6.3 a	6.0 a
T_8	771.2 ab	697.1	2.4 ab	2.2 ab	1012.8 c	920.9 d	3.1 d	2.8 d	1548.4 f	1453.0 e	4.8 f	4.5 f	1352.8 e	1269.3 e	4.2 f	3.9 e
LSD (0.05)	54.1	n.s	0.1	0.1	59.6	39.8	0.2	0.1	49.8	75.7	0.1	0.2	68.0	75.7	0.2	0.2

ns: Not significant

treatments and the lowest yield was obtained in T_8 treatment. But the T_3 treatment was in the same group with T_1 and T_2 treatments in 2006 (Table 4). The seeds yields varied from 4.0 to 2.4 tons ha^{-1} in the first year and 3.6 to 2.1 tons ha^{-1} in the second year. The seed yield in the first year was higher than the second year, and the variation between these years was 12% for T_1 treatment and 17% for T_8 treatment. It is possible to attribute this variation to the rainfall in R2 period in 2005. Additionally, as a result of this rainfall, the seeds yields were obtained very close to all drought treatments except T_8. Single drought-stress treatments (T_2, T_3, T_4 and T_6) produced 7 – 34 and 9 – 65% less seeds yields in the first and second years respectively in comparison to the T_1. Doss et al. (1974) and Sionet and Kramer (1977) found that the stress applied during either pod formation or pod filling resulted in greater yield reduction than the stress applied during flower induction or flowering.

Korte et al. (1983) reported that a single irrigation at flowering (F) had no effect on seed yield, whereas a single irrigation at pod elongation (P) or seed enlargement (S) significantly enhanced seed yields relative to the non-irrigation check (CK). Similarly, Ashley and Ethridge (1978), Huck et al. (1983) and Foroud et al. (1993) suggested that water deficit during flowering (R_2) had little effect on seed yield whereas deficits during pod elongation (R_3) and seed enlargement (R_5) had significant effects. In addition, Meckel et al. (1984), Smiciklas et al. (1992) and Frederick et al. (1991) noted that water stress during seed filling shortened the seed-filling period and reduced seed yield. In a previous study, it was also reported that deficit irrigation at R_2 stage reduced seed yield by 4%, while deficit irrigation at the R_5 stage reduced seed yield by 28%, in comparison to the control (non-stressed) (Karam et al., 2005).

The effect of drought stress on 1000-seed weight values was found insignificant in the first year, but it was found as significant in the second year. Non-significance in 1000-seed weight for the first year can be attributed to the rainfall in R2 period. 1000-seed weight values ranged between 125.1 and 132.3 g in the first year and 119.1 and 130.5 g in the second year. In the second year the significant decreases in 1000-seed weight were observed in the pod filling period in the stress applied T_6 and T_7 treatments and non-irrigated (T_8) treatment.

The effects of drought stress on biomass in both experimental years were found significant. The values of biomass were ranged between 6.1 and 10.75 tons ha^{-1} in the first year and 5.88 and 9.44 tons ha^{-1} in the second year.

Especially, the biomass was significantly dec-reased as a result of the application of drought stress in the pod filling period. The results obtained for 1000-seed weight and biomass values were similar to Karam et al. (2005).

Harvest index was not affected by drought stress treatments according to individual or 2-year average results. It was varied 37.0 – 39.1 in the first year, and 35.0 - 38.6 in the second year. Harvest index was not affected by drought stress treatments.

The maximum values in leaf area andleaf area index (LAI) were reached at R4 period. The effects of drought stress on leaf area and leaf area index was found significant except for V5 period and while the highest leaf area and LAI values were reached in T_7, the lowest values were reached in T_8 treatment (Table 5). These results are similar to those of Scott and Batchelor (1979), Huck et al. (1986). Karam et al. (2005) stated that moisture deficit at seed enlargement (R_5), LAI was reduced by 10%, compared with the R_4 stage and deficit irrigations at seed enlargement and mature seeds reduced LAI by an average of 30% with comparison to the control. The same researchers reported that growth parameters, such as leaf area index and dry matter accumulation, have been shown to be sensitive to water stress caused by deficit irrigations.

The impacts of drought stress on quality parameters

The drought stress treatments significantly affected crude protein percentage, crude protein yield, crude oil rate and crude oil yield in both experimental years (Table 6). The crude protein rate and crude protein yield values varied between 31.4 to 35.5%, 86.1 to 116.9 kg da^{-1} in the first year and 30.2 to 33.8%, 69.8 to 109.5 kg da^{-1} in the second year, respectively. The crude oil rate and crude oil yield values varied between 16.7 to 19.5%, 40.3 to 78.0 kg da^{-1} in the first year and 19.1 to 21.2%, 40.8 to 75.7 kg da^{-1} in the second year, respectively.

These results were in agreement with XiaoBing et al. (2004) and Kane et al. (1997). The crude protein yield and crude oil yield was significantly affected by drought stress on R_6 (T_6 and T_7 treatments) in comparison with the other irrigation treatments in both experimental years.

Conclusion

This study was carried out to determine the yield response of soybean to drought stress during different vegetative and reproductive periods in sub humid climate conditions.

According to the results, the seasonal evapo-transpiration 684 mm in the first year and 771 mm in the second year, respectively. The effects of drought stress on the seed yield, biomass, the number of seeds per plant and the height of the plant were found statistically significant and the highest and the lowest seed yields were obtained in T_1 and T_8 treatments, respectively. The average yield difference was 67%. In T_2, T_3, T_4 and T_6 treatments, where drought stress was applied only in one of the development periods, the yield differences were 6, 9, 12 and 36% respectively in comparison to T_1 treatment. The yield decreases in T_5 and T_7 treatments, where drought stress was applied in two periods, were 21 and 35%, respectively, in comparison to T_1 treatment. When these yield decreases were compared as a whole, it can be said that water deficit applied especially during the pod filling stage (T_6, T_7) reduces the crop yield substantially.

Results indicated that the seed yield in soybean was not affected by the drought stress during the vegetative development stage, whereas single or multiple drought-stress treatments applied during the reproductive deve-lopment stages, pod elongation or seed enlargement resulted in significant reductions of seed yield. The drought stress treatments have significant effects on qua-lity parameters and protein yield and oil yield was significantly affected by drought stress on R_6 in comparison with the other irrigation treatments. In spite of the fact that the highest seed yield was obtained in T_1 treatment when the WUE and IWUE values are taken into consideration, T_2 treatment and also T_3 and T_4 can be suggested in both experimental years based on the applied irrigation water. Under the conditions that water resources are scarce, it can be recommended that one of those water application levels should be used instead of T_1 irrigation treatment.

As a conclusion, this study indicated that seed yield in soybean was not affected by the drought stress during a vegetative development stage (V_5; 5th node on the main stem beginning with the unifoliate note) whereas single or multiple drought stress treatments applied during reproducetive development stages [flowering (R_2), pod elongation (R_4) or seed enlargement (R_6)] resulted in significant reductions of seed yield. Although there was a slight decrease in seed weight (1000 seed weight) during water stress at pod elongation (R_4) and seed enlarge-ment (R_6) periods, seed yield was significantly reduced due to a significant reduction in the number of pods per plant and number of seeds per plant. Seed per plant was the most sensitive yield component to drought stress during seed enlargement stage. It is concluded that soybean should be irrigated four times with full irrigation water at vegetative stage (V_5), flowering (R_2), pod elonga-tion (R_4) and seed enlargement (R_6) periods for high seed yield. However, these irrigation schemes must be re-considered in areas where water resources are more limited. In case of limited irrigation, reduced irrigation water during the R_2 + R_4 and R_2 + R_6 periods and single R_4 or R_6 stages should be avoided. When irrigation water was limited, deficit irrigation at V_5 stage was more profitable than irrigation deficit at any other soybean growth stages and did not cause significant reductions in seed yield.

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