A Smartphone Application for Scheduling Irrigation in Cotton

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Abstract. *The goal of this work was to develop an easy-to-use and engaging irrigation scheduling tool for cotton which operates on a smartphone platform. The Cotton SmartIrrigation App (Cotton App) uses an interactive ET-based soil water balance model. The Cotton App uses meteorological data from weather station networks, soil parameters, crop phenology, crop coefficients, and irrigation applications to estimate root zone soil water deficits (RZSWD) in terms of percent as well as of inches of water. The Cotton App sends notifications to the user when the RZSWD exceeds 40%, when phenological changes occur, and when rain is recorded at the nearest weather station. It operates on both iOS and Android operating systems and was released during March 2014. The Cotton App was evaluated in field trials for three years and performed well when compared to other irrigation scheduling tools. Its geographical footprint is currently limited to the states of Georgia and Florida, United States, because it uses meteorological data only from weather station networks in these states. A new version which will be released in 2017 uses national gridded meteorological data sets and will allow the Cotton App to be used in most cotton growing areas of the United States.*

Keywords: Smartphone, Irrigation, Cotton, Crop coefficient, Evapotranspiration, Phenology

Introduction

Cotton (*Gossypium hirsutum* L.) is the most important fiber crop in the world and one of the most important agronomic crops in the United States where in 2014 it had a production value in excess of USD 5 billion. In the United States, the cotton crop under irrigation has increased steadily over the past two decades because irrigation serves both to reduce risk of crop loss but also to build resiliency and yield stability. Approximately 40% of U.S. cotton is currently irrigated but 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. As a result, the organizations representing growers are investing in the development of irrigation scheduling tools which improve irrigation water use efficiency. In response, a significant amount of research has been conducted on this topic.

Cotton's water needs are a function of phenological stage (Fig. 1). Evapotranspiration (ET) is also an important factor in estimating cotton's daily water use and several cotton irrigation scheduling tools have been developed which use estimated crop ET (ETc) to develop irrigation recommendations. These models typically use a crop coefficient (Kc) which represents the crops phonological stage to calculate ETc from a reference ET (ETo) as shown in equation 1 (Jensen , 1968; Doorenbos and Pruitt 1975, 1977; Burman et al. 1980a, b; Allen et al. 1998).

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

Models which use only ETc to estimate irrigation requirements are simple and easy-to-use but they do not consider moisture available in the soil profile which sometimes leads to over-application of irrigation water. Incorporating soil water balance increases accuracy but also increases the number of parameters needed as well as the complexity of the model.

Recent technological advances that allow for widespread internet access through handheld devices such as tablets and smartphones provide a novel platform on which to deliver sophisticated yet easy-to-use ET-based irrigation scheduling tools. Smartphone tools, typically referred to as smartphone applications or apps, are being developed at exponential rates for every imaginable use. The functionality of an app differs from a web tool in that apps are with the user at all times since they reside on the smartphone, are readily accessible, and engage the user through notifications (Migliaccio et al., 2015; 2016). Some apps use notifications, similar to text messages, to prompt users to respond to critical events and eliminate the need to interact with the tool on a daily basis. Migliaccio et al. (2016) presented a suite of SmartIrrigation

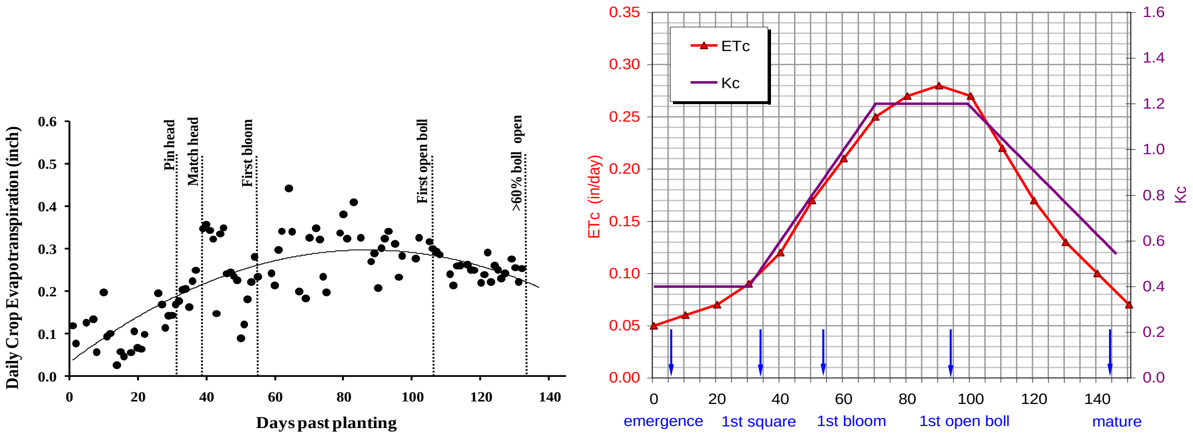


Figure 1. Measured crop water use (ETc) from a cotton field in Louisiana over the growing season (left) and water use and crop coefficient curve for cotton in Stoneville, Mississippi (right) (Perry and Barnes, 2012).

apps which were recently released to provide real-time irrigation schedules for avocado, citrus, cotton, soybean, strawberry, blueberries, turf, and vegetables. Information about and links to download these apps can be found at www.smartirrigationapps.org. This paper describes the Cotton SmartIrrigation App (hereafter referred to as the Cotton App) which was released in 2014. Our objectives were to develop a novel ET-based irrigation scheduling tool for cotton that requires minimal user interaction, is delivered to the user on a smartphone platform, and outperforms many other irrigation scheduling tools.

Materials and Methods

The model which drives the Cotton App 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 (RZSWD) in terms of percent and inches of water and provides these two pieces of information to the user. The model does not deliver direct irrigation application recommendations. However, the user may utilize the RZSWD information to make appropriate irrigation decisions.

ET and Kc

The model uses meteorological data to calculate ETo using the Penman–Monteith equation (Allen et al. 1998). This method, also known as FAO 56, is widely accepted for irrigation scheduling. The model then uses Kc to estimate ETc as shown in equation 1. For annual crops, Kc changes with phenological stage. Kc 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. We used information from published studies (Perry and Barnes, 2012) 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 by Vellidis et al. (2016b). In the model, changes in phenology and associated changes in Kc are driven by accumulated heat units commonly referred to as growing degree days (GDDs). 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. Figure 2 presents the relationship between GDDs and Kc, and the corresponding phenological stages as used in the model. GDDs required for phenological stages are derived from Ritchie et al. (2004).

Soil Water Balance Model

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. Plant available soil water is a function of the soil's plant available water holding capacity and current rooting depth. The model allows users to select from one of seven generic soils shown in Table 1. As the plant 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 0.15 m (6 in) and increases by 7.5 mm day^{-1} (0.3 in day^{-1}) until it reaches a maximum depth of 0.75 m (30 in). At emergence, the soil profile from 0 to 0.75 m is assumed to be at 85% 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 allows for three types of irrigation – high pressure overhead sprinkler, low-pressure overhead sprinkler, and subsurface drip. It

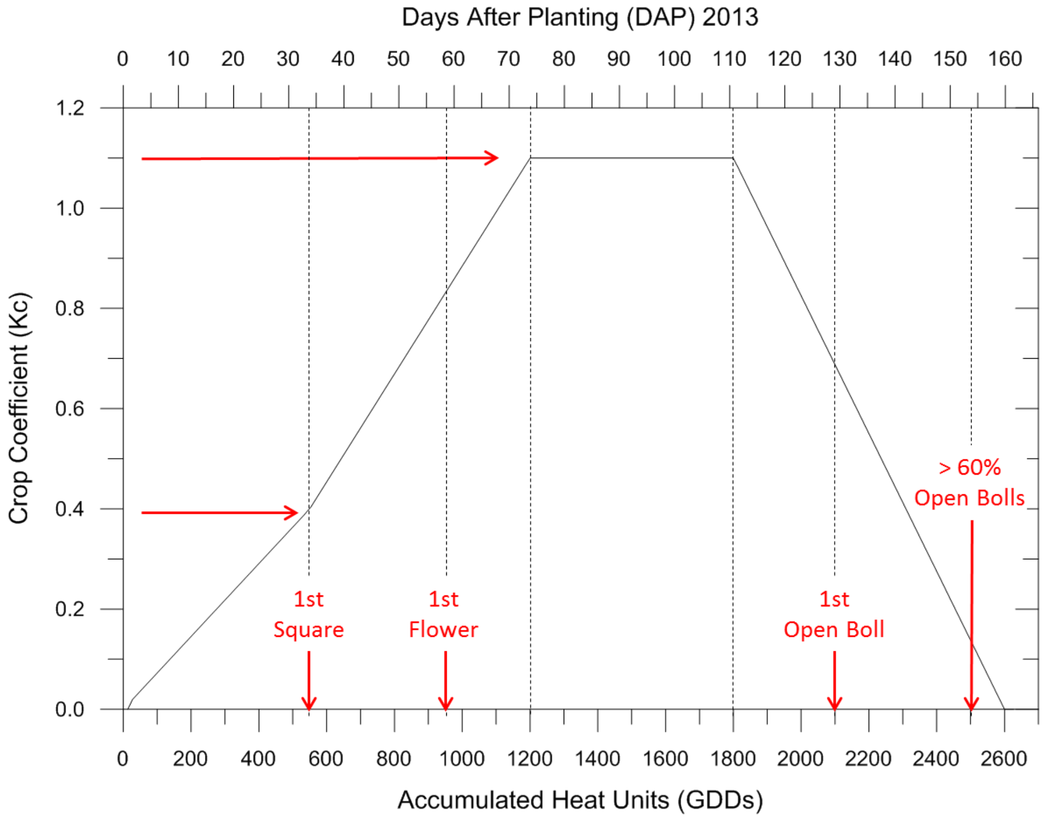


Figure 2. Kc curve used in the model. Maximum Kc is 1.1 which is maintained between 1200 and 1800 GDDs. An inflection point and Kc rate change occurs at 550 GDDs. The top axis indicates how DAP coincided with GDDs in 2013.

uses an efficiency factor of 75% for high pressure sprinkler and 85% for low pressure sprinkler to account for evaporation and drift before the water droplets reach the soil and a 90% efficiency factor for subsurface drip irrigation. The model also assumes that 90% of measured precipitation reaches the soil to account for canopy interception and other losses. A maximum of 25 mm (1 in) and a minimum of 5 mm (0.2 in) in daily precipitation is used in soil water balance calculations. The maximum is used because even if the RZSWD is greater than 25 mm, it is unlikely that more than that amount will infiltrate into the soil profile during a 24 hr period. The minimum is used because less than 5 mm of precipitation in a 24 hr period does not have an appreciable effect on soil moisture. All these parameters are used to calculate root zone soil water deficit (RZSWD) in inches and % RZSWD.

Table 1. Plant available water capacity (AWC), field capacity (FC), and wilting point (WP) of the seven generic soil types used in the Cotton App.

Soil type	AWC (cm^3 cm^{-3})	FC (cm^3 cm^{-3})	WP (cm^3 cm^{-3})
Sand	0.05	0.10	0.05
Loamy sand	0.06	0.12	0.06
Sandy loam	0.10	0.18	0.08
Loam	0.14	0.28	0.14
Silt loam	0.20	0.31	0.11
Clay loam	0.14	0.36	0.22
Clay	0.12	0.42	0.30

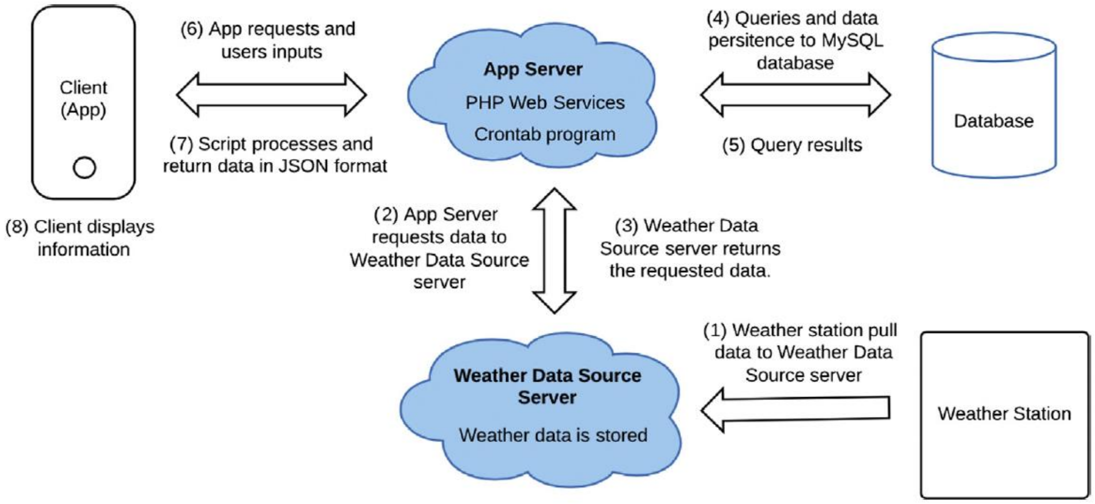


Figure 3. Diagram of interaction among client, server and weather stations (Migliaccio et al., 2015).

Model Calibration and Validation

During 2012 and 2013 we used large plots at the University of Georgia's Stripling Irrigation Research Park (SIRP) located near Camilla, GA to calibrate the model and in 2013 we used five producer fields located in southwestern Georgia to validate the model. In 2013, we used the model adjustments made following the 2012 growing season to schedule irrigation in the plots.

Meteorological Data

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) (http://weather.uga.edu) and the Florida Automated Weather Network (FAWN) (http://fawn.ifas.ufl.edu) thus currently limiting the Cotton App's footprint to these two states.

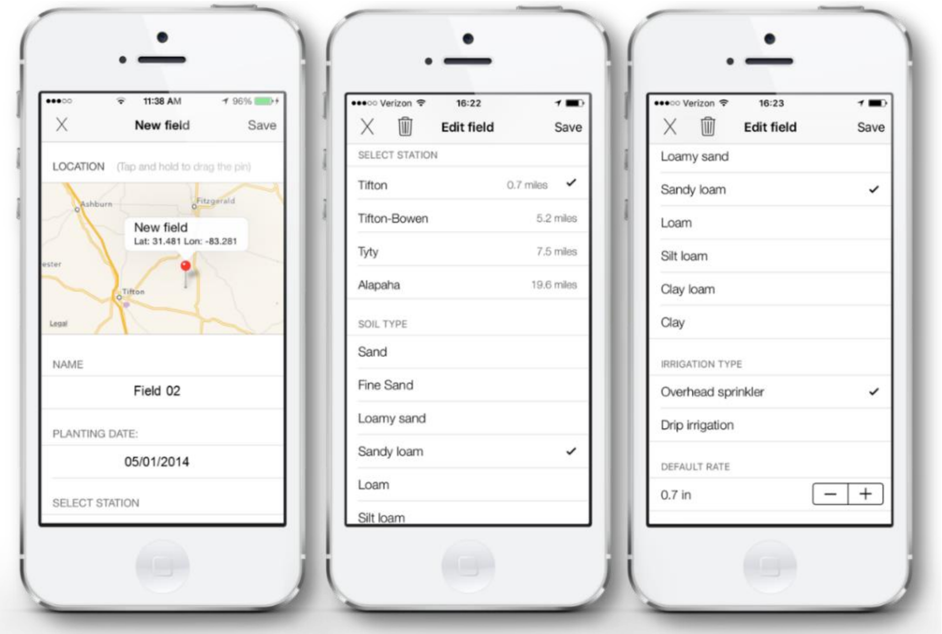
Smartphone App Development

Figure 3 presents the flow of information between the Cotton App, server, and automated weather station networks. 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 Cotton App would require minimum user input which, when necessary, it would solicit from the user by sending notifications. It would not be necessary for the user to check the Cotton App regularly. Finally the Cotton App would provide ready-to-use output and be engaging.

User Interaction

After initial setup, the user is directed to the field setup screen. A user may register multiple fields but only one at a time. Field registration begins with the field location. By default, the Cotton App pins the field on a map at the smartphone's location but the user may reposition the pin by dragging it to the desired location (Fig. 4). Accurately locating the field's position is important because it is used to locate the weather stations nearest to the field. The user then enters a unique field name and planting date. The Cotton App automatically selects the closest weather station but also displays the next four closest weather stations and the user has the option to select any of those. Finally, the user selects soil type from the options presented in Table 1, irrigation system type, and the default irrigation rate. The default irrigation rate is the amount of irrigation the user typically applies during an irrigation event.

The main user interface screen (Fig. 5) is field-specific but the user can move between fields by swiping the screen from left to right or right to left. The circles at the top of the screen indicate the number of



LOCATION (Tap and hold to drag the pin)

New field
Lat: 31.481 Lon: -83.281

NAME
Field 02

PLANTING DATE:
05/01/2014

SELECT STATION

SELECT STATION
Tifton 0.7 miles ✓
Tifton-Bowen 5.2 miles
Tyty 7.5 miles
Alapaha 19.6 miles

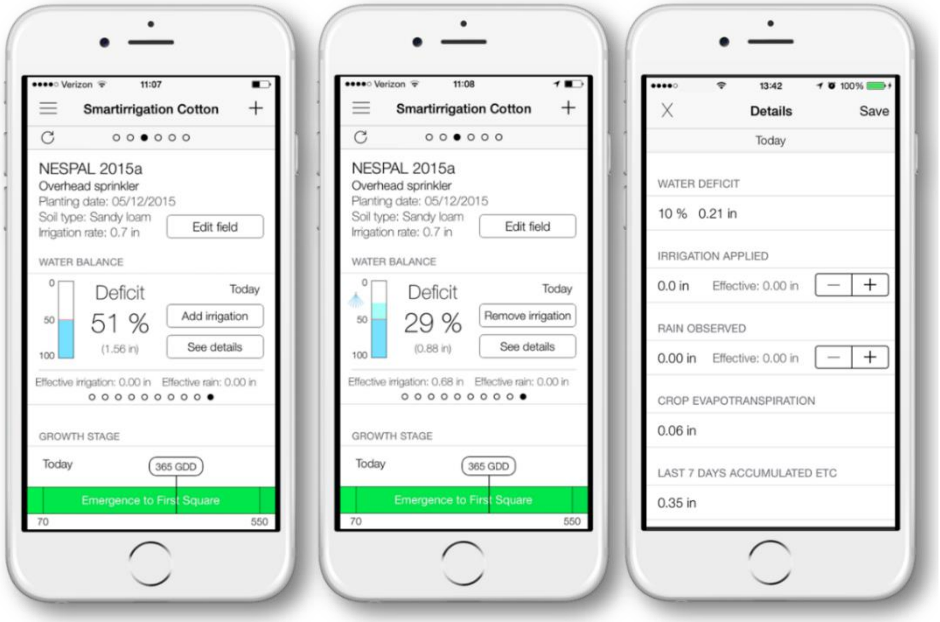
SOIL TYPE
Sand
Fine Sand
Loamy sand
Sandy loam ✓
Loam
Silt loam

Loamy sand
Sandy loam ✓
Loam
Silt loam
Clay loam
Clay

IRRIGATION TYPE
Overhead sprinkler ✓
Drip irrigation

DEFAULT RATE
0.7 in − +

Figure 4. Screenshots of an iPhone running the Cotton App with the new field setup screens. The Cotton App pins the field on a map at the smartphone's location but the user may reposition the field by dragging the pin (left). The Cotton App automatically selects the closest weather station (center) but also displays the next four closest weather stations and the user has the option to select any of those. The user then selects soil type (center), and irrigation system type and default irrigation rate (right).



NESPAL 2015a
Overhead sprinkler
Planting date: 05/12/2015
Soil type: Sandy loam
Irrigation rate: 0.7 in

WATER BALANCE
0
50
100
Deficit Today
51 %
(1.56 in)
Effective irrigation: 0.00 in Effective rain: 0.00 in

GROWTH STAGE
Today 365 GDD
Emergence to First Square
70 550

NESPAL 2015a
Overhead sprinkler
Planting date: 05/12/2015
Soil type: Sandy loam
Irrigation rate: 0.7 in

WATER BALANCE
0
50
100
Deficit Today
29 %
(0.88 in)
Effective irrigation: 0.68 in Effective rain: 0.00 in

GROWTH STAGE
Today 365 GDD
Emergence to First Square
70 550

Today

WATER DEFICIT
10 % 0.21 in

IRRIGATION APPLIED
0.0 in Effective: 0.00 in − +

RAIN OBSERVED
0.00 in Effective: 0.00 in − +

CROP EVAPOTRANSPIRATION
0.06 in

LAST 7 DAYS ACCUMULATED ETC
0.35 in

Figure 5. Screenshots showing the main user-interface screen of the Cotton App (left and center). On each of these screenshots, the user can view information about the 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, they can be added or removed.

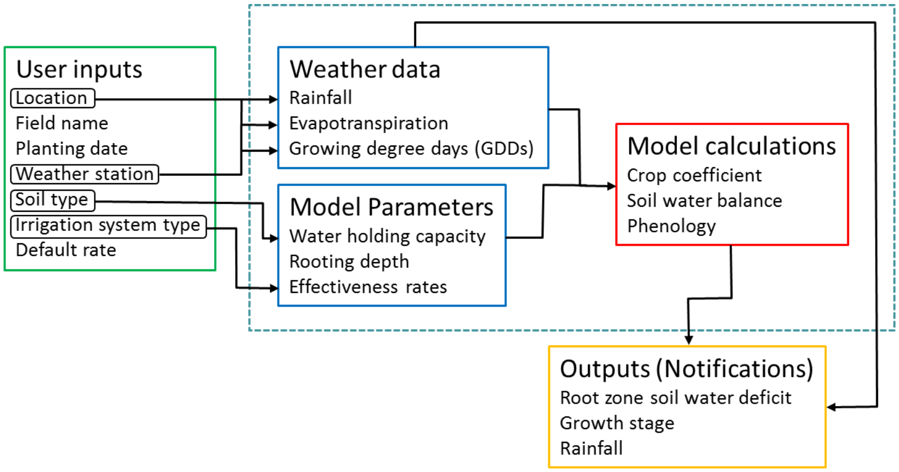


Figure 6. Flow of information in the Cotton App. Components internal to the model are enclosed by the dashed line.

fields registered by the user (in Fig. 5 there are six). The circles are added in the sequence in which fields are registered and the solid circle indicate the field currently being displayed. The *Edit Field* button allows the user to edit any of the information entered during field setup. Below that, the Cotton App displays the current RZSWD. The bar graph on the left is scaled from 0 to 100% RZSWD and moves downwards as soil water is depleted. To the right of the bar, the RZSWD is displayed numerically and below that, in parentheses, is the amount of irrigation water required to refill the profile to 100% capacity. When irrigation is applied, the user *must* record that irrigation by pressing the *Add irrigation* button. The Cotton App then credits the default irrigation amount (multiplied by the efficiency factor) to the soil water balance model. A sprinkler symbol indicates that an irrigation event has been added and the irrigation's effect on RZSWD is shown with a lighter shade of blue on the bar graph (Fig. 5).

Below the bar graph, the screen displays the amount of effective irrigation and effective rain added to the model on this day. If more or less than the default irrigation is added to the field or if the rain amount recorded at the nearest weather station is different from the rain received at the field, the user can adjust the amounts by touching the *See details* button (Fig. 5). Irrigation and rain amounts can be corrected retroactively for the past nine days. The Cotton App will perform best when precipitation data are accurate and the best way to provide these data is to use a local rain gage to adjust rain data recorded at the weather station.

The soil water balance model is run once a day early in the morning after the weather data for the past day are uploaded to the server. The display is updated the first time the user opens the Cotton App after the model run. The model also runs and the display updates if the user adds or removes an irrigation event, corrects rainfall amounts, or changes any of the field parameters (such as soil type) which may affect RZSWD. The Cotton App allows the user to view RZSWD, irrigation, and rain data, and growth stage data for the current day and the past nine days. Past data can be viewed by swiping along the series of ten circles located below the RZSWD display. The current day is represented by the circle at far right.

Estimated phenological development (growth stage) and accumulated GDDs are presented at the bottom of the screen. It is important that the user ground-truth the model's changes in phenological stage as they occur because as described earlier, this is the parameter that forces changes in Kc. If the crop is not progressing at the same rate as predicted by the Cotton App, then the Kc used may be too high or too low and the RZSWD will not reflect field conditions accurately. If the discrepancies are large, use of the Cotton App should be discontinued in this field. At this time, there is no provision for the user to adjust phenological stage. Figure 6 presents a schematic of how the Cotton App interacts with inputs and outputs.

SI Cotton 1h ago
The water deficit in SIRP Plots is 51%. Irrigation is recommended.

SI Cotton 1h ago
The water deficit in NESPAL is 55%. Irrigation is recommended.

SI Cotton 34m ago
A rain event of 0.01 in was observed in SIRP 2015a area yesterday. Adjust as appropriate.

SI Cotton 34m ago
SIRP 2015a is approaching the >60% Open Bolls phase.

Figure 7. Screenshots showing notifications for RZSWD (left), rain (right) and phenology change (right).

Notifications

Notifications are pushed to the user when a rain event is recorded at a weather station associated with a registered field, when phenological changes occur, and when RZSWD exceeds 40% (Fig. 7). A 50% RZSWD or depletion of 50% of plant available soil water is a commonly accepted irrigation threshold for many agronomic crops. The Cotton App begins to push daily notifications to the user when RZSWD exceeds 40% to allow the user time to trigger the required irrigation event.

Cotton App Performance

For three growing seasons, 2013 - 2015, the Cotton App was a treatment in a cotton irrigation scheduling study conducted at SIRP. Every year, the Cotton App was compared to other scheduling methods some of which changed from year to year. Throughout the three years, only two other treatments were used repeatedly – the University of Georgia Extension Checkbook Method hereafter referred to as the Checkbook Method which was used in 2013, 2014 and 2015 and Watermark® sensors with a 50 kPa irrigation threshold which was used in 2014 and 2015. Only the results from these three treatments will be discussed. Treatment yields were analyzed using an analysis of variance GLM procedure follow by means separation LSD test.

The Checkbook Method tabulates the amount of water a crop needs during each week of its life-cycle. Producers subtract the amount of precipitation received from the weekly requirements and add the remainder via irrigation. The Checkbook Method does not account for environmental conditions and so tends to over-irrigate when ET rates are low.

Results and Discussion

Table 2 summarizes the performance of the Cotton App compared to the Checkbook Method for 2013-2015 and compared to the Watermark® sensors with a 50 kPa irrigation threshold for 2014-2015. 2013 and 2015 were wetter than normal years while 2014 was a drier than normal year. The Cotton App outperformed the Checkbook Method in terms of mean yield regardless of tillage treatment and did this

Table 2. Performance of the Cotton App compared to other irrigation scheduling treatments conducted at the University of Georgia’s Stripling Irrigation Research Park. Cotton yield is reported as lint (fiber) yield. Treatment yields were analyzed using an analysis of variance GLM procedure follow by means separation LSD test. Means with the same t Grouping letter are not significantly different (from Vellidis et al., 2016b)

Year		Conventional Tillage			Conservation Tillage		
Rain (mm)[1]	Scheduling Method	Lint Yield (kg ha^{-1})	Irrigation (mm)	WUE[2] (kg ha^{-1} mm^{-1})	Lint Yield (kg ha^{-1})	Irrigation (mm)	WUE (kg ha^{-1} mm^{-1})
2013	Checkbook	1289^{b}	310	4.1	1513^{b}	323	4.6
(696)	Cotton App	1411^{a}	76	18.5	1664^{a}	76	21.8
2014	Checkbook	1915^{b}	388	4.9	1860^{b}	388	4.7
(285)	Cotton App	2067^{a}	231	8.9	2011^{a}	231	8.7
	Watermark 50 kPa Threshold	1974^{b}	315	6.2	1721^{c}	372	4.6
2015	Checkbook	1814^{a}	165	11	1748^{a}	165	10.6
(575)	Cotton App	1926^{a}	146	13.1	1841^{a}	127	14.5
	Watermark 50 kPa Threshold	1849^{a}	108	17.1	1953^{a}	108	18.0

[1] Precipitation in mm during the growing season.

2 WUE = water use efficiency

most effectively during the two wet years. However the differences were statistically significantly different only in 2013 and 2014 because of large intra-treatment variability in yield during 2015 (Vellidis et al., 2016a). The Cotton App also outperformed the Checkbook Method in water use efficiency. This is because the Checkbook Method does not take into account periods with low ET which occur frequently in wet years. The Cotton App outperformed the Watermark® sensors method in 2014 but in 2015, the Watermark® sensors conservation tillage treatment outperformed the Cotton App conservation tillage plots. The yield differences between these two irrigation treatments were statistically significant in 2014.

Expanding the Cotton App's Geographical Footprint

The Cotton App's geographical footprint is currently limited to Georgia and Florida for two reasons. The first is that the project team which developed the suite of SmartIrrigation Apps had already developed the protocols to use data from GAEMN and FAWN. Adding weather networks from other states which provide the meteorological data needed to calculate ETo using the Penman–Monteith equation requires additional resources but is relatively straightforward.

The second reason inhibiting use of the Cotton App in other states is that the Kc curve currently used in the model was calibrated to environmental conditions found in southern Georgia and northern Florida using varieties developed for this environment. Consequently the Kc curve may not be appropriate for the environmental conditions and varieties in other regions. To make the Cotton App useable across the U.S. cotton belt will require a library of Kc curves as well as widespread access to meteorological data.

One solution to the meteorological data problem may be to use national gridded meteorological datasets offered by the U.S. National Oceanic and Atmospheric Administration Weather Service (NOAA NWS). We evaluated the NOAA NWS 2.5km grid Real Time Mesoscale Analysis (RTMA) tool (http://www.nco.ncep.noaa.gov/pmb/products/rtma/) and found that it underestimates precipitation of large events during the summer. Summer precipitation in the southeastern United States is driven by localized convective thunderstorms. As a result, in-field precipitation amounts can be substantially different from those estimated for a 2.5-km grid as well as from precipitation recorded at the nearest meteorological station on any given day.

NOAA NWS also recently released an experimental forecast reference ET (FRET) tool http://1.usa.gov/1Poz2va which we evaluated during the 2015 growing season for 20 locations in Florida, Georgia, and South Carolina. FRET appears to overestimate daily ET when unusually low ET is calculated from weather station data. Overestimating ET during low ET days erodes the advantage that the Cotton App has over irrigation scheduling tools like the Checkbook Method. A trial version of the Cotton App using the NOAA NWS 2.5km grid RTMA precipitation estimation and FRET is currently under development and will be released prior to the 2017 growing season.

Conclusion

Meteorological station-driven precipitation is the Cotton App's weakest feature since in-field precipitation amounts can be significantly different from those recorded at the nearest weather station on any given day. For the Cotton App to be used *most effectively* and to produce the most accurate results, users should correct precipitation recorded at weather stations with data from the field. Because notifications are pushed to the user whenever precipitation is recorded at the weather station, this may be simple to do. A bigger problem may lie with rain received at the field but not recorded at the weather station, because in this case, users will not have knowledge of the event until they visit the field.

Since its release in 2014, the Cotton App has been used by 373 by growers, consultants, and researchers to schedule irrigation in 660 unique fields during the 2014, 2015, and 2016 growing seasons. Twenty updates have been released over this time period – 12 for the Android and eight for iOS platforms, respectively. Reviews from users are positive and the University of Georgia Extension Cooperative Extension Service is now actively promoting the use of the Cotton App in Georgia. An online tutorial is available at http://smartirrigationapps.org/cotton-app-development. Research trials have shown that the Cotton App has the potential to greatly increase water use efficiency when utilized for scheduling irrigation on cotton in the south Georgia/North Florida regions.

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