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

D. C. Nielsen
USDA-ARS
Akron, CO

B. R. Gardner
The Standard Oil Company of Ohio
Cleveland, OH

Abstract. 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 not been reported. The objective of this study was to demonstrate the effectiveness of scheduling irrigations of corn (*Zea mays* L.) with the CWSI as computed from measurements of infrared canopy temperature, air temperature, and vapor pressure deficit. The soil type of the plot area was a fine montmorillonitic mesic Pachic Argiustoll. Irrigations were initiated when CWSI reached threshold values of 0.1, 0.2, 0.4, or 0.6. These four threshold values resulted in total irrigation amounts of 211, 185, 112, and 65 mm applied in 11, 9, 6, and 3 irrigations to the 0.1, 0.2, 0.4, and 0.6 CWSI plots, respectively. Respective yields for these plots were 10,010, 9,293, 8,399, and 6,647 kg/ha. Crop Temperature Variability (CTV) and the standard deviation of replicate plot measurements of canopy temperature were not effective quantifiers of severity of water stress. 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 [6] has been shown to be closely related to extractable water in the root zone of a wheat crop [10], to plant water potential in wheat and alfalfa [7, 9] and cotton [12] and to leaf diffusion resistance and photosynthesis in cotton [8]. In experiments with graded amounts of irrigation water applied to guayule, Bucks et al. [2] 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. [11] found no significant difference in canopy temperatures among irrigation treatments.

Two other methods of crop water stress evaluation by infrared thermometry have been proposed. Clawson and Blad [3] proposed the use of crop temperature variability (CTV) as an indicator of the onset of water stress in corn. CTV is defined as the maximum temperature minus the minimum temperature from replicated measurements of canopy temperature. They suggested that CTV greater than 0.7°C indicated a need for irrigation. Gardner and Blad [4] reported that repeated measurements of corn canopy temperatures that resulted in standard deviations (STD) of +/− 0.3°C indicated a need for irrigation.

Irrigation scheduling based on infrared thermometer measurements of canopy temperature, especially as used to compute CWSI, appears to be promising for some crop species, but results of studies testing such a technique have not been reported. The objective of this study was to determine if the CWSI can be used to schedule irrigations in corn. Additional objectives were to determine if various application-threshold CWSI values would cause significant water application and yield differences, and to determine if CTV and STD of replicated measures of crop temperature are effective quantifiers of the severity of water stress as compared with CWSI.

Materials and Methods

This study was conducted during the 1985 growing season at the USDA Central Great Plains Research Station (40°9' N, 103°9' W, 1384 m above msl), 4 miles east of Akron, CO. The soil type at this location is a Rago silt loam (fine montmorillonitic mesic Pachic Argiustoll). Corn (*Zea mays* L., hybrid Pioneer 3732) was planted on 9 May 1985 to a final plant population of approximately 74,130 plants/ha (30,000 plants/A). The plot area was fertilized prior to planting with 184 kg/ha (165 lb/A) N and 61 kg/ha (55 lb/A) P. A herbicide mix of 2.5 kg/ha (2.2 lb/A) ai cyanazine (2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2yl] amino]-2-methylpropanentrile) and 1.8 kg/ha (1.6 lb/A) metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-

---

Contribution from the USDA-ARS and the Standard Oil Company of Ohio.

Address reprint requests to: D.C. Nielsen, Research Agronomist, USDA-ARS, P.O. Box K, Akron, CO 80720, U.S.A.

Applied Agricultural Research Vol. 2, No. 5, pp. 295–300

N-(2-methoxy-1-methylethyl) acetamide) effectively controlled weeds throughout the growing season.

The statistical design used was a randomized complete block with four replications of four threshold values of the crop water stress index (CWSI) at which to apply irrigations (i.e., CWSI = 0.1, 0.2, 0.4, or 0.6). Individual plots consisted of six, 76 cm (30 in.) east-west rows, 9 m (30 ft) long.

Canopy temperatures were measured with a hand-held infrared thermometer, IRT (Model 112 Agritherm, Everest Interscience, Fullerton, CA).* The IRT has a field of view of 3° and detects radiation in the 8 to 14 micron waveband. Measurements were made on weekdays between 1330 and 1500 MDT 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 the plots. Data were recorded by a portable data logger (Polycorder, model 516B, Omnidata International, Logan, Utah).* 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 (5 ft) above the soil surface until 22 July 1985. After this date increased canopy height necessitated mounting the IRT on a pole and carrying it at a height of approximately 2.4 m (8 ft). Spot size ranged from 0.2–0.5 m^2 (2.2–5.4 ft^2), depending on IRT height and canopy height. Air temperature and vapor pressure deficit were measured at a height of 1.5 m (5 ft) before and after each measurement period with an Assman psychrometer in an open area adjacent to the plots. The 12 canopy temperature measurements per plot were averaged and the CWSI calculated as

$$\mathrm{CWSI} = \frac{T_c - T_a - D_2}{D_1 - D_2} \quad (1)$$

where T_c = canopy temperature (C); T_a = air temperature (C); $D_2 = T_c - T_a$ predicted from baseline equation = 2.67 − 2.059 * VPD; VPD = vapor pressure deficit (kPa); D_1 = approximate maximum difference between T_c and T_a, set equal to 3°C.

The baseline equation, D_2, differs slightly from that given for corn by Idso [5], and was derived from temperature and humidity data collected over irrigated corn at the Sandhills Agricultural Laboratory, Tryon, NE (44°37' N, 100°50' W, 975 m above msl) (Dr. B.R. Gardner, SOHIO, Cleveland, Ohio, personal communication). Idso et al. [6] formulated CWSI values in which D_1 varied with air temperature. The variation of D_1 for corn is slight under clear-sky, midday, ambient field conditions, and a constant value of 3°C was used for D_1 in this study.

When the average CWSI for the four replications reached or exceeded the treatment threshold value, irrigation water was applied to all four plots associated with that treatment. The threshold scheduling values were adhered to as closely as possible given the constraints of a 5-day workweek and occasional cloudy conditions. Irrigations were applied through drip irrigation lines (Chapin Watermatics, Inc., Watertown, NY)* with generally 20 mm (0.8 in.) of water being applied per irrigation period. This water application rate was chosen to avoid runoff into adjacent plots. Irrigation scheduling began on 8 July 1985 and ended on 6 September 1985.

Initial gravimetric soil moisture samples taken in the plot area showed approximately 191 mm (7.5 in.) of available soil moisture in the surface to 1.83 m (6 ft) soil profile. A 3.05 m (10 ft) length of each of the two center rows of each plot was harvested for yield on 27 September 1985, which followed a killing frost on 24 September 1985. Samples were oven-dried for 96 hours at 65°C. Yield components were determined and analysis of variance was performed on the data.

Results and Discussion

Figure 1 shows the seasonal course of the 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 presumably became limiting to evapotranspiration. Following an irrigation or precipitation event the water stress was relieved and the CWSI declined. Actual seasonal CWSI values at the time of irrigation averaged over the entire season were 0.27, 0.33, 0.46, and 0.68 for the 0.1, 0.2, 0.4, and 0.6 CWSI plots, respectively. The four CWSI scheduling thresholds produced substantially different irrigation treatments.

It is interesting to note that for much of the season, CWSI values below 0.1 could not be maintained for more than a few days. In some cases, even after irrigation, CWSI values did not decrease below 0.1, necessitating another irrigation. Several possible explanations exist for this observation:

1. At our location the crop rapidly depleted soil moisture to the point where stress began occurring
2. Our baseline equation, D_2, may have been incorrect
3. There was so much deviation around the baseline that 0.1 CWSI may have been too low to be used as a practical irrigation scheduling index
4. Not enough irrigation water may have been applied at each irrigation due to irrigation system constraints.

Using a 0.2 CWSI to initiate irrigations resulted in two fewer irrigations. CWSI values after an irri-

---

* 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 authors, the U.S. Dept. of Agriculture, or The Standard Oil Company of Ohio.

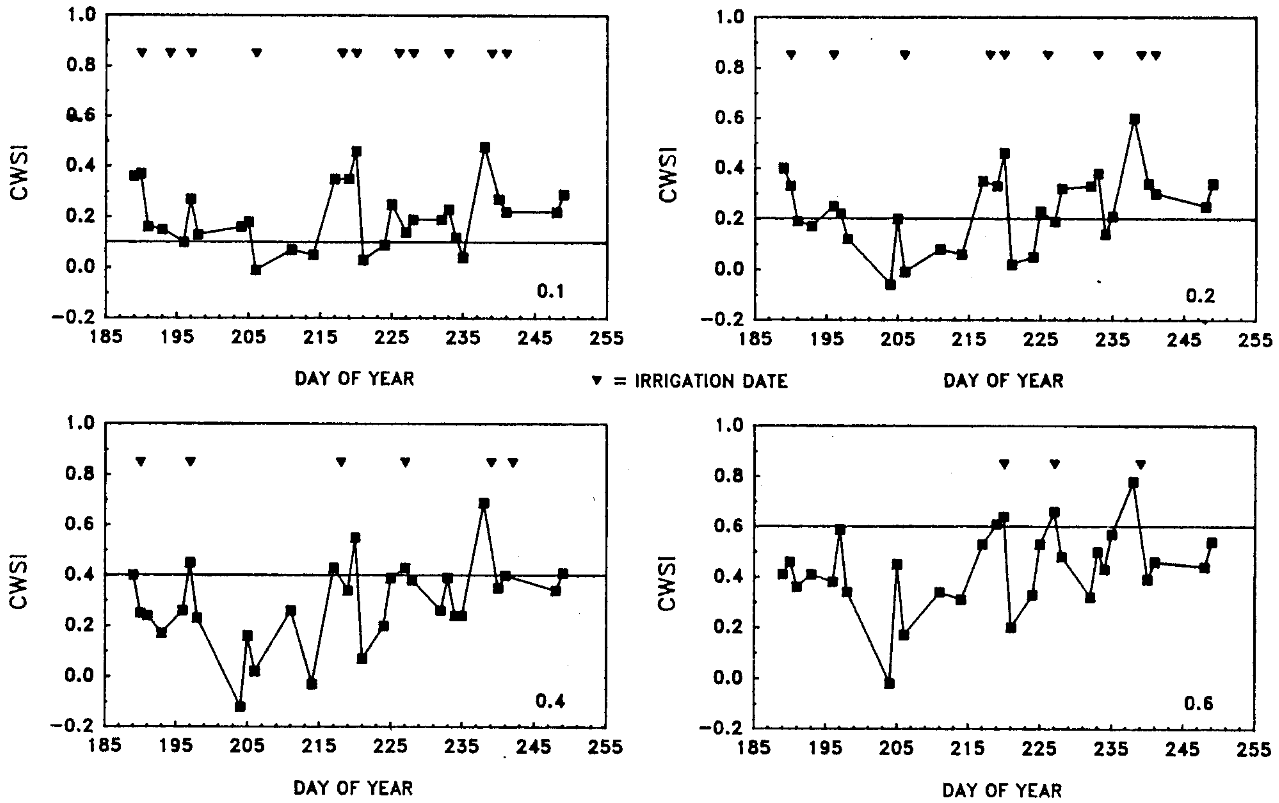

Fig. 1. Seasonal course of CWSI and times of irrigation for corn plots.

gation generally went below 0.2. After Day of Year (DOY) = 240, irrigations failed to reduce CWSI values below critical values for either 0.1 or 0.2 treatments. Rainfall totaling 35.1 mm (1.4 in.) on DOY 244, 245, and 247 should have eliminated water stress in all plots, but CWSI measurements made on DOY 248 and 249 indicated that all plots required irrigation. We, therefore, concluded that the baseline relationship, D_2, was no longer valid, and irrigation scheduling based on CWSI was terminated. The corn plants were at growth stage R5 (dent). The change in the baseline relationship was probably caused by the reduced ability of senescing plants to transpire, thus failing to reduce canopy temperature. These results suggest that critical values of CWSI for irrigation scheduling purposes may be dependent on the stage of plant development.

When a CWSI value of 0.4 was used, five fewer irrigations (than the 0.1 plots) were applied. CWSI values decreased below the critical value after each irrigation. The 0.6 CWSI plots received eight fewer irrigations than the 0.1 plots, with CWSI values decreasing well below 0.6 after each irrigation.

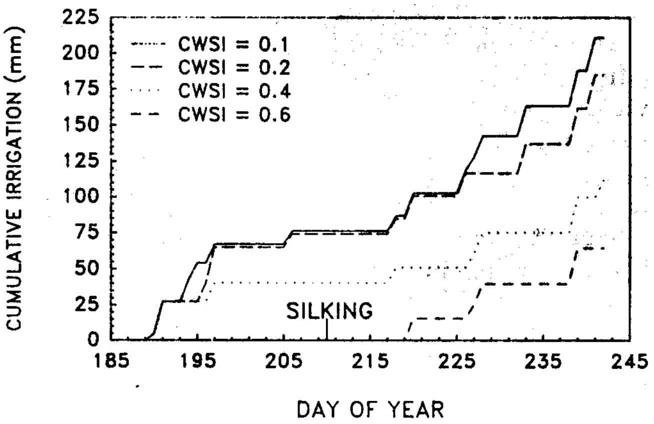

Fig. 2. Cumulative irrigation water applied to corn plots with irrigations scheduled by CWSI (mm * 0.039 = in.).

Figure 2 shows the cumulative irrigation water applied to the four treatments. By silking time (DOY = 210, 29 July 1985) no irrigation water had been applied to the 0.6 plots, and the 0.4 plots had received 41 mm (1.6 in.) of irrigation. The 0.1 and 0.2 plots had received approximately the same amount of irrigation, 74 mm (2.9 in.). The 0.1 plots received about 25 mm (1 in.) more irrigation at late blister stage (DOY = 227) than the 0.2 plots received, and thereafter received similar amounts of irrigation.

Table 1. Growing season precipitation for 1985 and 76-year average

Dates	1985 (mm)[a]	Average 1909–1984 (mm)[a]	Difference (mm)[a]	Cumulative difference (mm)[a]
5/09–5/31	68.3	76.5	−8.2	−8.2
6/01–6/30	33.3	63.8	−30.5	−38.7
7/01–7/31	115.3	67.3	+48.0	+9.3
8/01–8/31	23.9	50.8	−26.9	−17.6
9/01–9/25	51.6	31.0	+20.6	+3.0

[a] mm * 0.039 = in.

Table 2. Plant data for plots with irrigations scheduled by CWSI

CWSI	Stalk dry weights (grams)[a]	Ear lengths (m)[b]	Maximum crop height (m)[b]
0.1	2676 a[c]	.164 a	2.33 a
0.2	2204 bc	.151 ab	2.29 a
0.4	2390 b	.146 ab	2.24 b
0.6	1987 c	.118 c	2.08 c

[a] grams * 0.0022 = lbs.
[b] m * 0.039 = in.
[c] Means followed by the same letter are not significantly different at the 0.05 level as tested by LSD.

Total irrigation water applied was 211, 185, 112, and 65 mm (8.3, 7.3, 4.4, and 2.6 in.) in 11, 9, 6, and 3 irrigations to the 0.1, 0.2, 0.4, and 0.6 CWSI plots, respectively.

Seasonal precipitation data are given in Table 1. These data show that a total of 292.4 mm (11.5 in.) was received between planting and harvest. This total is slightly above the 76-year average. The data show that the cumulative precipitation was below normal early in the season but that heavy rains occurring near silking brought the cumulative total precipitation to somewhat above normal. The season turned dry again during the early grain-filling stages in August, and then wetter than normal during the late grain-filling stages in September.

The different irrigation treatments resulted in significant differences in growth, development, and yield of corn. Table 2 shows that plants were shorter under the higher CWSI threshold scheduling treatments. Similar effects were noted on ear lengths and stalk dry weights at harvest.

Table 3 gives the yield component data for this study. The number of ears per plant was not affected by the different irrigation treatments. As the value of the threshold CWSI increased, the number of seeds per ear, seed weight, and final grain yield declined. The difference in total grain yield between the 0.1 and 0.2 CWSI treatments was not statistically significant. Yields were increased 52% by receiving 41% more total seasonal water (precipitation + irrigation) with scheduling based on a CWSI value of 0.1 as opposed to 0.6. Differences in yield due to scheduling treatment could be expected to have been even more dramatic had the heavy rains at the critical silking time not occurred.

From a practical standpoint, scheduling irrigations for corn with a value of CWSI = 0.1 may not be possible with current technology in which center pivot sprinkler systems are capable of applying water on a 5- to 7-day schedule at the fastest. A more practical threshold, physically and economically, might be CWSI = 0.2, since grain yields were not significantly different between the 0.1 and 0.2 threshold levels, and irrigations are not required as frequently with the 0.2 level as with the 0.1 level. The use of 0.1 as a threshold level may be reserved for high cash value crops grown with rapid delivery irrigation systems.

We used the canopy temperature data collected in this study to evaluate the relationship among CTV, STD of repeated canopy temperature measurements, and CWSI. The equivalency of CTV and STD can be predicted from statistical theory. From a table of z values [13] approximately 99% of randomly distributed values exceeding a given mean are included in a region having a width of 2.3 STDs. Thus, a CTV value of 0.7 is equal to 2.3 times the STD of 0.3 reported by Gardner and Blad [4]. This also agrees closely with our observed relationship between CTV and STD (Fig. 3), where CTV = 2.28 * STD (r^2 = 0.99).

From an applied viewpoint the STD calculation has an important advantage over the CTV calculation. CTV calculations rely on only the minimum and maximum data points collected on a plot (all others are discarded). Consequently, CTV calculations are subject to potentially serious sampling problems, forcing a researcher to decide if the observed maximum and minimum are valid points or the result of sampling error. By contrast, STD calculations use all the data collected. By definition, then, STD calculations must be less subject to sampling errors than CTV calculations.

A comparison of STD with CWSI (Fig. 4) shows that there is no significant relationship between these variables. For the majority of observations (region 2), when CWSI exceeded 0.1, STD also exceeded 0.3. Thus, STD appears to be an effective delineator of the onset of water stress, but a poor quantifier of the relative degree of water stress.

Table 3. Yield component analysis for corn plots with irrigations scheduled by CWSI

CWSI	Plant population plants per hectare[a]	Ear no. ears per plant	Seed no. seeds per ear	Seed wt. grams per seed[b]	Grain yield kg/ha[c]
0.1	71,044 a[d]	0.992 a	575 a	0.247 a	10,010 a
0.2	75,351 a	0.993 a	509 b	0.244 a	9,293 a
0.4	78,039 a	0.979 a	493 bc	0.223 b	8,399 b
0.6	72,121 a	0.977 a	447 c	0.211 b	6,647 c

[a] plants $ha^{-1} * 0.405$ = plants $acre^{-1}$
[b] grams $seed^{-1} * 0.035$ = oz $seed^{-1}$
[c] kg $ha^{-1} * 0.89$ = lb $acre^{-1}$
[d] means followed by the same letter are not significantly different at the 0.05 level as tested by LSD.

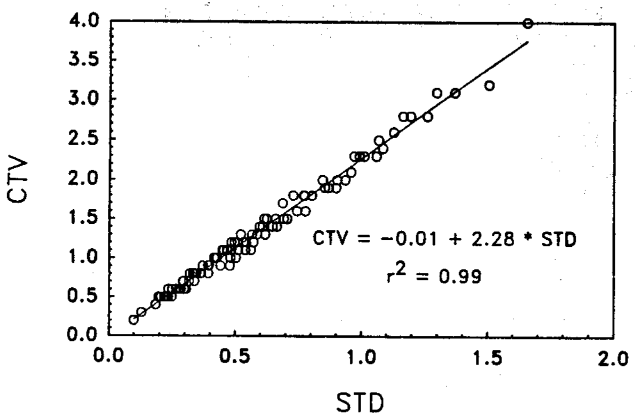

Fig. 3. Relationship between standard deviation (STD) and crop temperature variability (CTV).

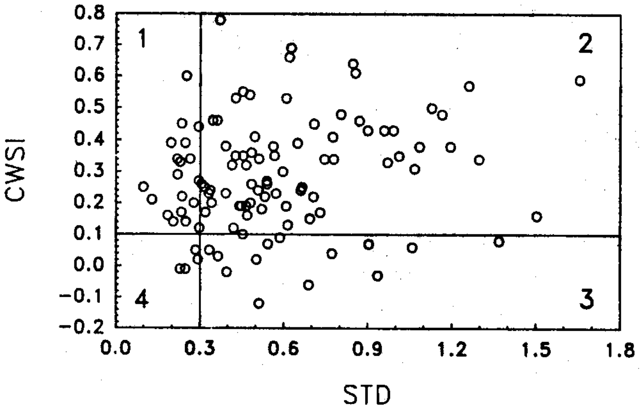

Fig. 4. Relationship between standard deviation (STD) and CWSI.

This agrees with observations of CTV made by Blad [1]. The value of STD for irrigation scheduling may lie in the detection of points which fall in region 3 (high STD, low CWSI). These points are most likely the result of measuring specific high stress areas under conditions when most of the plot area is under low or mild water stress. Use of STD would allow an irrigator to schedule irrigations based on the condition of these high stress areas as opposed to the average stress condition of the entire field.

It is worth noting the sky conditions of this region during the 1985 growing season since clear skies are necessary for accurate determination of steady-state canopy temperatures by infrared thermometry [14]. Cloudless sky conditions are a rare occurrence during summer afternoons on the Central Great Plains. But the period of time chosen for IRT measurements (1330–1500 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 which we wanted to make measurements. Thus, it appears that cloudy conditions in the early afternoon do not occur with sufficient frequency in the Central Great Plains to inhibit the timely use of the infrared thermometer for irrigation scheduling.

Summary and Conclusions

This study has shown the effectiveness of using CWSI to schedule irrigations on corn. The higher the threshold value of CWSI used to signal the need for irrigation, the lower the amount of total seasonal water applied, and the lower the final grain yield obtained. CTV and STD measurements are equivalent. When used in conjunction with CWSI measurements, STD measurements allow for the possibility of irrigating a field on the basis of specific high stress locations rather than average conditions. If used without CWSI measurements, STD would probably be an unreliable irrigation initiator. STD is a poor quantifier of the relative degree of water stress. Successful use of CWSI to schedule irrigations depends on the determination of the correct nonwater-stressed baseline. Further work needs to be done to determine if this baseline shifts significantly with growth stage throughout the growing season.

While it is true that the use of CWSI only indicates the onset of water stress and tells the irrigator nothing about the amount of water required, this should not be a detriment to its use for irrigation scheduling. Under many irrigation situations irrigation amounts are limited by such things as the irrigation system application rate and soil water intake rate. In such situations, knowing how much water to apply would have little benefit since the irrigator's system and soil limit the amount of water that can be applied. The CWSI effectively tells the irrigator when the previously applied water has been used up and when the irrigation system should be turned on again. If the irrigation system and soil type do not limit the amount of water that can be applied during a single irrigation, then the amount of water needed to recharge the soil profile could be estimated from water budget methods or soil probing. The CWSI still provides a valuable irrigation aid in that the plant's water stress condition is monitored and quantified.

With the amount of seasonal water applied as the major limiting factor to yield, use of an infrared thermometer and the CWSI would potentially allow a producer to select a degree of allowable moisture stress with its associated water requirement and potential yield. The infrared thermometer should become an increasingly important tool in irrigation scheduling as this type of management strategy is applied to reduce irrigation costs.

References

1. Blad, B.L. 1980. Remotely sensed crop temperature for water resources management. Agric. Meteor. Progress Report 80-5, Center for Agricultural Meteorology and Climatology, University of Nebraska, Lincoln. p. 247.
2. Bucks, D.A., F.S. Nakayama, O.F. French, W.W. Legard, and W.L. Alexander. 1985. Irrigated guayule—evapotranspiration and plant water stress. Agric. Water Manag. 10:61–79.
3. Clawson, K.L., and B.L. Blad. 1982. Infrared thermometry for scheduling irrigation of corn. Agron. J. 74:311–316.
4. Gardner, B.R., and B.L. Blad. 1980. Plant and canopy temperatures in corn as influenced by differential moisture stress. Agric. Meteor. Progress Report 80-1, Center for Agricultural Meteorology and Climatology, University of Nebraska, Lincoln, p. 119.
5. Idso, S.B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteor. 27:59–70.
6. Idso, S.B., R.D. Jackson, P.J. Pinter, Jr., R.J. Reginato, and J.L. Hatfield. 1981a. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteor. 24:45–55.
7. Idso, S.B., R.J. Reginato, R.D. Jackson, and P.J. Pinter. 1981b. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. Irrig. Sci. 2:205–212.
8. Idso, S.B., R.J. Reginato, and J.W. Radin. 1982. Leaf diffusion resistance and photosynthesis in cotton as related to a foliage temperature based plant water stress index. Agric. Meteor. 27:27–34.
9. Idso, S.B., R.J. Reginato, D.C. Reicosky, and J.L. Hatfield. 1981c. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J. 73:826–830.
10. Jackson, R.D., S.B. Idso, R.J. Reginato, and P.J. Pinter, Jr. 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res. 17:1133–1138.
11. Kirkham, M.B., D.E. Johnson, Jr., E.T. Kanemasu, and L.R. Stone. 1983. Canopy temperature and growth of differentially irrigated alfalfa. Agric. Meteor. 29:235–246.
12. Pinter, P.J., Jr., and R.J. Reginato. 1982. A thermal infrared technique for monitoring cotton water stress and scheduling irrigations. Trans. ASAE, 25:1651–1655.
13. Steel, R.G.D., and J.H. Torrie. 1960. Principles and procedures of statistics. McGraw-Hill, New York.
14. Stone, L.R., E.T. Kanemasu, and M.L Horton. 1975. Grain sorghum canopy temperature as influenced by clouds. Remote Sensing Environ. 4:177–181.