Tracking Spatial and Temporal Cotton ET Patterns with a Normalized Difference Vegetation Index

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Abstract

Crop coefficients (K_c) are widely used to estimate crop evapotranspiration (ET_c) for determining irrigation scheduling. Generalized K_c curves are limited to providing daily estimates of ET_c for the "typical" crop condition within a field. However, precision irrigation requires spatial and temporal ET_c information in order to determine the proper water replacement to each management zone. An irrigation experiment conducted during 2002 in Arizona explored the use of remotely-sensed surrogate basal crop coefficients (K_{cb}) for quantifying spatial and temporal differences in cotton ET_c. The main treatment included two irrigation scheduling approaches that were based on ET_c calculation procedures of the Food and Agriculture Organization Paper No. 56 (FAO-56) but differed only by the K_{cb} estimation: 1) a locally-derived FAO-56 K_{cb} curve (FAO), and 2) K_{cb} values based on ground-measured normalized difference vegetation index (NDVI) using a previously defined K_{cb}-NDVI relationship (developed for a different cotton cultivar and row-orientation than for the experiment). Additional variables (3 plant densities, 2 N levels) were included to induce variations for crop ET_c patterns within irrigation scheduling treatments. The ET_c estimation and irrigation scheduling using the FAO-56 K_{cb} curve provided better irrigation management than the previously defined K_{cb}-NDVI relationship, resulting in significantly higher yields for FAO than NDVI. The K_{cb}-NDVI relationship employed in the experiment underestimated measured K_{cb} values during much of the season. The primary problem was related to factors, e.g., the different row-orientation, that effectively lowered NDVI values compared to those that occurred in the previous experiments and were used to develop the relationship. However, measured NDVI tracked the spatial and temporal variations in measured K_{cb} exceptionally well during the season. New K_{cb}-NDVI relationships based on the 2002 data were presented and are currently being tested during 2003 under a similar cotton irrigation scheduling experiment. Although additional research is needed to develop more robust NDVI-based K_{cb} prediction, findings to date indicate the potential for NDVI to provide near-real-time feedback for attaining K_{cb} that closely track actual crop ET_c trends within a field, a technique that could help govern site-specific cotton irrigation scheduling.

Introduction

A fundamental need for precision irrigation is an ability to quantify spatial and temporal differences for crop evapotranspiration (ET_c) to provide irrigation water replacement targets for various zones within irrigated systems. Sadler et al. (2000) proposed several methods for optimizing irrigation water management for spatial and seasonal variability, such as integrated global positioning systems, geographic information systems, "smart" sensors, remote sensing, and computer modeling. A promising approach for precision irrigation management involves the use of surrogate crop coefficients that are based on remotely-sensed observations for providing near-real-time ET_c estimates within spatially variable zones.

Crop coefficient (K_c) estimation of ET_c (Doorenbos and Pruitt, 1977) is a practical and widely applied method, which involves multiplying an appropriate K_c by grass-reference evapotranspiration (ET_o) to compute crop ET_c. A K_c curve for an entire the cropping season is traditionally expressed as a continuous function in time or some other time-related index, such as thermal units. The Food and Agricultural Organization (FAO) of the UN, Paper 56 [FAO-56] (Allen et al., 1998) presented revised crop coefficient procedures for estimating ET_c, which are expected to become the *de facto* crop coefficient standard for the US and abroad. In addition to the single K_c approach, FAO-56 introduced dual crop coefficient procedures where the single K_c is separated into a basal crop coefficient, or K_{cb} (primary crop transpiration), and a soil evaporation coefficient (K_e). The dual crop coefficient method with K_{cb} and K_e allows computation of more precise estimates of daily ET_c, particularly for days following irrigation or rain.

The FAO-56 dual procedures provide an excellent framework for calculating daily ET_c. However, successful application is highly dependent on the ability to derive an appropriate K_{cb} curve that matches the actual crop growth and ET_c conditions that occur during a given season (Allen et al., 1998). Because the K_{cb} curves used with FAO-56 procedures are time-based, they often lack the flexibility required to capture atypical crop development and water use patterns caused by weather anomalies (Bausch and Neale, 1989). The FAO K_{cb} curves are intended to represent ET_c for optimum agronomic and water management conditions, and as such, K_{cb} adjustment procedures to estimate ET_c when crop growth and water use deviate from "standard" conditions due to nutrient, crop density, pest, or other factors are not easily implemented. Whereas precision irrigation management requires information for determining variable ET_c conditions, accounting for spatial variations of water use with FAO-56 procedures is extremely difficult.

Remote sensing offers a means to overcome some of the shortcomings of time-driven K_{cb} curves by providing real-time spatial information on K_{cb} and crop ET_c use as influenced by the actual crop patterns. Multispectral vegetation indices (VIs), computed as differences, ratios, or linear combinations of reflected light in the visible (blue, green, or red) and near infrared (NIR) have been found to be closely related to several crop growth parameters (Moran et al., 1995). The simple ratio (NIR/red) and the normalized difference vegetation index, or NDVI [NDVI=(NIR-red)/(NIR+red)] have gained wide acceptance for estimating plant cover, plant biomass, and leaf area index. The potential for using VIs as near real-time surrogates for crop coefficients was proposed over two decades ago by Jackson et al. (1980). The concept was eventually established by Bausch and Neale (1987) who derived K_{cb} for corn in Colorado based on several VIs. Bausch and Neale (1989) and Bausch (1995) incorporated VI-based corn crop coefficients with existing scheduling algorithms and reported improvements in corn irrigation scheduling due to better estimation of water use and more appropriate timing of irrigations. Although limited research has been conducted to expand the development of VI-based crop coefficients for crops other than corn, simulation studies suggest that VIs could be used to obtain crop coefficients for several other important agricultural crops (Choudhury et al., 1994). Hunsaker et al. (2003) using data from previous cotton experiments developed relationships to estimate cotton K_{cb} with NDVI measurements. The objective of this research was to test a strategy, which implemented the NDVI-based K_{cb} for cotton within the FAO-56 dual procedures, for predicting real-time spatial water use patterns for determining appropriate irrigation scheduling.

Methods and Materials

An irrigation scheduling experiment with cotton was conducted during 2002 on a 1.3-ha field site, located in central Arizona at the University of Arizona, Maricopa Agricultural Center (MAC). The soil is classified as a Casa Grande series with sandy loam to sandy clay loam textures (Post et al., 1988). Deltapine 458BR (*Gossypium hirsutum* L.), a mid-to-full maturing transgenic cotton variety grown in the state, was planted on 16 to17 April, 2002, in dry soil on raised beds, spaced 1.02 m apart, in a north-south orientation. Prior to planting, the field was precision leveled to zero-grade, and then flood-irrigated on 18 to 20 March to enable subsequent soil bed preparations and equipment installations. The date of crop initiation was assumed to occur on 22 April, when the first post-plant irrigation was given. The cotton was defoliated on 21 September and harvested in October.

Experimental Treatments

Thirty-two plots (each 11.2 by 21 m) were randomly assigned to 12 different experimental treatments (table 1). The primary treatment consisted of two irrigation scheduling approaches that were both based on the FAO-56 dual crop coefficient procedures, but differed in the method used to estimate the basal crop coefficient, K_{cb}. The first approach (FAO) used a locally derived cotton K_{cb} curve following FAO-56 guidelines (fig. 1). The second (NDVI) used K_{cb} estimates based on ground-measured NDVI and a previously defined relationship between K_{cb} and NDVI for cotton. However, the K_{cb}-NDVI relationship (described by Hunsaker et al., 2003) used was not developed under crop and field conditions similar to those in the present study. That is, the cotton was a different cultivar that exhibited somewhat atypical water use patterns expected for a full-season cotton. The cotton was also grown in an east-west row orientation rather than the present north-south orientation, and the soil type was a clay loam rather than a sandy clay loam. Despite these differences, the K_{cb}-NDVI relationship was the only one that existed for cotton at the time of the experiment. The relationship consisted of two regression relations: a linear function used from early vegetative growth to effective full cover, and a multiple regression of K_{cb} as a function of NDVI and cumulative growing-degree-days (GDD) after effective full cover. The K_{cb} values were restricted to 0.15 or larger for both the NDVI and FAO treatments.

Table 1. Summary of treatments for the 2002 Cotton Irrigation Scheduling Experiment at the Maricopa Agricultural Center.

	Experimental Variables			
Treatment name	Irrigation scheduling	Plant density	Nitrogen level	Number of replicates
FSH	FAO	Sparse	High	2
FSL	FAO	Sparse	Low	2
FTH	FAO	Typical	High	4
FTL	FAO	Typical	Low	4
FDH	FAO	Dense	High	2
FDL	FAO	Dense	Low	2
NSH	NDVI	Sparse	High	2
NSL	NDVI	Sparse	Low	2
NTH	NDVI	Typical	High	4
NTL	NDVI	Typical	Low	4
NDH	NDVI	Dense	High	2
NDL	NDVI	Dense	Low	2

Additional sub-treatment variables (table 1) were imposed to create conditions expected to alter crop water use, yet are not commonly nor easily accounted for in a typical implementation of FAO-56 ET_c procedures. Sub-treatments, equally embedded within the irrigation scheduling treatments, included three plant densities: Typical (T) ≈10 plants/m^2, single-line planting; Sparse (S) ≈5 plants/m^2, single-line planting; and Dense (D): ≈20 plants/m^2, double-line planting and two N fertilization levels: High (H), split N applications, based on optimum local practices; and Low (L), no N application.

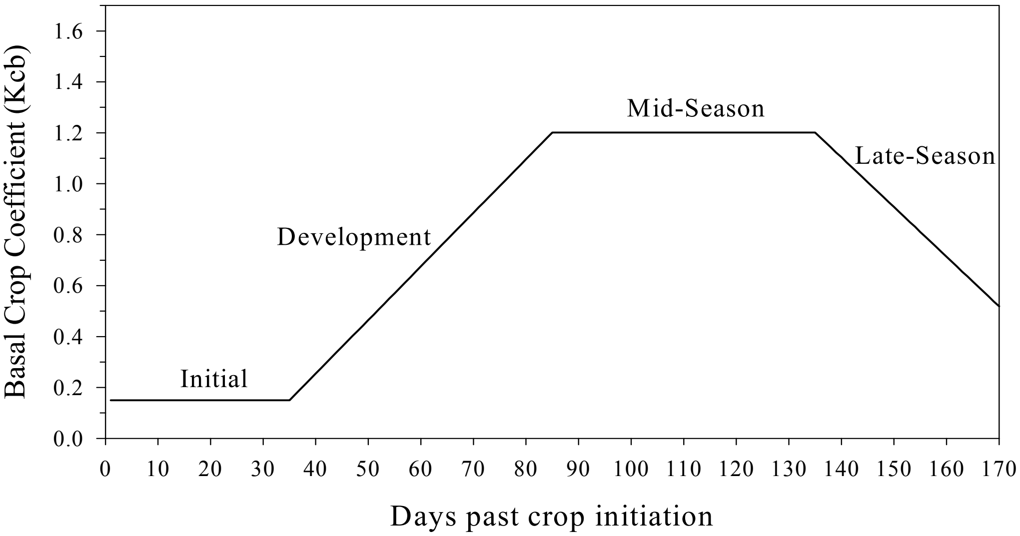

Figure 1. Locally derived FAO Kcb curve for Maricopa, Arizona, based on FAO-56 procedures.

Field Layout and Irrigation System

The 32 treatment plots were aligned in the field in a 4 (north-south) X 8 (east-west) array, each plot surrounded by border dikes. Two gated pipe systems, 152-mm in diameter, were installed in the east-west direction and extended the length of the field. Each system provided irrigation water for 16 treatment plots. Irrigation water was controlled by two alfalfa-valves located at the west-end of the gated pipe systems. Gated ports at 1.02 m spacings along the pipe were used to control separate water delivery to individual plots at flow rates ≈18 to 20 L s^{-1}. The irrigation water was measured with an in-line propeller-type water meter that had both a rate meter and a volume totalizer.

Crop Management and Irrigation Scheduling

Difficulties encountered in germination of the dry-planted cotton and in obtaining the desired plant densities resulted in replanting seeds within various plot areas. Consequently, a total of six irrigation applications were given to all plots from 22 April to 4 June to establish the crop. Experimental irrigation treatment scheduling was begun following the 4 June irrigation, upon establishment of the target plant densities.

Daily crop ET_c in mm was calculated as $ET_c = (K_{cb}\ K_s + K_e)\ ET_o$, where K_s is the soil water stress coefficient. Daily meteorological data, provided by an AZMET weather station (Brown, 1989) located on a well-watered grass site ≈ 200 m from the field site, were used to calculate the FAO-56 equation (Allen et al., 1998) for daily ET_o. Daily soil water balance computations were made separately for each treatment plot based on the FAO-56 procedures. Soil parameters from Post et al. (1988) and other parameters used for the FAO calculations are listed in table 2. The daily crop rooting depth (Z_r) and canopy height (h) for each plot were increased proportionately with K_{cb} up to maximum values of 1.7 and 1.2 m for Z_r and h, respectively, when the maximum K_{cb} for the plot was attained.

Table 2. Soil and crop parameters used in the FAO-56 dual crop coefficient procedures (Allen et al., 1998) for the 2002 FAO Cotton Irrigation Scheduling Experiment at the Maricopa Agricultural Center.

Parameter	FAO-56 acronym	Value and unit
Soil water content at field capacity	θ_{FC}	0.24 m^3 m^{-3}
Soil water content at wilting point	θ_{WP}	0.12 m^3 m^{-3}
Crop rooting depth	Z_r	1.7 m (maximum)
Depth of soil surface evaporation layer	Z_e	0.11 m
Total evaporable water	TEW	20 mm
Readily evaporable water	REW	9 mm
Fraction of soil surface covered by vegetation	f_c	Eq. 76 in FAO-56 (dimensionless)
Fraction of soil surface wetted by irrigation	f_w	0.95 (dimensionless)
Crop height	h	1.2 m (maximum)

Irrigations were applied to treatment plots when the estimated depletion of available soil water within the root zone reached 44%, an allowable depletion (AD) that was expected to minimize soil water stress for all treatments. The amount of water applied from irrigation replaced 100% percent of the estimated depletion, plus an additional 10% to account for nonuniformity of irrigation. Note that after 4 June, all FAO treatments were irrigated on the same days with equal amounts of water. For NDVI treatments, irrigation was applied on the same day to all replicates, but the irrigation date was based on the median day among replicates at which the AD reached 44%. Consequently, certain replicates within an NDVI treatment often received irrigation a day or two before or after their AD had been reached. However, individual NDVI replicates did receive their estimated soil water depletion on the day the actual irrigation occurred, plus 10%.

Final irrigations for all NDVI treatment plots occurred between 15 to17 August. The amount of water given to FAO plots for their final irrigation on 23 August was adjusted to increase their soil water level to the approximate level estimated for the NDVI treatments plots on 23 Aug. With the exception of the final irrigation for FAO treatments, the irrigation scheduling after 4 June was not altered from the methodologies above for any treatments, regardless of feedback from measurements, or other factors.

Fertilizer as urea ammonium nitrate (UAN-32) solution was injected into the gated pipe systems during irrigations of all High N treatment plots on 4 June, a rate that provided 84 kg N ha^{-1} to plots. A second application (7 to 14 July) of UAN-32 provided an additional 56 kg N ha^{-1} to the High N plots.

Field Measurements

Crop canopy reflectance factors were measured two to four times per week for all 32 treatment plots during the growing season. A total of 53 canopy reflectance measurements were made between 25 April and 24 Sept. Observations, taken across a 6-m long transect spanning the north edge of the final harvest area of each plot, were made with a hand-held, 4-band Exotech radiometer (Model BX-100; Exotech, Inc., Gaithersburg, MD) equipped with 15° field-of-view optics. Data were collected over a morning time-period corresponding to a nominal solar zenith angle of 45°. The NDVI was computed from reflectance factors in near infrared (0.76-0.90 μm) and red (0.63-0.69 μm) wavebands as: NDVI = (NIR-red)/(NIR+red). NDVI data measured on cloudy days or on days when wet soil within a plot affected reflectances were not used to calculate the K_{cb}. The acceptable NDVI measurements for each plot were interpolated linearly, generating daily NDVI values for the entire season.

Volumetric soil water contents were measured for each plot ≈ twice per week and included measurements made immediately before and several days after each plot irrigation. Soil water content measurements were taken at depths from 0.20 m to 3.0 m, at 0.20-m increments, with site-calibrated neutron probes. Soil water in the 0 to 0.30-m soil layer was measured by time-domain-reflectometry (TDR). Neutron access tubes and waveguides for TDR were placed near the middle of each plot in a central cotton bed. Plant measurements, including crop height and crop width, were taken for all plots on a weekly basis during the season starting on 12 June.

Cotton was hand-harvested on 8-10 October in an undisturbed central area within each plot, 6 rows wide by 4 m long, to determine treatment yields.

Irrigation Scheduling Evaluation

Neither the soil water content nor canopy measurements were used as inputs within the FAO-56 procedures to “correct” irrigation scheduling during the experiment. However, the soil water data, along with relevant canopy measurements, were used within the FAO-56 procedures to quantify actual ET_c and to determine “actual” K_{cb} values for all plots using the back-calculation methodology described in Hunsaker et al. (2003). The NDVI-based K_{cb} and FAO K_{cb} curve and resulting irrigation management were evaluated in light of treatment yield performance and their ability to track the actual K_{cb} and ET_c conditions. Statistical analyses of yield, ET_c, and irrigation data were performed using the General Linear Models procedure of SAS (SAS, Inc., 1998).

Results and Discussion

Mean yield for the FAO irrigation scheduling treatment was significantly greater (16%) than for the NDVI treatment at 0.01 probability, indicating that better water management was provided for FAO treatments. Whereas the effect on yield due to plant density was not significant, final yield was greater ($p<0.01$) for the Low than High N treatment, suggesting that crop management was not optimum for the High N treatments for this experiment. For a given plant density and irrigation method, yield differences between nitrogen treatments varied from 5 to 17%, and averaged 10% across all treatments (fig. 2). Data for cumulative irrigation applied (table 3) reveals that for a given plant density and nitrogen level, NDVI treatments received 7 to 9% (78 to 92 mm) less irrigation water than their FAO treatment counterparts, with the exception of the NDH treatment, which received only 4% less than that for the FDH treatment. Statistically, differences for cumulative irrigation water applied were significant for the irrigation method ($p<0.01$), but not for nitrogen level. Less irrigation water applied to the NDVI treatments corresponded to a significant decrease ($p<0.01$) for their measured cumulative ET_c, which varied 5 to 9% lower, and averaged 7% less, than the measured cumulative ET_c for their FAO treatment counterparts (table 3).

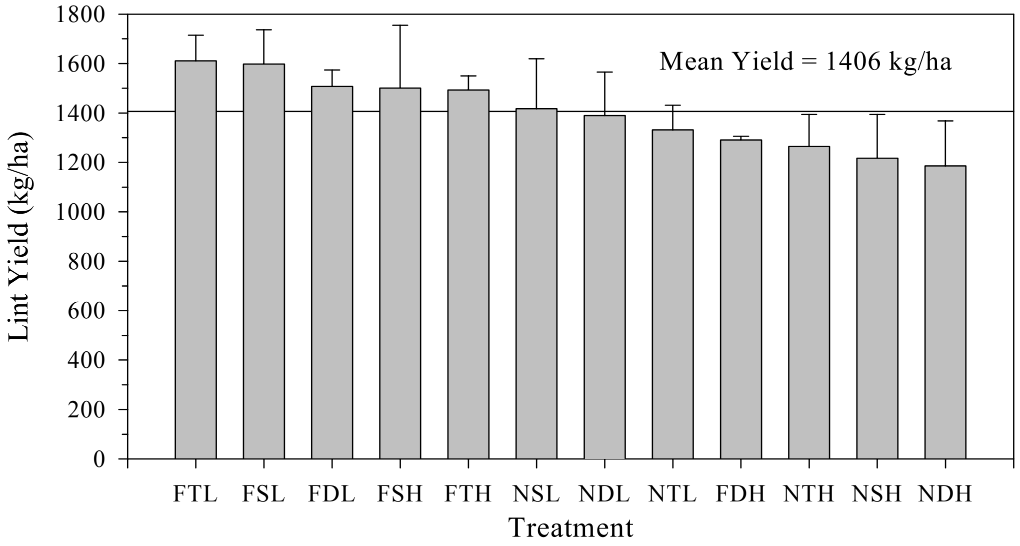

Figure 2. Yield averages for treatments shown in descending order for the 2002 Cotton Irrigation Experiment. Error bars indicate standard deviations. Treatments acronyms are explained in table 1.

Table 3. Measured irrigation, evapotranspiration, and lint yield treatment averages and parameter ratios between NDVI and FAO irrigation scheduling methods for treatments with the same nitrogen level, and plant density for the 2002 FAO Cotton Irrigation Scheduling Experiment.

	Sparse treatments			Typical treatments			Dense treatments		
Low nitrogen treatments	NDVI	FAO	Ratio*	NDVI	FAO	Ratio*	NDVI	FAO	Ratio*
Cumulative Irrigation (mm)	1019	1111	0.92	1017	1119	0.91	1036	1114	0.93
Cumulative ET_c (mm)†	884	961	0.92	916	982	0.93	931	990	0.94
Final Lint Yield (kg/ha)	1417	1598	0.89	1332	1610	0.83	1389	1507	0.92
High nitrogen treatments									
Cumulative Irrigation (mm)	1013	1102	0.92	1038	1122	0.92	1067	1112	0.96
Cumulative ET_c (mm)†	897	955	0.94	914	986	0.93	953	1004	0.95
Final Lint Yield (kg/ha)	1217	1501	0.81	1264	1493	0.85	1186	1291	0.92

*Ratio of NDVI and FAO treatment.

†Cumulative ET_c measured from 25 April to 21 September.

The FAO K_{cb} curve underestimated K_{cb} by a substantial amount for Typical and Dense stands within the High N level (FTH and FDH, respectively) during the first 75-80 days after crop initiation (fig 3a). Cumulative measured ET_c (Fig. 3b) for FTH and FDH on the 75th day exceeded estimated cumulative ET_c by 12 and 19%, respectively. This suggests that irrigation scheduling based on the lower than measured FAO K_{cb} curve ET_c estimates may have introduced water stress during the first half of the season, particularly for the FDH treatment. Following the last irrigation for FAO treatments, which occurred 124 days after crop initiation, K_{cb} and ET_c decreased relative to estimated values. Consequently, differences between the measured and estimated ET_c became closer at the end of the season where the measured seasonal cumulative ET_c for FTH and FDH

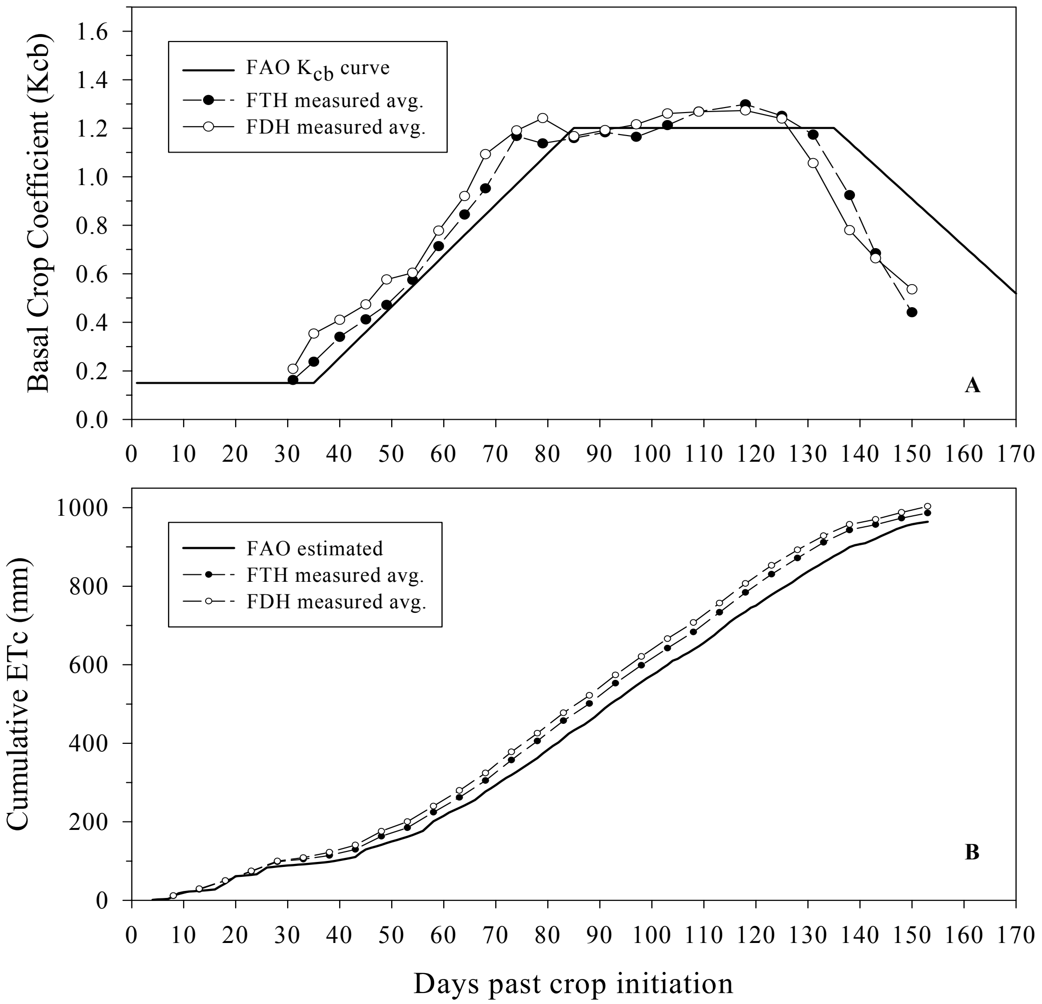

Figure 3. Estimated Kcb (a) and cumulative ETc (b) compared to average measured values for the FTH and FDH treatments for the 2002 Cotton Irrigation Scheduling Experiment.

were only about 2 and 4% greater than the 964 mm estimated using the FAO K_{cb} curve and procedures. Although Sparse treatments under FAO irrigation scheduling had smaller cumulative ET_c than the Typical and Dense treatments (table 3), they produced some of the highest yields (fig. 2), which may indicate the FAO scheduling caused less water stress within Sparse plots. For example, 75 days after crop initiation, the measured cumulative ET_c for the FSH (FAO-Sparse-High N treatment) exceeded estimated cumulative ET_c by 8%, compared to 12 and 19% for FTH and FDH, respectively.

The K_{cb}-NDVI relationship used in irrigation scheduling tracked measured K_{cb} poorly throughout much of the season for all NDVI treatments, as illustrated in figure 4a for the Typical and Dense stands within the High N level (NTH and NDH, respectively). The primary problem was that the NDVI values used to calibrate the K_{cb}-NDVI relationship were higher than the NDVI values of the present study until about mid-season. Trends for NDVI, normalized to days past crop initiation and cumulative GDDs, for the two NDVI data sets revealed that values were offset initially by about 50%, ≈ 25 days after crop initiation. Separation slowly decreased until the NDVI values for the two data sets eventually coincided ≈ 70 days after crop initiation. Whereas measured K_{cb} values, normalized for crop day and cumulative GDDs, were consistent between the calibration and

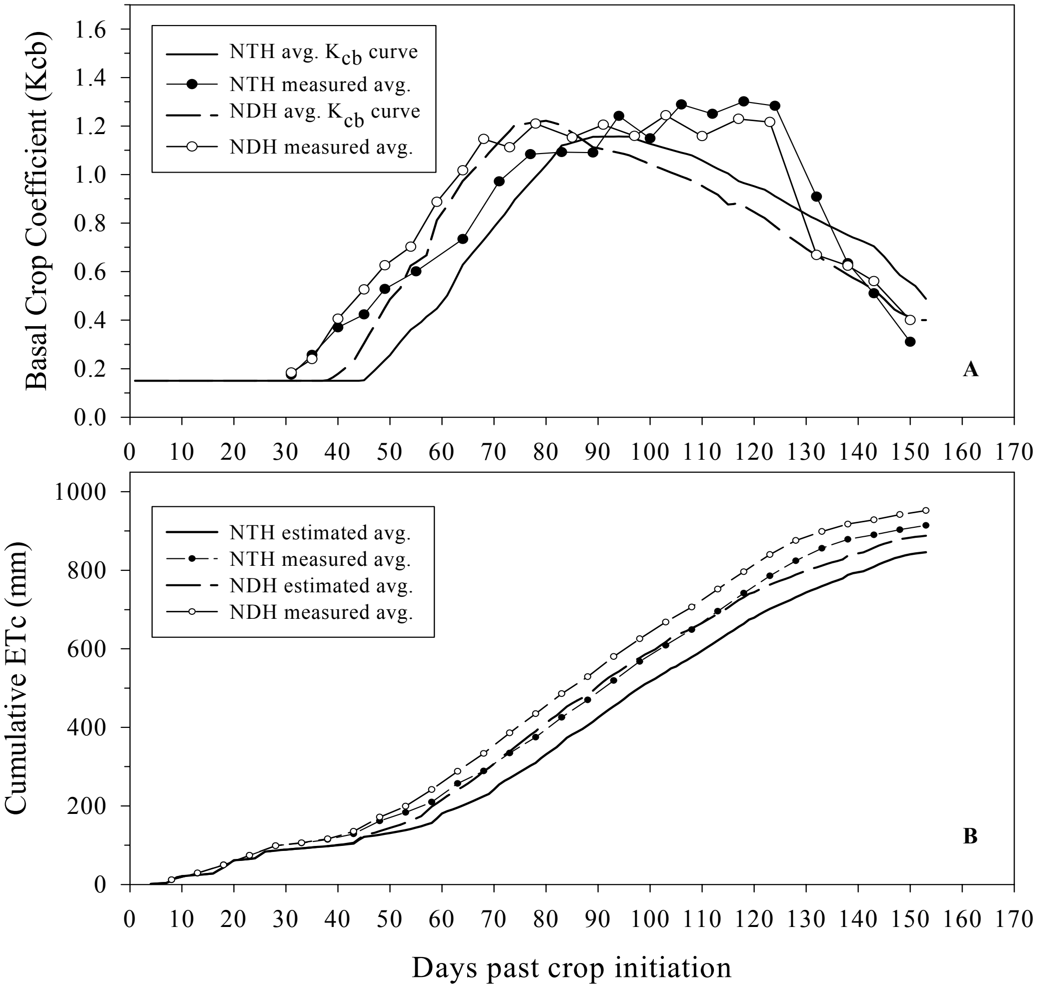

Figure 4. Estimated Kcb (a) and cumulative ETc (b) compared to average measured values for the NTH and NDH treatments of the 2002 Cotton Irrigation Scheduling Experiment.

experimental data during the first 70 to 80 days past crop initiation, the lower NDVI caused the K_{cb}-NDVI relationship to greatly underestimate the measured K_{cb} until mid-season (fig. 4a). Reasons offered for the variation in NDVI values between the two data sets include the differences in soil background effects, row-orientation, cotton cultivar, waveband width used for NIR and red, and irrigation system.
Cumulative measured ET_c (fig. 4b) for NTH and NDH from 55 to 75 days after initiation exceeded the estimated cumulative ET_c by 23-33% and by 13-26%, respectively, indicating the poor irrigation scheduling for the treatments during the first half of the season. Following a brief period near mid-season in which the estimated K_{cb} curves tracked measured K_{cb} reasonably well, the K_{cb}-NDVI relationship once again greatly underestimated measured K_{cb} until late in the growing season.

The lack of success in tracking actual K_{cb} with the initial K_{cb}-NDVI relationship led to an accumulation of larger soil water deficits for NDVI than FAO plots and resulted in delayed and inappropriate irrigation application amounts, which often were smaller than that required to refill the crop rooting zone for NDVI treatments. Overall, the effects on FAO treatments caused by the ET_c underestimation were less pronounced in terms of yield and cumulative measured ET_c than for NDVI treatments. There was a strong negative correlation (r = -0.88) between final yield and the average measured depletion of the available soil water just prior to irrigation applications. For NDVI treatment plots, measured available soil water depletion at irrigation was often 55-60%.

Based on the results, the previously defined K_{cb}-NDVI relationship proved inappropriate for scheduling irrigations for the particular cotton cultivar and row-orientation used in this experiment. On the other hand, the variability in the measured K_{cb} data (fig. 5) demonstrates that a single FAO K_{cb} curve would be inadequate to quantify spatial and temporal differences for crop water use that occurred. Although the particular K_{cb}-NDVI relationship used in the experiment failed to calculate appropriate K_{cb} values, NDVI data actually tracked the measured K_{cb} variability for 2002 exceptionally well. Consequently, new K_{cb}-NDVI relationships were developed from the 2002 data, which are presently being tested during a second cotton irrigation scheduling experiment in 2003. The primary relationship (fig. 6) describes the cotton K_{cb} as a function of NDVI from initial growth through approximately the end of the mid-season stage. The primary curve, fit to a 4th order polynomial with a resulting r^2 of 0.98, included the K_{cb} and NDVI data for each treatment plot from initial growth until the NDVI of the particular plot decreased more than 0.0135 below the maximum NDVI value attained for the plot. When NDVI decreased more than 0.0135 below maximum NDVI (which was ≈0.90 for most plots), the K_{cb}-NDVI trend did not follow the primary relationship. This point was typically reached for all plots near cutout, about 130 days after crop initiation. Consequently, a late-season K_{cb}-NDVI relationship (fig. 6) was fit to a 3rd order polynomial (r^2 =0.62) to more adequately estimate K_{cb} during the latter stages of the growing season.

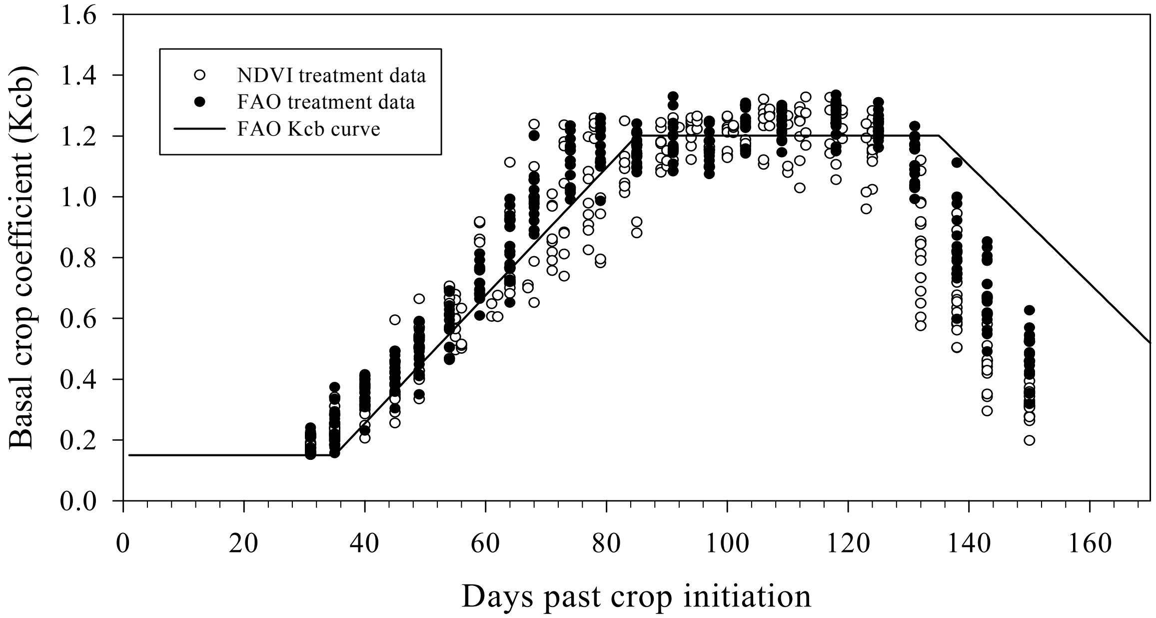

Figure 5. Measured Kcb data and FAO Kcb curve as a function of days past crop initiation for 2002 cotton irrigation scheduling experiment.

Preliminary results from the 2003 experiment (data not shown) indicate that the new primary relationship is tracking the differences in K_{cb} and providing appropriate irrigation schedules for the NDVI treatments.

Conclusions

NDVI appears to be a useful parameter for tracking cotton K_{cb} values needed in ET_c estimation and irrigation scheduling. A locally derived FAO K_{cb} curve should give reasonable ET_c estimates for average cotton conditions, but adjusting K_{cb} to estimate spatially variable crop water needs for precision irrigation management will be difficult without some type of remote sensing technique. Implementing VI-based crop coefficients within FAO-56 procedures for precision irrigation scheduling could potentially be more successful and far-reaching than other remote sensing methods, because of the widespread familiarity and use of the crop coefficient methodology. NDVI data, which can be routinely measured either on the ground, in the air, or by satellite, would be required frequently, but not daily, since the smooth general shape of the K_{cb} curve over a growing season would allow data to be extrapolated over a period of up to a week. The soil adjusted VI (SAVI) which is less sensitive to soil background effects than NDVI may provide improved estimates for K_{cb} during early season conditions. However, the variability observed for SAVI as the crop approaches and reaches full canopy may preclude SAVI as a reliable VI surrogate for K_{cb} during critical portions of the season.

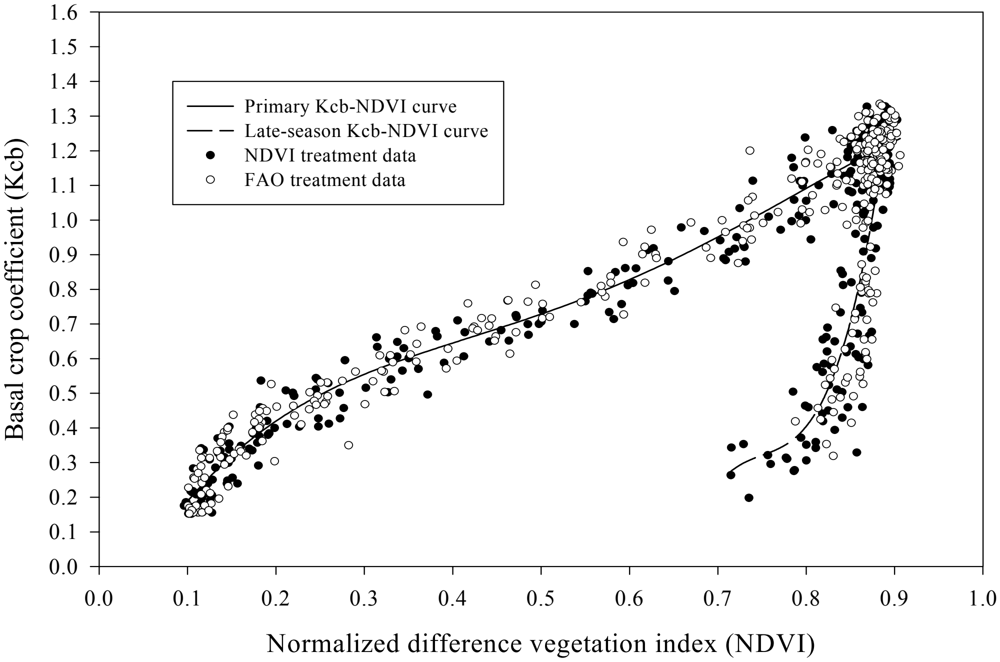

Figure 6. Primary and late-season Kcb-NDVI relationships developed from treatment data of the 2002 cotton irrigation scheduling experiment.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. FAO Irrigation and Drainage Paper 56, Food and Agricultural Organization of the United Nations, Rome

Bausch WC (1995) Remote sensing of crop coefficients for improving the irrigation scheduling of corn. Agric Water Manage 27:55-68

Bausch WC, Neale CMU (1987) Crop coefficients derived from reflected canopy radiation: A concept. TRANS ASAE 30(3):703-709

Bausch WC, Neale CMU (1989) Spectral inputs improve corn crop coefficients and irrigation scheduling. TRANS of ASAE 32(6):1901-1908

Brown PW (1989) Accessing the Arizona Meteorological Network (AZMET) by computer. Ext Rep 8733 The University of Arizona, Tucson

Choudhury BJ, Amhed NU, Idso SB, Reginato RJ, Daughtry CS (1994) Relations between evaporation coefficients and vegetation indices studied by model simulations. Remote Sens Environ 50:1-17

Doorenbos J, Pruitt WO (1977) Crop water requirements. FAO Irrigation and Drainage Paper 24, Food and Agricultural Organization of the United Nations, Rome

Hunsaker DJ, Pinter PJ Jr, Barnes EM, Kimball BA (2003) Estimating cotton evapotranspiration crop coefficients with a multispectral vegetation index. Irrigation science (in press)

Jackson RD, Idso SB, Reginato RJ, Pinter PJ Jr (1980) Remotely sensed crop temperatures and reflectances as inputs to irrigation scheduling. In: Irrig Drain Spec Conf Proc, 23-25 July, Boise, Idaho, ASCE, New York, pp 390-397

Moran MS, Mass SJ, Pinter PJ Jr (1995) Combining remote sensing and modeling for estimating surface evaporation and biomass production. Remote Sensing Review 12:335-353

Post, DF, Mack, C, Camp, PD, Sulliman, AS (1988) Mapping and characterization of the soils on the University of Arizona, Maricopa Agricultural Center. In: Proc. of Hydrology and Water Resources in Arizona and the Southwest. Univ. of Arizona, Tucson, AZ, pp. 49-60

Sadler EJ, Evans RG, Buchleiter GW, King BA, Camp CR (2000) Design considerations for site specific management. In: Evans RG, Benham BL, Trooien TP (eds), Proc 4th Decennial Nat Irrig Sym, 14-16 Nov 2000, Phoenix, Ariz, ASAE, St Joseph, Mich, pp 304-315

SAS, Inc. (1998) SAS User’s Guide, Release 7.00. Cary, NC:SAS Institute, Inc.