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Automatic Irrigation Scheduling of Grain Sorghum Using a CWSI and Time Threshold

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Abstract. *The crop water stress index (CWSI) has been investigated extensively as a quantification of plant water stress and a threshold to time irrigations. Most studies have calculated this thermal-based index by taking instantaneous measurements or by averaging values over a short period of time, usually near midday. Although useful for quantifying stress, measurements over a short period of time have not been particularly stable. This study was conducted to compare the yield response and water use efficiencies of a short-season hybrid grain sorghum obtained from automatic irrigations triggered by a CWSI and time threshold versus those obtained from manual best-practice irrigation scheduling. Irrigation amounts of 80%, 55%, 30% and 0% of full irrigation were applied. Grain yields across the 80% and 0% treatments were not significantly different between manual and automatic irrigation control methods. The only significant difference in water use efficiency between irrigation control methods occurred in the 30% treatment plots where the largest variability in the initial soil water profile existed. Irrigation water use efficiency was similar between irrigation methods in the 55% and 30% treatments, but significantly greater in the 80% automatically controlled treatments at* $p \leq 0.05$*. These results indicate that the CWSI and time threshold index has the potential to be utilized as a tool for deficit irrigation scheduling of grain sorghum. Further research is required to investigate its stability over different growing seasons.*

Keywords. Automation and control, center pivot irrigation, CWSI, sorghum

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Introduction

Sorghum is an important forage crop and is widely used as feedstock for ethanol production. In the Northern High Plains of Texas, 40% of grain sorghum is irrigated, resulting in yields double to those from dryland farming (Colaizzi et al., 2008). However, maintaining sustainable crop productivity under declining well yields or potential regulatory water-use policy in the Ogallala Aquifer region requires improvements in irrigation management. Automatic irrigation scheduling triggered by canopy temperature and time thresholds has been successful in trials for corn, cotton and soybean (Evett et al., 2006; Peters and Evett, 2008). Key attributes of such automatic irrigation scheduling are the control of crop water stress and water use efficiency by delivering irrigations only when required and by applying the necessary amount of water without compromising yield or quality.

The CWSI has been related to leaf water potential (Howell et al., 1984; Ben-Asher et al., 1992; Jackson, 1991; Oliva et al., 1994; Cohen et al., 2005), linked to soil water content (Idso and Reginato, 1982; Colaizzi et al., 2003), used to characterize crop water stress (Idso et al., 1981; Allen and Nakayama, 1988; Yazar et al., 1999; Yuan et al., 2004; Möeller et al., 2007), and evaluated as a tool for irrigation timing (Throssel et al., 1987; Nielsen, 1990; Garrot et al., 1994; Gontia and Tiwari, 2008). This thermal based index provides a relative measure of plant stress which can be derived from radiant leaf temperatures and ambient meteorological parameters (Pinter et al., 1983). The theoretical CWSI developed by Jackson et al. (1981) incorporated incoming solar radiation, relative humidity, air temperature, wind speed, canopy resistance at potential evapotranspiration, and crop height. Its general form is given as:

$$\mathrm{CWSI} = \frac{(T_\mathrm{c} - T_\mathrm{a}) - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}}{(T_\mathrm{c} - T_\mathrm{a})_\mathrm{ul} - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}} \qquad [1]$$

where T_c is crop canopy temperature, T_a is air temperature, $(T_c\text{-}T_a)_{ll}$ is the lower limit representing the temperature difference for a well watered crop, $(T_c\text{-}T_a)_{ul}$ is the upper limit representing the temperature difference between the crop canopy and ambient air when the plants are severely stressed (Jackson et al., 1988). The upper limit was calculated using the equation: $(T_c - T_a)_{ul} = r_a (R_n - G) / pC_p$, where, R_n is net radiation, p is the density of air, and C_p is heat capacity of air (J kg^{-1} $^oC^{-1}$). Inputs were the minute values averaged from 5 sec measurements. The aerodynamic resistance, r_a (s m^{-1}), was calculated using eqn. 2:

$$r_a = \left\{ \frac{\left[\dfrac{\ln(z - 0.63h)}{(0.13h)}\right]\left[\dfrac{\ln(z - 0.63h)}{(0.013h)}\right]}{\left(k^2 U\right)} \right\} \qquad [2]$$

where z is the reference anemometer height (m), k is the von Karman constant (0.41), U is the wind speed (m s^{-1}) at height z, and h is the vegetation height (m). The CWSI tends towards 0 after irrigations and progressively increases towards 1 as soil water is being depleted.

Sorghum is typically grown in areas too hot or too dry for corn production. Yield of early maturing sorghum is generally considered to be more stable than that of later maturing varieties when grown under low rainfall and semi-arid conditions. There are two identified growth stages when distinct responses to significant stress are experienced by sorghum. The first occurs from panicle differentiation until flowering and is known as the “pre-flowering” stage. The second response can occur after flowering during the “late-season” when the crop is under severe water stress during the grain filling stage (Rosenow et al., 1983). Successful irrigation scheduling should provide adequate water to avoid episodes of significant stress during these stages.

The objectives of this study were to: (1) use a CWSI and time threshold as the trigger in an automatic irrigation scheduling and control system. The time threshold is a cumulative value (minutes per a 24 hour day) for which the calculated CWSI threshold is exceeded; and (2) evaluate the impact of the irrigation scheduling methods on yield and water use efficiency of early season hybrid sorghum as influenced by irrigation amount and compared with manual methods of irrigation scheduling and control.

Methods and Materials:

Agronomy

An early maturing grain sorghum hybrid (*Sorghum bicolor* (L.) Moench, NC+5C35[1]) was planted under a three span center pivot sprinkler. The crop was seeded at a rate of 197,000 seeds ha^{-1} (80,000 seeds ac^{-1}) on day of year (DOY) 175, 2009, in 18-row plots on beds spaced 0.76-m apart at Bushland, Texas (35˚ 11’ N, 102˚ 06’ W, 1174 m above mean sea level). Postplant nitrogen was applied by fertigation at a rate of 56 kg (N) ha^{-1} on DOY 191 (July 10) and 28 kg (N) ha^{-1} on DOY 196 (July 15). Irrigations were applied to diked furrows with low elevation application (LEPA) drag socks (Lyle and Bordovsky, 1983) in every other furrow. Manual irrigations were scheduled weekly on odd-numbered days of the year (DOY) based on 80%, 55%, 30%, and 0% (designated $I_{80\%M}$, $I_{55\%M}$, $I_{30\%M}$, and $I_{0\%M,}$ respectively) of full replenishment of soil water depletion below field capacity in the top 1.5 m of soil. For this purpose, neutron probe (NP) measurements of soil water content were taken weekly at 10-cm depth to 230-cm depth in 20-cm increments in the $I_{80\%M}$ treatment plots. Measurements were taken at those depths in all other treatment plots several times during the season in order to calculate crop water use. The NP was calibrated and readings were taken using methods described by Evett (2008). Automatic irrigations were 80%, 55%, 30%, and 0% (designated $I_{80\%A}$, $I_{55\%A}$, $I_{30\%A}$, and $I_{0\%A}$, respectively) of peak water use for a two-day period established from well-watered sorghum grown in lysimeter fields at Bushland, Texas. Treatment plots were arranged in six blocks arc-wise around half of the center pivot circle (Fig. 1) with manually controlled and automatically controlled blocks alternating. Within each block, irrigation amounts were randomly assigned within each of two sub-blocks arranged radially from the pivot point. Blocking was designed to allow for effects of position along the lateral on irrigation application rate and effects of possible runoff.

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[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Automatic Irrigation Scheduling

Irrigation scheduling for the automatic treatments was based on a CWSI and a region specific time threshold. Historical data from well-watered sorghum grown on lysimeters at Bushland were analyzed to determine these threshold values. A total of 16 infrared thermometer sensors (IRTs) (Exergen model IRt/c.5:1-Type T, Watertown, Mass.) were mounted on the pivot lateral. One sensor each was placed at the edge of each concentric treatment plot (Fig.1), with the two sensors facing inwards towards the canopy at an oblique angle. Sensors were placed at opposing edges of each concentric plot (Fig. 1) with the two sensors from each plot facing inwards towards the canopy at an oblique angle in order to reduce sun angle effects. The sensors were mounted onto vertical masts forward of the drop hoses and located approximately 1.5 m above the crop canopy. When the pivot was moving, crop canopy temperatures were scaled using the method of Peters and Evett (2004). Air temperature (T_a, ºC), relative humidity (RH, %), solar radiation, and wind speed were measured every 10 sec and reported as 5-min mean values using in-field sensors mounted at a height of 2 m (Evett, 2002) on a mast and wired to a data logger (model CR10X, Campbell Scientific, Logan, Utah). The upper (T_{ul}) and lower temperature (T_{ll}) boundaries of the CWSI were calculated from measured environmental parameters paired with scaled canopy temperature data using equations similar to those discussed by O'Shaughnessy et al. (2008). Automatic irrigations, if triggered, were scheduled on even DOY.

The soil was a Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff, 2004). The field capacity and wilting point water contents were assumed uniform across the center pivot field. Water use (evapotranspiration, ET, mm) was calculated using the soil water balance equation (Evett, 2002):

$$\mathrm{ET} = P + I + F - \Delta S - R \qquad [3]$$

where ET is evapotranspiration, ΔS is the change in soil water stored in the profile as determined using the NP, R is runoff, P is precipitation, I is the irrigation water applied, and F is flux across the lower boundary of the control volume (taken as positive when entering the control volume), all in units of mm. Runoff and flux were assumed to be negligible because the field was furrow diked, plots were large enough that horizontal fluxes were important only in plot borders, and NP measurements indicated negligible flux (water content did not change) in the 2.1 to 2.3-m depth range.

Samples for grain yields were harvested from a 10 m^2 area in each of the 48 treatment plots. Water use efficiency (kg m^{-3}) was calculated as:

$$\mathrm{WUE} = \frac{Y_g}{\mathrm{ET}} \qquad [4]$$

where Y_g is the economic yield (g m^{-2}), and ET is the seasonal crop water use (mm, 0.001 m = 1 kg H_2O m^{-2} at a water density of 1000 kg m^{-3}). Irrigation water use efficiency (IWUE, kg m^{-3}) was calculated as

$$\mathrm{IWUE} = \frac{\left(Y_{gi} - Y_{gd}\right)}{\mathrm{IRR}_i} \qquad [5]$$

where Y_{gi} is the economic yield (g m^{-2}), Y_{gd} is the dryland yield (g m^{-2}), and IRR is the total season irrigation water applied (mm), Howell (2002).

Statistical Analysis

Results were analyzed using mixed measures (Proc Mixed) Analysis, Analysis of Variance (ANOVA), linear regression, and the Fisher Least Significant Difference (LSD) test using SAS software (SAS 9.1, SAS Institute Inc., Cary, NC).

Results

Rainfall for growing season 2009 totaled 240 mm which was typical for the area and time of year. Monthly average daily grass reference ET (ET_o) values were greatest for June, July, and August, as expected, and then decreased by approximately 2 mm day^{-1} in September (Table 1).

Table 1. Climatic conditions for 2009 growing season.

Month	Min Temp (°C)	Max Temp (°C)	Min RH (%)	Max RH (%)	Precipitation (mm)	Solar Irradiance (MJ m^{-2} d^{-1})	Average Daily ET_o[1] (mm)
May	9.5	24.9	31.3	81.8	12.6	22.7	5.8
June	16.8	31.3	23.1	87.6	61.1	24.4	7.1
July	16.8	32.2	28.1	85.9	68.2	26.0	7.3
August	16.2	31.4	27.8	85.2	48.3	24.9	6.7
Sept	10.9	26.5	30.2	88.2	10.8	19.5	4.9
Oct	4.0	18.8	37.8	88.8	39.4	11.9	3.3

[1]Reference evapotranspiration (ET_o) data for grass from the Texas High Plains Evapotranspiration (TXHPET) Network.

Irrigations and CWSI values

Over the irrigation scheduling period (DOY 204 – 272), the manual treatments received 8-13% more water than those in the automatically irrigated blocks. The manually irrigated plots in Block I received less irrigation (16 mm, 11 mm, and 6 mm for the 80, 55, and 30% irrigation treatment levels, respectively) than those in Blocks II and III due to the pivot missing a control signal to stop irrigations over Manual Blocks II and III on an automatic day (Table 2). All automatic treatments used significantly less water than did corresponding manual treatments at the 80, 55, 30 and 0% levels.

There was a positive linear relationship between the calculated CWSI and time threshold values for the automatic treatment plots and the irrigation treatment levels. For example, on DOY 221 the calculated CWSI and time threshold values were 421, 440, 471 and 475 for the treatment levels of 80%, 55%, 30%, and 0%, respectively. Cumulative automatic irrigations kept up with manual irrigations until DOY 255 (Sept 12), Fig. 2. Small differences between air and canopy temperatures and higher levels of RH values (40.15% and 92.3%, minimum and maximum averages) between DOY 255 and DOY 264 contributed to reduced stress index values and prevented irrigation scheduling during this period.

Table 2. Irrigations

Preplant	All Treatments received 158 mm			
Post plant & prior to automatic irrigation scheduling	$I_{80\%}$, $I_{55\%}$, $I_{30\%}$ received 86 mm; $I_{0\%}$ received 66 mm			
Cumulative Scheduled Irrigations	$I_{80\%}$	$I_{55\%}$	$I_{30\%}$	$I_{0\%}$
Manual Block I (mm)	258	178	97	0
Blocks II & II (mm)	269	185	101	0
Automatic Blocks I, II & III (mm)	238	164	89	0

Grain Yields and Water Use Efficiency

Plant densities were not significantly different between the different irrigation control methods for any of the irrigation amount treatments. Average head densities for the $I_{80\%M}$ were significantly different than those in the $I_{80\%A}$ treatment plots. Dry grain yield values were not significantly greater between irrigation control methods for the 80% and 0% treatments. However, the yields in the $I_{55\%M}$ and $I_{30\%M}$ treatments were significantly greater than those in the corresponding treatments irrigated automatically, with p values = 0.047 and 0.032, respectively (Table 3).

Table 3. Treatment mean plant counts, head counts, grain yields, water use, water use efficiencies (WUE) and irrigation water use efficiencies (IWUE). Numbers in a column followed by the same letter were not significantly different at the 5% level. Data were analyzed using Proc Mixed in SAS with irrigation control method as a fixed effect and LSM difference.

	Irrigation Amount Treatment			
	I_{80}	I_{55}	I_{30}	I_0
Control Method	Plant Density (plants m^{-2})			
Manual	21 a	19 a	17 a	18 a
Automatic	20 a	18 a	17 a	18 a
	Panicle Density (panicle m^{-2})			
Manual	25 a	21 a	19 a	18 a
Automatic	24 b	21 a	20 a	18 a
	Yield (g m^{-2}) [dry basis]			
Manual	810 a	772 a	542 a	224 a
Automatic	917 a	724 b	476 b	224 a
F statistic	0.13	5.15	6.17	0.00
p value	($p \leq 0.73$)	($p \leq 0.047$)	($p \leq 0.032$)	($p \leq 0.98$)
	Water Use (mm)			
Manual	469 a	397 a	334 a	233 a
Automatic	437 b	354 b	329 b	235 a
	WUE (kg m^{-3})			
Manual	1.7 a	1.9 a	1.6 a	0.96 a
Automatic	1.9 a	2.0 a	1.4 b	0.95 a
	IWUE (kg m^{-3})			
Manual	2.1 b	2.8 a	2.8 a	
Automatic	2.3 a	2.8 a	2.4 a	

A curvilinear model, $Y= -6E-05\ IRR^2 + 0.04\ IRR + 2.13$, estimating average grain yield (Y, Mg ha^{-1}) as a function of irrigation depth (IRR, mm, for water applied during the irrigation scheduling period) for both irrigation control methods, provided a good fit across all treatment levels (Fig. 3).

Water use efficiency in the $I_{30\%A}$ was significantly less than the $I_{30\%M}$ treatment due to the low grain yield produced in this treatment. However, IWUE for the 55% and 30% treatments were not significantly different between irrigation methods, and the IWUE for the $I_{80\%A}$ was significantly greater than the $I_{80\%M}$ treatment.

Non-optimal preplanting field conditions likely contributed to reduced grain yields. It is typical that alternating halves of the pivot fields are cropped for experimentation and a cover crop is grown on the opposite semi-circle to help even-out the soil water profile that was left in a non-uniform condition by the previous year's experiment. In 2009, it was necessary to plant sorghum on the same half of the field where cotton was grown in the previous year, which had areas of soil water variability that biased the initial soil water condition between the manual and automatic treatment plots at the beginning of the 2009 growing season (Table 4).

Table 4. Treatment mean water contents in the top 1.5-m of the soil profile on day of year (DOY) 187 and 261, and differences in profile water content between manual (Man) and automatic (Auto) irrigation control methods at the same irrigation level (Irrig_Lvl).

		DOY 187	Difference	DOY 261	Difference
Treatments		Water content	Manual - Auto	Water content	Manual – Auto
Irrig_Lvl	Control Method	(mm)	(mm)	(mm)	(mm)
0%	Man	394	-1	323	4
30%	Man	417	15	376	25
55%	Man	398	2	382	25
80%	Man	421	9	454	53
0%	Auto	395		319	
30%	Auto	401		350	
55%	Auto	397		357	
80%	Auto	413		401	

For the 0% treatment plots, profile water contents were similar for the manual and automatic treatments to the 1.5-m depth at the beginning, middle and end of season. Below 1.5 m, water content in the automatic treatment was larger than that in the manual treatment, but negligible root water uptake occurred below the 1.5-m depth in the 0% treatments ($I_{0\%A}$ and $I_{0\%M}$). For the 30% treatment plots, initial water contents were larger for the manual treatments at the 50- through 230-cm depths. Water contents in the Auto treatments remained less than those in the Manual treatments at depths greater than 50 cm throughout the season; however, there was little root water uptake at depths greater than 90 cm. For the 55% treatments, initial water contents were larger for the Man treatments below the 70-cm depth. Water contents in the Auto treatments remained less than those in the Man treatments at depths greater than 70 cm throughout the season; however, there was little root water uptake at depths greater than 90 cm.

For the 80% treatment plots ($I_{80\%A}$ and $I_{80\%M}$), initial water contents were larger for the manual treatment at the 50- and 70-cm depths. There was no clear difference in water contents between the manual and the automatic treatments at 90-cm depth and below throughout the season. There was little root water uptake at depths greater than130 cm; and, there was some evidence of storage increases at the 90- and 110-cm depths.

Treatment mean profile water contents for the automatic irrigation method at the 30%, 55% and 80% irrigation levels fell below those for the corresponding manual treatments by 25, 25, and 53 mm, respectively by DOY 261. This occurred even though cumulative irrigation depth was the same for manual and automatic control methods at the 80% level through DOY 254 (Fig. 2). In the seven days after DOY 254, three irrigations totaling 73 mm were applied to the manually controlled 80% treatment plots, while the automatically controlled treatments received only one irrigation of 16 mm on the 80% treatment plots ($I_{80\%A}$). This occurred because of small T_a and greater RH levels occurring on DOY 255, 257, and 261.

Unger and Wiese (1979) reported an increase in sorghum yield of 17.6 kg ha^{-1} for each mm (1.76 kg m^{-3}) increase in profile water content measured to 1.8-m depth at planting. If applied to the differential in profile water content on DOY 187, this would give an estimated 268 kg ha^{-1} yield increase for manual irrigation at the 30% level ($I_{30\%M}$), and a 27 kg ha^{-1} yield increase for manual irrigation at the 55% level ($I_{55\%M}$), which would explain in part the smaller yields from the automatic treatments at the 30% and 55% irrigation levels ($I_{30\%A}$ and $I_{55\%A}$, respectively).

Conclusion

In this study, a CWSI and time threshold were used to trigger irrigations for an early season variety of grain sorghum. The theoretically based CWSI provided a stable assessment of crop water stress through the majority of the irrigation season. Grain yields for the 80% and 0% treatments were not significantly different between irrigation control methods (manual and automatic). A curvilinear model expressing dry grain yield as a function of irrigation depth fit well for yields obtained from both irrigation control methods. Variability in the initial amounts of water stored in the soil profile in $I_{30\%A}$ and $I_{55\%A}$ and throughout the irrigation season in the $I_{30\%A}$ treatments influenced grain yield production. Further research is necessary to investigate whether the stability of a CWSI and time threshold is consistent for grain sorghum in this region.

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References

Allen, S.G., and F.S. Nakayama. 1988. Relationship between crop water stress index and other physiological plant water status indicators in guayule. *Field Crops Research* 18(4): 287-296

Ben-Asher, J., C.J. Phene, and A. Kinarti. 1992. Canopy temperature to assess daily evapotranspiration and management of high frequency drip irrigation systems. *Agric. Water Manage.* 22(4): 379-390.

Cohen, Y., V. Alchanatis, M. Meron , Y. Saranga, and J. Tsipris. 2005. Estimation of leaf water potential by thermal imagery and spatial analysis. *J. Exp. Botany* 56(417): 1843-1852.

Colaizzi, P.D., E.M. Barnes, T.R. Clarke, C.Y. Choi, and P.M. Waller. 2003. Estimating soil moisture under low–frequency surface irrigation using Crop Water Stress Index. *ASCE J. Irrigation and Drainage Engr.* 129(1): 27-35.

Colaizzi, P.D., P.H. Gowda, T.H. Marek, and D.O. Porter. 2008. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *Irrigation and Drainage*. DOI: 10.1002/ird.418.

Evett, S.R. 2002. Water and energy balances at soil-plant-atmospheric interfaces. pp. 128-188. In A.W. Warrick (Ed.). *The Soil Physics Companion*. CRC Press, Boca Raton, Fl.

Evett, S.R. 2008. Neutron moisture meters. Chapters 2-3 In S.R. Evett, L.K. Heng and P. Moutonnet (eds.) *Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology*. International Atomic Energy Agency, Vienna, Austria.

Evett, S.R., R.T. Peters, and T.A. Howell. 2006. Controlling water use efficiency with irrigation automation: Cases from drip and center pivot irrigation of corn and soybean. Pp. 57-66 In *Proc. 28th Annual Southern Conservation Systems Conference*, Amarillo Tex., June 26-28, 2006.

Garrot, D.J., M.J. Ottman, D.D. Fangmeier, and S.H. Husman. 1994. Quantifying wheat water stress with the crop water stress index to schedule irrigations. *Agron. J.* 86(1): 195-199.

Gontia, N.K., and K.N. Kiwari. 2008. Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry. *Agric. Water Manage.* 95(10): 1144-1152.

Howell, T.A., J.L. Hatfield, H. Yamada, and K.R. Davis. 1984. Evaluation of Cotton Canopy Temperature to detect crop water stress. *Trans. ASAE* 27(1): 84-88.

Howell, T.A. 2002. Irrigation Efficiency. Lal, R. Editor. *Encyclopedia of Soil Science*. Marcel Dekker, Inc., New York, N.Y., pp. 736-741.

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

Idso, S.B. and R.J. Reginato. 1982. Soil- and atmosphere- induced plant water stress in cotton as inferred from foliage temperatures. *Water Resources* 18(4): 1143-1148.

Jackson, S.H. 1991. Relationships between normalized leaf water potential and crop water stress index values for acala cotton. *Agric. Water Manage.* 19(2): 135-149.

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

Jackson, R.D., W.P. Kustas, and B.J. Choudhury. 1988. A reexamination of the crop water stress index. *Irrig Sci.* 9: 309-317.

Lyle, W.M., J.P Bordovsky. 1983. LEPA irrigation system evaluation. *Trans. ASAE* 26(3): 776-781.

Möeller, M., V. Alchanatis, Y. Cohen, M. Meron, J. Tsipris, A. Naor, V. Ostrovsky, M. Sprintsin and S. Cohen. 2007. Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *J. of Exp. Botany* 58(4): 827-838.

Nielsen, D.C. 1990. Scheduling irrigations for soybeans with the Crop Water Stress Index. *Field Crop Research* 23(2): 103-116.

Oliva, R.N., J.J. Steiner, and W.C. Young, III. 1994. White clover seed production: I. Crop water requirements and irrigation timing. *Crop Science* 34(3): 762-767.

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi, and T.A. Howell. 2008. Soil water measurement and thermal indices for center pivot irrigation scheduling. In: *Proc. Irrigation Association Show 2008*, Anaheim, Calif., Nov 2-4, IA09-1000: pp. 1-17.

Peters, R.T., and S.R. Evett. 2004. Modeling diurnal canopy temperature dynamics using one-time-of-day measurements and a reference temperature curve. *Agron. J.* 96(6): 1553–1561.

Peters, R.T. and S.R. Evett. 2008. automation of a center pivot using the temperature-time-threshold method of irrigation scheduling. *J. Irrig. Drainage Engr.* 134 (3): 286-290.

Pinter, P.J., K.E. Fry, G. Guinn, and J.R. Mauney. 1983. Infrared thermometry: A remote sensing technique for predicting yield in water-stressed cotton. *Agric. Water Manage.* 6(4): 385-395.

Rosenow, D.T., J.E. Quisenberry, C.W. Wendt, and L.E. Clark. 1983. Drought tolerant sorghum and cotton germplasm. *Agric. Water Manage.* 7(1-3): 207-222.

Soil Survey Staff. 2004. National Soil Survey Characterization Data. Soil Survey Laboratory, National Soil Survey Center, USDA-NRCS - Lincoln, NE. Verified: Friday, October 01, 2004.

Throssel, C.S., R.N. Carrow, and G.A. Milliken. 1987. Canopy temperature based irrigation scheduling indices for Kentucky Bluegrass turf. *Crop Science* 27(1): 126-131.

Unger, P.W. and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. *Soil Sci. Soc. Am. J.* 43: 582-588.

Yazar, A., T.A. Howell, D.A. Dusek, and K.S. Copeland. 1999. Evaluation of crop water stress index for LEPA irrigated corn. *Irrig. Sci.* 18(4): 171-180.

Yuan, G., Y. Luo, X. Sun, and D. Tang. 2004. Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain. *Agric. Water Manage.* 64(1): 29-40.

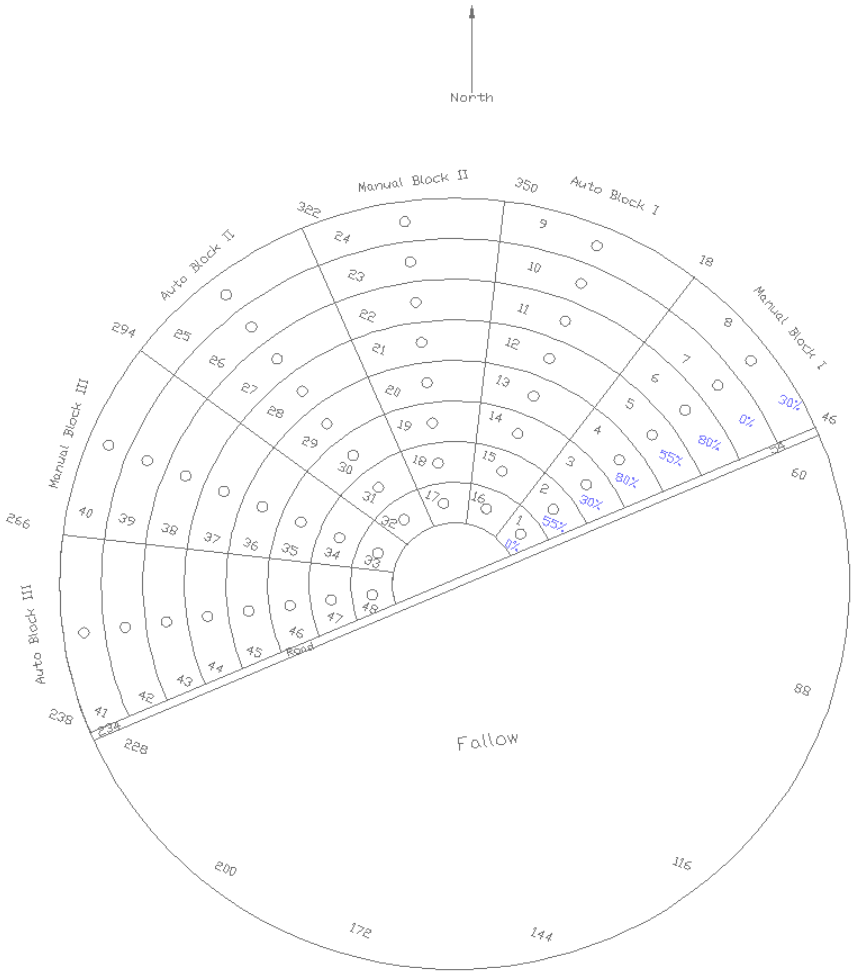

Figure 1. Layout of three-span center pivot field for the summer 2009 experiment showing 48 treatment plots, general location of neutron access tubes for soil water content readings, nozzling for irrigation amount treatments (80%, 55%, 30%, and 0%) with replications extending radially in blocks, and blocking for manual and automatic control methods arc-wise around the half circle. Infrared thermometers (IRt/cs) were mounted on masts forward of the drop hoses and at stationary positions in the field (not shown).

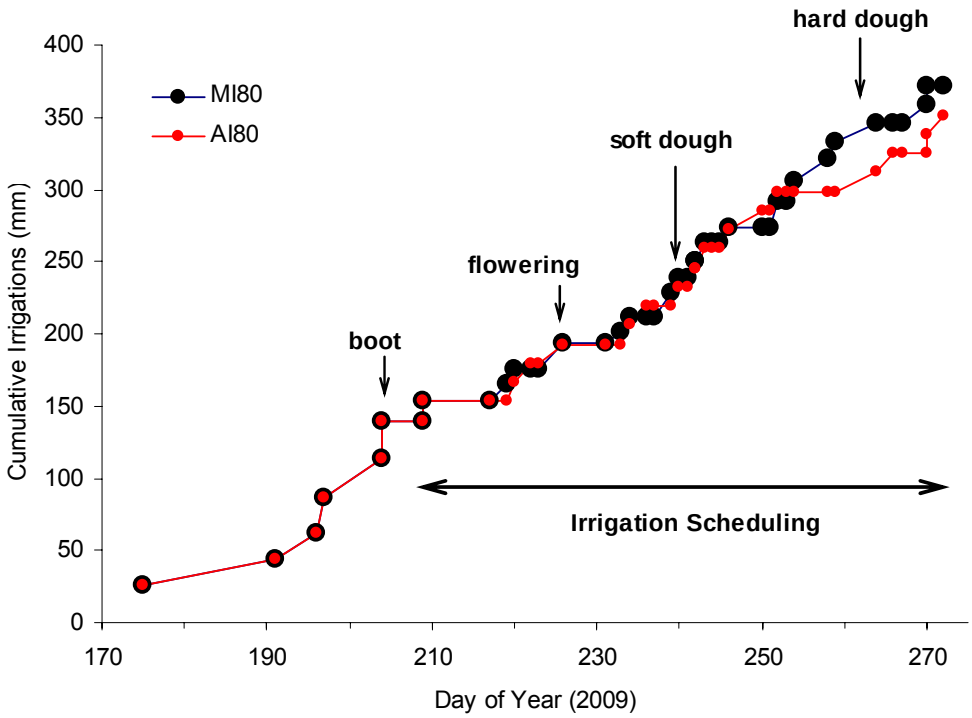

Figure 2. Cumulative irrigations for the manual and automatic irrigation control methods plotted against time and key growth stages.

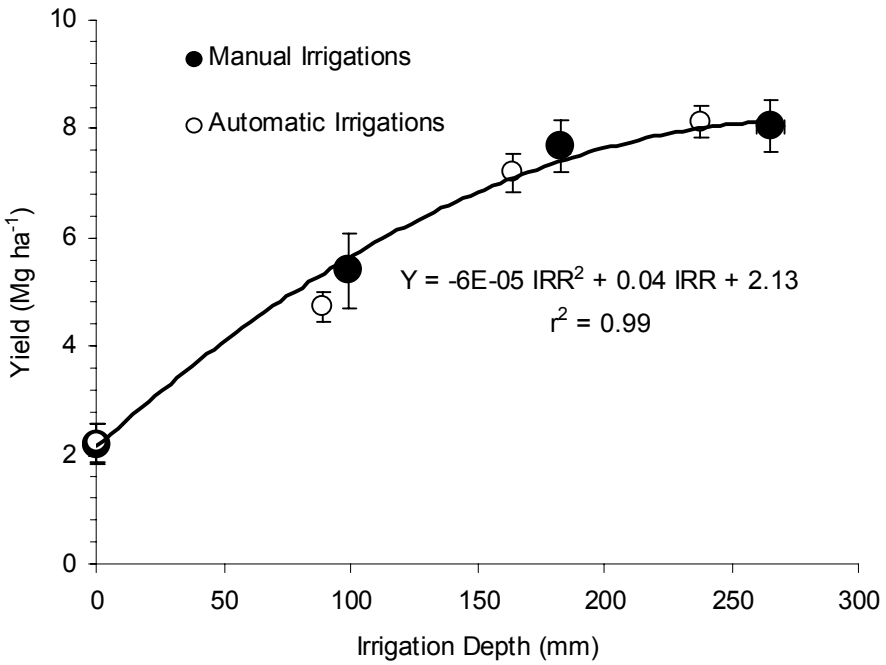

Figure 3. Grain yield versus cumulative irrigation depths applied during the scheduling period of growing season 2009. Vertical error bars indicate standard deviations in yield and horizontal error bars indicate standard deviations in irrigation amounts.