Field Crops Research, 23 (1990) 103-116
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Scheduling Irrigations for Soybeans with the Crop Water Stress Index (CWSI)

D.C. NIELSEN

USDA-ARS, Central Great Plains Research Station, P.O. Box 400, Akron, CO 80720 (U.S.A.)

(Accepted 16 October 1989)

ABSTRACT

Nielsen, D.C., 1990. Scheduling irrigations for soybeans with the Crop Water Stress Index (CWSI). *Field Crops Res.*, 23: 103-116.

A Crop Water Stress Index (CWSI) has been related to water use and plant water-stress parameters, but irrigation scheduling based on CWSI values has only been reported for corn and wheat. The objectives of this study were to evaluate irrigation scheduling of soybean (*Glycine max* L. Merrill) with CWSI as computed from measurements of infrared canopy temperature, air temperature, and vapor-pressure deficit, and to determine if amount of water applied per irrigation influenced water use and yield obtained from irrigation scheduling by CWSI. Soybeans were grown in field plots with drip irrigation (25 mm water per irrigation) and under a rainout shelter with flood irrigation (25 or 51 mm water per irrigation). Irrigations were initiated when CWSI reached threshold values of 0.1, 0.2, 0.4, or 0.6. Analysis of the data showed the CWSI baseline equation to be incorrect. A new baseline was computed and reanalysis of the CWSI data showed true irrigation thresholds had been 0.2, 0.3, 0.4, and 0.5. These four threshold values resulted in total irrigation amounts of 181, 180, 174, and 145 mm applied to the drip-irrigated plots, respectively. Under the rainout shelter, total irrigation amounts of 347, 271, 195, and 195 mm when 25 mm was applied per irrigation, and 406, 356, 356, and 305 mm when 51 mm was applied per irrigation, resulted from the 0.2, 0.3, 0.4, and 0.5 CWSI thresholds, respectively. Respective yields for these plots were 2656, 2566, 2430, and 2189 kg ha^{-1} for the drip-irrigated plots, 3375, 2826, 2435, and 2365 kg ha^{-1} for the rainout-shelter plots with 25 mm per irrigation, and 3575, 3551, 3110, and 2108 kg ha^{-1} for the rainout-shelter plots with 51 mm per irrigation.Under deficit-irrigation conditions the relationship between CWSI, soil water content, and leaf water-potential appears to change. Knowing how much water to apply per irrigation is important information for effectively using CWSI to schedule irrigations in soybeans. Cloudy sky conditions do not occur with sufficient frequency in the central Great Plains to inhibit the timely use of the infrared thermometer for irrigation scheduling.

INTRODUCTION

A crop water stress index (CWSI) normalized for environmental variability (Idso et al., 1981a) has been shown to be closely related to extractable water in the root zone of a wheat crop (Jackson et al., 1981), to plant water-potential in wheat and alfalfa (Idso et al., 1981b,c) and cotton (Pinter and Reginato,

Elsevier Science Publishers B.V.

1982), and to leaf diffusion resistance and photosynthesis in cotton (Idso et al., 1982). In experiments with graded amounts of irrigation water applied to guayule, Bucks et al. (1985) observed consistent variation of the CWSI, with higher values of the CWSI under lower irrigation levels. In a similar experiment with alfalfa, Kirkham et al. (1983) found no significant difference in canopy temperatures among irrigation treatments.

Irrigation scheduling based upon values of the CWSI appears to be promising for some crop species, but results of studies testing such a technique have only been reported for cereals, e.g. corn (Nielsen and Gardner, 1987) and wheat (Garrot et al., 1986). The objectives of this study were to determine: (i) if the CWSI can be used to schedule irrigations in soybean (a grain legume); (ii) if the previously published non-water-stressed baseline equation is valid; (iii) what size of yield and water-application variation could be expected by initiating irrigations with several threshold values of the CWSI; and (iv) if amount of water applied per irrigation influenced plant/water relationships, water use, and yield of soybeans with irrigations scheduled by CWSI.

MATERIALS AND METHODS

This study was conducted during the 1985 and 1986 growing-seasons at the USDA Central Great Plains Research Station (40°9′N, 103°9′W, 1384 m a.m.s.l.), 6.4 km east of Akron, CO. The soil type at this location is a Rago silt loam (fine montmorillonitic mesic Pachic Argiustoll). Soybeans (*Glycine max* (L.) Merrill, hybrid Pioneer brand 9291) were planted into unfertilized plot areas. Details of planting date, plant population, row spacing, and plot dimensions are given in Table 1. In 1985 and 1986, the experiment was conducted in plots that were covered automatically by a rainout shelter (hereafter referred to as RO plots) during precipitation events. In 1986, the experiment was also conducted in a conventional field location where plots were drip-irrigated (hereafter referred to as drip plots). These plots were sprayed with trifluralin (α,α,α-trifluoro-2,6-dinitro-*N*-*N*-dipropyl-*p*-toluidine) at 1.1 kg ha^{-1} which was disk-incorporated prior to planting to control weeds throughout the grow-

TABLE 1

Plot specifications and beginning and ending irrigation-scheduling dates for soybeans, 1985 and 1986 growing-seasons

Year	Planting date	Irrig. method	Water applied irrigation^{-1}	Row spacing	Population (plants ha^{-1})	Plot size (m)	Replications	Area sampled for yield (m^2)	Dates and stages for irrigation scheduling	
									Begin	End
1985	28 May	Flood	25 mm	0.53 m	331 000	2.7×2.7	3	3.2	23 Jul (V7)	16 Sep (R7)
1986	20 May	Flood	51 mm	0.53 m	394 000	2.7×2.7	3	3.2	15 Jul (V6)	4 Sep (R6)
1986	20 May	Drip	25 mm	0.76 m	271 000	4.6×9.0	4	6.4	15 Jul (V6)	4 Sep (R6)

ing-season. Soybean seed was inoculated with *Bradyrhizobium japonicum*. The RO plots were hand-weeded.

The statistical design was a randomized complete block with four treatments of threshold values of the crop water stress index (CWSI) at which to initiate irrigations (i.e., CWSI=0.1, 0.2, 0.4, or 0.6).

Canopy temperatures were measured with a hand-held infrared thermometer, IRT (Model 112 Agritherm, Everest Interscience, Fullerton, CA)[1]. The IRT has a field of view of 3° and detects radiation in the 8–14-μm waveband. Measurements were made on weekdays between 13:00 and 14:00 MDT[2], when the sun was unobscured by clouds. Three instantaneous measurements were made on each of the two center rows from the east and west sides of each drip plot. In each RO plot, six instantaneous measurements were made on the center row from the north and south sides. Data were recorded with a portable data logger (Polycorder, model 516B, Omnidata International, Logan, UT). The infrared thermometer was calibrated before and after each daily measurement period using a blackbody reference. The IRT was hand-held at approximately 1.5 m above the soil surface. Spot size ranged from 0.19 m^2 to 0.25 m^2, depending on canopy height. Air temperature and vapor-pressure deficit were measured at a height of 1.5 m before and after each measurement period with an Assman-type psychrometer in an open area adjacent to the plots. The 12 canopy-temperature measurements per plot were averaged and the CWSI calculated as:

$$\text{CWSI} = (T_c - T_a - D_2)/(D_1 - D_2) \quad (1)$$

where : T_c is average canopy temperature (°C); T_a, air temperature (°C); D_2, $T_c - T_a$, predicted from baseline equation $1.44 - 1.34 * \text{VPD}$; VPD, vapor pressure deficit (kPa); and D_1, maximum difference between T_c and T_a (calculated as given in Idso et al., 1981a).

The baseline equation, D_2, was that given for soybeans by Idso (1982), and was derived from temperature and humidity data collected over soybeans at Manhattan, Kansas and Fargo, North Dakota.

At the same time that the canopy temperatures were being measured with the IRT in the drip plots, measurements were being made of leaf photosynthesis, transpiration, and stomatal resistance with a portable photosynthesis system (LI-6000, LICOR, Inc., Lincoln, NE) on the center leaflet of an upper-canopy, fully sunlit trifoliate of 6 plants per treatment. Also, 6 other upper-canopy, fully sunlit trifoliates per treatment were sampled for leaf water-potential with a pressure bomb (Water Status Console, Model 3003, Soil Moisture Equipment Corp., Santa Barbara, CA). The procedure outlined by Turner

[1]Trade names and company names are included for the benefit of the reader, and do not imply any endorsement or preferential treatment of the product by the author or the USDA.
[2]MDT, Mountain Daylight Time.

(1987) was followed with immediate covering of the leaf with a plastic sheath after excision. Typically, less than 20 s passed between excision and pressurization.

When the average CWSI for the five replications in the drip plots (three replications in the RO plots) reached or exceeded the treatment threshold value, all plots associated with that treatment were irrigated. Irrigations were applied through drip-irrigation lines (Chapin Watermatics, Inc., Watertown, NY) with approximately 25 mm of water being applied per irrigation period. The rainout-shelter plots were flood-irrigated with 25 mm of water per irrigation in 1985 (51 mm in 1986) when the threshold value was reached or exceeded. Dates and growth stages when irrigation scheduling began and ended are given in Table 1.

Soil water was measured twice each week with a neutron probe at depths of 0.15, 0.46, 0.76, 1.06, 1.37, and 1.68 m. The data were used to calculate evapotranspiration by the water balance method. The neutron probe was calibrated at the beginning of the season against the gravimetric data collected at the time of access-tube installation. Initial gravimetric soil-water samples taken in the drip-plot area showed approximately 191 mm of available soil water in the surface-to-1.83-m soil profile. The RO plots contained approximately 169 and 197 mm of available soil water in the surface-to-1.83-m profile in 1985 and 1986, respectively. Crop height and stage of development (Fehr and Caviness, 1977) were also measured twice weekly on six randomly selected plants in the center of each plot.

A 3.1-m length of each of the two center rows of each drip plot was harvested for yield on 25 September 1986. A 2.0-m length of each of the three center rows of each RO plot was harvested for yield on 31 September 1985 and 25 September 1986. Yield components were determined and analysis of variance performed on the data.

RESULTS AND DISCUSSION

The variation of CWSI with time was similar for all three experiments, so only the results of the 1986 drip plots will be discussed in detail. Precipitation for the growing-season was 29% below average, creating a substantially water-deficit environment for growing soybeans (Table 2). June was the only month with above-normal precipitation.

Figure 1 shows the seasonal course of CWSI and the dates of irrigation for the four treatments. The graphs show the increase in the CWSI that occurred with time as soil water was consumed in evapotranspiration (E_t) and presumably became limiting to E_t. Following an irrigation or precipitation event, the water stress was relieved and the CWSI declined. Similar results were found for the RO plots (data not shown). A problem that can be seen in the results is that, on a number of occasions, CWSI exceeded the theoretical bounds of 0.0 (no

TABLE 2

Growing-season precipitation (mm) for 1986, and 79-year average

Dates	1986	Average 1908–1986	Difference	Cumulative Difference
1-31 May	63.0	76.2	−13.2	−13.2
1-30 June	90.4	63.5	+26.9	+13.7
1-31 July	8.9	67.0	−58.1	−44.4
1-31 Aug.	25.7	50.3	−24.6	−69.0
1-30 Sept.	17.0	31.0	−14.0	−83.0

water stress) and 1.0 (maximum water stress) by more than 0.2. This indicates that the baseline equation used was probably incorrect. Analysis of canopy-temperature data from 0.1- and 0.2-CWSI plots on the day following irrigation periods (Fig. 2) gave us a significantly different baseline equation of:

$$D_2 = 2.51 - 2.02 * \text{VPD} \qquad (2)$$

When the CWSI data were recalculated using the new baseline, none of the values exceeded 1.0 and only a few were below the minimum value of 0.0 (Fig. 3). The tendency for low values of CWSI to be occasionally negative can be attributed to the scatter in the data used to construct the baseline regression.

Although the irrigation-treatment threshold values adhered to were 0.1, 0.2, 0.4, and 0.6 when CWSI values were computed with the improper baseline equation, the actual threshold values used to initiate irrigations were 0.2, 0.3, 0.4, and 0.5 when calculated with the correct baseline equation.

On several occasions throughout the growing-season, there were gaps in the data collected due to weekends or cloudy conditions. During those periods the plants continued to use water, so that when the next CWSI measurement occurred, the value recorded had already exceeded the threshold value. Consequently, the average CWSI values at irrigation time were significantly higher than the established threshold values (Table 3). Measurements of leaf photosynthesis, transpiration, and stomatal resistance indicated that stomatal resistance was low and leaf photosynthesis and transpiration rates were high at CWSI values <0.2 (Fig. 4). However, the average CWSI at irrigation for the 0.2 CWSI plots ranged between 0.32 and 0.37, so even this irrigation treatment experienced some potentially yield-reducing water stress. The fairly wide variation in maximum photosynthesis rate and transpiration rate at low CWSI values can be attributed to the wide range of ambient air temperature over the measurement periods noted in the Figure. For example, for the measurements made between 14 July and 8 August, ambient air temperature varied from 25 °C to 35 °C.

For the drip plots, irrigation based on increasingly higher threshold-CWSI values resulted in significantly shorter plants, with nonsignificant trends for

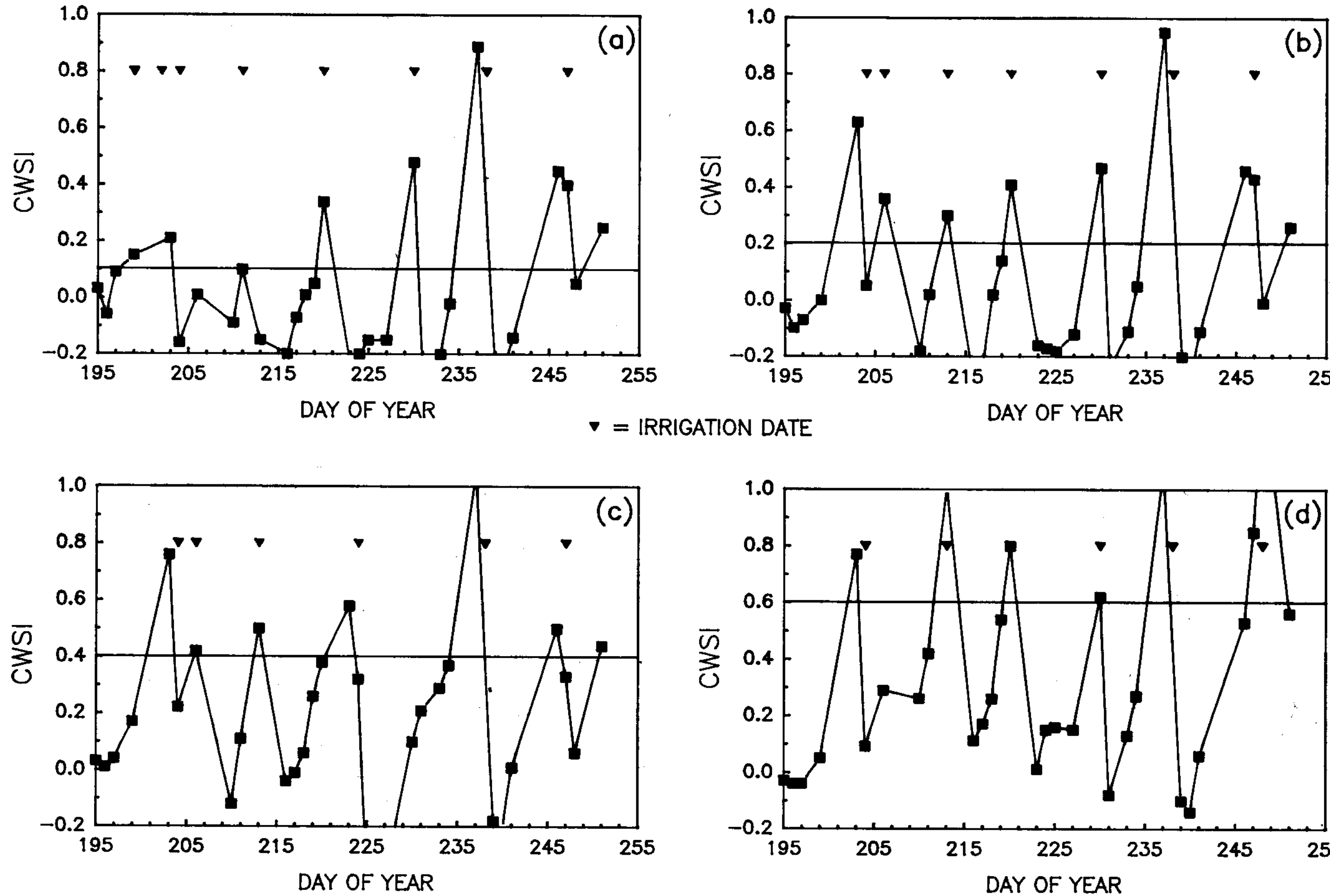


Fig. 1. Seasonal course of CWSI and time of irrigation for drip-irrigated soybean plots: (a) threshold=0.1; (b) threshold=0.2; (c) threshold=0.4; (d) threshold=0.6. (CWSI computed from Idso et al. (1981a) baseline).

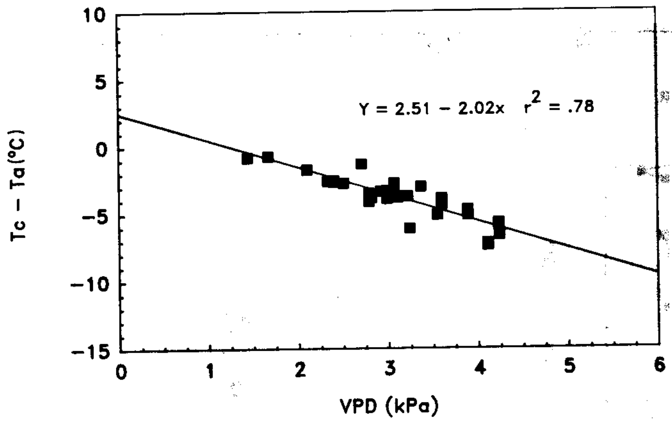


Fig. 2. Baseline equation computed from recently irrigated soybean plots grown in Akron, Colorado, 1986.

fewer nodes plant^{-1} and smaller seeds (Table 4). This resulted in a significant treatment effect on final seed yield. Yields were 17.6% less when the irrigation threshold was 0.5 as opposed to 0.2. Similar results were found for the RO plots.

After Day of Year (DOY) 259 in 1985 and DOY 251 in 1986, irrigations and precipitation failed to reduce CWSI values due to significant leaf senescence. Irrigation scheduling was terminated on this date. Plants were at development-stage R6–R7 (full-seed to beginning-maturity) and about 50% of the leaves in most plots had turned yellow.

Irrigating with a higher threshold CWSI value resulted in lower seasonal irrigation and lower seasonal E_t (Table 5). Differences in irrigation, E_t, and seed yield between the drip plots and the RO plots were noted. Significantly more water was applied to the RO plots in 1986 than to the drip plots for any given CWSI threshold value, resulting in greater E_t and seed yield. The seed yields are plotted in Fig. 5 against seasonal E_t for all plots. The 1985 data spanned the range of the 1986 data, which appear to fall in two distinct areas of the graph. The data from the drip plots fall on very nearly the same yield/E_t relationship as the data from the RO plots (kg ha^{-1}=65.3∗Cumulative E_t (mm)−113). This suggests that if we had added more water to the drip plots we would have obtained similarly high yields. This points out a potential problem with CWSI scheduling in that CWSI tells us when to irrigate, but not how much water to apply.

The drip plots were irrigated with approximately 25 mm of water per irrigation. This value was chosen to avoid runoff problems between adjacent plots. The RO plots were flood-irrigated with 25 mm per irrigation in 1985 and 51 mm per irrigation in 1986. Plot borders kept irrigations within a given plot. Figure 6 shows the soil water contents (as percent of field capacity in the active root zone) just prior to irrigation for the four scheduling treatments in the drip

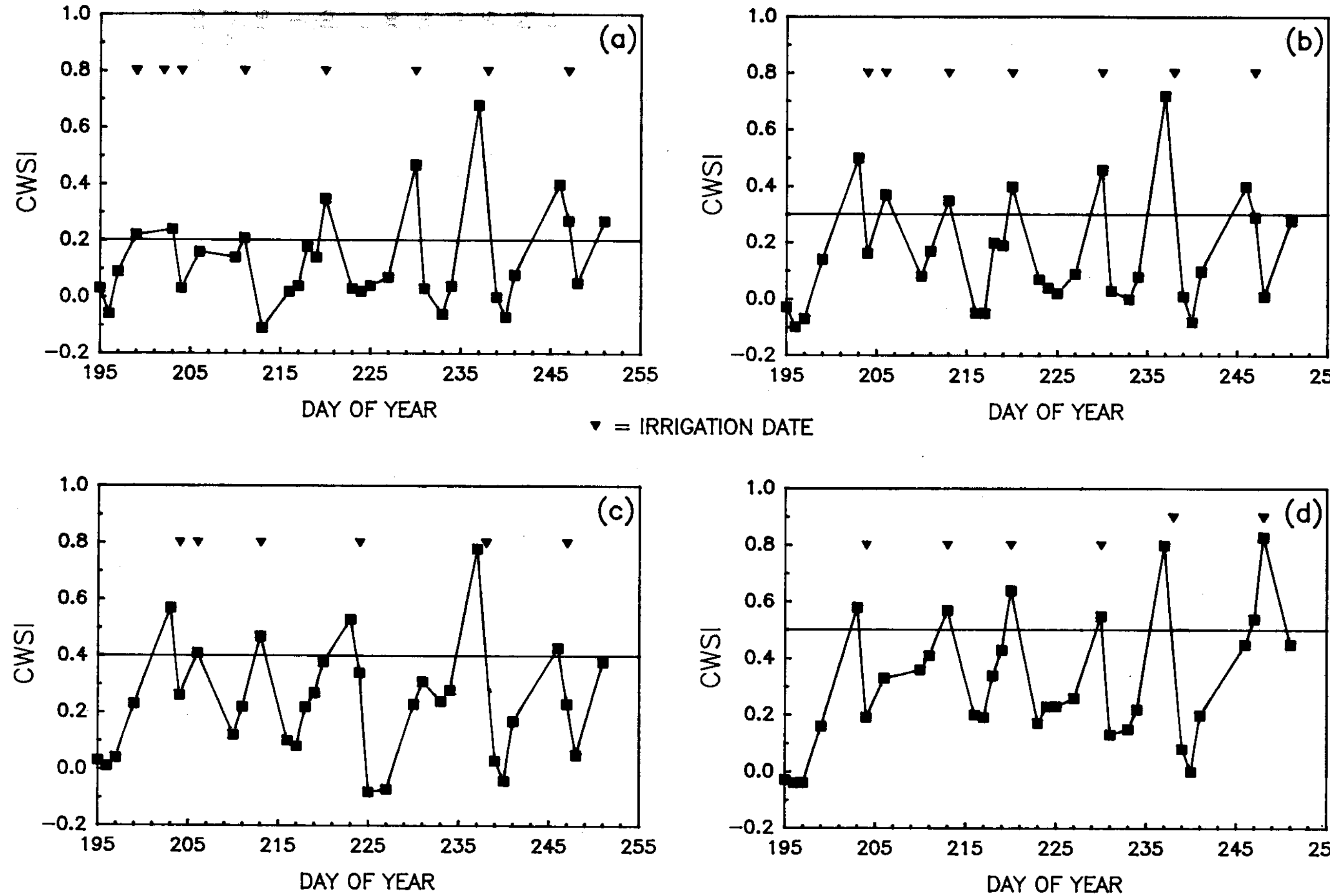


Fig. 3. Seasonal course of CWSI and time of irrigation for drip-irrigated soybean plots: (a) threshold=0.2; (b) threshold=0.3; (c) threshold=0.4; (d) threshold=0.5. (CWSI computed from 1986 Akron baseline).

TABLE 3

Average Crop Water Stress Index (CWSI) at irrigation times for four threshold CWSI irrigation-scheduling treatments

Year	Plot[1]	CWSI Threshold			
		0.2	0.3	0.4	0.5
1985	RO	0.32	0.56	0.56	0.70
1986	RO	0.36	0.39	0.51	0.65
1986	drip	0.37	0.43	0.49	0.66

[1]RO, rainout-shelter plots; drip, drip-irrigated plots.

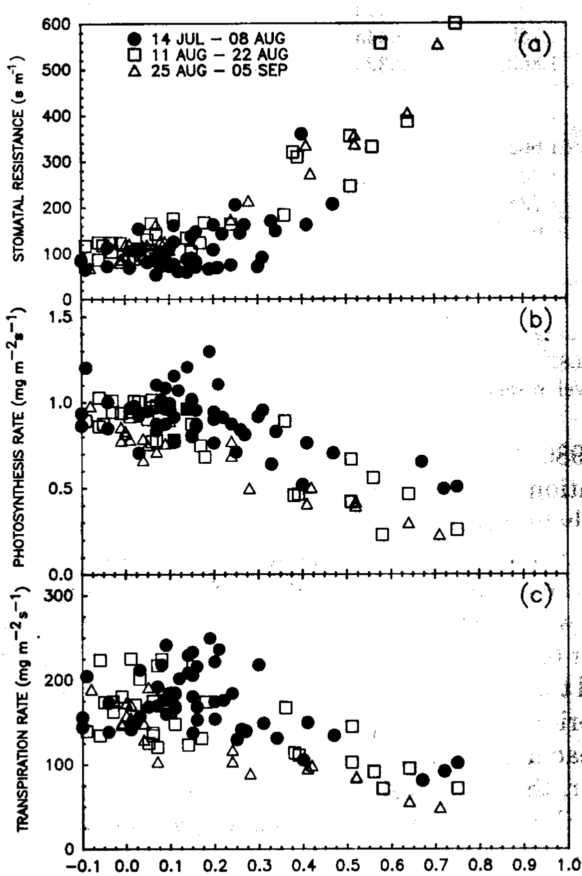


Fig. 4. Stomatal resistance (a), leaf photosynthesis rate (b), and leaf transpiration rate (c) as a function of Crop Water Stress Index from drip-irrigated soybeans.

TABLE 4

Maximum plant height and yield component analysis for soybean plots with irrigation scheduled by CWSI

CWSI	Height (cm)	Nodes $plant^{-1}$	Pods $node^{-1}$	Seeds pod^{-1}	Seed weight (g)	Seed yield[1] ($kg\ ha^{-1}$)
Rainout-shelter plots, 1985						
0.2	59.7a[2]	10.26a	2.02a	2.43a	0.192a	3375a
0.3	49.3a	9.53ab	2.02a	2.42a	0.182b	2826b
0.4	50.0a	9.01b	1.90a	2.43a	0.168c	2435b
0.5	49.3a	8.95b	1.89a	2.41a	0.167c	2365b
ANOVA[3]	n.s.	n.s.	n.s.	n.s.	**	*
Rainout-shelter plots, 1986						
0.2	55.1a	10.18b	1.94ab	2.37a	0.181a	3575a
0.3	53.4a	10.50a	2.05a	2.26a	0.180a	3551a
0.4	50.8a	9.39c	1.78b	2.44a	0.188a	3110b
0.5	50.9a	9.36c	1.80b	2.32a	0.186a	3108b
ANOVA	n.s.	*	*	n.s.	n.s.	*
Drip-irrigated plots, 1986						
0.2	62.2a	12.38a	1.66a	2.52a	0.175a	2656a
0.3	61.3a	12.18a	1.70a	2.53a	0.173a	2566ab
0.4	59.2a	12.06a	1.72a	2.48a	0.173a	2430b
0.5	54.3b	11.15a	1.67a	2.47a	10.70a	2189c
ANOVA	**	n.s.	n.s.	n.s.	n.s.	**

[1]@ 13% moisture.
[2]Means within a given year/location data set followed by the same letter are not significantly different at the 0.05 level as tested by LSD.
[3]*,**Significant at the 0.05 and 0.01 level, respectively; n.s., nonsignificant.

plots and in the RO plots in 1986. In all cases, there was a general decline in the soil water content at irrigation as the season progressed. The level of soil water at irrigation was generally higher in the RO plots than in the drip plots. In the RO plots, higher CWSI threshold treatments had lower percent available water at irrigation times than the lower CWSI threshold treatments. The data from the drip plots did not show this separation. The data from the 1985 RO plots (not shown) were similar to the 1986 RO plot data, in that there was a decline prior to irrigations, and that the higher CWSI threshold treatments had lower soil water contents just prior to irrigation than the lower CWSI threshold treatments. Also, the large spread in soil water between treatments was similar to the 1986 RO plots. However, the actual values of soil water content for a given treatment were more similar to the 1986 drip plots, which were also irrigated with 25 mm per irrigation.

Since irrigations did not bring soil water contents back to near field-capacity levels, water-stress conditioning through osmotic adjustment may have been promoted. There is some disagreement as to whether osmotic adjustment oc-

TABLE 5

Irrigation amounts (mm) and total seasonal evapotranspiration (E_t; mm) for irrigated soybeans, 1985 and 1986

CWSI	Rainout shelter				Drip-irrigated	
	1985		1986		1986	
	Irrigation	E_t	Irrigation	E_t	Irrigation	E_t
0.2	347	525a[1]	406	545a	181	371a
0.3	271	453b	356	548a	180	371a
0.4	195	377c	356	522a	174	354b
0.5	195	363c	305	492a	145	325c
ANOVA[2]		**		n.s.		**

[1]Means within a given year/location data set followed by the same letter are not significantly different at the 0.05 level as tested by LSD.
[2]**, Significant at the 0.01 level; n.s., nonsignificant.

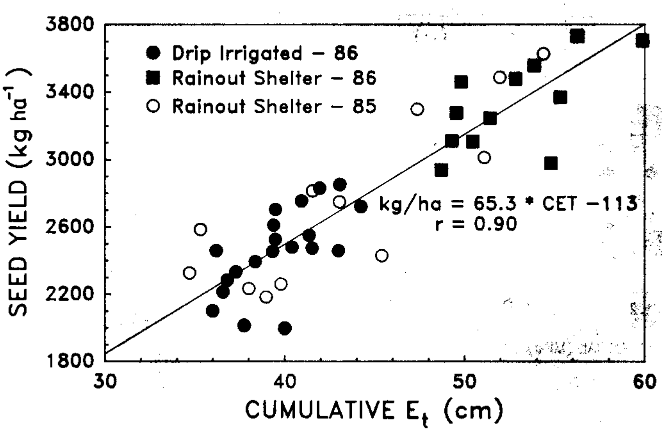


Fig. 5. Yield/E_t relationship for Drip and RO soybeans.

curs in soybeans (Turner and Jones, 1980; Ashley, 1983). Evidence of osmotic adjustment can be seen in the shifting relationship between leaf water-potential (ψ_l) and stomatal resistance as the growing-season progressed (Fig. 7a). The critical ψ_l for stomatal closure in the second week of July was about -0.9 MPa; by the end of August the critical value was about -1.6 MPa.

Similar results were found when comparing ψ_l to CWSI (Fig. 7b). In late July and early August, CWSI$=0.1$ corresponded to $\psi_l=-0.8$ MPa; in the middle of August, CWSI$=0.1$ corresponded to $\psi_l=-1.2$ MPa; by the end of August and beginning of September, CWSI$=0.1$ corresponded to $\psi_l=-1.4$ MPa. Since ψ_l is a function of the water-potential of the soil, the soil water-content decline

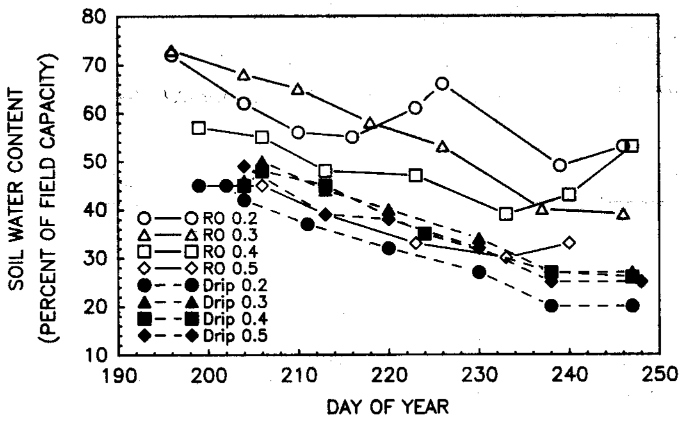
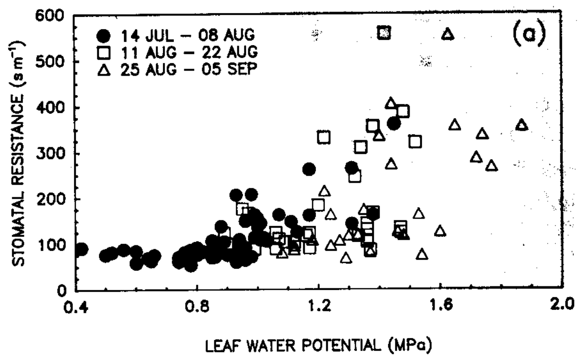


Fig. 6. Soil water content at time of irrigation for Drip and RO soybean plots under four irrigation-scheduling treatments (RO, rainout-shelter plots; Drip, drip-irrigated plots).



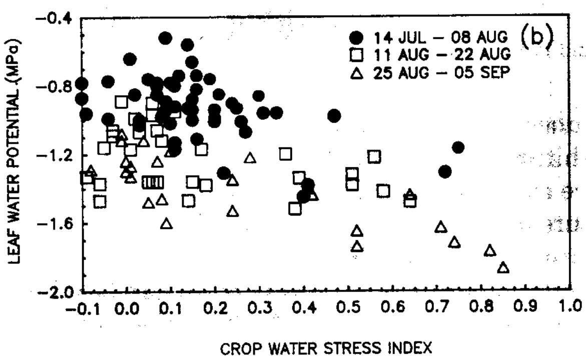


Fig. 7. Stomatal resistance as a function of leaf water-potential (a), and leaf water-potential as a function of Crop Water Stress Index (b) from drip-irrigated soybeans.

with time at irrigation initiation while using the same CWSI scheduling threshold thoughout the season would be expected. The higher E_t rates and higher yields for the RO plots compared with the drip plots in 1986 may be due to practicing a less-severe deficit-irrigation strategy by applying 51 mm per irrigation as opposed to 25 mm. This indicates that, for soybeans, knowing how much water to apply may be as important as knowing when to apply water. This result needs to be considered if irrigation scheduling of soybeans by CWSI will result in deficit irrigations. Where the capabilities of an irrigation system, soil type, and soil-water-measurement system allow, irrigations should bring soil water content to field capacity to avoid shifts in the relationship between CWSI, soil water content, and leaf water-potential due to water-stress conditioning. An explanation for the greater range of water use and yield in the 1985 RO plots than observed in 1986, using the same irrigation-threshold criteria, is not readily apparent.

Noting the sky conditions of this region during the 1985 and 1986 growing-seasons is important since constant, full-sun conditions are necessary for use of the infrared thermometer in irrigation scheduling (Stone et al., 1975). Cloudless sky conditions are a rare occurrence during the early afternoons in the central Great Plains, but the period of time chosen for IRT measurements (13:00–14:00 MDT) was just before the typical period of rapid convective cumulus development. We were, therefore, able to make measurements on 82% of the days in 1985 and 78% of the days in 1986 of which we wanted to make measurements. Therefore, in areas of the world with growing-season climates similar to the central Great Plains of the United States, cloudy conditions in the early afternoon would not occur with sufficient frequency to inhibit the timely use of the infrared thermometer for irrigation scheduling.

SUMMARY AND CONCLUSIONS

This study has demonstrated irrigation scheduling of soybeans using the Crop Water Stress Index (CWSI). The higher the threshold value of CWSI used to signal the need for irrigation, the lower the amount of total seaonal water applied, and the lower the final grain-yield obtained. The previously reported CWSI baseline equation was incorrect for computing CWSI at this location. A baseline equation with a steeper slope produced CWSI values more nearly within the theoretical limits of 0.0 and 1.0. Researchers and producers using CWSI to quantify water stress and schedule irrigations should conduct preliminary studies to determine an appropriate non-water-stressed baseline equation for their locations. When a deficit-irrigation strategy was employed, the relationship between soil water content and CWSI changed as plants were conditioned to water stress. This may have implications for the importance of knowing how much irrigation water to apply when CWSI signals that it is time for an irrigation.

ACKNOWLEDGMENTS

The author expresses his appreciation to Jane Diamond and Mike Klauman for valuable assistance in collecting the field data and in data processing.

REFERENCES

Ashley, D.A., 1983. Soybean. In: I.D. Teare and M.M. Peet (Editors), Crop-Water Relations. Wiley, New York, pp. 389-422.

Bucks, D.A., Nakayama, F.S., French, O.F., Legard, W.W. and Alexander, W.L., 1985. Irrigated guayule - evapotranspiration and plant water stress. Agric. Water Manage., 10: 61-79.

Fehr, W.R. and Caviness, C.E., 1977. Stages of soybean development. Iowa State University, Ames, Spec. Rep. 80.

Garrot, D.J., Fangmeier, D.D., Husman, S.H. and Ottman, M.J., 1986. Scheduling irrigation to maximize winter wheat yields using the Crop Water Stress Index. In: Agronomy Abstracts, ASA, Madison, WI, p. 13.

Idso, S.B., 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteorol., 27: 59-70.

Idso, S.B., Jackson, R.D., Pinter, P.J., Jr., Reginato, R.J. and Hatfield, J.L., 1981a. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteorol., 24: 45-55.

Isdo, S.B., Reginato, R.J., Jackson, R.D. and Pinter, P.J., Jr., 1981b. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. Irrig. Sci., 2: 205-212.

Idso, S.B., Reginato, R.J., Reicosky, D.C. and Hatfield, J.L., 1981c. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J., 73: 826-830.

Idso, S.B., Reginato, R.J. and Radin, J.W., 1982. Leaf diffusion resistance and photosynthesis in cotton as related to a foliage temperature based plant water stress index. Agric. Meteorol., 27: 27-34.

Jackson, R.D., Idso, S.B., Reginato, R.J. and Pinter, P.J., Jr., 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res., 17: 1133-1138.

Kirkham, M.B., Johnson, D.E. Jr., Kanemasu, E.T. and Stone, L.R., 1983. Canopy temperature and growth of differentially irrigated alfalfa. Agric. Meteorol., 29: 235-246.

Nielsen, D.C. and Gardner, B.R., 1987. Scheduling irrigations for corn with the Crop Water Stress Index (CWSI). Appl. Agric. Res., 2: 295-300.

Pinter, P.J., Jr. and Reginato, R.J., 1982. A thermal infrared technique for monitoring cotton water stress and scheduling irrigations. Trans. ASAE, 25: 1651-1655.

Stone, L.R., Kanemasu, E.T. and Horton, M.L., 1975. Grain sorghum canopy temperature as influenced by clouds. Remote Sensing Environ., 4: 177-181.

Turner, N.C., 1987. The use of the pressure chamber in studies of plant water status. In: Proc. Int. Conf. Measurement of Soil and Plant Water Status, Logan, UT, 6-10 July 1987. Utah State University, Logan, Vol. 2, pp. 13-24.

Turner, N.C., and Jones, M.M., 1980. Turgor maintenance by osmotic adjustment: A review and evaluation. In: N.C. Turner and P.J. Kramer (Editors), Adaptation of Plants to Water and High Temperature Stress. Wiley, New York, pp. 87-103.