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ORIGINAL PAPER

Deficit irrigation in a production setting: canopy temperature as an adjunct to ET estimates

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Abstract Water available for agricultural use is declining worldwide as a result of both declining water resources and increasing application costs. Managing crop irrigation under conditions where the water need cannot be fully met represents the future of irrigation in many areas. On the southern high plains of Texas there is interest among producers to reduce the amount of water applied to cotton. In this study, a producer's efforts to reduce water application to a cotton crop were assessed in terms of a comparison between evapotranspiration, rainfall, and irrigation that is widely used in the region. The producer was able to reduce water application to meet intended reductions relative to the evapotranspiration estimates but, depending on the method used for calculating the crop water need, he tended to over water the crop in two out of three intended deficit irrigation regimes. Analysis of continuously monitored canopy temperatures provided verification of over-irrigation. Continuously monitored canopy temperature is proposed as a useful adjunct to evapotranspiration approaches to deficit irrigation management.

Introduction

From a global perspective, limited water resources are becoming one of the greatest challenges facing agriculture and thus civilization in this nascent century (Howell 2001; Faurèsa et al. 2003). Rhoades (1997) postulated that increases in food production in developing countries will primarily come from irrigated lands. Agricultural water on the southern high plains of Texas was once inexpensive and abundant; today it is increasingly expensive and scarce. In particular, the increased energy costs associated with pumping of water from irrigation wells have increased the cost of a typical irrigation event by a factor of almost four over the last 15 years. Irrigated land accounts for approximately 50% of crop production in the region of Texas that relies on the Ogallala aquifer (Pate and Johnson 2010). In addition to the increased energy costs, agricultural producers in the region are confronted with decreasing water resources that are increasingly a focus of political and societal concern. The combined effects of rising cost and diminished availability are creating a need for new irrigation approaches that are tailored to this situation.

Improved water transport and storage systems, mechanized irrigation systems and drip systems have all increased the efficiency of irrigation in terms of delivering water to the crop in a timely manner to produce maximum yield. In some irrigation systems there is still the opportunity to improve irrigation efficiency through improved water transport and application. Such "engineering" approaches are straightforward and the water efficiencies they provide can be substantial. However, regardless of the engineered efficiency of the water management, there is the potential to improve the physiological efficiency of water use by the crop. Such "physiological" approaches, based on the biology of plant water use, provide opportunities to manage both water use and yield in terms of an economic balance. The costs of irrigation and other crop inputs that are incurred in pursuit of maximum yield at some point will result in a reduced total economic return from the crop.

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There is a growing interest in defining the economic efficiency of irrigated agricultural systems with an eye toward maximizing economic returns as opposed to yield. There is a growing interest among agricultural producers in irrigation approaches to reduce the amount of water applied to crops and a stated willingness to accept some yield reduction if it can be offset by reduced water costs (Pate and Johnson 2010). Thus, there is a renewed interest in new approaches to irrigation management on the southern high plains of Texas with the ultimate goal of reducing the amount of water used for irrigation.

On the southern high plains of Texas irrigation well capacities are limited to the point that many center pivot irrigation systems cannot apply water at a rate that will meet the maximal crop demand in mid season (Trout and Kincaid 2007). In the region the accepted irrigation strategy over the past few decades has been an approach that relies on early and frequent irrigation that is intended to exceed the water requirements of the plant early in the season so that moisture can be accumulated, or "banked" in the soil for use by the plant later in the season. This approach has been relatively successful as evidenced by the continued success of the region's cotton industry. While the concept of banking soil moisture in order to preempt water deficits later in the season is appealing, such an approach severely limits efforts to actually reduce the amount of water applied.

The desire to reduce the amount of water used in crop production is not limited to the southern high plains of Texas, since water for irrigation is becoming increasingly scarce on a global basis. Reductions in agricultural irrigations are of interest in that, if done correctly, it is possible that water savings can be realized with yield reductions that could be economically acceptable. It is the balance between water savings and yield reductions that will ultimately determine the acceptability of any irrigation approach that is designed to reduce the amount of water applied to the crop.

Any effort to reduce water use in a cropping system will require both a scientific understanding of the relationship between water and crop performance and a means of assessing the water status of the crop. The level of complexity associated with a determination of the water requirement of a crop is, of course, related to the accuracy required. Under irrigation regimes that approach full irrigation (fully meeting the water requirement of the crop) plant performance becomes insensitive to water at the upper end of the irrigation continuum and variation in plant performance due to errors in assessing water requirements are not readily apparent. Many of the producers on the southern high plains of Texas can still irrigate in amounts that are of a magnitude such that small variation does not significantly affect performance. Substantial water savings will require irrigation management methods that render plant performance sensitive to irrigation amount and produce a situation where irrigation errors will be readily detectable.

If indeed irrigation on the southern high plains of Texas will require increased reliance on controlled deficits for sustainability, then improved approaches to water management will be needed (Baumhardt et al. 2009). The most commonly used irrigation management approaches are based on accounting methods that attempt to monitor moisture added to the soil in the form of irrigation and rain and balance those amounts against an estimate of the water lost from the soil as drainage, evaporation and transpiration. While evapotranspiration approaches have proven adequate for use in irrigation that attempts to fully meet the demand of the crop, they may not be sufficiently accurate for use in managed deficit irrigation that is designed to reduce water applied to the crop.

Irrigation on a deficit level, in which success requires a more precise balance between water application and crop water status, will most likely benefit from measurements of crop water status (Jones 2004). Such direct measurements of crop water status, when used in conjunction with estimates of soil moisture and accurate measurements of rain and irrigation may best provide the accuracy required for managing water deficits and reducing water applied to the crop.

In this study we have used continuous measurement of canopy temperature as a direct indicator of crop water status over time (Wanjura et al. 1995). A commercially available wireless infrared thermometry system was used to continuously monitor the temperature of the cotton canopy during the irrigation period of the crop. The stated goal of the producer in this study was to reduce water application to a cotton crop near Plainview, Texas (Hale County). The producer was responsible for all phases of the study with the exception of the canopy temperature measurements. Canopy temperature monitoring has been previously used for irrigation scheduling in this region by the researchers and this producer. In this instance, the goal of monitoring temperature was to investigate canopy temperature monitoring as a tool for validating and refining water management in an agricultural setting in which evapotranspiration is relied on for irrigation management.

Materials and methods

The study consisted of observations of a cotton crop on a private farm near Plainview, Texas, in 2009. All crop management was determined and carried out by the producer. The investigators were responsible for canopy temperature monitoring, calculating water applied, and analysis of various evapotranspiration (ET) estimations. The investigators did not set up the irrigation treatments or participate in any of the crop management.

Cotton crop

Cultural practices were standard for the region and were developed and carried out by the producer. Cotton was planted on 15 May 2009. A pre-plant irrigation and subsequent rain events provided sufficient moisture for establishment of the crop. Differential irrigation regimes were initiated on DOY 185 (July 4). The field experienced an infestation of verticillium wilt that was concluded to have affected yield and quality in the highest irrigation regime. The cotton was harvested at the end of the season by the producer who provided yield data.

Irrigation regimes

The producer established three irrigation regimes in the cotton crop to investigate water and yield relationships. High, medium and low irrigation regimes were established with the goal of applying 85, 65, and 50%, respectively, of the crops' seasonal water need based upon the 100% reference ET value reported from a regional weather station site. The producer routinely uses the reference ET value from this site as an estimate of crop water requirement and as a basis for irrigation management.

Rain

During the irrigation period there were 24 rain events that totaled 178 mm (Fig. 1). The smallest rain amount was 0.32 mm and the largest was 22 mm. Rain events were well distributed over the season.

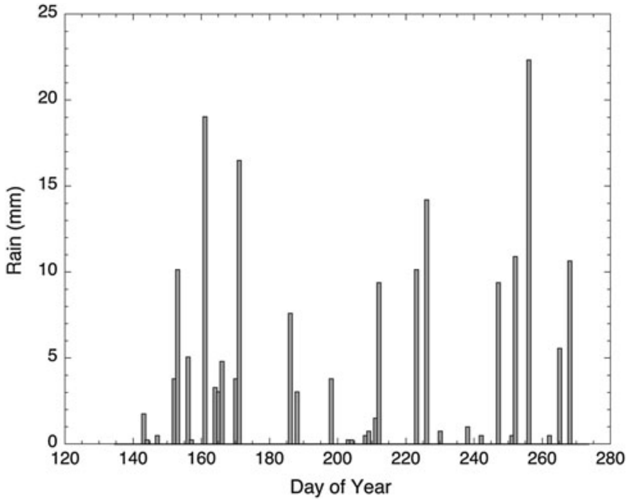

Fig. 1 Rainfall events at the field site near Plainview TX during the 2009 growing season. Total amount was 178 mm

Irrigation

Irrigation was applied with a center pivot irrigation system that covered an area of 54 ha (134 acres). One half of the field was planted with cotton with the other half planted with grain sorghum that was irrigated in the same manner as the cotton. The cotton field was 26 ha (65 acres) in size. The pivot required approximately 72 h to apply an irrigation to the cotton and, when the time required to irrigate the sorghum is included, the cotton could be irrigated once every 5–6 days. The producer delayed irrigation in response to rain on several occasions. Well-flow was monitored at the pivot with a flow meter (Net Irrigate, Bloomington, Indiana, USA, http://netirrigate.com). The system provided approximately 35 mm of water per hectare for each irrigation event on the highest water regime. The medium and low irrigation regimes consisted of 8 adjacent rows for each regime (in the center of the pivot circle) that were nozzled to provide 20 and 35% less water than the highest irrigation regime. The volume of water delivered to the crop by each of the irrigation regimes was verified with end-of-season volumetric validation. Seven irrigations were applied over the course of the growing season on a schedule determined by the producer. The medium and low irrigation regimes received approximately 27 and 21 mm of water per irrigation, respectively. All regimes were irrigated simultaneously.

Temperature monitoring

Canopy temperatures were monitored over the growing season using a SmartCrop wireless infrared thermometer (IRT) system (Smartfield Inc., Lubbock, Texas, USA, http://smartfield.com). The SmartCrop system has been previously described (Mahan and Yeater 2008; Mahan et al. 2010). The system uses a combination of wireless remote IRT sensors placed in the field and a remote base station on the edge of the field to continuously collect canopy temperature. The remote IRT sensors were positioned approximately 20 cm above the canopy at a view angle of approximately 60° downward, from the horizontal and perpendicular to the row. The remote IRT sensors were adjusted weekly to maintain the 20 cm height as the crop canopy developed. The sensor has a 1:1 field of view and the observed area of canopy monitored was approximately 20 cm in diameter. At the earliest monitoring dates (DOY 176 to DOY 189) the canopy did not completely fill the IRT sensor's field of view and the measured canopy temperature thus included a mixture of leaf and bare soil. After DOY 190, the field of view was comprised largely of plant canopy. The canopy temperature was measured at 1-min intervals with 15-min averages calculated by the remote sensors for automated transmission to the base unit once every

15 min. The collected canopy temperature data were transmitted via a cellular data link once every 2 h to a website for archiving and subsequent analysis. Data quality was good with only 72 h (out of a total of 1,440 h) of data "lost" over the season. One remote IRT sensor was used in each of the three irrigation regimes. Placement was determined on the basis of a representative canopy with the sensors along a radial line from the center of the pivot. The sensors were approximately 20 m apart along the radius of the pivot. The sensors remained in the same location during the entire measurement period. Air temperature was measured at 2 m above ground level by the SmartCrop remote base station on the edge of the field surrounded by the crop on the same measurement interval as the remote IRT canopy temperature. Collecting canopy temperature data was relatively simple. Installation of the systems in the field required approximately 1 h. The producer checked the sensors at least weekly for height adjustment and all data were collected remotely.

ET estimates

Four estimates of evapotranspiration were used in the study: *Agrilife/Lockney ET*—reference ET from the Texas Agrilife website for Lockney, Texas (20 km from field site), *Private ET*—reference ET from the website of the private company providing pivot monitoring for the producer, *Private cropET*—crop ET estimated by the private company providing pivot monitoring for the producer and adjusted with crop coefficients for cotton, and *Agrilife/Lockney cropET*—Crop ET calculated by the FAO 56 method with crop coefficients for cotton and weather data from the Texas Agrilife site for Lockney, Texas (20 km from field site). The producer used *Agrilife/Lockney ET* as the basis for his irrigation management. The other ET estimates are presented as an example of the data that are available to the typical cotton producer in the region for irrigation management. The intent is not to debate the appropriateness of any individual estimate but rather the limitations inherent in the use of such estimates as a class.

Results/discussion

Expected versus actual results

The producer intended to reduce the application of water to provide as little as 50% of the seasonal water requirement of the crop based on a 601 mm estimate of the seasonal ET obtained from the *Agrilife/Lockney ET* value. This ET estimate is derived from a weather station approximately 20 km from his field. The pivot was nozzled to produce differential irrigation that was intended to provide approximately 85, 65, and 50% of the seasonal water requirement of the crop as determined by an ET calculation. This range of applied water would be expected to result in differential water stress in the crop of a magnitude that would result in substantial yield reductions. The water and yield results for the season are shown in Table 1. The 2009 growing season was typical for the region with intermittent in-season rainfall totaling 178 mm occurring in 24 events (Fig. 1). Over the course of the season, the three irrigation regimes received differential irrigation amounting to 249, 199 and 162 mm, which with rainfall of 178 mm, resulted in total water to the crop of 427, 377, and 340 mm. Given the producer's irrigation targets of 85, 65 and 50% of seasonal ET and his ET estimate of 601 mm, the irrigation regimes provided 71, 62 and 56% of the seasonal ET estimate. The water amounts, which are relatively close to the targets, suggest that substantial yield reductions might be expected to have occurred.

Yield and water relationships

The yield data from the water treatments did not follow the expected trend (Table 1). The highest yield, 1,540 kg/ha was associated with the 65% target irrigation regime with the 50% target irrigation producing a somewhat lower yield of 1,396 kg/ha. The lowest yield, 1,003 kg/ha was produced by the 85% target regime. Clearly this was not the intended outcome given that the producer's goal was to generate information on the potential yield reductions associated with targeted irrigation water savings. While water application

Table 1 Summary of water data for the interval DOY 135 to DOY 273

Target treatment (%)	ETref (mm)	ETcrop (mm)	Irrigation (mm)	Total rain + irrigation (mm)	Total water vs. ETref (%)	Total water vs. ETcrop (%)	Yield (kg/ha)
100	610	381	–	–	–	–	–
85	508	330	249	427	71	112	1,003
65	381	229	199	377	62	99	1,540
50	305	191	162	340	57	89	1,396

ETref is reference ET from the Texas Agrilife site for Lockney TX (*Agrilife/Lockney ET*) and ETcrop is crop ET calculated with crop coefficients for cotton (*Private cropET*) provided to the producer by the commercial pivot monitoring company. Rain total was 178 mm was indeed reduced relative to the reference ET (potential evapotranspiration of a grass reference crop), if yield and water relationships are taken at "face value", the conclusion would be that reducing irrigation would not only save water, but also would increase yield as well. An attractive result but clearly one that strongly suggests a problem somewhere else in the analysis.

The producer wanted to save water on his cotton crop and his efforts resulted in differential water use but no substantial reduction in yield. This indicates some of the difficulties associated with water management in production environments. The most obvious conclusions are that (1) the crop did not experience the degree of water stress that was expected and (2) the amount of water received by the crop was sufficient to meet much of crop's demand. The following sections provide a post hoc analysis of the water management of the crop in an effort to explain the failure of the putative irrigation reductions to induce the expected yield reductions.

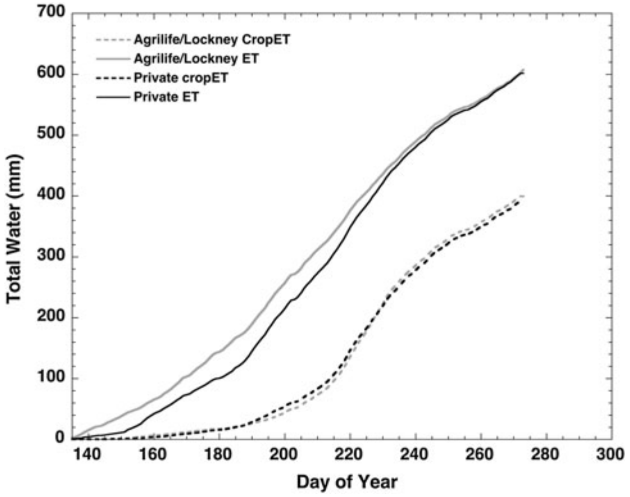

Fig. 2 Cumulative ET estimates of over the interval DOY 135–DOY 273 for a cotton crop near Plainview TX in 2009. Evapotranspiration was calculated as a daily value using weather data from the region

The water requirement of the crop

The water requirement of the crop, which is the basis for the putative water deficits, is an estimated (calculated) value that is dependent on a number of assumptions about the crop. In order to effectively manage crop water through an ET estimate the producer must have a reliable estimate of ET over the course of the season. The variability associated with estimations of crop water requirement in terms of ET that are available to a producer is shown in Fig. 2 which displays the cumulative crop water requirement based on a planting date of 15 May 2009. The following estimates of a cotton crop water requirement at the Plainview TX field site for 2009 are: 610 mm estimated by the *Agrilife/Lockney ET*, 610 mm obtained from the *Private ET* source, 381 mm obtained from the *Private cropET* source, and 381 mm obtained from the *Agrilife/Lockney cropET* source. While the pattern of reference ET calculated by the *Private ET* and the *Agrilife/Lockney ET* sources differ over time, the seasonal totals are virtually identical. The crop-adjusted values from the *Private cropET* and *Agrilife/Lockney cropET* sources differ only slightly over time with the seasonal totals once again virtually identical.

By the end of the season, water amounts received by the crop, relative to the estimated crop need, varied depending on the source of the ET estimate. Since the pivot nozzles established the irrigation regimes, the proportional differences among the regimes were constant regardless of the ET estimate. Only the 100% ET values are shown on Fig. 2. Though they differ slightly from one another, the four ET estimates are scientifically based and can be used as a guide for crop water management. Given the producer's ability to easily acquire several estimates of the crop water requirement, the question facing the producer in any effort to manage irrigation based on ET is which of the several alternatives is the most appropriate. The producer in this instance based his estimates of ET on the *Agrilife/Lockney ET* value of 610 mm. This value does not include any adjustment based on a crop coefficient and is a reference ET value. This value will in general overestimate the water need of the crop and will require modification with seasonally adjusted crop coefficients to appropriately estimate the water requirement of the crop. In practice the producer in the study typically bases his full irrigation regime on the reference ET and attempts to apply 85% of that value as an indication of the crop water requirement. This approach is probably based on the fact that the producer has been growing the same crop, on the same land, with the same pivot and well, with similar planting dates for 20 years. The idea of using a reference ET in place of a crop ET approach apparently gets the producer "close enough" for his purposes. Whether the approach is the best or simply suitable, it is what the producer has found useful.

Figure 3 represents the seasonal water input of the crop based on the *Agrilife/Lockney ET* 601 mm value as the estimate of the crop's water requirement and the measured irrigation and rain amounts. It is evident that this approach should have produced significant water deficits in the crop with the amount of irrigation and rainfall below the estimated environmental demand throughout the entire season. As previously stated, the yield data did not agree with water deficits of the magnitude suggested by the producer's intended outcome.

Since the ET number is an estimate for a hypothetical reference surface, it is appropriate to adjust it in order to reach agreement with the measured irrigation and plant

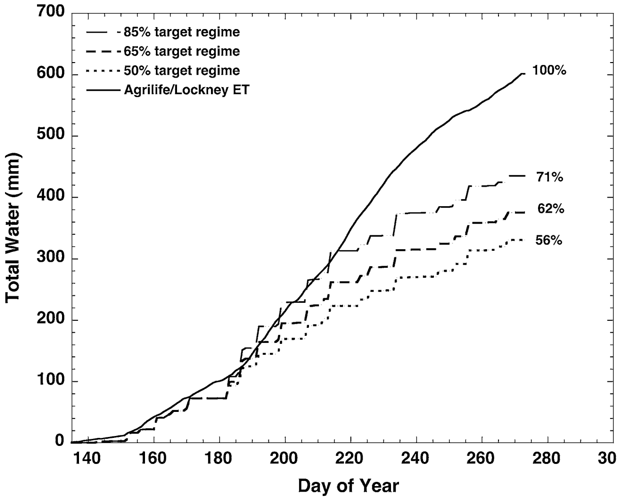

Fig. 3 Producer's estimate of seasonal ET as obtained from the Agrilife/Lockney ET source during the summer of 2009. The website is operated by Texas Agrilife for use by producers. The estimate represents reference ET for the site and was used by the producer as an estimate of crop water use and was the basis of 85, 65, and 50% target regimes. The seasonal ET estimate on this basis was 601 mm. Rain and irrigation on a daily basis for the three target regimes are 427, 377 and 340 mm. The values indicate the percentage of the ET target that was achieved by the irrigation regimes based on the 601 mm ET estimate

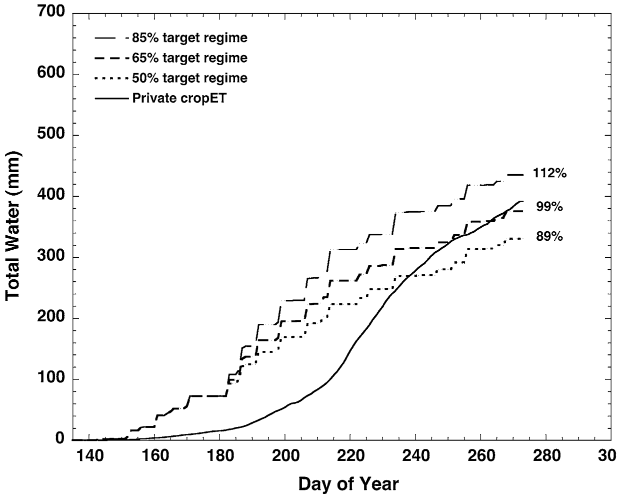

Fig. 4 Estimate of seasonal crop ET (Private cropET) using variable crop coefficients as provided to the producer by a pivot monitoring company during the summer of 2009. The values indicate the percentage of the estimated ET that was achieved by the irrigation target regimes based on the 381 mm Private cropET source estimate

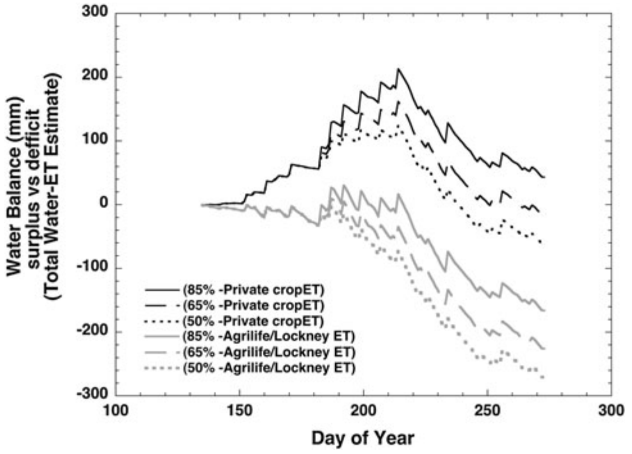

Fig. 5 Estimates of water balance for a cotton crop in 2009 near Plainview TX based on two ET estimates for three irrigation regimes. Agrilife/Lockney ET is reference ET and Private cropET is ET adjusted with crop coefficients for cotton irrigation regime provided by a pivot monitoring company

parameters. Figure 4 illustrates the effect of using the crop coefficient to adjust the reference ET over the season. The *Agrilife/Lockney cropET* and *Private cropET* pivot company ET crop values were quite similar and the *Private cropET* source values have been used in Fig. 4.

Incorporation of an estimate of crop ET in the analysis results in a very different water scenario for the crop. The 85% target regime received a seasonal total of 112% of the crop ET-based requirement thus exceeding the crop water need. Under this regime, water (irrigation and rainfall) exceeded crop demand at all times during the season. The 65% target regime provided 99% of the estimated water need of the crop with only one short period of deficit toward the end of the season. The 50% target irrigation regime resulted in 89% of the crop demand being met on a seasonal basis. Over the interval from DOY 134–238, water exceeded the crop demand and only after DOY 238 did a water deficit develop in the low (50%) target regime. Thus, the water deficit developed rather late in the season in terms of crop and fiber development. One of the potential drawbacks of using reference ET is that the development of a water "surplus" early in the season makes it difficult to achieve reductions in water use in the early season. It is probable that in an indeterminate crop like cotton such early season water surpluses alter the growth and development of the crop in a manner that work against optimal water use. The plant is, in the end, a biological organism that will respond to its actual water status as opposed to an intended seasonal water balance that exists on paper (Fig. 5).

Crop water use as estimated by the crop ET is in general agreement with the yield data in that the highest yield was associated with the irrigation regime that most closely approached the water need of the crop without exceeding it. The treatment that received 112% of the crop ET showed reduced yield relative to the 99 and 89% applications. It is well established that excessive water application in an indeterminate crop, such as cotton, can result in excess vegetative growth and reductions in fiber yield and quality (Tennakoon and Milroy 2003; Hearn 1995; Hake and Grimes 2010). The field in this study was subject to a late season disease problem (verticillium wilt) that was probably exacerbated by the excessive water application that possibly contributed to reduced yield at the highest water level. The yields for the lower two irrigation regimes were in the range that would be expected based on the fraction of the crop water requirement that was provided.

The balance between water requirement and water supply over the season is shown for the 601 mm reference ET from the *Agrilife/Lockney ET* source and the 381 mm crop ET estimate from the *Private cropET* source. The *Agrilife/Lockney ET* estimate shows a deficit of crop water over the entire season while the *Private cropET* estimate indicates a water surplus condition up until approximately DOY 214 with the irrigation and rain falling below crop ET for the remainder of the season.

The results of the water management of the cotton crop in this study can be summarized as follows: (1) the producer created three irrigation regimes that according to his understanding should have resulted in noticeable effects on yield, (2) yield did not vary in accord with the predictions based on putative water deficits in the crop, and (3) different estimates of ET provide very different explanations of the water status of the crop over time.

Analysis of canopy temperature data

Based on the preceding analysis of the ET-based irrigation management the following question was asked, “Can the continuously monitored canopy temperature data collected over the season provide additional insight into the water relations of the crop?”. The following sections will attempt to answer the question.

It is evident that ET estimates from a variety of sources can provide a good foundation for irrigation management though misuse of ET estimates can complicate and even confound producer’s efforts to precisely manage irrigation. The inclusion of a direct measurement of crop water status may provide information that will enhance the ability to manage irrigation under deficit conditions. It has been known for decades that canopy temperatures are sensitive to the water status of the plant (Pinter et al. 2003; Wanjura and Mahan 1994; Peters and Evett 2004) and much research has been devoted to remotely sensed canopy temperature as a crop management tool. One of the impediments to the adoption of such approaches in production agriculture has been the cost and complexity of temperature monitoring equipment. Mahan and Yeater (2008) and Mahan et al. (2010) have recently described the performance of a relatively low-cost infrared thermometry system that is designed for use in agricultural production settings. This system is commercially available and is in use by researchers and producers. With such a system it is now possible to continuously monitor canopy temperatures in crops and the use of canopy temperature by producers as a management tool may soon be routinely practiced.

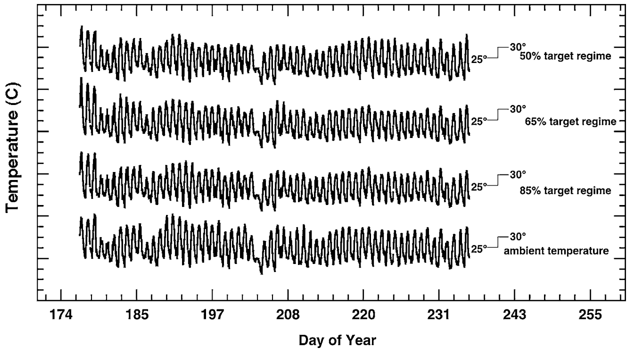

Fig. 6 Cotton canopy temperature for the three target irrigation regimes during the interval from DOY 176 to DOY 236 in 2009 near Plainview TX. Air temperature measured a 2 m height in turn row. Temperature scale is shown on *inset*

The BIOTIC irrigation protocol that was developed by the USDA/ARS over a period of years provided a novel approach to the use of canopy temperature measurement for irrigation scheduling in full irrigation regimes (Upchurch et al. 1996). It has been commercialized and is now available under the trade name SmartCrop. The limitations on water supply and cost are changing the focus from full to deficit irrigation that will require some modifications of the BITOIC protocol. In this study, the use of canopy temperatures as a tool for managing deficit irrigation in cotton has been investigated.

In this study, the researchers used canopy temperature data to elucidate differences in irrigation management approaches that help to explain the results of efforts to reduce water application in a commercial cotton crop. By using seasonal canopy temperature data in conjunction with traditional ET-based irrigation management, the producer was able to assess the appropriateness of various ET estimates for deficit irrigation management.

Canopy temperatures were measured continuously over the time period from DOY 176 to DOY 236 (DAP 41–101) on an 1-min interval with 15-min averages used for analysis. The canopy temperature for the three irrigation regimes and the air temperature for the season are shown in Fig. 6. While such a representation of the data clearly demonstrates the continuity of the measurements, the differences and similarities among treatments are not readily apparent. One of the difficulties associated with continuous canopy temperature measurements is the shear magnitude of the number of observations that are collected. Since each sensor is capable of collecting 10,000 observations in a season, there are approximately 40,000 observations of air and canopy temperature.

In an effort to use canopy temperature as an indicator of crop water status, it needs to be recognized that diurnal temperature data includes a large number of measurements that are not strongly indicative of water status. Canopy temperatures during periods of darkness and cool cloudy days are not particularly sensitive to the water status of the crop. It is a simple matter to reduce the dataset by excluding night temperatures. The removal of night data serves to "break" the diurnal pattern and makes it easier to focus on the water-related temperature variation. While eliminating nighttime temperature reduces the visual clutter on the graph, it does not convey information on the potential effect of specific temperatures on the metabolism of the plant. The metabolic ramifications of the thermal variation can be incorporated into the analysis by comparing the canopy temperatures to a base temperature that is based on a metabolic indicator. According to the BIOTIC protocol (Wanjura et al. 1995; Upchurch et al. 1996; Mahan et al. 2005), canopy temperatures in excess of the biological optimum are a useful indicator of water deficits and their possible effects on plant metabolism. In Fig. 7, canopy temperatures have been filtered to remove values that are below 27°C which is 1°C less than the 28°C BIOTIC temperature optimal for cotton (Burke et al. 1988). The temperature scale on the figure is indicated by the shaded "bar" with a range from 28 to 32°C. The temperatures above the optimal temperature "bar" indicate potential water and metabolic stress in the crop. In these graphs the temperatures are vertically scaled the same for purposes of comparison. Thus, the heights of the peaks represent the same magnitude of temperature. When "filtered" with respect to optimal temperatures, the pattern of canopy temperature provides a view of the magnitude of stresses and the temporal pattern of the stresses. These biologically filtered, multi-day patterns of elevated canopy temperatures represent "stress signatures" for the periods of interest. Since a large number of stress signatures can be arranged on a single page, the arrangement of small multiples allows rapid visual comparisons of relationships among crops, water treatments, irrigation systems and years. In this format the viewer can visualize the temporal pattern of potential water deficits and their potential severity.

Figure 7 shows the stress signatures of this irrigation management study involving multiple irrigation treatments. The stress signatures for the three irrigations regimes indicate the temporal pattern and magnitude of thermal/metabolic stresses over the growing season. During the early stages of crop development (DOY 176–DOY 192) there is thermal/metabolic stress evident in all three water treatments. During this period stress is present in all irrigation regimes with some portion of the elevated temperatures associated with the presence of background soil in the field of view at the canopy develops. After DOY 192 the stress levels in the irrigation regimes are similar and suggest that water deficits were not prevalent. This is in agreement with the predicted water relations of the crop (Fig. 4). The development of increased canopy temperatures in the 50% target regime as compared to the 85 and 65% target regimes is evident at about DOY 215. This stress signal development suggests a transition of the crop from a well watered to water deficit condition at this point in the season.

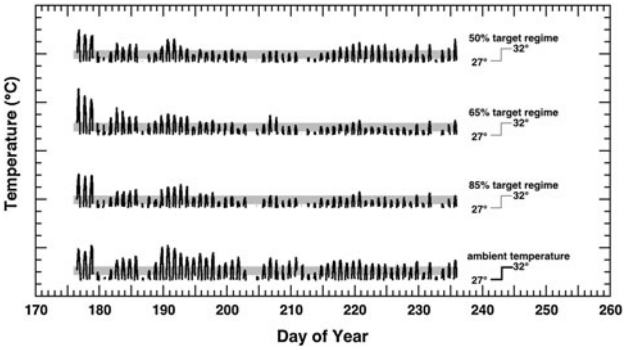

Fig. 7 Cotton stress signatures for the three target irrigation regimes during the interval from DOY 176 to DOY 236 in 2009 near Plainview TX. Temperature scale is shown on *inset*. Canopy temperatures are filtered to show only temperatures that are above 27°C in order to emphasize temperatures that are associated with water deficits. The *shaded bar* represents the temperature range of 28–32°C that is an indicator of optimal metabolic temperature for cotton. Temperatures above the *shaded bar* are proposed to be indicative of water and metabolic stress in the crop. Gaps in signatures indicate temperatures below 27°C as opposed to missing data. Air temperature measured at 2 m height in the field

Canopy temperature difference signatures

To further explore the differences in canopy temperature among the target irrigation regimes, the canopy temperatures of the 85% target regime were subtracted from the 65 and 50% target regime temperatures to produce temperature differential signatures (Fig. 8, bar graph). Since the 85% target regime received the highest amount of water it has been used as the basis of comparison and canopy temperature differences are calculated as: 65% canopy temperature − 85% canopy temperature and 50% canopy temperature − 85% canopy temperature. In this figure values of zero indicate that the temperature of the regimes is equal to the 85% target regime, negative values indicate temperatures cooler than the 85% target regime and positive values indicate temperatures warmer than the 85% target regime. Prior to DOY 214 (vertical dashed line), the pattern of the differences among the three treatments is similar with more or less random variation about the 85% target canopy temperature (zero value) in both the 65 and 50% target treatments indicating no systematic differences among the three irrigation regimes. After approximately DOY 214 the canopy temperatures of the 50% target regimes begin to rise relative to the 85 and 65% target regimes indicating elevated canopy temperatures and

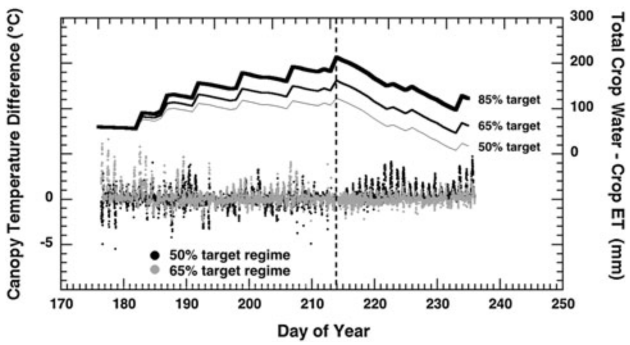

Fig. 8 Canopy temperature differences among the 85, 65, and 50% target regimes of irrigation. Canopy temperatures of the 85% target regime (control) were subtracted from the 65 and 50% target. The *upper panel* indicates the balance between crop water and estimated crop ET. For each target regime, the cumulative daily crop ET (Private cropET) estimate was subtracted from cumulative irrigation and rain. *Vertical line* at DOY 214 indicates transition from surplus to deficit condition

suggesting the onset of a differential water status among the three regimes. This finding is in agreement with the suggestion that the 85 and 65% target regimes probably received full or excessive irrigation. During the period from DOY 214 to the end of the season the canopy temperatures of the 50% target regime were higher than the 85% target regime and the 65% target regime was most similar to the 85% target. The upper panel in Fig. 8 shows the difference between crop water and estimated crop ET that is an indication of crop water status in terms of surplus and deficit (positive and negative values, respectively). It is evident that the temperature deviation in the 50% target regime occurs at the same time (DOY 214) that the crop water status begins to transition from surplus to deficit. This relationship suggests that the canopy temperature is a useful adjunct to evapotranspiration information in understanding the water status of the crop over time.

Irrigation management in an age of declining water availability

Physical limitations and economic factors together are limiting water available for agricultural use virtually worldwide. These declining water resources coupled with continued population growth combine to create a future in which agricultural water problems will no longer be solved through increased efficiency of irrigation systems. While every effort to increase the timely and efficient provision of water to crops should be undertaken, researchers must continue to define the extent to which plant water deficits can be managed to reduce and optimize the balance between reduced water application and crop productivity.

Most irrigation management tools are based on inferring the water need of the crop based upon a measurement of the environment, i.e., the soil or the air. While these inferential methods are scalable and adequate to the needs of most full irrigation regimes, future demands for reduced irrigation in crops necessitate the development of new tools and approaches. To move beyond the current methodology, it may be useful to include a direct measure of the physiological state of the plant. Water potential, transpiration and gas exchange are often used successfully in research settings (Lascano et al. 1992; Trambouze and Voltz 2001; Jones 2004; Stöckle and Dugas 1992) though they are not easily adaptable to production agriculture. Continuous measurement of canopy temperature represents a useful approach in that it is relatively inexpensive, easily automated and readily adapted to production settings.

Crop canopy temperature as an irrigation management tool

What exactly can the producer discern from continuous canopy temperature measurements that can be used to reduce irrigation in production environments? There are several levels at which canopy temperature data can be instructive. In real time or short (daily or weekly) timescales the temperatures can be monitored to indicate such things as irrigation system performance, rainfall utilization and the current stress status of the plant.

The installation of a number of IR sensors strategically placed within a pivot or irrigation management zone will allow the producer to see water deficits spatially within an irrigation system. Incorrect nozzling of sections of a pivot or differential water application along the pivot or within the circle can be identified in terms of thermal variation.

In a region in which in-season rainfall can provide a significant portion of the crop's water requirement altering irrigation in response to in-season rainfall events represents an avenue to the actual reduction in the amount of water used by a crop. To accomplish this, the producer must balance the advantages of suspending irrigation following rain against the possibility that irrigation is not resumed in a timely manner resulting in a crop water deficit. Since it is difficult to ascertain when the crop has exhausted the rainwater, many producers are hesitant to suspend irrigation after a rain. Continuously monitored canopy temperature can provide a basis for identifying the crop response to rain events. The rise in canopy temperatures following the depletion of the rain-associated moisture may provide a useful signal for the re-initiation of irrigation.

When the producer's goal is to use irrigation to manage water deficits as opposed to prevent them, knowledge of the crop water status on a somewhat quantitative and relatively short time interval may be desirable. Canopy temperature can provide plant-based information on the water status of the crop. Because it can be collected on short time intervals (15 min in this study), it can provide a level of resolution that is unequaled by virtually all other measures of the plant. The analytical approaches in this study represent only an initial attempt to elucidate the relationships between canopy temperature and plant water status and performance. Obvious extensions include analysis of the relationships between canopy temperature and environmental factors such as relative humidity, vapor pressure deficits and radiation. Inclusion of such information in the interpretation of canopy temperatures may indeed improve their use as indicators of plant water status on a production relevant scale.

Conclusions

This study demonstrates the potential difficulties associated with efforts to reduce water use in agricultural settings. In this instance the efforts of a producer to reduce water application on a cotton crop to the point of yield reductions have been monitored. The producer-implemented irrigation regimes that were designed to result in total water of 85, 65, and 50% of the seasonal crop demand. Yield was not reduced as anticipated from the water supplied to the crop. The 50% target regime in fact provided a near optimal balance between irrigation and yield. The result certainly looks like pleasant outcome (less water with no yield reduction) but certainly not as expected. End-of-season comparisons of ET estimates, well-flow data and canopy temperature signatures all indicated that the producer's target irrigation regimes of 85, 65 and 50% actually resulted in total water of 112, 99, and 89% of an ET estimate incorporating seasonally adjusted crop coefficients.

While the ET estimates are useful for managing crop water use, particularly in a post hoc analysis, the inclusion of crop coefficients is critical to the accurate assessment of crop water use. In this instance the producer was using a reference ET value for water management, which resulted in over-irrigation. Anecdotal information suggests that this practice may be surprisingly common. It points to the problem that while ET estimates are often the basis for irrigation management, the implementation may often be less than optimal.

Of the methods employed in this study to characterize the water status of the crop, the canopy temperature measurements were available to the producer in real time from a commercially available device with little-to-no investment of time in-season. The canopy temperature based stress signatures in this study provided evidence of the similar water status in the 85 and 65% regimes and detected the change in crop water status of the 50% treatment at approximately DOY 214.

It is proposed that continuous measurement of canopy temperature using a wireless system of the type employed in this study can provide the producer with continuous information on the water status of the crop that is based on the crop itself. A wireless infrared thermometry system is simple to use and compatible with production agriculture settings. The use of a measured as opposed to inferred indicator of crop water status will provide the producer with another means of assessing the efficacy of irrigation practices.

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