A SMARTPHONE APP FOR SCHEDULING IRRIGATION ON COTTON

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Abstract

Irrigation has become essential to crop production in many agricultural areas of the United States and especially across the cotton producing regions of the USA. As a result, the competition for available fresh water supplies is increasing and in some regions, cotton producers are faced with diminishing water supplies. If irrigated agriculture is to survive in this competitive environment, we must use irrigation water efficiently and more cost-effectively. The goal of the work described here was to develop an interactive ET-based irrigation scheduling tool for cotton which operates on a smartphone platform. The model uses meteorological data to calculate FAO 56 evapotranspiration (ETo) and a phenology-based crop coefficient (Kc) to estimate crop evapotranspiration (ETc). The model uses ETc, precipitation from the meteorological data, and irrigation events to estimate a daily plant-available soil water balance within the crop's root zone. The model reports a daily root zone plant-available soil water deficit in terms of inches of water and percent of total. We converted the model into an interactive smartphone application (app) for iOS and Android operating systems. The Cotton App provides notifications to the user when actions such as irrigation are needed. For example, the Cotton App sends the user a notification when the root zone plant available soil water deficit exceeds 50% indicating that irrigation is recommended. We calibrated and validated our model during 2012 and 2013 using data from replicated plot experiments and commercial fields. Both were instrumented with soil moisture sensors which continuously monitored soil water tension.

Introduction

One of the most important crops in the USA is cotton. It is grown in 17 US states from Virginia to California with the annual production acreage ranging from 5.1 to 6.3 million ha. Cotton is an intensively managed crop which requires careful nitrogen applications to prevent rank growth, plant growth regulators (PGRs) to maintain a balance between vegetative and reproductive growth, defoliants at the end of the season to allow for mechanized harvesting, insecticides for pest management, and varying amounts of water during its phenological stages to maximize yield (Vellidis et al. 2009; 2010). Approximately 40% of U.S cotton is currently produced under irrigated conditions. Because irrigation water is becoming limited in many cotton growing areas such as the Texas high plains, Arizona, and California, and competition for water is increasing rapidly in areas normally associated with plentiful water resources, many cotton producers and the organizations representing cotton producers are interested in irrigation scheduling strategies which improve water use efficiency. Included in these strategies are deficit irrigation methods. As a result, a significant amount of research has recently been conducted on this topic.

Researchers quickly understood that cotton's water needs are a function of phenological stage (Figure 1). For example, McGuckin et al. (1987) optimized irrigation scheduling using accumulated heat units and not a chronological frame. Researchers also realized that evapotranspiration (ET) is also an important factor in estimating daily plant water use. Several irrigation scheduling tools have been developed which use estimated crop ET (ETc)

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to develop irrigation recommendations. These models typically use a crop coefficient (Kc) to calculate ETc from a reference ET (ETo) as shown in equation 1. Crop coefficients will be discussed in detail below.

$$ET_c = ETo \times Kc \tag{1}$$

Although models which use only ETc to estimate irrigation requirements have been used extensively because they are simple, they do not consider the moisture available in the soil profile and do not calculate a soil water balance. This sometimes leads to over-application of irrigation water. Incorporating soil water balance increases the number of parameters needed as well as the complexity of the model. Dejonge et al. (2012) used ET along with other meteorological, soil, crop management activities, and the crops phenological stage to simulate environmental stresses, soil water balance, crop growth and yield in a dynamic agroecosystem model. The SiSPAT model (Braud et al.2013) was created to estimate irrigation needs in southern France. The model estimates the heat and water transfer in the soil while taking into account the water vapor transfer, the soil heterogeneity, the root size, the interception of rainfall by the vegetation and climatic variables such as solar and wave radiation, air temperature and humidity, wind speed and rainfall. Five-Core (Chopart et al. 2007), an irrigation scheduling model for sugarcane, is another model which computes daily water balance. It used as inputs rainfall, temperature, ETo, crop coefficients and farmers practices. AquaCrop (Steduto et al. 2009) is a more complex model. It requires soil and meteorological data in order to estimate crop development and soil water balance. By simulating the incoming and outgoing water in the soil, it estimates water stored in the root zone. Root zone depletion determines the magnitude of a set of water stress coefficients influencing green canopy expansion, stomatal conductance, root system deepening rate and canopy senescence. The Cropping System Model (CSM)-CROPGRO-Cotton is part of the suite of crop simulation models that encompass DSSAT – the Decision Support System for Agrotechnology Transfer (Jones et al., 2003; Hoogenboom et al., 2004). The model simulates growth, development, and yield of cotton for different weather and soil conditions and management practices. Guerra et al. (2007) used the model to develop irrigation use estimates for farming regions. The required inputs were weather variables such as solar radiation, maximum and minimum air temperature, and total rainfall, crop and soil parameters and management practices. The most interesting point at this model was the estimation of the daily changes in water content at different soil layers due to infiltration of rainfall and irrigation, vertical drainage, soil evaporation, and root water uptake. The available water content was calculated based on the difference of soil water holding capacity and permanent wilting point while an irrigation event was triggered when the soil water content was below the available water content. The amount of water used was equal with the amount needed to refill the profile up to the available water content. But because of the large number of variables used, this model is difficult to parameterize.

The crop simulation models described in the previous paragraph are excellent research tools but are not suited for use by crop consultants, farmers, or other professionals making daily irrigation decisions. Consultants and farmers desire sophisticated yet easy-to-use tools. Recent technological advances that allow for widespread internet access through handheld devices such as smartphones and tablets provide an exciting platform on which to deploy

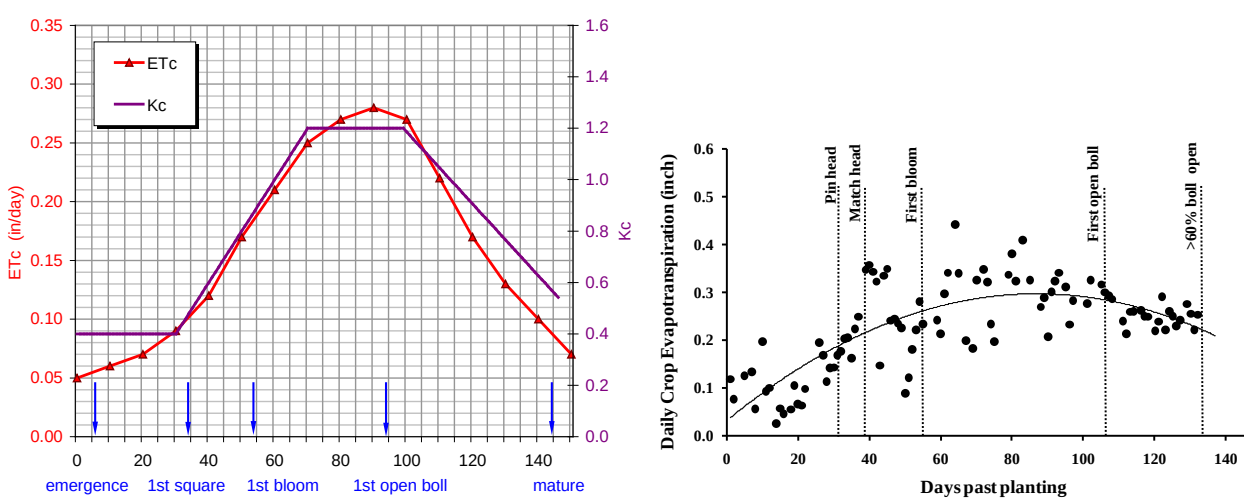

Figure 1. Water use and crop coefficient function for cotton in Stoneville, Mississippi (left) and measured crop water use (ETc) from a cotton field in Louisiana over the growing season (left) (Perry and Barnes, 2012).

sophisticated yet easy-to-use irrigation scheduling tools. Smartphone tools, typically referred to as smartphone applications or apps, are being developed at exponential rates for every imaginable use. Agricultural researchers and extension specialists are also entering the fray and offering apps for a variety of uses ranging from pest identification to irrigation scheduling recommendations. Migliaccio et al. (2013) described a suite of smartphone apps for scheduling irrigation including apps for citrus, strawberries urban turf, and cotton. The citrus, strawberry and urban turf apps were released in 2013 (www.smartirrigationapps.org). This paper describes the Cotton App and the model behind the app in detail. The Cotton App was released in 2014.

Materials and Methods

The Cotton App model is an interactive ET-based soil water balance model. It uses meteorological data, soil parameters, crop phenology, crop coefficients, and irrigation applications to estimate root zone soil water deficits in terms of inches of water and percent of total. The app provides these two pieces of information to the user. The model does not deliver irrigation application recommendations. However, the user can utilize the root zone soil water deficit information to make appropriate irrigation decisions.

ET and Kc

The model uses meteorological data to calculate reference ET (ETo) using the Penman–Monteith equation (Allen et al. 1998). This method, also known as FAO 56, is commonly accepted for irrigation scheduling. The model's daily ETo is a 5-day running average of calculated ETo. The model then uses a crop coefficient (Kc) to estimate crop ET (ETc) as shown in equation 1. The crop coefficient (Kc) is widely used to estimate crop water use and to schedule irrigation. The concept was introduced by Jensen (1968) and further developed by the other researchers (Doorenbos and Pruitt 1975, 1977; Burman et al. 1980a, b; Allen et al. 1998). Kc changes during the life cycle of the plant. For annual crops, it typically begins with small values after emergence and increases to 1.0 or above when the crop has the greatest water demand. Kc decreases as crops reach maturity and begin to senesce. Figure 1 presents measured water use and crop coefficient functions for cotton in Mississippi and Louisiana (Perry and Barnes, 2012). We used information from these and other studies to develop a prototype Kc curve for southern Georgia and northern Florida conditions. The curve was calibrated and validated with a series of plot and field studies in 2012 and 2013. Details of the calibration and validation effort are provided below. In the model, changes in Kc are driven by accumulated heat units commonly referred to as growing degree days (GDDs) as shown in Figure 2. GDDs are calculated using equation 2.

$$GDD = \frac{T_{max}+T_{min}}{2} - T_{base} \tag{2}$$

For cotton, T_{base} is 60°F. Any temperature below T_{base} is set to T_{base} before calculating the average. Table 1 presents GDDs used to trigger Kc changes in the model and the corresponding phenological stages. GDDs required for phenological stages are derived from Ritchie et al. (2004).

Soil Water Balance

ETc is used by the model to estimate daily crop water use. ETc, measured precipitation and irrigation are then used to estimate the plant available soil water as shown in Figure 3. Plant available soil water is a function of the soils plant water holding capacity which is determined from USDA-NRCS soils data and current rooting depth. As the plants rooting system grows, the depth of the profile from which the plant can extract water also increases. In the model, the initial rooting zone depth is 6in and increases by 0.3in/day until it reaches a maximum depth of 30in. At emergence, the soil profile from 0 to 30in is assumed to be at 90% of maximum plant available soil water holding capacity. Today's plant available soil water is calculated by subtracting yesterday's ETc from yesterday's plant available soil water and adding any precipitation or irrigation measured. The model uses an effectiveness factor of 85% for all sprinkler irrigation events to account for evaporation and drift before the water droplets reach the soil. The model assumes that 90% of measured precipitation reaches the soil to account for canopy interception and other possible losses. All these parameters are used to calculate root zone soil water deficit (RZSWD) in inches and % RZSWD (Figure 3).

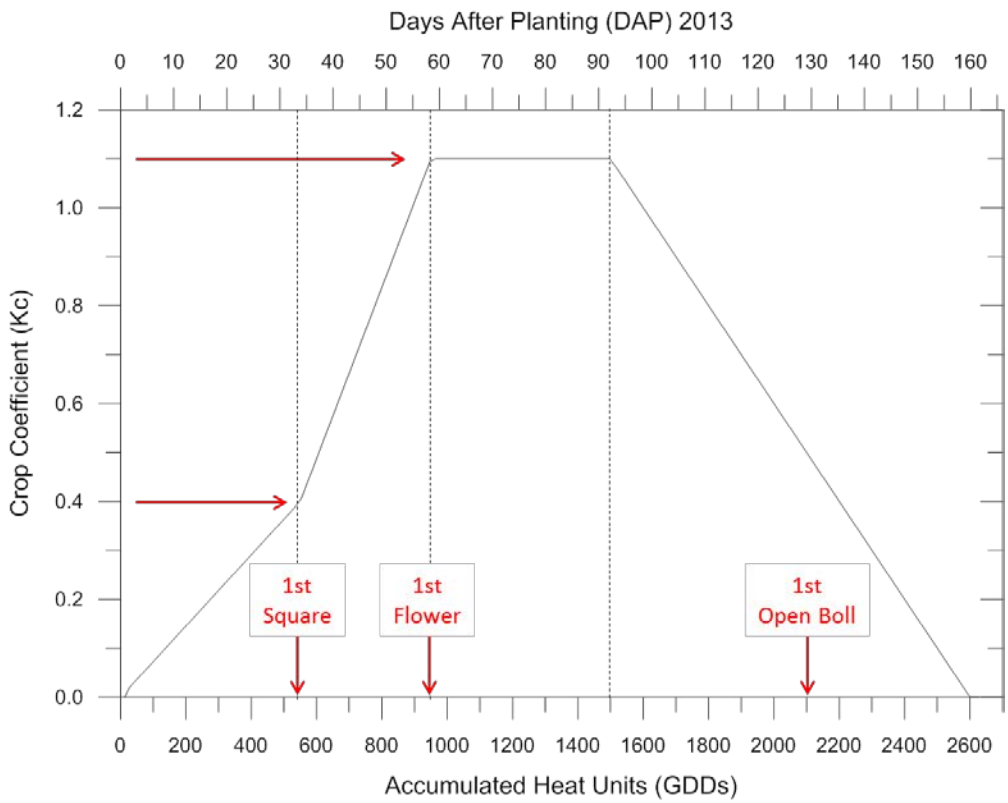

Figure 2. Kc curve used in the model. Maximum Kc is 1.1 which is maintained between 950 and 1500 GDDs. A major inflection point and Kc rate change occurs at 550 GDDs.

DATE	DAP	Crop Coefficient based on GDD (Kc)	ETo (from GAEMN) (in/day)	ETo 5-Day Moving Avg (in/day)	ETc (Kc*ETo avg) (in/day)	Rooting Depth (in)	Available Soil Water (in)	Irrigation Applied (in)	Effective Irrigation (in)	Rain (in)	Effective Rain (in)	Irrigation + Rain (in)	Root Zone Water Defecit (in)	Root Zone Water Defecit (%) (Keep Under 50% to Avoid Stress)
12-Jun-13	27	0.34	0.23	0.17	0.06	14.10	1.55	-	-	-	-	-	0.05	3%
13-Jun-13	28	0.36	0.24	0.18	0.06	14.40	1.58	-	-	-	-	-	0.11	7%
14-Jun-13	29	0.37	0.21	0.20	0.08	14.70	1.62	-	-	-	-	-	0.17	11%
15-Jun-13	30	0.39	0.24	0.23	0.09	15.00	1.65	-	-	-	-	-	0.25	15%
16-Jun-13	31	0.40	0.22	0.23	0.09	15.30	1.68	-	-	-	-	-	0.34	20%
17-Jun-13	32	0.43	0.22	0.23	0.10	15.60	1.72	-	-	-	-	-	0.43	25%
18-Jun-13	33	0.46	0.22	0.22	0.10	15.90	1.75	-	-	-	-	-	0.53	30%
19-Jun-13	34	0.48	0.17	0.22	0.10	16.20	1.78	-	-	-	-	-	0.63	35%
20-Jun-13	35	0.50	0.19	0.21	0.10	16.50	1.82	-	-	-	-	-	0.74	41%
21-Jun-13	36	0.53	0.24	0.21	0.11	16.80	1.85	-	-	-	-	-	0.84	45%
22-Jun-13	37	0.55	0.18	0.20	0.11	17.10	1.88	-	-	-	-	-	0.95	51%
23-Jun-13	38	0.57	0.15	0.18	0.11	17.40	1.91	0.75	0.64	-	-	0.64	1.06	55%
24-Jun-13	39	0.59	0.14	0.18	0.10	17.70	1.95	-	-	-	-	-	0.53	27%
25-Jun-13	40	0.61	0.23	0.19	0.11	18.00	1.98	-	-	-	-	-	0.63	32%
26-Jun-13	41	0.64	0.24	0.19	0.12	18.30	2.01	-	-	-	-	-	0.75	37%
27-Jun-13	42	0.66	0.14	0.18	0.12	18.60	2.05	-	-	0.20	0.18	0.18	0.87	42%
28-Jun-13	43	0.68	0.10	0.17	0.12	18.90	2.08	-	-	1.37	1.23	1.23	0.80	39%
29-Jun-13	44	0.71	0.14	0.17	0.12	19.20	2.11	-	-	0.12	0.11	0.11	0.00	0%
30-Jun-13	45	0.72	0.09	0.14	0.10	19.50	2.15	-	-	1.76	1.59	1.59	0.01	1%

Figure 3. Snapshot of a spreadsheet segment showing several of the model's parameters. Kc is increasing linearly with GDDs. ETo is calculated from the meteorological parameters retrieved from GAEMN. ETc is calculated by multiplying the 5-day moving average of ETo by Kc. Rooting depth is increasing at a rate of 0.3in/day. Root Zone Soil Water Deficit (RZSWD) is increasing steadily until an irrigation event was applied on 23 June when %RZSWD exceeded 50%.

Model Calibration and Validation

We used replicated field plots to calibrate the model and producer fields to validate the model. During 2012 and 2013 year we used 4 large plots at the University of Georgia's Stripling Irrigation Research Park (SIRP) and 5 producer fields located in southwestern Georgia. Both the plots and fields were instrumented with the University of Georgia Smart Sensor Array (UGA SSA). The UGA SSA is a fully wireless soil moisture sensing system which measures soil water tension at 8, 16, and 24in using Watermark™ sensors (Vellidis et al., 2013). We used the soil water tension data from the plots in 2012 and 2013 to retroactively adjust the model's Kc curve so that 50% RZSWD coincided with a weighted root zone average soil water tension of approximately 40kPa. Our experience with irrigation scheduling indicates that 40kPa is a good irrigation threshold for cotton. In 2013, we used the model adjustments made following the 2012 growing season to schedule irrigation in the plots. Two of the plots were in conservation tillage and two were in conventional tillage. The model does not currently account for tillage systems so all plots were irrigated the same way.

Each of the producer fields were instrumented with up to 10 nodes of the UGA SSA so we had available soil water tension data from 50 or more individual locations each year. Because of the large soil variability in these fields, soil water tension data within fields was also quite variable. We did not manage irrigation scheduling in these fields. The individual producers managed irrigation using information from the UGA SSA but producers did not always adhere to the 40kPa threshold. Our validation process consisted of applying the model to each of these 100 locations (50 locations per year × 2 years) using local precipitation and irrigation depths as recorded by an onsite tipping bucket rain gage connected to a Hobo™ data logger and observing the pattern of the RZSWD. Our benchmark was for 50% RZSWD to coincide with a weighted root zone average soil water tension of approximately 40kPa.

Smartphone App Development

Our design principles for the Cotton App were that it should provide the most accurate, site-specific, real-time information we could offer the user. In addition, the App would require minimum user input which, when necessary, we would solicit from the user by sending notifications. It would not be necessary for the user to check the App regularly. Finally the App would provide ready-to-use output and be engaging.

Meteorological data, and especially accurate precipitation data, are critical to the Cotton App. In its current version, the Cotton App pulls meteorological data from the Georgia Automated Environmental Monitoring Network (GAEMN) and the Florida Automated Weather Network (FAWN). GAEMN maintains 83 automated meteorological stations while FAWN maintains 35 stations thus limiting the Cotton App's footprint to these two states. We are however evaluating the National Weather Service's 4km grid data as a possible alternative source of information which would greatly increase the Cotton App's footprint.

The Cotton App recommends irrigation whenever RZSWD exceeds 50%. Notifications are pushed to the user when the 50% threshold is exceeded. The user is notified that an irrigation event was added. The user is required to "add" the irrigation event to the App. The App then credits the default irrigation amount (entered by the user during setup). If the user irrigated a different amount than the default value, the user can easily change the irrigation value.

The Cotton App, as well as the companion Citrus, Strawberry, and Urban Turf apps, were designed to operate on the iOS and Android platforms and are available through the Apple and Google stores. Links to the stores are provided at the project website – www.smartirrigationapps.org.

Results and Discussion

Figure 4 presents the calibration results from the two conservation tillage plots at SIRP for 2013. The solid black line in both graphs indicates % RZSWD. The colored line associated with the lower x-axis shows a weighted average of soil water tension at 8in (50%), 16in (30%), and 24in (20%). It is clear that the patterns of % RZSWD and soil water tension are similar although the 50% RZSWD threshold does not always match well with the 40kPa irrigation threshold. Table 1 presents the yield results from the SIRP in 2013. The year was unusually wet and consequently not the best year for irrigation scheduling research. Nevertheless, the results indicate that scheduling irrigation with the app resulted in good yields and significantly less irrigation water use than the standard checkbook method recommended by the University of Georgia Extension Service. The checkbook method schedules irrigation by replacing the maximum expected weekly crop water use minus measured precipitation and is thus a very conservative scheduling tool. Figure 5 presents validation results from two different locations within one field in

Table 1. Yield and water use results from irrigation scheduling experiment at the Stripling Irrigation Research Park during 2013. Variety = DP 1252 B2RF, Planting Date = 16 May 2013, Harvest Date = 15 Nov 2013, Rainfall = 27.4 inch

Method	Conservation Tillage		Conventional Tillage	
	Lint Yield (lb/ac)	Water Use (in)	Lint Yield (lb/ac)	Water Use (in)
Checkbook	1350	12.7	1150	12.2
Cotton App	1485	3.0	1259	3.0
Crop Water Stress Index	1430	5.0	1305	2.3
Irrigator Pro	1455	2.8	1200	4.3
Rainfed	1450	1.5	-	-

2012 and 2013. The results from 2013 show that the model performance is greatly improved compared to 2012.

The Cotton App

Upon first use of the Cotton App, the user is required to create a new field. Information about the field is stored on the project's server so that it is not lost if the user's smartphone is damaged or replaced. The location of the field can be logged by either entering geographical coordinates or by allowing the smartphone's embedded GPS to log the current location. The Cotton App then automatically locates the closest GAEMN or FAWN meteorological stations and allows the user to select which station will be the field's home station. Additional model variables entered at this time include soil type (the user must choose from sand, sandy loam, loam, silt loam, clay loam, or clay), irrigation system type, and default irrigation depth (in), and planting date. The Cotton App interacts with the user through notifications and direct data input when necessary. These interactions are best illustrated with Figures 6-8 which present a series of snapshots from the Cotton App. Captions beneath the figures describe the content of the snapshots and describe how the user would use the information displayed.

The Cotton App was released March, 2014. During the 2014 growing season, we will beta-test the Cotton App with cotton producers in southern Georgia and northern Florida. We are encouraging county agents to familiarize themselves with the Cotton App while using it in conjunction with cotton producers. We will be extending the footprint of the Cotton App by incorporating automated weather networks in Alabama and South Carolina and developing region specific Kc curves for cotton. In the future, when a user initiates the Cotton App and selects the location of the field, the Cotton App will automatically select a region-specific Kc curve in addition to the closest meteorological stations. Longer range plans include incorporating the National Weather Service's 4km grid data as a possible alternative source of meteorological data which would increase the App's footprint. Meteorological station-driven precipitation is the Cotton App's weakest feature as summer precipitation in the southeastern USA is driven by highly variable convective thunderstorms. As a result, in-field precipitation amounts can be significantly different from those recorded at the nearest meteorological station on any given day. For the Cotton App to be used *most effectively* and to produce the most accurate results, users must record in-field precipitation until other options become available. We will also be incorporating drought strategies into the Cotton App.

Summary

The goal of the work described here was to develop an interactive ET-based irrigation scheduling tool for cotton which operates on a smartphone platform. The model uses meteorological data to calculate FAO 56 evapotranspiration (ETo), a phenology-based crop coefficient (kc) to estimate crop evapotranspiration (ETc). The model uses ETc, precipitation from the meteorological data, and irrigation events to estimate a daily plant-available soil water balance within the crop's root zone. The model reports a daily root zone plant-available soil water deficit in terms of inches of water and percent of total. We converted the model into an interactive smartphone application (app) for iOS and Android operating systems. The Cotton App provides notifications to the user when actions such as irrigation are needed. For example, the Cotton App sends the user a notification when the root zone plant available soil water deficit exceeds 50% indicating that irrigation is recommended. We evaluated the model during 2012 and 2013 in replicated plot experiments and in commercial fields. The model predictions matched the observed soil moisture curves reasonably well. The Cotton App was released March, 2014.

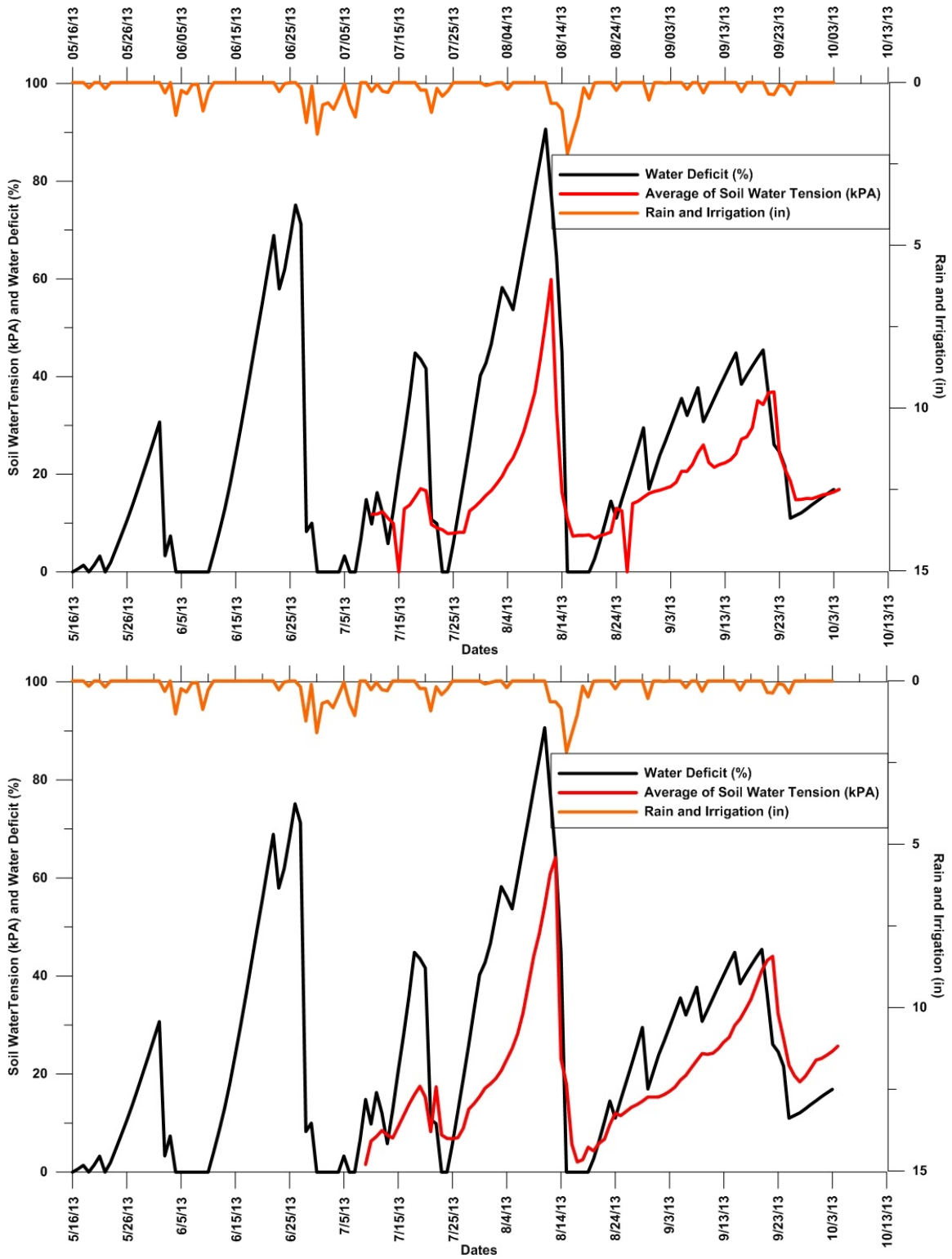

Figure 4. Comparison of weighted soil water tension and percent Root Zone Soil Water Deficit (% RZSWD) in the two conservation tillage plots at Stripling Irrigation Research Park during 2013. The plots were irrigated using the Cotton App as modified after the 2012 growing season. The % RZSWD curve shown here reflects changes in the Kc and rooting depth to better calibrate the model made after the 2013 growing season. The soil water tension curves are the average of soil water tension at 8in (50%), 16in (30%), and 24in (20%).

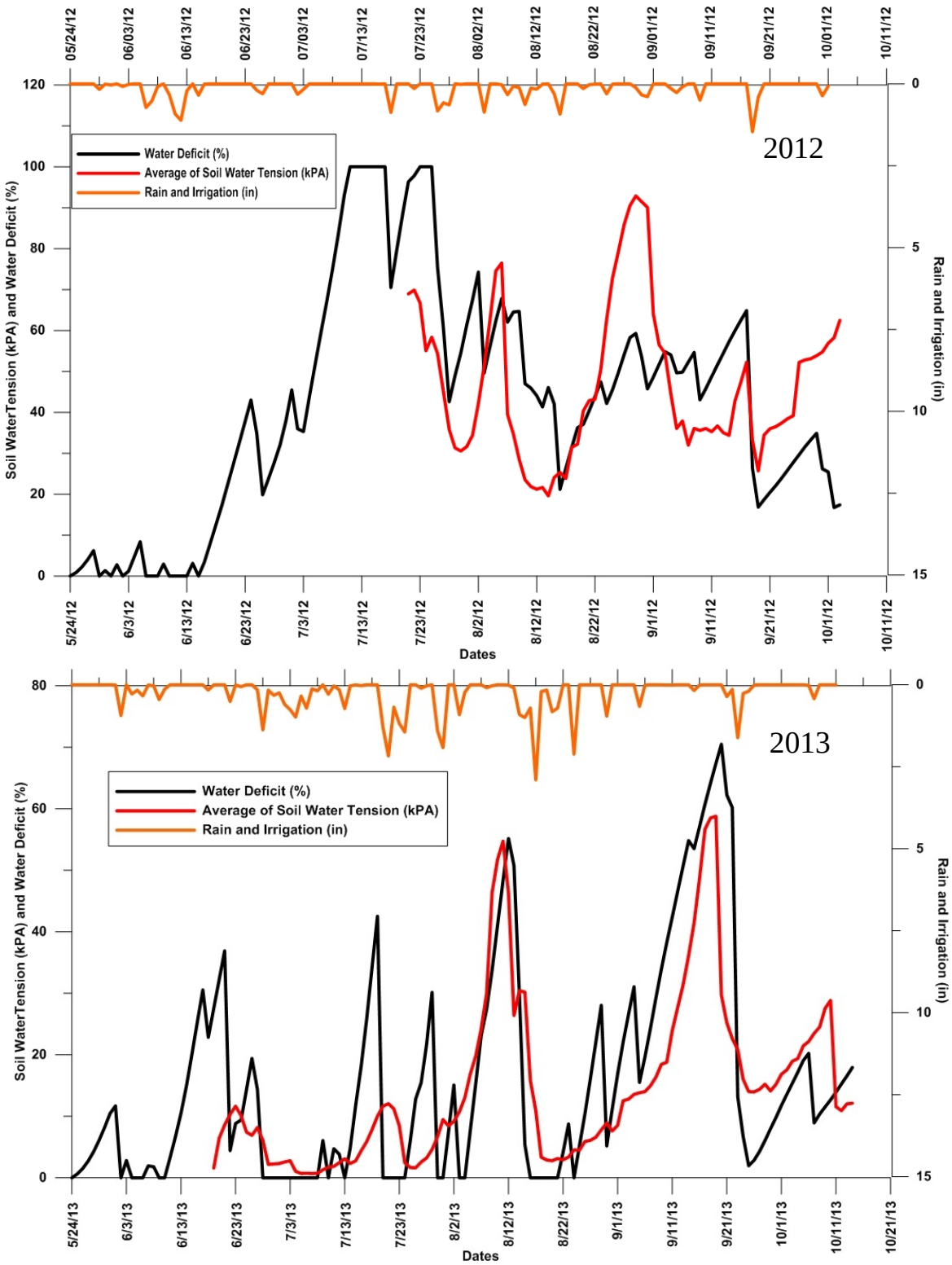

Figure 5. Validation of percent Root Zone Soil Water Deficit (% RZSWD) versus weighted soil water tension in in the same location of a producer's cotton field in 2012 (top) and 2013 (bottom). Irrigation was **not** scheduled using the Cotton App. The % RZSWD curve shown here reflects calibrations made to the model after the 2013 growing season. The soil water tension curves are the average of soil water tension at 8in (50%), 16in (30%), and 24in (20%).

Acknowledgements

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Figure 6. Screenshots of an iPhone showing the icons for the SmartIrrigation Strawberry, Citrus, Urban Turf, and Cotton Apps (left); Cotton App new field screen showing the user input information required to establish the field (center); and Cotton App meteorological station and soil type selection screen (right).

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Figure 7. Screenshots of an iPhone showing the most commonly used user-interface screen of the Cotton App (left and center). On each of these screenshots, the user can view information about the soil water balance, the condition of the Root Zone Soil Water Deficit (RZSWD), whether precipitation was recorded or irrigation was applied within the past day, as well as the phenological stage of the crop. Any of this information can be edited by tapping on the "See details" button. If irrigation events were not recorded properly, the can be changed by tapping on the "Add irrigation" or "Remove irrigation" buttons. The screenshot on the right shows a notification that the RZSWD has exceeded 50% and that irrigation is recommended.

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Figure 8. Screenshots of an iPhone showing a notification that a phenological stage change is approaching (left). The Cotton App allows the user to adjust both the accumulated GDDs and the phenological stage of the crop (center). In addition, almost all model parameters can be adjusted although the most commonly adjusted parameters are “Irrigation Applied” and “Rain Observed”.

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