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Comparison of traditional and ET-based irrigation scheduling of surface-irrigated cotton in the arid southwestern USA

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ABSTRACT

The use of irrigation scheduling tools to produce cotton under-surface irrigation in the arid southwestern USA is minimal. In the State of Arizona, where traditional irrigation scheduling is the norm, producers use an average of 1460 mm annually to grow a cotton crop. The purpose of this paper was to determine whether or not the use of ET-based irrigation scheduling methods could improve lint yield and irrigation water use productivity over traditional cotton border irrigation scheduling practices in the region. A field study with four irrigation scheduling treatments replicated in 4 blocks was conducted for two cotton seasons (2009 and 2011) in 16, 12-m × 168-m cotton borders at the Maricopa Agricultural Center (MAC), in Arizona, USA. Remotely-sensed vegetation indices (VI) were used to estimate basal crop coefficients (Kcb) at 40, 4-m × 8-m zones within borders for two treatments, denoted as VI_A and VI_B, whereas a single Kcb curve was applied to all zones in borders for a third treatment (FAO). Daily ETc for these three treatments was estimated using FAO-56 dual crop coefficient procedures with local weather data and irrigation scheduling for the three treatments were based on soil water balance predictions of soil water depletion (SWD). For the VI_A and FAO treatments, irrigations were given when predicted SWD of all 160 zones in the treatment averaged 45% of total available water (TAW). For the VI_B treatment, irrigations were given when 5% of the 160 zones in the treatment were predicted to be at 65% SWD. A fourth treatment (MAC) represented the traditional irrigation scheduling treatment and was scheduled solely by the MAC farm irrigation manager using only experience as a guide. The study showed that the lint yields attained under the MAC farm manager's irrigation scheduling equaled or exceeded the yields for the three ET-based irrigation scheduling treatments. Although the MAC irrigation scheduling resulted in somewhat higher irrigation input than for the other treatments, the MAC treatment maintained or exceeded the irrigation water productivity attained for other treatments that had lower irrigation inputs. A major conclusion of the study was that present-day irrigation water use for cotton in surface-irrigated fields could be substantially reduced. When compared to Arizona state cotton averages, any of the four treatments presented in the study could potentially offer methods to significantly reduce cotton irrigation water use while maintaining or increasing current lint yields levels.

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1. Introduction

Limited and expensive water supplies in the arid western United States of America (USA) require growers to reduce irrigation water quantities, while maintaining or increasing yield production levels. Cotton (*Gossypium hirsutum* L.) is a major crop produced under irrigation in arid regions of the southwestern USA, including the states of Arizona and California where a combined total of about 230,000 ha of cotton was harvested in 2012 (NASS, 2014). According to the data within the most recent Farm and Ranch Irrigation Survey for the year 2008, 91% of the cotton land in these two states were irrigated using gravity flow surface irrigation systems (NASS, 2010). In the state of Arizona, the state-average total irrigation water applied to cotton by surface irrigation was 1460 mm in the

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year 2008 (NASS, 2010). Historically, the seasonal crop evapotranspiration (ETc) of fully-irrigated cotton grown in central Arizona, where most of the cotton is grown in the state, is on the order of 1000–1060 mm (Erie et al., 1982; Bucks et al., 1988; Hunsaker et al., 2005). The Arizona average total irrigation applied by surface irrigation for cotton in 2008 suggests low efficiency of irrigation water use based on historical ETc requirements. In contrast, an average of 1160 mm of total irrigation water was applied in 2008 on the 5% of the cotton farms in Arizona using micro irrigation systems (NASS, 2010). According to the survey, the 2008 Arizona-average cotton lint yields achieved were 1690 kg/ha and 1950 kg/ha for surface and micro irrigation methods, respectively. The irrigation water productivity (WP_I) can be expressed as the ratio between lint yield and total irrigation water (Pereira et al., 2012). Calculation for the 2008 Arizona cotton data indicates a WP_I for surface irrigation of about 0.12 kg/m^3 or about a 40% reduction when compared to the WP_I for micro irrigation fields in 2008 in Arizona.

Typically, the cotton-field soils in the arid Southwest are extremely dry prior to planting in early spring. For surface-irrigated cotton, heavy, pre-plant irrigations (≈250–350 mm) are applied to provide deep soil moisture to about 1.8 m, the ≈maximum depth of cotton soil water extraction (Erie et al., 1892). The cotton seed is then planted along rows spaced 1.0 m apart about 15–20 days later in "wet" soil moisture. The stored soil moisture in deep soil layers from pre-plant irrigation allows plants to establish an effective rooting depth early in the season and may also be utilized by the cotton later in the season, particularly after irrigation applications are terminated.

The complexities of managing surface irrigation systems in arid regions are well known (Ben-Hur et al., 1987; Horst et al., 2007). Surface irrigation is often perceived as a poor water control method having non-uniform application of water with excessive deep percolation and runoff (Strelkoff et al., 2009). However, the development of laser-levelling equipment in the 1970's led to adoption of graded-furrow and level-basin irrigation by cotton growers in Arizona (Dedrick, 1984). As evaluated by Clemmens (2000), level-basin irrigation systems when properly designed and managed, can achieve yield and irrigation uniformity comparable to pressurized irrigation systems. By 1990, the adoption of laser-leveled surface irrigation was nearly 100% along the lower Colorado River and had approximately doubled in the central Arizona from the prior decade (Clemmens, 2000). However, despite the increasing use of these modernized surface irrigation systems the disparity in cotton irrigation water use and productivity between surface irrigation and micro irrigation in 2008 suggests that managing water for surface irrigation remains a challenge.

Studies conducted in various parts of the world have shown that improved irrigation scheduling practices have an important role in achieving higher water savings and irrigation water productivity for surface-irrigated cotton systems (Bucks et al., 1988; Hunsaker et al., 1998; Pereira et al., 2009 Darouich et al., 2014). However, present-day adoption of irrigation scheduling tools that provide information for applying the proper amount of water at the right time is less than 10% in the USA (Schaible and Aillery, 2012). This may stem from the increased level of management and information needed in utilizing irrigation scheduling tools, but may also be due to a lack of comprehensive studies showing significant water-savings and yield improvements resulting from scientific irrigation scheduling. In the arid southwestern USA, traditional irrigation scheduling remains in use for surface irrigation systems. The most common of these include irrigation scheduling according to a set calendar schedule, the number of days elapsed since the last irrigation, visual detection of a change in crop color or wilting leaves, and/or according to how dry the soil feels (Martin, 2009). Calendar scheduling does not take into account weather extremes, which may cause problems from year to year. None of these traditional methods can provide information on how much irrigation water to apply.

Jones (2004) provided detailed information about the two primary scientific irrigation scheduling methods that have been developed, (1) soil water balance (SWB), and (2) plant sensing (e.g., plant temperature). The SWB methods either directly measure or estimate the change in soil water contents within the crop root zone over a period of time given the water inputs during the period, i.e., irrigation and rain, and the water losses, including crop evapotranspiration, deep percolation, and runoff (Evett et al., 2012). A soil water balance method that estimates ETc by the reference crop evapotranspiration multiplied by crop-specific coefficients has been in practice for decades and continues to be an acceptable method for irrigation scheduling within the scientific community, and by providers and managers of irrigation water (Jensen et al., 1990; Allen et al., 2005). Plant-based methods for irrigation scheduling have been a subject of research for many decades beginning with ground-breaking work on canopy temperature sensing for assessing crop stress by Jackson et al. (1981). Applications of some plant-based methods have shown enormous potential for site-specific irrigation scheduling (Peters and Evett, 2008; Kim and Evans, 2009), particularly utilizing self-propelled sprinklers.

In this paper, we consider methods for improving cotton surface irrigation scheduling that combine site-specific spatial information of crop coefficients, soil water retention, and irrigation water uniformity within a SWB framework. The premise is to provide growers with a technique to judge irrigation scheduling decisions of large cotton fields at smaller spatial scales, for example, a set of irrigation borders, or even an individual cotton border. Although a surface irrigation border is likely the smallest feasible irrigation scheduling unit, it is suggested here that improved irrigation scheduling decisions for surface-irrigated fields could be made by taking advantage of within-field crop, irrigation, and soil information at smaller spatial scales. In this sense, irrigation scheduling based on information at spatial scales smaller than an entire field could maximize overall crop productivity and increase the efficiency of the water applied.

Crop evapotranspiration estimation is a key component of SWB irrigation scheduling. For all practical purposes, spatially distributed estimation of ETc requires remote sensing (RS) observations. Two primary RS methods have been developed to estimate spatially distributed ETc from local and regional landscapes; (1) surface energy balance (SEB) modeling and (2) vegetation index (VI) estimation of crop coefficients combined with reference evapotranspiration (Gonzalez-Dugo et al., 2009). The two methods include use of visible and near infrared bands (VNIR), predominately red (≈670 nm) and near infrared (≈790 nm), and for SEB, the inclusion of thermal infrared (TIR) bands, predominated by bands over 10–13.5 μm. Surface energy balance models use measurement of land surface temperatures (LST) derived from TIR data to produce physically-based instantaneous estimates of actual plant evapotranspiration. Preeminent SEB models include one-source, contextual models such as SEBAL (Bastiaanssen et al., 1998), its open-source variant, METRIC (Allen et al., 2007), and the two-source energy balance, TSEB (Norman et al., 1995). A major advantage of utilizing thermal infrared with SEB is that it provides the potential to detect water-related plant stress and reduced ETc that would otherwise be missed when using vegetation indices (Gonzalez-Dugo et al., 2009). However, unless TIR data are available on a one or two-day basis, little would be gained for real-time irrigation management with infrequent evaluation of plant water stress. Furthermore, SEB models need additional procedures to temporally scale and extrapolate instantaneous ETc to daily values, and gap-filling procedures are necessary when filling estimates in between infrequent data (Kalma et al., 2008).

Because vegetation indices derived from remotely-sensed canopy reflectance data closely monitor the crop canopy development, they provide accurate spatial estimates of the basal crop coefficient (Kcb) (Hunsaker et al., 2005, 2007; Jayanthi et al., 2007). Thus, accurate estimates of Kcb obtained by RS provide should provide good estimates of actual spatial ETc when adjusted Kcb are adjusted by reference evapotranspiration (ETo) calculated from daily local weather station data (Gonzalez-Dugo et al., 2009). Implementing VI-based crop coefficients for irrigation scheduling could potentially be a successful technique for improving water management and water-savings (Glenn et al., 2011). In addition, VI data can be routinely measured either on the ground, in the air, or by satellite. Determining daily crop ET with the VI-based crop coefficient would require frequent, but not daily, VI measurements, since the smooth general shape of the Kcb curve over a growing season allows data to be extrapolated over a period of up to a week until full cover is reached, after which even less frequent RS data would be needed. As pointed out by Gonzalez-Dugo et al. (2009), effective applications of VI-based irrigation scheduling with small spatial scales require reliable ancillary data, such as soil characteristics and irrigation, to account for the typical soil water variability inherent in fields.

Geo-referenced, electromagnetic (EM) induction measurements of apparent soil electrical conductivity (EC_a) are considered a reliable way to map the spatial variation of soil properties at field scales (Corwin and Lesch, 2005). Applications of EM spatial surveys have been classically used to map soil salinity (Corwin and Rhoades, 1982). However, in non-saline soils, EC_a mapping is used to characterize other soil properties including texture and bulk density (Sudduth et al., 2005; Corwin and Lesch, 2005). Studies have shown that in soils without significant salinity, EC_a data is highly correlated to soil texture when the EM survey is conducted with the soil near field capacity (Godwin and Miller, 2003). Lesch et al. (2005) demonstrated the use of EM surveying and statistical soil sampling procedures (Lesch et al. (2000) for generating precision soil texture maps. A relevant EM survey application in irrigation scheduling studies was presented by Hedley and Yule (2009), who used EC_a measurements to predict soil texture and available soil water holding capacity (SWHC) for three, spatially-unique soil zones within a 32-ha, irrigated maize field in New Zealand. They used the data for calculating zone-specific soil water deficits within daily soil water balance models to schedule irrigations. Study results indicated increasing the number of EC_a-defined zones within the field would lead to improved prediction for irrigation scheduling.

The infiltration of water in surface-irrigated fields is inherently non-uniform. Depending on the design and hydraulic behavior of the irrigation system, and the effects of variability in soil intake rate and surface elevation, infiltration of water in surface-irrigated fields will be spatially variable. The distribution of infiltrated water, or irrigation uniformity, will also likely change over the course of the season due to cultivation activities, initial soil moisture conditions, etc. (Hunsaker et al., 1999). Collection of field evaluation data is an important aspect to understanding the performance of surface irrigation systems (Walker, 1989). Field evaluation data, e.g., measurements of advance and recession times and flow rates, can be analyzed with tools such as WinSRFR simulation software (Bautista et al., 2009) to estimate the hydraulic performance of the system, including the infiltrated depth profile along the length of the field. Such information can then be used to spatially characterize infiltrated depths to various parts of the field.

A two-year, irrigation scheduling study was conducted in central Arizona with cotton grown in surface irrigation borders. Treatments included three irrigation scheduling approaches that utilized weather-based ETc, remote sensing, and other ancillary field data to calculate soil water balances in small, multiple zones within the borders. A fourth treatment included in the study represented the traditional irrigation scheduling used for cotton borders. The purpose of this paper was to evaluate whether the use of real-time irrigation scheduling tools improved the yield and irrigation water use productivity over traditional cotton irrigation scheduling as practiced in the region.

2. Methods and materials

2.1. Experimental site, pre-season field preparations, and planting

An irrigation scheduling experiment was conducted for two cotton seasons, one in 2009, the other in 2011, on a 4.9-ha field at the University of Arizona, Maricopa Agricultural Center (MAC) (33°04′N, 111°58′W, elevation 361 m above mean sea level), in Maricopa, Arizona, USA. The field soil at the site is classified as a Casa Grande sandy clay loam (reclaimed fine-loamy, mixed, superactive, hyperthermic, typic Natriargid; Post et al., 1988). In the fall of 2008, prior to the 2009 experiment, dried dairy manure was incorporated into the field site soil at a rate of 33 Mg/ha. In early March 2009, raised beds were formed at 1.0-m row spacing. The entire field was then surface-irrigated on March 12, 2009 with 300 mm of water to saturate the soil profile. This was followed by EM surveys of the field site made eight days later on March 20, 2009 when the soil moisture in the profile was at ≈ field capacity (FC). On April 6, 2009, a second pre-plant surface irrigation of ≈100 mm was applied to moisten the raised beds prior to planting cotton on Apr. 22, 2009 (day of year (DOY) 112). Upland cotton (*G. hirsutum* L., 'Deltapine 1044B2RF')[1] was planted at a rate of ≈14.6 kg seed/ha in the moist beds at 1.0-m spacing. Following the harvest of the 2009 cotton experiment in October and the removal of remaining cotton plant material, the field site was fallowed until early Nov., 2010. A winter cover crop of barley was grown between Nov. 3, 2010 and mid-Feb., 2011. The barley was green chopped and removed prior to field preparations for the 2011 cotton experiment. Pre-plant surface irrigation for the 2011 cotton was on March 28–30 with 300 mm of water. On Apr. 20, 2011 (DOY 110), cotton was planted in moist raised beds with the same cotton variety, seeding rate, and row spacing as in 2009. Field preparations for both cotton experiments included laser-grading the field to a slope of 0.02% in the south to north direction (direction of irrigation water flow).

2.2. Experimental design, irrigation treatments, and nitrogen management

The irrigation scheduling experiment consisted of 16 irrigation borders (each 168 m long), oriented north–south, each containing 12 cotton rows (Fig. 1a). Borders were separated by two, 1.0-m wide skip-rows (unplanted) to allow machinery access for spraying pesticides later in the seasons. Twelve borders fit into bench one, whereas the remaining four borders were located within an adjacent second bench, separated by a distance of 14 m. In both experiments, four rows between the two benches were also planted to cotton, as were additional rows on both the eastern and western edges of the experimental borders that served as planted buffers.

The 16 experimental borders were randomized in a complete block design that consisted of four irrigation scheduling treatments within each of four block replicates (Fig. 1b and Table 1). The locations of the experimental treatment borders were identical for both years of study. A control treatment (denoted as MAC) represented the traditional irrigation scheduling practice for cotton borders

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[1] Mention of product names is for the benefit of the reader and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

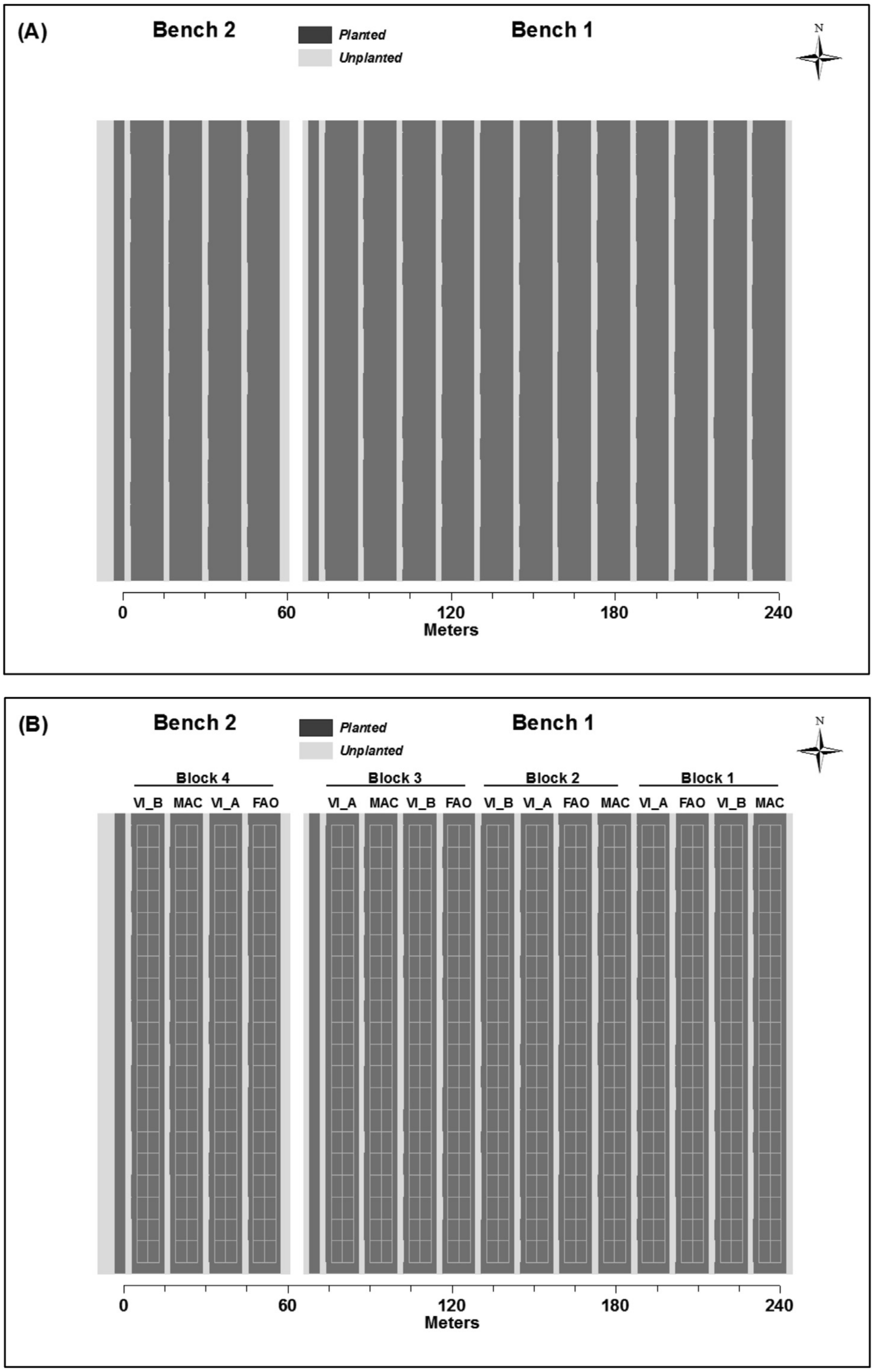

Fig. 1. Cotton irrigation experimental field showing the 16 planted borders, unplanted skip rows, and bench separation area (wide light area) (a), and showing the randomized border assignments to the four irrigation scheduling treatments (VI_A, VI_B, FAO, and MAC) in four blocks and the outlined zones of the 40, geo-referenced zones in each border, each zone comprising four planted rows (4 m) by 8 m long (b). Treatment description details can be found in Table 1.

Table 1
Summary of experimental cotton irrigation scheduling treatments implemented in 2009 and 2011 field studies at the Maricopa Agricultural Center (MAC), in Maricopa, AZ.

Treatment	Summary	ETc method	Soil water depletion (SWD) irrigation criteria
VI_A	Vegetation index (A schedule)	NDVI-estimated Kcb	45% mean for all zones
VI_B	Vegetation index (B schedule)	NDVI-estimated Kcb	5% of zones at 65% SWD
FAO	FAO-56	FAO-56-estimated Kcb	45% mean for all zones
MAC	Farm manager schedule	None	None

used in the region. The irrigation scheduling of the treatment was determined by the farm irrigation manager at MAC who combined years of cotton irrigation experience, visual crop observations, and the number of days since the last irrigation to decide when and how much water to apply. Irrigation scheduling for the other three treatments denoted in Fig. 1b were governed by daily soil water balance calculations of the crop root zone. These treatments utilized daily grass-reference evapotranspiration (ETo) and crop coefficients to compute daily crop evapotranspiration (ETc). Daily ETc was computed using the Food and Agricultural Organization (FAO)-56 dual crop coefficient procedures (Allen et al., 1998):

$$\mathrm{ETc} = (\mathrm{Kcb} \times \mathrm{Ks} + \mathrm{Ke})\,\mathrm{ETo} \quad (1)$$

where ETc is in mm/d, Kcb is the basal crop coefficient, Ks is the water stress coefficient, Ke is the soil evaporation coefficient, and ETo is grass-reference evapotranspiration in mm/d. Measured daily meteorological data were used to compute daily ETo using the FAO-56 Penman–Monteith equation (Allen et al., 1998). The meteorological data were provided by a University of Arizona, Meteorological Network (AzMet; ag.arizona.edu/azmet) weather station located at MAC, about 1.7 km from the field site. For the treatment denoted as FAO (Fig. 1b), a single Kcb curve for cotton was constructed following procedures described in the FAO-56 manual (Allen et al., 1998). Vegetation index (VI) treatments (VI_A and VI_B in Fig. 1b) utilized periodic aerial and ground-based remote sensing observations of the normalized difference vegetation index (NDVI) to estimate Kcb. For these two VI treatments, an equation which calculates Kcb as a function of NDVI, previously developed and described in Hunsaker et al. (2005), was used. Daily estimates of the Ks and Ke coefficients in Eq. (1) were made in conjunction with daily soil water balance calculations for the crop root depth (Zr) and the surface evaporation layer (Ze), respectively. Soil water contents at field capacity (FC) and permanent wilting point (PWP), used in determining daily Ks and Ke, were estimated from the pre-season EM-38 survey data and analyses that will be described in the next section. Additional parameters needed to evaluate Ks and Ke coefficients by FAO-56, require estimation of the daily crop root depth, the daily canopy height, and daily fractional canopy cover, all of which were estimated from daily Kcb using the guides presented in Annex 8 of the FAO-56 manual. The effective depth of the soil evaporation layer, Ze, was considered to be 0.12 m, as recommended in FAO-56

Irrigation scheduling determination for treatments VI_A, VI_B, and FAO were made by calculating the daily SWB for individual zones within each of the treatment border replicates. Spreadsheets, similar to the ones developed in Hunsaker et al. (2005), and originally patterned after Annex 8 in FAO-56, were developed to provide individual SWB estimates at each of the 40, 4-m × 8-m zones within each treatment border (Fig. 1b), excluding the MAC treatment. For the SWB calculations, inputs of irrigation water application depths for each zone were determined from irrigation field evaluation measurements and surface irrigation simulation (described later). Rainfall was assumed to be uniform for all zones. For the VI_A and FAO treatments, irrigations were given when the SWB calculated the total available water (TAW) of the crop root zone had been depleted by ≈45%, as averaged for all 160 zones within the particular treatment. The criterion used to determine irrigation timing for the VI_B treatment was when 5% of the 160 zones in that treatment had been depleted to 65% of the TAW. The irrigation amounts applied to these treatments was the average soil water depletion amount, in mm, averaged over all 160 zones of the particular treatment on the day prior to irrigation.

Following planting, within-season nitrogen fertilizer requirements were determined via NO_3–N analysis of cotton petioles samples (Doerge et al., 1991). Beginning in May in each experiment, 20 petiole samples were collected about every two weeks in all borders. For each date, the NO_3–N contents determined in the laboratory were averaged for all samples and then evaluated using the fertilizer-interpretation chart for cotton provided in Doerge et al. (1991). Using these procedures, it was determined that the cotton needed one N application in late spring in each experiment. On DOY 147 (May 27) in 2009 and DOY 152 (June 1) in 2011, 56 kg N ha^{-1}, as liquid urea-ammonium-nitrate (32% g N/kg), was knifed in bands along the furrow in all treatment borders.

2.3. *EC_a surveys, soil texture, and soil water retention*

The pre-experiment EM surveys made on March 20, 2009 provided spatial assessment of soil EC_a variability over the field site. Surveys were made on bare soil using an EM-38 electromagnetic induction meter (Geonics Ltd, Mississauga, ON, Canada) affixed to a tractor-mounted, PVC pipe sled. An on-board data recorder and RTK differential GPS (Trimble Navigation Limited, Sunnyvale, CA) provided data collection and simultaneous positional information. The surveys were made with the EM-38 sensor first placed in the vertical coil direction (effective soil measurement depth ≈1.5 m) and then placed in the horizontal coil direction for the second survey (effective measurement depth of ≈0.75 m). For both surveys, EM-38 measurements were made along the top of raised beds at 2-m spacing with measurements recorded every 1 m along the beds in the north south direction. Filtered data for each survey including latitude, longitude, time, and EC_a (ms/m), were imported into ArcGIS 9.1 (Environmental Systems Research Institute, ESRI, 2009). Imagine software (Imagine Software, Charlotte, NC) was used to re-sample the EC_a data for each survey in the ArcGIS field images into a 2 × 2 m grids generating over 10,000 cells in each survey. The EC_a gird data for the horizontal EM survey exhibited an increasing trend from east to west (Fig. 2), indicating apparent soil textural differences across the field. The trend for the vertical EC_a survey (not shown) was similar though not as prominent in variation as that for the horizontal survey.

Soil sample locations used in calibrating the EC_a gird data to soil texture used the "directed-sampling" approach developed specifically for EM surveys by Lesch et al. (2005). The EC_a gird data for each survey were separately analyzed using EC_e, Sampling, Assessment, and Prediction (ESAP) software (Lesch et al., 2000) to select 12, statistically-optimized locations to sample for soil texture determination (i.e., 12 optimal locations that best describe the variability of EC_a data over the entire field). The 12 sample locations selected with the directed-sampling approach for the horizontal survey, shown in Fig. 2, were widely dispersed across the field. For the 12 selected locations, soil samples were collected in 0.3-m increments from 0 to 0.6 m for the horizontal survey, whereas they were collected in 0.3-m increments from 0 to 1.2 m for the vertical survey (i.e., a total of 24 and 48 soil samples were collected for the horizontal and vertical locations, respectively). Each soil sample was analyzed for soil particle size fraction using the Bouyoucos hydrometer method (Gee and Bauder, 1986). Regression modeling analyses were performed with ESAP-Calibrate (Lesch et al., 2000), where the sampled average sand, silt, and clay fractions in the 0 to 0.6 m and the 0.6–1.2 m profiles were regressed against the against the co-located gird EC_a data from the horizontal and vertical surveys, respectively. The regression results indicated that the sand fraction was the best soil texture fraction predicted by EC_a (coefficients of determination, r^2 of 0.7–0.8) for both horizontal and vertical surveys (Table 2). The sand fraction vs EC_a regression equation derived from the horizontal survey and sampling was used to calculate an average sand fraction for the 0–0.6 m soil profile for each 4-m by 8-m zone (i.e., from EC_a data from the four, 2-m × 2-m cells within the larger zone). Similarly, the sand vs EC_a regression equation from the vertical survey was used to calculate an average sand fraction for the 0.6–1.2 m soil profile for each 4-m by 8-m zones. In addi-

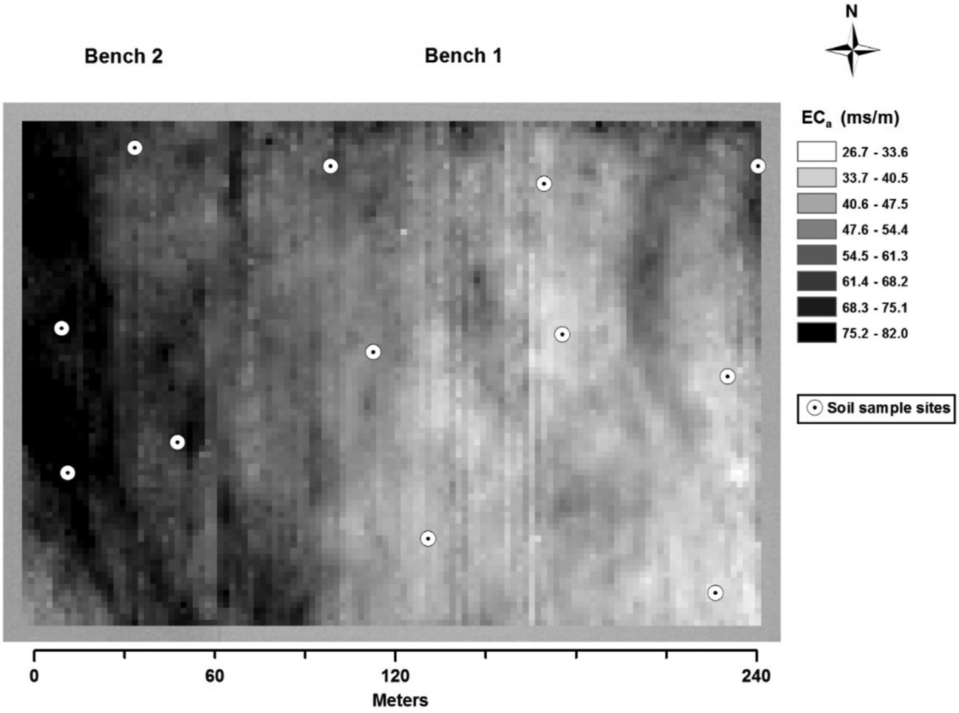

Fig. 2. Apparent soil electrical conductivity (ECa) gird map of study site from EM-38 survey made in horizontal mode on March 20, 2009 and the 12 directed soil sampling locations selected using the ECa data within ESAP software. An additional 12 directed soil sampling locations (not shown) were also selected from the vertical EM-38 survey data made in the vertical mode.

tion to soil texture, soil water retention at −33 kPa (field capacity) and −1500 kPa (permanent wilting point) were also determined for all 72 soil samples using pressure membrane extractors (Model 1000, Soilmoisture Equipment Corp., Santa Barbara, CA). The 72 sample data set was then used to develop regression relationships to estimate both the field capacity (FC) and permanent wilting point (PWP) volumetric soil water content as a function of sand content (Fig. 3). This was unlike the method of Hedley and Yule (2009) who used a direct correlation between measured FC and PWP versus EC$_a$ to estimate total plant available water. In the present study, 160 individual 4-m by 8-m zones for the VI_A, VI_B, and FAO treatments had separate soil water balance calculations based on soil water retention derived from the sand fraction contents that were estimated by EC$_a$. Therefore, sand content estimated at the upper (0–0.6-m) and lower soil (0.6–1.2-m) profiles for each zone in the treatments determined the FC and PWP values for the zone as calculated from the regression equations given in Fig. 3. The daily total available water of the crop root zone (TAW) for each of the zones was calculated as FC minus PWP times the daily crop rooting depth.

2.4. Irrigation system and uniformity evaluation

Irrigation water to borders was delivered by a concrete-lined irrigation ditch located on the south end of the field. Irrigation water to the field was controlled by a 305-mm, swivel valve, which was hard-plumbed to the concrete-lined ditch at the eastern edge of the field. Water flowed from the valve through an in-line propeller flow meter, and then through 305-mm diameter, polypipe from the east edge to the west edge of the field site. Gates were installed along the polypipe at 1.0 m spacing to allow an individual flow stream to each furrow in the border. The furrows within each border were open-ended at the far end to allow water from faster-advancing furrows to wrap around and flow into the end of slower-advancing furrows. Water flow rate and total volume applied were measured for irrigations of each border.

Soil water balance calculations for the VI_A, VI_B. and FAO treatments included separate infiltrated depth estimates for the zones within the treatment borders derived from field measurement data and analyses. Prior to each irrigation event of treatments borders, seven water-sensor timers, manufactured in-house (Hunsaker

Table 2
Mean sand, silt, and clay percentages for the 0–0.6-m soil profile and for the 0.6–1.2-m soil profile determined from lab analyses of 12, directed sampling locations for both soil profiles. Coefficients of determination and root mean square error are results of linear regression between the co-located gird soil texture variables and the horizontal EC$_a$ values (0–0.6-m profile) and the vertical EC$_a$ values (0.6–1.2-m profile).

Soil texture variable (%)	Soil depth increment (m)	Soil texture mean (%)	Coefficient of determination (r^2)	Root mean square error (%)
Sand	0–0.6	60.4	0.716	4.5
	0.6–1.2	64.7	0.827	2.5
Silt	0–0.6	14.9	0.112	3.0
	0.6–1.2	14.2	0.405	2.2
Clay	0–0.6	24.5	0.755	3.5
	0.6–1.2	21.1	0.608	2.8

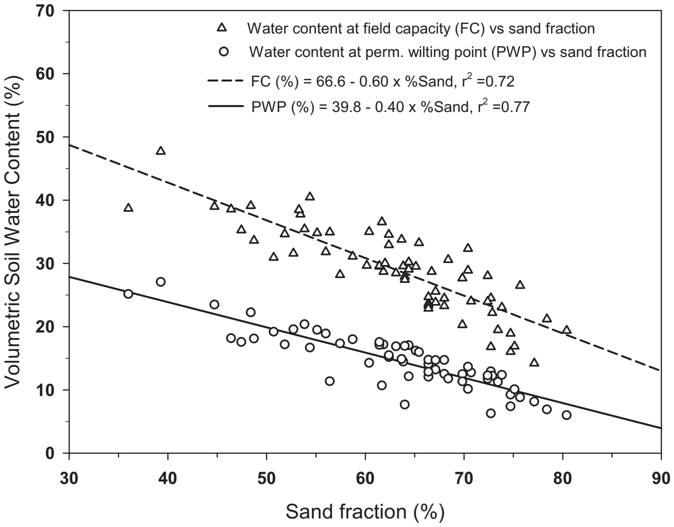

Fig. 3. Laboratory-analyzed volumetric water contents at −33 kPa (field capacity) and at −1500 kPa (permanent wilting point) with percent sand contents for the 72 soil samples collected using ESAP directed sampling procedures in March 2009, and the linear regression prediction functions derived for estimating field capacity and wilting point for zones in treatments as a function of percent sand content.

et al., 2011), were placed along the length of a central furrow in each border. The first sensor was placed at a distance of 5 m from the furrow water entry point and the remaining six sensors were placed every 25 m along the length of the furrow. The sensors recorded the time water arrived (advance time), as well as the time water had completely receded below the soil surface (recession time). For each irrigation event, measured data of flow rate, furrow geometry, and irrigation watering duration, advance, and recession were evaluated in the Event Analysis component within WinSRFR simulation software (Bautista et al., 2009). The WinSRFR analyses resulted in infiltration water depth profiles for each irrigation event. Interpolation of the profiles was made to derive infiltrated depths for each zone within the VI_A, VI_B, and FAO treatment borders. The same data collection and WinSRFR analyses were also performed for the MAC treatment, although the information was not used for the MAC irrigation scheduling. The low-quarter distribution uniformity (DU_{LQ}) for all irrigation events was calculated following the definition of Burt et al. (1997).

2.5. Remote sensing acquisition and analysis

Remote sensing observations of canopy reflectance were collected periodically over the cotton field using three platforms: aircraft, ground-based by farm vehicle, and ground-based by human transport. As described by French et al. (2015), airborne remote sensing surveys were conducted on DOY 126, 147, 154, 211, and 258 during the 2009 experiment and on DOY 146, 160, 188, 202, 216, 230, and 251 during 2011. For 2009, a 3-band, Duncan MS3100 camera (Optech Inc., West Henrietta, NY), mounted on a Hiller UH-12 helicopter, obtained red and near infrared (NIR) reflectance data using 10 nm bandwidth filters centered at 670 and 790 nm, respectively. The flight elevation of the helicopter was ≈800 m above ground level. The camera field of view was 15° × 20° and the pixel resolution for the experiments was ≈0.5 m. Ground reflectances from the Duncan camera data were determined using four, 8 × 8 m reflectance tarps, (Group VII Technologies, Provo, UT) having 4%, 8%, 48%, and 64% reflectances, deployed on the edge of the field. Image processing included geo-registration and masking. Raw imagery was first converted to reflectance (ρ) and then to NDVI as described by Tucker, (1979):

$$\mathrm{NDVI} = \frac{\rho_{790} - \rho_{670}}{\rho_{790} + \rho_{670}} \qquad (2)$$

NDVI data were also obtained using active crop canopy sensors (Crop Circle ACS-470, Holland Scientific, Lincoln, NE) mounted on the frame of a high-clearance tractor (Model Hi-G, Hefty Tractor Co., Juneau, WI). The three-band sensors obtained canopy reflectance in the red and NIR centered at bands 670 and 820 nm, respectively, in 20 nm bandwidths and use the 670 and 820 nm bands to calculate NDVI. A third band (red edge) centered at 720 nm was also collected but not used in the experiments. Four crop circle sensors were mounted on the front of the tractor such that each unit was directly above a cotton row. The height of the mounted radiometers was 1.9 m above the ground surface, each viewing approximately a 12 mm by 0.6 m wide area. The Trimble GPS was mounted on the frame supporting the radiometers and was used to geo-locate the NDVI data as the vehicle traveled at a speed of 0.89 m/s. In 2009, tractor-mounted surveys of NDVI were made on DOY 153, 176, and 188. During surveys, NDVI data were acquired about every 1.0 m along each of the inner eight crop rows of all borders, including the MAC and FAO treatments.

After an electronic failure, the Duncan camera was replaced for the 2011 experiment: first with a pair of 8-bit machine vision cameras (EO-1312 M, Edmund Optics, Barrington, New Jersey) and later with a new 3-band multispectral camera (MS4100, Geospatial Systems, Inc., Rochester, New York). However, the airborne remote sensing data were not used for the VI_A and VI_B treatments in 2011 due to problems related to delays in processing the data in real-time for NDVI. Instead, NDVI data were obtained using the Crop Circle active sensors with GPS and data logger, either machine-driven (on DOY 131) or transported on foot (DOY 179, 201, 214, and 223). When transported on foot, radiometer height was maintained at ≈1.0 m above the canopy for all runs.

2.6. Neutron probe soil water content measurements

Beginning in late April in both years, seven, 3.0-m long, metal access tubes were installed along one cotton row in each of the 16 experimental borders (112 access tubes total) using a tractor-mounted Giddings soil sampler (Model 25-TS, Giddings Machine Company, Windsor, CO). The row selected was the 4th cotton row from the eastern edge of each border. The first access tube along the row was placed 5.0 m north of the irrigation water entry point of the border. The remaining six tubes for each border were then placed along the same row every 25 m. During installation of the neutron access tubes, soil samples in 0.3-m increments were collected at each location to a depth of 1.8 m. The 672 soil samples were later analyzed for −33 kPa and −1500 kPa soil water retention and soil particle size fraction using the same analyses used for the EC_a survey soil samples. Volumetric soil water content measurements at the access tube locations began on May 19 (DOY 139), 2009, and on May 11 (DOY 131), 2011. Field-calibrated neutron moisture meters (Model 503, Campbell Pacific Nuclear, CPN, Martinez, CA) were used to measure volumetric soil water content (θ_v) from 0.1 m to 2.9 m in 0.2 m incremental depths. The θ_v measurements were collected for all 16 borders on 21 to 22 days through September 23, (DOY 266) in 2009, and on 18–20 days through September 19 (DOY 262) in 2011. Measurements of θ_v for treatments generally included measurements made one day before irrigation of a particular treatment, and then again four-five days after the irrigation. The soil water content and soil water retention measurements at the access tube locations were not used as inputs to the soil water balance calculations for the treatments. The use and application of these data are described in the next section.

2.7. Measured ETc and soil water depletion evaluations

Separate soil water balance calculations were made for all 112 probe locations (28 per treatment) using field measurement data in each year. Eqs. (3) and (4) (Hunsaker et al., 2005) were used to calculate the ETc that occurred between any two successive soil water content measurements made on the first measurement date, denoted as day $i = 1$, and made four to ten days later on day n:

$$\mathrm{ETc} = \sum_{i=1}^{10} (S_{i,1} - S_{i,n-1}) + \sum_{j=1}^{n-1} (R_j + \mathrm{IW}_j) - \mathrm{DP} \tag{3}$$

$$\mathrm{DP} = \sum_{i=11}^{15} (S_{i,1} - S_{i,n-1}) \tag{4}$$

where ETc is the total evapotranspiration and DP is the total deep percolation occurring from day 1 to the end of day $n - 1$, $S_{i,1}$ and $S_{i,n-1}$ are respectively the water storage measurements at soil depth increment i at the beginning of day 1 and end of day $n - 1$, and R_j and IW_j are respectively the rainfall and applied irrigation depths received on day j. Eq. (3) was used with DP equal to zero if Eq. (4) resulted in DP less than zero. Soil depth increments 1 through 10 were used to estimate the change in soil water storage within the estimated crop root zone and corresponded to actual soil depths of 0.1–1.9 m. Soil depth increments 11 through 15 were used to estimate deep percolation and corresponded to actual soil depths of 2.1–2.9 m. All variables in Eqs. (3) and (4) were in mm units.

Irrigation depth was determined for each measurement location from the field measurement and WinSRFR evaluation, as described earlier in Section 2.4. Rainfall amounts were those measured at the AzMet weather station at MAC. Daily rates of ETc were obtained by dividing ETc obtained in Eq. (3) by the number of days in the interval. Measured cumulative ETc was the summation of ETc through DOY 265 (September 22) 2009 and DOY 261 (September 18) 2011, just prior to crop defoliation.

2.8. Plant, yield, and water productivity measurements

Cotton plant population counts were made one to two months after planting at three to six locations along the length of border in both experiments. The number of plants in one linear meter was counted at these locations. Canopy heights and cover measurements were collected at three locations in each border starting in early June and in mid-May in 2009 and 2011, respectively. These measurements were made approximately every 10 days through early August and late August in 2009 and 2011, respectively. Cotton was machine-harvested with a two-row picker (Model 782, International, Goldsboro, NC) in all borders from 23 to 28 October 23 to 28 (DOY 296–301) in 2009 and from October 11 to 14 (DOY 284–288) in 2011. Only the inner 8 cotton rows of each border were harvested for yield determination. Seed cotton yields were bagged individually in 16-m incremental lengths along the rows of the borders. Thus, there were a total of 40 bagged harvests in each border. The yield samples were immediately weighed in the field and then smaller sub-samples from each bag were ginned to determine lint turnout. For each 16-m length, the two bags from two adjacent rows were averaged to obtain a yield from the 4-m × 16-m zone giving 20 yields for each border. Water productivity in terms of crop evapotranspiration ($\mathrm{WP_{ET}}$) was calculated for each border using the mean lint yield divided by the cumulative measured ETc of the border. Irrigation water productivity ($\mathrm{WP_I}$) for borders was calculated as mean lint yield divided by the total measured irrigation water applied, including that applied as pre-plant irrigation.

2.9. Statistical analyses

Treatment effects for measured water and yield variables were analyzed statistically for each experiment using a randomized complete block model within the Proc Mixed procedures of SAS (SAS Institute Inc., 2009). Block and block x treatment were considered random effects. The error term had nine degrees of freedom. Treatment means were separated using Pdiff (least significance difference, LSD, at $p = 0.05$) in SAS. The COVTEST option in Proc Mixed was used to test the block effect. For each treatment, differences for water and yield variables between years were tested using t tests, in which the standard errors of difference for each year from the Proc Mixed procedures were pooled for the t tests. These tests had six degrees of freedom.

3. Results and discussion

3.1. Climatic conditions

The climatic conditions during the two cotton experiments are given in Table 3, and the Maricopa location historical data are presented for comparison. In general, the climate data for 2009 and 2011 were not markedly different than historical means for the location, albeit low summer rainfall during the months of July and August in 2011 was not typical. Mean monthly maximum and minimum temperatures during early cotton growth in May were higher for 2009 than in 2011. However, as cotton plants were fully developing during the month of June, 2011 experienced higher maximum temperatures than in 2009. The June climate was also drier and less cloudy in 2011 than 2009, as noted by the differences in vapor pressure deficit and solar radiation during June for the two seasons. Mean wind speeds at the 2-m elevation were similar in both seasons and were typical for Maricopa. The mean daily FAO-56 reference evapotranspiration (ETo) for the two seasons were similar and nearly identical to the historical ETo means, except for the month of August where ETo was higher than normal in both seasons.

3.2. Irrigation scheduling and uniformity

After planting each cotton crop in April, all experimental treatment borders received an equal amount of irrigation provided by two, light, early-season irrigation applications. The purpose of these early-season irrigations was to provide all borders with sufficient watering so that cotton crop stand would be as uniform possible prior to imposing differential irrigation scheduling. The irrigations were applied using alternate (every-other) row irrigation, a standard practice used in the region for early-season cotton border irrigation. For 2009, a mean of 41 mm and 53 mm of irrigation water was applied to each border on Day of Year (DOY) 141–143 (May 21–23) and on DOY 153–154 (June 2–3), respectively. For 2011, a mean of 53 mm of IW was applied to all borders on both DOY 132–133 (May 12–13) and on DOY 154–155 (June 3–4). The timing of the two, early-season irrigations in each experiment were based on a mean soil water depletion (SWD) between 55 and 65% of the160 zones of the VI_A treatment. Differential irrigation treatment scheduling commenced in mid-June (DOY 165–168) for each experiment. In 2009, each treatment received a total of nine in-season irrigations. In addition to IW, 67 mm of in-season rainfall (R) occurred in 2009 (Table 3). Total in-season IW for the 2009 MAC treatment was 14%, 7%, and 5% greater than that for the FAO, VI_B, and VI_A, treatments, respectively, and the means of IW were significantly different for all treatments in 2009 (Table 4). During 2011, the VI_A, VI_B, and MAC treatments received a total of nine in-season irrigations, whereas the FAO treatment received a total of

Table 3
Monthly climate data summary during the 2009 and 2011 cotton experiments and historical 22-year means (1990–2011) at the Maricopa Agricultural Center, in Maricopa Arizona.

Year 2009	Monthly daily means						Monthly total
Month	T_{max} (°C)	T_{min} (°C)	Rad. (MJ/m^2)	2-m wind (m/s)	VPD (kPa)	ETo (mm)	Rain (mm)
May	36.7	18.8	27.3	2.1	3.3	7.8	4
June	37.0	19.9	27.5	2.2	3.4	8.1	0
July	41.9	25.9	26.9	2.2	4.0	8.5	42
August	40.8	23.9	26.2	1.9	3.9	7.6	11
September[a]	37.3	21.0	22.3	1.8	2.8	6.1	10
Year 2011							
May	32.3	14.1	29.6	2.6	2.7	7.8	0
June	39.5	19.8	30.6	2.1	4.0	8.7	0
July	40.4	24.4	27.4	2.2	3.6	8.3	11
August	41.5	26.4	23.9	2.0	3.9	7.6	0
September[a]	38.0	21.6	21.9	1.8	2.9	6.2	10
Year 1990–2011							
May	34.6	15.4	28.9	2.2	2.9	7.8	5
June	39.5	19.6	30.1	2.1	3.8	8.7	2
July	40.5	24.1	27.0	2.1	3.5	8.1	21
August	39.5	23.9	24.6	1.9	3.0	7.1	20
September[a]	37.7	20.7	22.3	1.8	2.6	6.1	12

Note: T_{max}: maximum temperature; T_{min}: minimum temperature; Rad.: radiation (solar); 2-m wind: wind speed at 2.0-m height; VDP: vapor pressure deficit; ETo: grass reference evapotranspiration. Data were obtained from the AzMet weather station (Brown, 1989) located at the Maricopa Agricultural Center.

[a] Means and rain for September were through crop defoliation (September 23, 2009 and September 19, 2011) and were through September 21 for 1990–2011.

Table 4
Treatment means[a] for seasonal total cotton soil water balance components in 2009, where IW is measured irrigation applied, *R* is measured rainfall, Δ*S* is the measured change in soil water storage of the crop root zone, DP is measured deep percolation, and ETc is total crop evapotranspiration. Soil water balance components were determined from planting (DOY 112) through crop defoliation (DOY 265), 2009.

Treatment	IW (mm)	*R* (mm)	Δ*S* (mm)	DP (mm)	ETc (mm)
VI_A	821b	67	151a	15b	1024ab
VI_B	805c	67	151a	16b	1007b
FAO	755d	67	154a	13b	963c
MAC	862a	67	139a	29a	1039a
LSD[b]	3.3	Na	20.6	12.1	21.7

Note: VI_A is NDVI-based Kcb irrigation treatment scheduled when mean soil water depletion (SWD) for zones is 45%; VI_B is NDVI-based Kcb irrigation treatment scheduled when 5% of zones are at 65% SWD; FAO is FAO-56-based Kcb irrigation treatment scheduled when mean SWD for zones is 45%; MAC is irrigation treatment scheduled by the MAC farm supervisor.

[a] Treatment means in a column followed with different lowercase letters were significantly different at $p = 0.05$.

[b] LSD at the bottom of each column is the least significant difference.

Table 5
Treatment means[a] for seasonal total cotton soil water balance components in 2011, where IW is measured irrigation applied, *R* is measured rainfall, Δ*S* is the measured change in soil water storage of the crop root zone, DP is measured deep percolation, and ETc is total crop evapotranspiration. Soil water balance components were determined from planting (DOY 110) through crop defoliation (DOY 262), 2011.

Treatment	IW (mm)	*R* (mm)	Δ*S* (mm)	DP (mm)	ETc (mm)
VI_A	812b	21	144ab	19a	959ab
VI_B	852a	21	139ab	20a	992a
FAO	767c	21	164a	22a	930b
MAC	855a	21	131b	28a	979a
LSD[b]	17.5	na	27.4	13.2	42.0

Note: VI_A is NDVI-based Kcb irrigation treatment scheduled when mean soil water depletion (SWD) for zones is 45%; VI_B is NDVI-based Kcb irrigation treatment scheduled when 5% of zones are at 65% SWD; FAO is FAO-56-based Kcb irrigation treatment scheduled when mean SWD for zones is 45%; MAC is irrigation treatment scheduled by the MAC farm supervisor.

[a] Treatment means in a column followed with different lowercase letters were significantly different at $p = 0.05$.

[b] LSD at the bottom of each column is the least significant difference.

eight in-season irrigations. In addition to IW, 21 mm of *R* occurred in 2011 (Table 3). The total in-season IW for the 2011 MAC treatment was 11%, 0%, and 5% greater than that for the FAO, VI_B, and VI_A, treatments, respectively, and mean IW for MAC in 2011 was significantly great than those for the FAO and VI_A, but not for VI_B (Table 5).

Seasonal trends in accumulated irrigation water indicate that the FAO treatment lagged behind all other three treatments in IW depth applied starting around DOY 160 (June 9) in 2009 (Fig. 4a). The two VI treatments had similar growth in cumulative IW in 2009, though timing of irrigations for the VI_B treatment fell behind that for the VI_A by several days beginning around DOY 190 (July 9). The primary irrigation scheduling differences between MAC and the VI-based treatments was that MAC was generally irrigated at longer time intervals and received larger depths of IW per irrigation through about DOY 200. Therefore, at various times during 2009 the cumulative IW depth for the MAC treatment would fluctuate both over and below that for other treatments (Fig. 4a). Treatment differences in cumulative IW for 2011 were less pronounced than in 2009, although the FAO treatment again received the least IW for treatments (Fig. 4b). The VI_A and VI_B trends in IW were nearly identical in 2011, except at end of the season where cumulative IW for the VI_B treatment increased above that of the VI_A. In 2011, the MAC irrigator applied less water per irrigation during the first half of the season than that in 2009, though irrigation frequencies were similar throughout both years. This resulted in cumulative IW for MAC that fell somewhat behind the VI_A and VI_B treatments until the second half of the season (Fig. 4b).

Measured advance and recession data are shown in Fig. 5a for the third irrigation of the 2009 season (June 16, DOY 167) for the VI_A treatment border in block 1 (Fig. 1b). Typically, times to advance to the end of the field were on the order of 100 min or less for all treatments. Depending on the volume of water applied for a particular border irrigation, completion of advance would vary from about 60–120 min prior to the time of irrigation water cutoff. For this particular irrigation, the average furrow flow rate was 0.21 m^3/s, water was cutoff after 150 min, while the advance was complete by 85 min (Fig. 4a). Recession times were relatively uniform across all locations measured for this irrigation, varying only from 350 to 375 min (Fig. 5a). Uniform recession times were typical for most border irrigations, though recession times increased to 450–500 min in most borders, as depth of IW applied increased during the seasons. For each border irrigation, advance and reces-

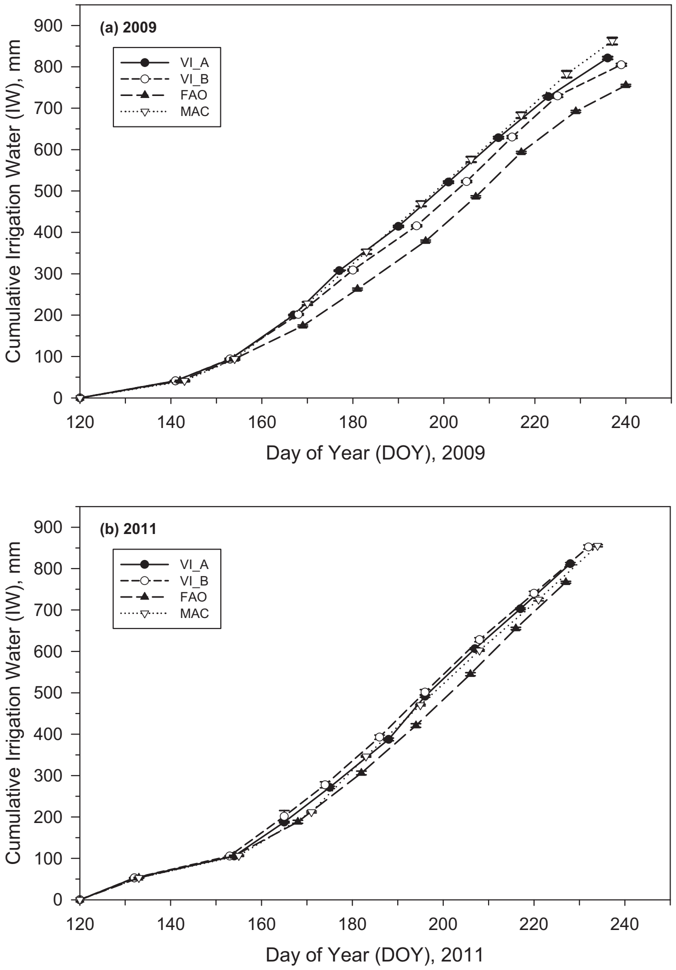

Fig. 4. Means of measured cumulative irrigation water (IW) depth applied with time for the VI_A, VI_B, FAO, and MAC treatments for 2009 (a) and 2011 (b). Note that the dates of irrigation are indicated by symbols for each treatment and error bars are ± 1 standard deviation about the symbol means. Treatment description details can be found in Table 1.

sion measurements, along with additional measurements of flow rate, furrow geometry, etc., were inputs to the WinSRFR simulation software, which resulted in an infiltrated depth profile along the length of the furrow. The infiltrated depth profile for the VI_A irrigation border on DOY 167, shows an average depth of infiltrated water of 108 mm, and a low-quarter distribution uniformity (DU_{LQ}) of 94% (fig. 5b). The treatment means of the DU_{LQ} for all in-season irrigations varied slightly in 2009, from a low of 91% for MAC to a high of 94% for FAO. These DU_{LQ} values were not significantly different among treatments, however, and are considered highly acceptable for surface irrigation systems. For 2011, the treatment mean DU_{LQ} for in-season irrigations varied from 85% for VI_A to 89% for the VI_B, but treatment mean differences were not significant. However, for all treatments, the mean DU_{LQ} for 2011 were lower than those for 2009, and were significantly lower for the VI_A and FAO treatments. The decreased irrigation uniformity in 2011 than 2009 was attributed to generally lower flow rates for irrigation applications (thus, somewhat longer advance times) due to greater water demand by other users on the supply canal in 2011 than in 2009.

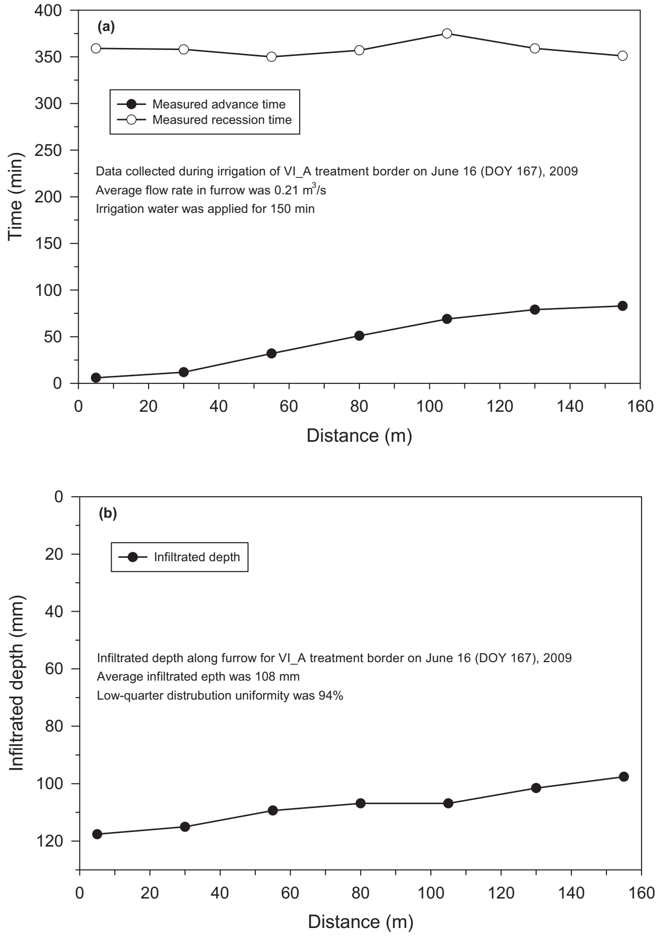

Fig. 5. Measured advance and recession times on June 16, 2009 at seven locations along a central furrow for a border within the VI_A treatment (a), and infiltrated depth profile along the length of the furrow resulting from evaluation of advance/recession and other field data using WinSRFR (Bautista et al., 2009).

3.3. Crop development

Measured crop height and green canopy cover illustrate the cotton development in each season for the four irrigation treatments (Fig. 6a, 2009 and Fig. 6b, 2011). In both season, crop height and cover for the FAO lagged behind the development for the other treatments. However, 100% canopy cover was obtained for the FAO treatment, but occurred after all other treatments had reached full cover. In both seasons, the MAC crop height development was slower than that for the VI_A treatment but was similar in trend to the VI_B treatment. The lag in crop height and cover for the FAO compared to other treatments corresponded to the FAO lag in cumulative irrigation water (Fig. 4). A comparison for a given treatment between the two seasons shows slower crop height and canopy cover development in 2011 than 2009. Besides more favorable early-season temperatures in 2009, more rapid development in 2009 than 2011 may have been affected by plant density differences (20 plants/m in 2009 versus 15 plants/m in 2011).

3.4. Crop evapotranspiration and soil water balance

The cumulative ETc with time is presented for all treatments in Figs. 7 and 8 for 2009 and 2011, respectively. The predicted daily ETc (mean of 160 zones per treatment) in 2009 accumulated more rapidly with time for both the VI_A and VI_B than for the FAO treatment (Fig. 7a, b and c, respectively). Thus, higher predicted ET rates resulted in higher predicted daily soil water depletion for the two VI-based treatments than the FAO, which led to greater total in-season irrigation water applied than to the FAO (Table 4). In 2011, daily predicted ETc with time for the two VI treatments was also more rapid than for the FAO treatment

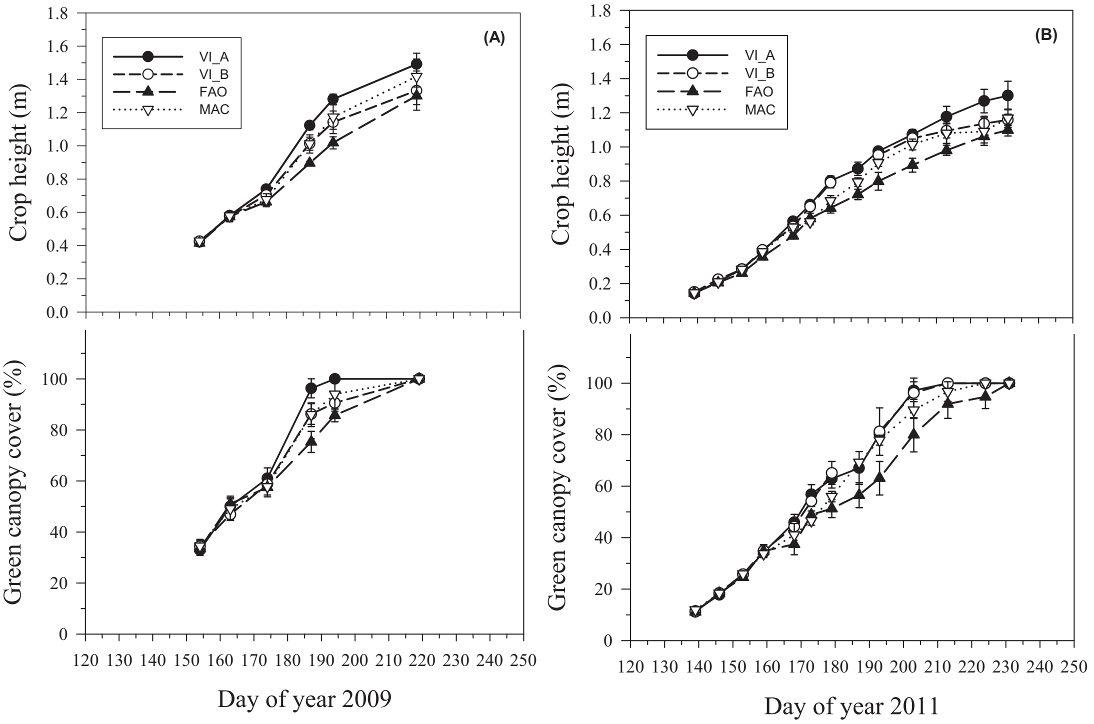

Fig. 6. Measured mean cotton growth parameters for the VI_A, VI_B, FAO, and MAC treatments in 2009 (a) and 2011 (b) at Maricopa, Arizona. Error bars are ± one standard deviation about the means. Treatment description details can be found in Table 1.

(Fig. 8a–c), though not as extensively as in 2009. However, due to lower predicted ETc for FAO, the treatment ultimately received significantly less cumulative irrigation water applied than for VI treatments in 2011 (Table 5). Although predictions of ETc were influenced by several factors, including estimated SWHC, soil evaporation rates, and irrigation depth applied, the higher predicted ETc for the two VI treatments was primarily influenced by those treatments having daily estimated basal crop coefficients that rose more rapidly during the first half of the two seasons than those for the FAO single Kcb curve. The total predicted cumulative ETc was also lower in 2011 than in 2009 for the VI_A, VI_B, and FAO treatments. The predicted total cumulative mean ETc for the 160 zones of the VI_A treatment was 1068 mm in 2009 but only 974 mm in 2011. For the VI_B treatment predicted cumulative mean ETc was 1058 and 1006 in 2009 and 2011, respectively. Similarly, predicted mean cumulative ETc fell from 985 mm in 2009 to 912 mm in 2011. Factors that likely contributed to lower predicted ETc for the VI-based Kcb treatments in 2011 were measured plant density

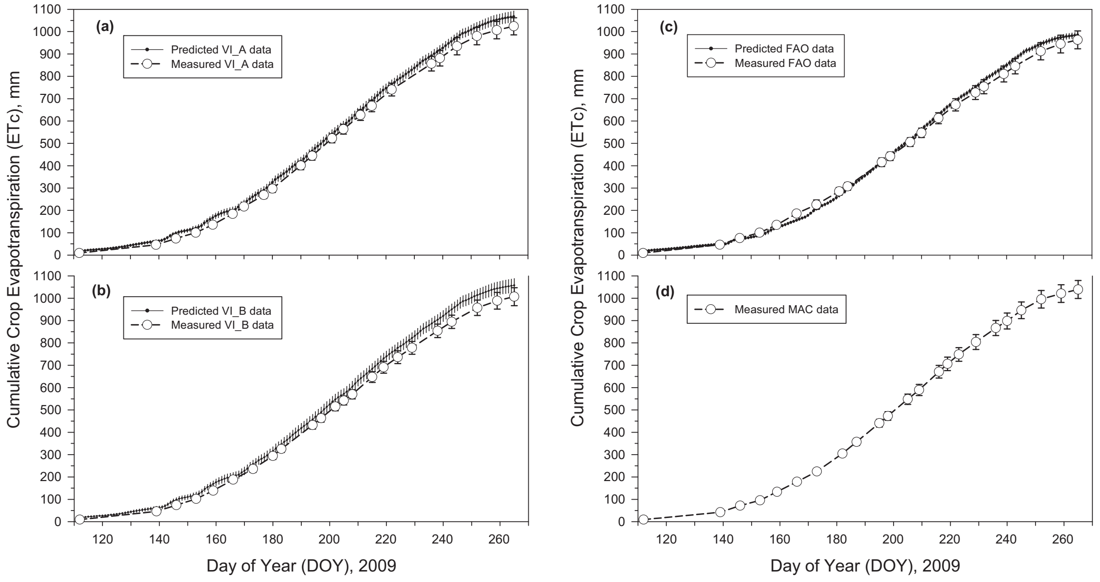

Fig. 7. Means of daily cumulative predicted crop evapotranspiration (ETc) along with means of measured cumulative ETc with time in 2009 for the VI_A (a), VI_B (b), and FAO (c) treatments for 2009 and measured cumulative ETc for the MAC treatment (d). Means are from 160 predicted zones in each treatment and from 28 soil water measurement locations in each treatment. Error bars are ± one standard deviation about the means (larger-capped error bars are for measurements). Treatment description details can be found in Table 1.

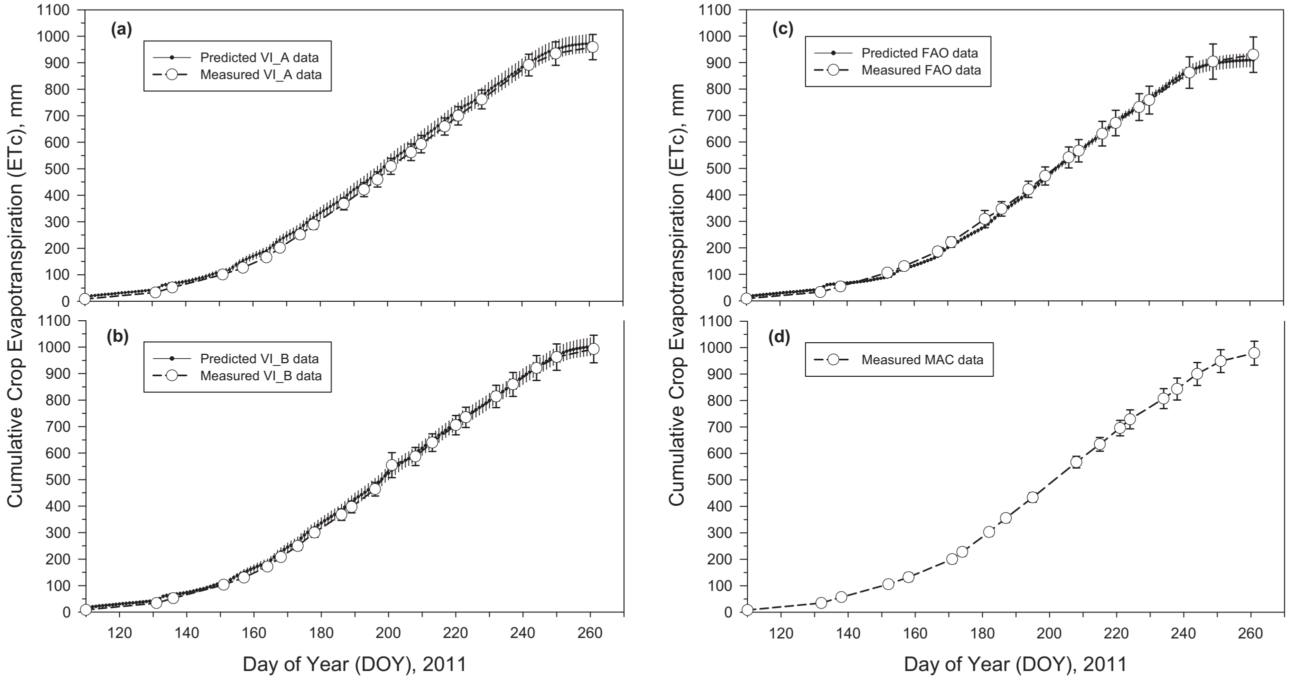

Fig. 8. Means of cumulative predicted crop evapotranspiration (ETc) along with means of measured cumulative ETc with time in 2011 for the VI_A (a), VI_B (b), and FAO (c) treatments for 2011 and measured cumulative ETc for the MAC treatment (d). Means are from 160 predicted zones in each treatment and from 28 soil water measurement locations in each treatment. Error bars are ± one standard deviation about the means (larger-capped error bars are for measurements). Treatment description details can be found in Table 1.

that was lower than in 2009, as mentioned earlier, and treatment canopy cover development that was slower than in 2009 (Fig. 6). These factors affected the NDVI that were used in Kcb estimation. The MAC treatment did not follow a calculated water balance in either experiment and therefore did not have predicted ETc.

The mean measured cumulative ETc were calculated from 28 soil water monitoring locations in each treatment using the measured soil water balance components presented in Table 4 (2009) and Table 5 (2011). In 2009, seasonal cotton ETc was highest for the MAC treatment (1039 mm). This was significantly greater than that for the VI_B (1007 mm) and FAO (963 mm) treatments, but not for the VI_A treatment (Table 4). Both the VI_A and VI_B treatment means for total ETc were significantly greater than the FAO treatment mean in 2009. The mean measured cumulative ETc in 2011 was highest for the VI_B treatment (992 mm, Table 5), but was only significantly higher than that for the FAO treatment (930 mm). Soil water balance indicates that deep percolation (DP) was significantly greater (29 mm) for the MAC than all other treatments in 2009 (Table 4). Deep percolation, while again highest for the MAC treatment in 2011 (28 mm), was not significantly different than for the other treatments (Table 5). Thus, the penalty for water lost to DP associated with the higher irrigation water applied for the MAC treatment practice compared to other treatments was minimal (i.e., less than 15 mm). Consequently, the three scientifically-based irrigation scheduling treatments did not realize significant water-savings compared to the traditional practice used in MAC. Similarly, differences among treatments in stored soil water (ΔS) use were small and only significant between the less-irrigated FAO treatment and MAC treatment in 2011. Across all treatments, measured cumulative ETc means were higher by 15 mm to 65 mm in 2009 than in 2011, and were significantly different between years for all but the VI_B treatment. The higher measured cumulative ETc in 2009 than 2011 was likely due to several differences that occurred between the two years. These include higher plant density and more frequent rain events in 2009 than 2011. Another possible factor was early-season weather condition differences between years, which were more favorable for cotton growth during the first 35 days after planting in 2009 than 2011 (e.g., monthly mean air temperatures in May were over 4.0 C warmer in 2009 than 2011; Table 3).

Seasonal progression of root zone volumetric soil water content is presented for all treatments in Figs. 9 and 10 for 2009 and 2011, respectively. Predicted daily soil water content for the VI_A, VI_B, and FAO treatments in 2009 are shown as means derived from all 160 spatial zones within the particular treatment (Fig. 9a, b and c, respectively). Bars showing ± one standard deviation about the means indicate that the variability of predicted soil water content gradually decreased as the season progressed until late in the season after irrigations were terminated for treatments (≈DOY 240 in 2009). The higher variability in late season predicted soil water content was attributed primarily to variable predicted soil water stress and their effects on ETc reduction, as calculated in FAO-56. Fig. 9 also shows the mean soil water contents for treatments (28 locations per treatment) measured periodically during the 2009 season. Predicted and measured means of soil water content were in good agreement for both the VI_A (Fig. 9a) and VI_B (Fig. 9b) treatments throughout the 2009 season, whereas the variability of predicted soil water contents was typically lower than the measured variability for the VI_A treatment but higher than the measured variability for the VI_B treatment. The measured soil water content for the FAO treatment of 2009 was under-predicted by the SWB calculations through DOY 188 (Fig. 9c). This corresponds to under-predicted measured ETc during the first half of the season for the FAO treatment. As the season progressed after DOY 188, predicted and measured mean soil water contents came into better agreement for the FAO treatment. For the MAC treatment of 2009 (fig. 9d), measured soil water contents exhibited more consistent trends throughout the season compared to the other treatments. The irrigation scheduling used by the MAC farm manager also resulted in less variability in measured soil water contents compared to that among the other treatments.

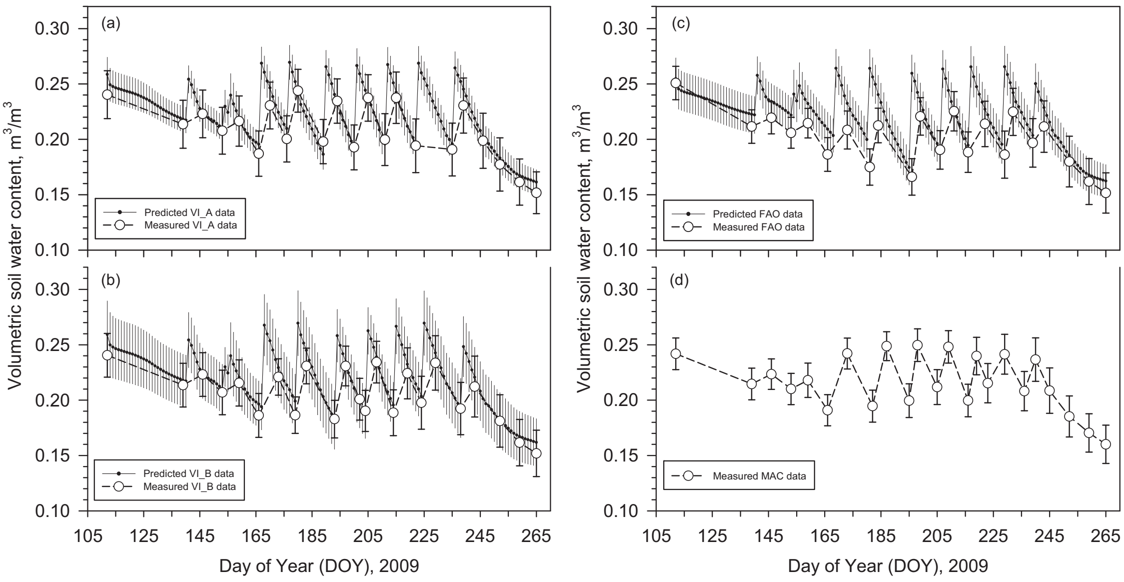

Fig. 9. Means of daily predicted soil water content along with means of measured soil water content with time in 2009 for the VI_A (a), VI_B (b), and FAO (c) treatments for 2009 and measured cumulative ETc for the MAC treatment (d). Means are from 160 predicted zones in each treatment and from 28 soil water measurement locations in each treatment. Error bars are ± one standard deviation about the means (larger-capped error bars are for measurements). Treatment description details can be found in Table 1.

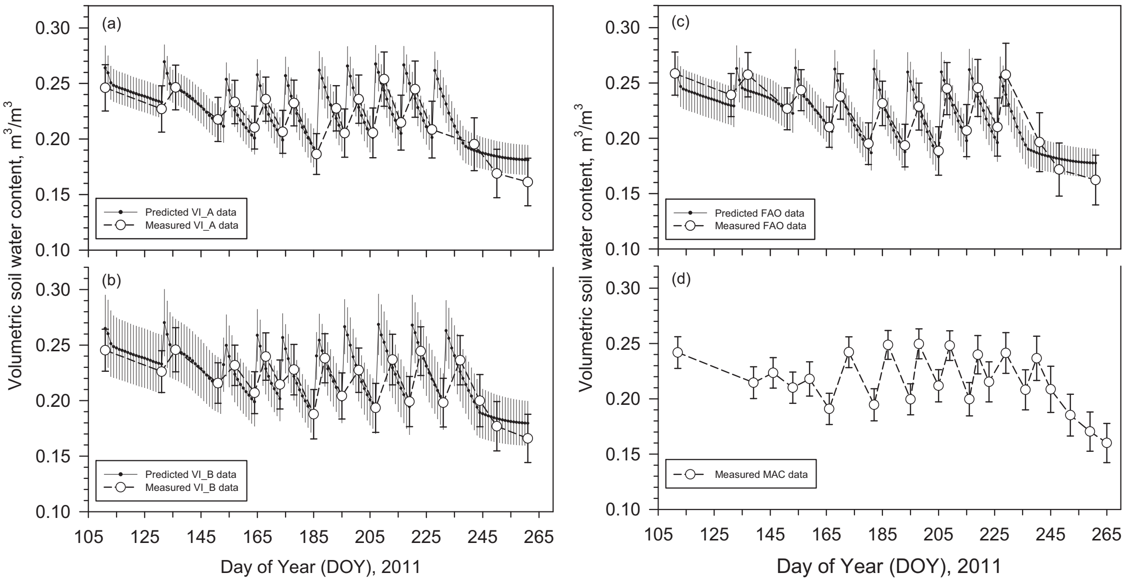

Fig. 10. Means of daily predicted soil water content along with means of measured soil water content with time in 2011 for the VI_A (a), VI_B (b), and FAO (c) treatments for 2011 and measured cumulative ETc for the MAC treatment (d). Means are from 160 predicted zones in each treatment and from 28 soil water measurement locations in each treatment. Error bars are ± one standard deviation about the means (larger-capped error bars are for measurements). Treatment description details can be found in Table 1.

In 2011, the predicted and measured mean soil water contents were in close agreement throughout the season for the VI_A, VI_B, and FAO treatment (Fig. 10a, b and c, respectively). The variability for predicted soil water content was similar to that for measured for the VI_A treatment in 2011 (Fig. 10a). However, predicted soil water content variability was somewhat higher than the measured soil water content variability for the VI_B treatment through DOY 172, but was similar afterwards (Fig. 10b). While agreement between predicted and measured mean soil water contents means was better for the FAO treatment in 2011 (Fig. 10c) than in 2009, the measured variability for FAO was considerably higher in 2011 than it had been in 2009 (Fig. 9c). The measured soil water contents for the MAC treatment in 2011 (Fig. 10d) again showed the most consistency and lowest variability among all treatments. The larger irrigation depths applied by the MAC manager resulted in small increases in DP but provided more uniform soil water contents throughout the plots.

3.5. *Measured lint yield and water productivity*

The measured mean lint yield for the four border replicates within each treatment and each year is shown as a function of the mean total water applied to each border (including the preplant irrigations plus the in-season IW applied and in-season rain) (Fig. 11a) and as a function of the measured mean seasonal total ETc for each border replicates (Fig. 11b). Each of the 16 treatment yield data points in each year represent a mean of 20, 4 × 16 m, lint yield determinations. A linear relationship for lint yield with total water applied in 2009 was apparent (Fig. 11a). The linearity of the curve suggests an increasing lint yield benefit with increased

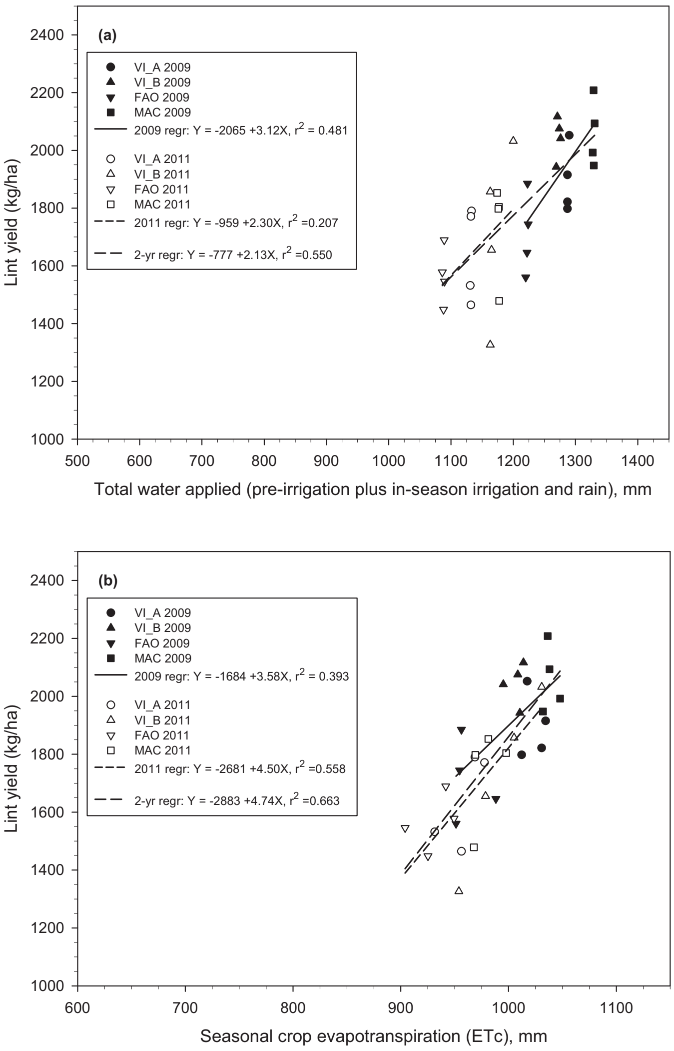

Fig. 11. Measured cotton lint yield as a function of total water applied, i.e., pre-plant irrigation, plus in-season irrigation and rain (a) and as a function of seasonal crop evapotranspiration [ETc] (b) for treatments in 2009 and 2011. Data points are mean lint yields obtained from all harvest samples of a border replicate, mean total water applied to a border replicate, and mean seasonal ETc obtained from seven measured locations within each border replicate. Treatment descriptions are given in Table 1.

Table 6
Treatment means[a] of measured final lint yield, ETc water productivity ($\mathrm{WP_{ET}}$) based on measured seasonal ETc, and irrigation water productivity ($\mathrm{WP_I}$) based on measured in-season (IW) plus pre-plant irrigations for the four irrigation scheduling treatments of the 2009 cotton experiment.

Treatment	Measured lint yield (kg/ha)	Measured $\mathrm{WP_{ET}}$ (kg/m^3)	Measured $\mathrm{WP_I}$ (kg/m^3)
VI_A	1897b	0.185bc	0.155bc
VI_B	2052a	0.203a	0.170a
FAO	1725c	0.178c	0.148c
MAC	2061a	0.198ab	0.163ab
LSD[b]	138.4	0.015	0.011

Note: VI_A is NDVI-based Kcb irrigation treatment scheduled when mean soil water depletion (SWD) for zones is 45%; VI_B is NDVI-based Kcb irrigation treatment scheduled when 5% of zones are at 65% SWD; FAO is FAO-56-based Kcb irrigation treatment scheduled when mean SWD for zones is 45%; MAC is irrigation treatment scheduled by the MAC farm supervisor.

[a] Treatment means in a column followed with different lowercase letters were significantly different at $p = 0.05$.

[b] LSD at the bottom of each column is the least significant difference.

Table 7
Treatment means[a] of measured final lint yield, ETc water productivity ($\mathrm{WP_{ET}}$) based on measured seasonal ETc, and irrigation water productivity ($\mathrm{WP_I}$) based on measured in-season (IW) plus pre-plant irrigations for the four irrigation scheduling treatments of the 2011 cotton experiment.

Treatment	Measured lint yield (kg/ha)	Measured $\mathrm{WP_{ET}}$ (kg/m^3)	Measured $\mathrm{WP_I}$ (kg/m^3)
VI_A	1639a	0.171a	0.147a
VI_B	1718a	0.173a	0.149a
FAO	1565a	0.168a	0.147a
MAC	1733a	0.177a	0.150a
LSD[b]	370.2	0.030	0.023

Note: VI_A is NDVI-based Kcb irrigation treatment scheduled when mean soil water depletion (SWD) for zones is 45%; VI_B is NDVI-based Kcb irrigation treatment scheduled when 5% of zones are at 65% SWD; FAO is FAO-56-based Kcb irrigation treatment scheduled when mean SWD for zones is 45%; MAC is irrigation treatment scheduled by the MAC farm supervisor.

[a] Treatment means in a column followed with different lowercase letters were significantly different at $p = 0.05$.

[b] LSD at the bottom of each column is the least significant difference.

water applied, at least within the range of the experimental levels of water input. The relationship of 2009 shows a maximum lint yield of 2090 kg/ha with total water applied of 1330 mm, which was the MAC treatment amount. As expected from the linear curve of 2009, lint yields for treatments that received less total water applied than MAC had significantly lower lint yields (Table 6). A notable exception was that the VI_B treatment achieved the same lint yield as for MAC, but did so with 57 mm less total water (i.e., 1273 mm). This might suggest potential water-savings could be attained using the irrigation scheduling criteria for the VI_B treatment, i.e., basing irrigation timing on spatially-predicted soil water depletion extremes.

In 2011, lint yield was more variable among treatments and replicates than in 2009 and was not as well-correlated with total water applied (Fig. 11a). Due to higher yield variability, however, lint yields were not significantly different among treatments (Table 7). Nevertheless, the linear relationship for 2011 indicates the same general result as in 2009, i.e., MAC had the most water applied and the highest lint yields, though once again lint yield for the VI_B was comparable to MAC. Although yields were not significantly different in 2011, the ranked order of the 2011 yields was the same for treatments as in 2009, e.g., the MAC treatment had the highest lint yields in both years. The stronger linear relationship obtained combining all data from both years (Fig. 11a) suggests that a case could be made that more water should have been applied in 2011 (MAC had only 1178 mm total water compared to 1330 mm in 2009). Major factors that caused less total water to be applied in 2011 than 2009 were cooler early-season climate conditions (Table 3) leading to slower early-season growth (Fig. 6) and irrigation requirements. In addition, the 2011 cotton received less in-season rain, and 100 mm less pre-plant irrigation water than in 2009.

Linear relationships between mean lint yields and measured mean seasonal ETc for the 16 treatment borders were obtained separately by year (Fig. 11b). Lint yield variability was described by measured ETc better in 2011 than in 2009, although both year's regression coefficients of determination (r^2 values) were significant at the 0.05 level. It appeared that the yield versus ETc data generally fell about the same linear slope for the separate years and when the data for the two years were combined (Fig. 11b). However, the intercepts of the zero-yield point versus ETc of the regression lines were different for the two years, 470 mm for 2009 and 595 for 2011. The threshold value for zero lint yield for both years were higher than would be normally expected for this environment (≈250 mm). The higher thresholds in this experiment were understandable, since all irrigation treatments for these experiments were achieved at the upper end of the irrigation spectrum (though somewhat depressed for the FAO treatment). However, most cotton production curves in the literature will be produced based on significantly lower irrigation levels for cotton (e.g., Jalota et al., 2006).

As seen in Table 6, the water productivity for treatments in 2009 was highest for the VI_B treatment for both WP_{ET} (0.203 kg/m^3) and WP_I (0.170 kg/m^3). These values were significantly higher than the WP_{ET} and WP_I attained for the VI_A and FAO but not for those of the MAC treatment (0.198 kg/m^3 and 0.163 kg/m^3, respectively). As with lint yield, differences between treatments for either WP_{ET} and WP_I were small and not significant in 2011 (Table 7). The mean crop ETc productivity for all 16 borders in 2009 (0.191 kg/m^3) was about 11% greater than that in 2011 (0.172 kg/m^3). The difference between years for WP_I was smaller than for WP_{ET}, where in 2009 the mean WP_I for all treatments (0.159 kg/m^3) was only about 7% greater than that in 2011 (0.148 kg/m^3).

Like the lint yield results, usage of the scientifically-based irrigation scheduling methods did not improve water productivity over the traditional irrigation scheduling used in the MAC treatment. However, the irrigation water productivities attained for all treatments and both years varied from 22% to 41% higher than the average WP_I of 0.12 kg/m^3 for surface-irrigated cotton in this area, as reported for 2008 Arizona data by NASS (2010). The NASS (2010) survey reported that in 2008 the average irrigation water use for surface-irrigated cotton in Arizona was 1460 mm and the state-average lint yield was 1690 kg/m^3. For the 2009 and 2011 experiment treatments, seasonal irrigation water applied (including pre-plant irrigation but excluding rainfall) varied from 1155 to 1262 mm (2009) and from 1067 to 1155 mm (2011). Therefore, total irrigation water use for the 2009 and 2011 experiments was 14 to 27% lower than that of the seasonal average applied to cotton in Arizona 2008. Treatment lint yields for the experiments were −7% to 23% that of the state average yield in 2008.

The MAC farm manager's experience with cotton irrigation was a key factor in achieving high yields without any form of scientific irrigation scheduling. Consequently, the MAC irrigation scheduling proved to be a more effective method than the three ET-based treatments. In achieving these results, the MAC irrigation manager used a combination of factors in his decision making. The primary decision factor used was the number of days since the last irrigation. The manager choose to apply early-season irrigation based on the number of days since the last irrigation. From June through mid-July in both seasons, the irrigation frequency used by MAC was between 14 and 17 days. However, irrigation depths applied during this period were the also about 20% higher than the treatments during this period. From mid-July onward, the MAC manager applied irrigation on a fairly regular basis, about every 11–12 days.

4. Summary and conclusions

Irrigation water use for cotton is particularly high in arid Western States of the USA, including Arizona, where surface irrigation is the main method of irrigation. The most recent irrigation information available indicates that surface irrigation producers in Arizona use about 1460 mm of irrigation water annually to grow a cotton crop, which is about 300 mm more water used by micro-irrigation cotton producers in the state. Increasingly, limited and expensive water supplies in the region will necessitate surface irrigation producers to use management practices that reduce irrigation and increase irrigation water use productivity. However, the use of any scientific-based irrigation scheduling methods that could positively impact cotton water use productivity is very limited in the region. The primary focus of this paper was to evaluate whether the use of real-time irrigation scheduling tools could improve cotton lint yield and reduce irrigation water use over traditional cotton irrigation scheduling as practiced in the region.

A field study in 2009 and 2011 on a 4.9-ha cotton field in central Arizona evaluated the effectiveness of irrigation scheduling decisions governed by spatial inputs. Two treatments (VI_A and VI_B) utilized the full set of spatial inputs estimated at zones that included remote sensing estimates of Kcb to calculate ETc, whereas a third treatment (FAO) differed by utilizing a single Kcb curve, uniformly applied to all zones. A fourth treatment (MAC) did not use data input or an irrigation model. Instead, the treatment relied solely on the many years of experience of the MAC irrigation manager to schedule the irrigations. A major conclusion of the study was that the present-day irrigation volumes being applied to cotton in surface-irrigated fields in this region could be substantially reduced. When compared to the average 2008 Arizona data any of the four treatments presented in the study could potentially offer methods to significantly reduce cotton irrigation water use while maintaining or increasing current lint yields levels. However, the two-year experiment also showed that the lint yields attained under the MAC farm manager's irrigation scheduling were equal to or higher than any of three real-time ET-based irrigation scheduling treatments in the experiment. While the MAC treatment resulted in somewhat higher irrigation amounts than for the other treatments, it maintained or exceeded the irrigation water productivity attained for any other treatment. The primary difference between the MAC irrigation scheduling and the VI-based treatments was that the MAC manager choose to apply larger irrigation depths at longer irrigation frequencies from crop development in early June crop through full cover at mid-July. During this period the MAC treatment allowed a higher soil water depletion to occur prior to irrigation than that for the VI-based treatments. However, soil water contents were returned to field capacity for the MAC treatment after each irrigation. Compared to the 2008 average traditionally-irrigated cotton fields in Arizona, the MAC treatment attained higher lint yields with less total irrigation water in both years. Cotton growers in the region could benefit by patterning their irrigation scheduling after the MAC treatment criteria described herein.

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