Infrared Thermometry as a Tool for Site-Specific Irrigation Scheduling

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Abstract. Ground-based infrared thermometry has been used as a tool to provide a non-invasive method to detect crop water stress and schedule irrigations. However, studies are limited on the use of infrared thermometry for irrigation scheduling with variable rate irrigation (VRI) systems. This study describes preliminary results of a wireless network of infrared thermometers (IRTs) integrated with a commercial VRI system to build dynamic prescription maps, and automatically control site-specific irrigation scheduling for cotton. A center pivot field was divided into manual and automatic- irrigation scheduling treatment plots. Measured lint yield, crop water use, crop water use efficiency, and irrigation water use efficiency were compared between the two irrigation-scheduling methods at three irrigation treatment levels (75%, 50%, and 25% of full as defined by either replenishment of crop water use to field capacity or by the equivalent threshold for the IRT sensor crop water stress). Lint yields were not significantly different between the manually and automatically controlled plots at the 75% irrigation treatment (1612 and 1621 lb ac^{-1}) and 50% irrigation treatment (1300 and 1460 lb ac^{-1}) levels, respectively. However, at the 25% treatment level, twice the amount of irrigation was applied to the automatically controlled plots compared with manually irrigated treatment plots. These preliminary results demonstrate that it is plausible to use a plant feedback system based on infrared thermometry to control a VRI system to achieve site-specific irrigation scheduling for cotton at reasonable deficit irrigation levels. However, maintaining automatic deficit irrigation at a level equivalent to 25% of crop water use to field capacity would require further research.

Keywords: center pivot, crop water stress index, infrared thermometers, variable rate irrigation

Introduction

Infrared Thermometry

The canopy temperature of healthy transpiring crops will often be less than that of air temperature due to evaporative cooling at the leaf surface. However, when the potential rate for transpiration becomes limited, because of diminishing plant available water or climatic conditions, transpiration is reduced. As a result, crop canopy temperature increases. The characterization of crop water stress by measuring differences in canopy and air temperature is the basis for using infrared thermometry as a tool for irrigation scheduling. Infrared thermometers were used as early as the 1960s in agricultural field experiments to detect crop water stress remotely (Tanner, 1963; Wiegand and Namken, 1966). Initially the infrared thermometers that were used were hand-held instruments. Measurements made with these portable devices were of temperatures integrated over a small portion of the canopy and usually taken over a short period, i.e. midday, usually between 11:00 am and 14:00 pm (Hattendorf et al., 1988; Barbosa da Silva and Rao, 2005). The spatial and temporal limitations of measurements from hand-held infrared thermometers are problematic in that they do not necessarily represent crop water status of the entire field, and it is cumbersome to make daily measurements.

Advancements in technology have led to wired and wireless thermal infrared instrumentation, which allows for direct and continuous recording of temperatures with various electronic data loggers and computer base stations, resulting in continuous crop surface temperature monitoring. A moving irrigation system such as a center pivot has been shown to be a suitable platform for sensors, which can measure multiple locations in the field (Phene et al., 1985; O'Shaughnessy et al., 2014). Geo-referenced canopy temperature measurements made over a large area allow for spatiotemporal mapping of crop water stress (Sadler et al., 2002; Peters and Evett, 2008; O'Shaughnessy et al., 2011), and yield predictions (Pinter et al., 1985; O'Shaughnessy et al., 2011).

Crop Water Stress Index and Thresholds

Quantification of crop water stress is typically established using a stress index, the theoretical crop water stress index (CWSI) developed by Jackson et al. (1981) uses an energy balance to compute the upper (non-transpiring crop) and lower (fully-transpiring) bounds of canopy-air temperature differences. Relative to the empirical CWSI developed by Idso et al. (1981), the theoretical CWSI requires the additional measurement of net radiation and wind. However, the more complicated equations (1.a, 1.b, and 1.c) can account for temperature differences due to radiation and wind speed (Jackson et al., 1988).

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}} \quad [1.a]$$

where $(T_c\text{-}T_a)$ is the measured difference between crop canopy temperature (T_c) ($^\circ$C) and air temperature (T_a) ($^\circ$C), $(T_c\text{-}T_a)_{ll}$ is the calculated lower limit representing the temperature difference of a healthy well-watered crop, $(T_c\text{-}T_a)_{ul}$ is the calculated upper limit representing the temperature difference between a severely stressed (i.e., non-transpiring) canopy and the ambient air (Jackson et al., 1988). The upper limit can be calculated using eq. 1.b:

$$(T_c - T_a)_{ul} = r_a (R_n - G) / \rho C_p \quad [1.b]$$

where R_n (net radiation) is derived from R_s (short wave radiation) (MJ m^{-2} d^{-1}), R_{lw_in} (incoming long wave radiation) (MJ m^{-2} d^{-1}), R_{lw_out} (outgoing long wave radiation)(MJ m^{-2} d^{-1}), ρ (density of air approximated as a function of elevation) (kg m^{-3}), C_p (heat capacity of air) (J kg^{-1} $^{\circ}$C^{-1}), and R_n= [(1-α) R_s + R_{lw_in} – R_{lw_out}])(MJ m^{-2} d^{-1}), where α is the albedo of the surface. The lower limit, $(T_c\text{-}T_a)_{ll}$ is calculated using eq. 1.c:

$$(T_c - T_a)_{ll} = \frac{r_a R_n}{\rho C_p} * \frac{\gamma}{\Delta + \gamma} - \frac{e_s - e_a}{\Delta + \gamma} \quad [1.c]$$

where r_a is aerodynamic resistance (s m^{-1}) (Allen et al., 1998), *γ* is the psychrometric constant (P_a °C^{-1}), and Δ is the slope of the saturated vapor pressure – temperature relationship, e_s (P_a) is saturated vapor pressure and e_a (P_a) is actual vapor pressure at T_a.

Since canopy temperature measurements are from IRTs on a moving irrigation system, the temperatures recorded at the base-station computer are from different locations in the field over different times of the day. However, diurnal canopy temperature (T_c) for each remote measurement can be estimated using a temperature-scaling algorithm (Peters and Evett, 2004) (equation 2):

$$T_c = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \quad [2]$$

where T_e (°C) was the predawn canopy temperature; T_{ref} (°C) was the reference canopy temperature at the same time interval as T_c (°C); $T_{rmt,t}$ was the one-time-of-day canopy temperature measurement at the plot (remote location, denoted by subscript rmt) at any daylight time *t* measured by the IRTs on the pivot lateral; and $T_{ref,t}$ (°C) was the measured reference temperature for the time *t* that the plot (remote) temperature measurement was taken.

An integrated CWSI ($_i$CWSI), i.e. the summation of the CWSI calculated for each time (*t*) over daylight hours for each location of measurement, can represent the crop water stress status of a management zone. Actual irrigation scheduling with crop water stress indices requires use of water stress index thresholds. There are a number of studies in the literature that report measured crop thermal stress levels resulting from deficit irrigation treatments (Nakayama and Bucks, 1983; Hattendorf et al., 1988; Nielsen and Anderson, 1989; Olufayo et al., 1996). Differential irrigation levels can be achieved by varying the stress index thresholds (Nielsen and Gardner, 1987; Garrot et al., 1994; Evett et al., 1996, 2002; Barbosa da Silva and Rao, 2005; Gontia and Tiwari, 2008) with the expectation of higher threshold levels resulting in less frequent irrigation and/or less irrigation application amounts. Experiments using differential irrigation amounts have demonstrated that seasonal average crop thermal stress indices tend to have a negative linear relationship with crop yield (Wanjura et al., 1988; Yazar et al., 1999; O'Shaughnessy et al., 2011). Using historical canopy temperature data, integrated CWSI values for differentially irrigated crops can be used to specify CWSI thresholds (O'Shaughnessy et al., 2014).

VRI Systems

Variable rate irrigation systems (VRI) make it possible to apply variable amounts of water along a moving irrigation lateral and in the direction of its travel. Catch-can tests (Dukes and Perry, 2006, Han et al., 2009; Chavez et al., 2010; and O'Shaughnessy et al., 2013) have demonstrated that irrigations applied radially and arc-wise by commercial VRI systems are uniform; i.e. coefficients of uniformity were greater than 80% within an irrigation management zone. The functionality of the VRI hardware should make it possible to meet variable crop water needs, if spatiotemporal crop water stress can be detected in near real-time. Since moving sprinkler irrigation systems now constitute more than 84% of pressurized irrigation systems in the United States (National Agricultural Statistic Service, 2008), outfitting such systems with VRI equipment can help provide site-specific irrigation and improve crop water use efficiency.

Study Objectives

Although thermal stress indices have been used for irrigation scheduling with mechanical move irrigation systems, there are limited studies using infrared thermometry with variable rate irrigation equipment. Currently, site-specific irrigation using a wireless network of infrared thermometers, plant feedback algorithms, and commercial variable rate irrigation (VRI) hardware and software is under investigation at the USDA-ARS Conservation and Production Research Laboratory (CPRL) in Bushland, Texas. The objectives of this work are to develop and evaluate dynamic prescription maps using measurements from infrared thermometry; and to evaluate site-specific irrigation control for a cotton crop with a center pivot system.

Materials and Methods

For the 2012 growing season, one-half of a three-span center pivot field was planted to cotton on May 19, day of year (DOY) 140. The variety was Delta Pine, DP1212B2RF[1]. The experiment was conducted at the USDA-ARS Conservation & Production Research Laboratory (CPRL), Bushland, Texas. Twenty-eight treatment plots, each 60 ft. wide, were arranged in a randomized block design, with irrigation methods (manual and automatic) and treatment levels (75%, 50%, and 25%) as main effects (Figure 1). Four quasi-dryland plots (designated as $I_{0\%}$) were included to allow calculation of irrigation water use efficiency (IWUE).

These plots were not irrigated past plant stand establishment. Three integrated CWSI ($_i$CWSI) threshold values were established at 260, 290, and 344 (no units) to undertake the automatic treatments, $I_{75\%C}$, $I_{50\%C}$, and $I_{25\%C,}$ respectively. The threshold values were determined by averaging the CWSI calculated from equations 1.a, 1.b, and 1.c over daylight hours using canopy temperature data from cotton experiments with differential irrigations at Bushland in 2007 and 2008. The three-span center pivot system was retrofitted with a variable rate irrigation (VRI) package (Valmont Industries, Valley, Nebr.). Irrigations were applied using low energy precision application (LEPA) drag socks (Lyle and Bordovsky, 1983) in alternating cross-diked furrows. The main components of the commercial VRI system were a programmable logic controller (PLC), variable rate towers with electronic solenoid valves to control banks of hydraulic valves on each drop hose [drop hoses were spaced 5 ft. apart, and a geographical positioning system (GPS). A set of six-drop hoses was configured as a single bank and controlled by an electronic solenoid valve. The PLC actuated the electronic solenoid valves, which controlled the pulsing frequency of each hydraulic valve. The PLC achieved differential irrigation amounts by pulsing the hydraulic valves at different rates. Commercial software was used to direct the operation of the PLC.

A wireless network of infrared thermometers and a base station computer were integrated with the commercial VRI system (O'Shaughnessy et al., 2014). The computer system, located at the pivot point, collected canopy temperature, GPS, microclimatological, and operational pivot data from the pivot's control panel. Every two days, prescription maps were constructed based on the calculated stress index for each automatic-control plot and were manually input for manually-scheduled treatment plots. The prescription map was then uploaded to the center pivot control panel using a software interface.

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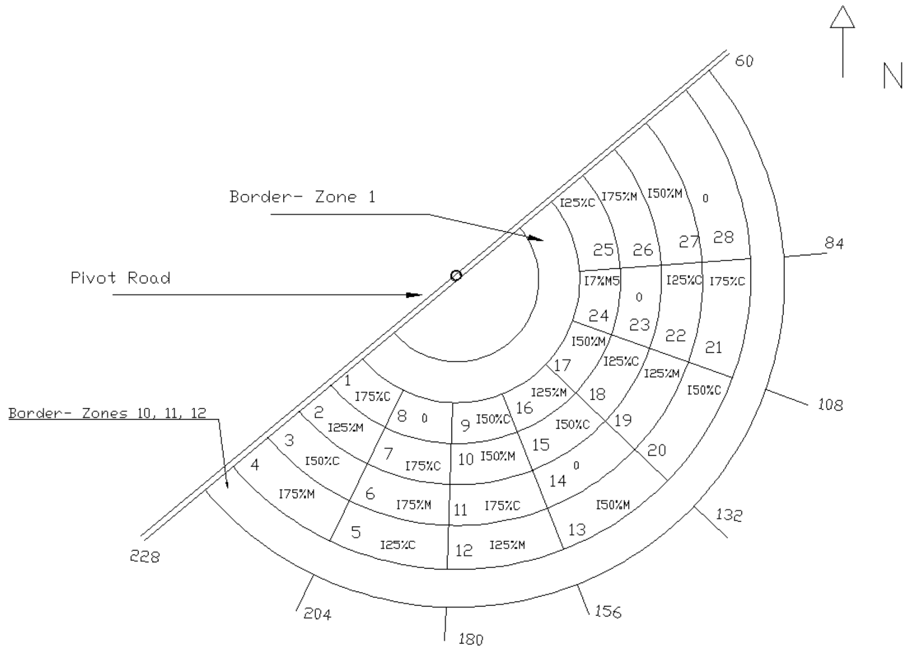
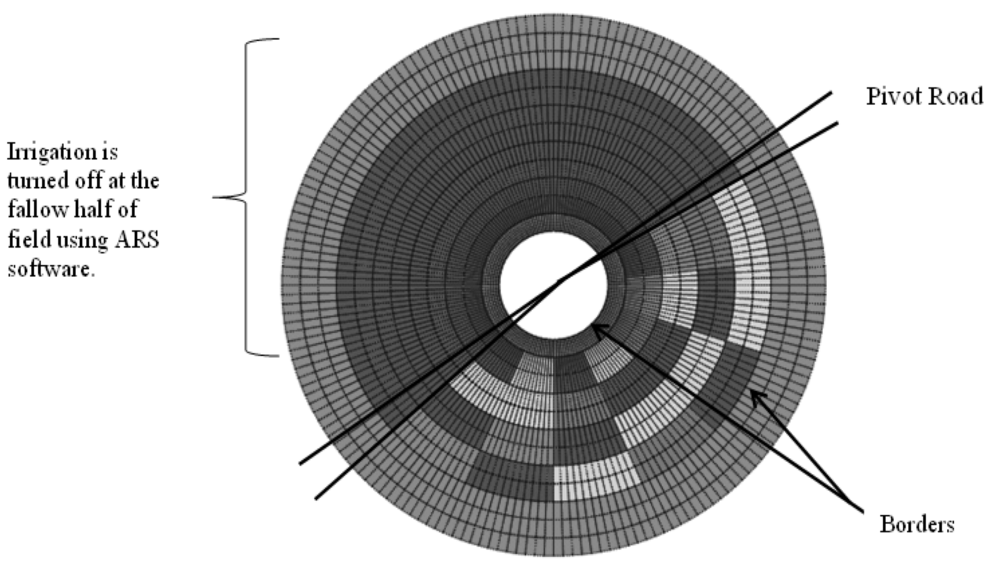


(a)



(b)

Figure 1. (a) Experimental plot plan for cotton planted under a 3-span center pivot. Irrigation methods are annotated by letter (C=irrigation scheduling controlled by the CWSI, M= manual irrigation methods using neutron probe) and irrigation treatment levels by number (75, 50, 25, and 0); (b) prescription map indicating watering levels for the southeast half of the pivot field.

Manually-irrigated treatment plots, designated $I_{75\%M}$, $I_{50\%M}$, and $I_{25\%M,}$ received 75%, 50%, and 25% replenishment of soil water depletion to field capacity based on weekly neutron probe readings. An application of 0.78 in. (twice the peak daily water use for cotton at Bushland) was delivered to each automatically-controlled plot, *p,* if the $_i$CWSI$_p$ calculated from canopy temperature over that plot was greater than the pre-established threshold (260, 290, and 344 for irrigation levels of 75%, 50%, 25%, respectively and designated $I_{75\%C}$, $I_{50\%C}$, and $I_{25\%C}$ (Fig. 1). Thresholds were established from data collected at the CPRL over differentially irrigated cotton in 2007 and 2008. The maximum application depth of the irrigation system was fixed at 0.78 in. for this experiment by setting and maintaining the pivot travel speed at the end tower to 143.7 ft hr^{-1} (19° hr^{-1}). The sprinkler banks delivering water to automatically-controlled plots receiving an irrigation signal were coded at 100%. For irrigation of the manually-scheduled plots, the irrigation amount required to replenish 100% of crop water use to field capacity was entered into the ARS-written graphical user interface. Irrigation amounts delivered to the manual designated plots were achieved by pulsing the appropriate sprinkler banks at rates equivalent to 75%, 50%, and 25% of the entered application depth. The instructions for irrigating the semi-circle and its graphical representation (prescription map) were coded using Microsoft Visual Studio 2010[1] (version 10.0.4). Treatment plot boundaries were fixed and defined by sectors and sprinkler irrigation zones. The start and completion of irrigations were automated using software previously developed by the USDA-Agricultural Research Service (ARS). Plant height and width measurements were recorded approximately every 14 days throughout the growing season and used to adjust plant height estimates required for the calculation of aerodynamic resistance, r_a. Hand-samples of lint-yield from each treatment plot were acquired from a 107.6 ft^2 sub-plot near each neutron access tube. Fiber samples from the ginned-cotton were analyzed by the Fiber & Biopolymer Research Institute at Texas Tech University, Lubbock, Texas.

Calculations

An $_i$CWSI was calculated for each management zone (treatment plot), by estimating diurnal canopy temperature (eq. 2), calculating a CWSI for each estimated temperature using equations 1.a, 1.b., and 1.c., and summing the CWSI values for daylight hours.

Crop water use or ET_c was calculated using the soil water balance equation:

$$ET_c = P + I + F - \Delta S - R \qquad [3]$$

where ET is evapotranspiration, ΔS is the change in soil water stored in the profile, *R* is runoff, *P* is precipitation (in.), *I* is the irrigation water applied (in.), and *F* is flux across the lower boundary of the control volume (taken as positive when entering the control volume), all in units of inches. The *F* and *R* components were controlled by deficit irrigation scheduling and furrow dikes, and were therefore considered negligible.

Water use efficiency (lb ac^{-1} in^{-1}) was calculated as

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

where Y_g is the economic yield (lb ac^{-1}), and ET is the crop water use (in.).

Irrigation water use efficiency (lb ac^{-1} in^{-1}) was calculated as

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

where Y_g is the economic yield (lb ac^{-1}), Y_{gd} is the dryland yield (lb ac^{-1}), and IRR is the irrigation water applied (in.) (Howell, 2002).

Statistical Analysis

Results were analyzed using Mixed Models in the PROC MIXED models procedures (Littell et al., 2006) with SAS statistical software[1] (SAS 9.3, SAS Institute Inc., Cary, NC). The main factors of irrigation method (automatic and manual) and irrigation treatments were treated as fixed effects. Concentric plots were considered random effects. Multiple means comparisons were performed using the *Tukey-Kramer* method at p = 0.05.

Results

Climatology

Moderate to severe drought conditions persisted during most of the 2012 summer growing season at Bushland, Texas. Precipitation during the months of May through Aug totaled only 2.82 in., which is approximately 66% less than the average amount received for the past 70 years during this same period. The maximum daily air temperatures were highest Jun through Aug, and mean wind speeds ranged from 7.4 mph to 11.0 mph, May – Oct (Table 1).

Table 1. Climatological data for the 2012 growing season in Bushland, Texas, represented by mean monthly values.

Month	Min RH (%)	ET_o (in.) [a]	Max RH (%)	Min Air Temp (°F)	Max Air Temp (°F)	Precipitation (in.)	Wind speed (mph)
May	21.1	0.29	72.6	51.3	82.0	1.1	9.2
June	23.1	0.33	78.7	61.7	91.2	1.3	11.0
July	21.3	0.32	68.2	65.3	93.2	0.0	8.7
Aug	21.7	0.28	72.7	62.8	93.0	0.3	7.8
Sep	26.0	0.21	78.9	54.1	82.6	1.6	7.4
Oct	27.4	0.16	76.7	41.2	70.3	0.2	8.5

[a] ET_o is reference evapotranspiration calculated from an adjacent weather station at Bushland, Texas using the ASCE-EWRI method (2005).

Irrigation amounts and timing

The total irrigation applied to manual treatment plots ($I_{75\%M}$, $I_{50\%M}$, and $I_{25\%M}$) were 18.7 in., 12.6 in., and 5.9 in., respectively. Average irrigation amounts (and standard deviations) applied to the automatic-control plots ($I_{75\%C}$, $I_{50\%C}$, and $I_{25\%C}$) were 16.5 ± 1.6 in., 14.4 ± 1.1 in., and 13.1 in. ± 1 in., respectively.

Lint yields were not significantly different between the $I_{75\%M}$ and $I_{75\%C}$ treatments or between the $I_{50\%\,M}$ and $I_{50\%\,C}$ (Table 2). Water use efficiency was greatest at the $I_{75\%C}$ treatment level (66.1 lb ac^{-1} in^{-1}), but not significantly different from any other irrigation method or treatment level. However, mean lint yield for the $I_{25\%C}$ treatment plots was significantly greater than the mean yield for the $I_{25\%M}$ treatment plots due to greater application (78%) of irrigation water by the plant feedback system. This likely occurred for two reasons, early in the irrigation season, canopy temperature readings were grossly high, resulting in false-positive irrigation signals. The second reason is that later in the irrigation season, deficit or infrequent irrigations could have resulted in leaf wilt, allowing soil background to influence the measured temperatures in these plots.

Table 2. Cotton response (2012) to manual and automatic methods of irrigation scheduling, irrigation level, and the interaction of method and irrigation level. Means for each category followed by the same letter in the column are not significantly different.

Growing Season 2012				
Category	Lint yield ($lb\ ac^{-1}$)	ET_c (in.)	WUE ($lb\ ac^{-1}\ in.^{-1}$)	IWUE ($lb\ ac^{-1}\ in.^{-1}$)
Irrigation Treatment Level				
75	1621a	25.6a	63.3a	78.1a
50	1380b	22.2b	62.4a	83.9a
25	1042c	18.5c	56.1a	87.3a
0	249d	9.9d	25.1b	-
Irrigation Method X Irrigation Treatment				
M75	1612a	26.7a	60.4a	73.1a
C75	1621a	24.6b	66.1a	83.3a
M50	1300b	21.3c	61.1a	83.7a
C50	1460ab	22.8bc	64.0a	83.9a
M25	819c	15.2d	53.8a	97.3a
C25	1264b	21.7c	58.1a	76.9a

Discussion and Conclusion

In this study, a commercial VRI system was outfitted with a WSN system to automate the development of prescription maps and control site-specific irrigation scheduling of cotton. The field was divided into 28-treatment plots, including four dryland plots ($I_{0\%}$), and four replications of each treatment method (automatic and manual) and irrigation level (75%, 50%, and 25%). The dryland plots were only irrigated until a uniform plant stand was established and their yields were used to calculate IWUE. A comparison of lint yield, ET_c, WUE and irrigation WUE demonstrated that this control system was effective for site-specific deficit irrigation scheduling for cotton irrigated at the $I_{75\%}$ treatment level. At the $I_{25\%}$ treatment level, automatic irrigations were applied in excess of the manual irrigations. Automatic irrigations in excess of manual amounts were likely due to false positive triggers resulting from temperature contribution of a larger area of soil due to less canopy cover at the beginning of the irrigation season. Future work is needed to develop a sensor that distinguishes canopy and soil temperature measurements from a moving array of infrared thermometers viewing row crops, and to evaluate algorithms such as a two-source energy balance model where canopy and soil temperatures are estimated from composite surface temperature measurements (Colaizzi et al., 2012).

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