SMARTPHONE APPS FOR IRRIGATION SCHEDULING

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emerging technologies for sustainable irrigation ASABE

A Tribute to the Career of Terry Howell, Sr.

ABSTRACT. *SmartIrrigation apps were developed to provide real-time irrigation schedules for selected crops (i.e., avocado, citrus, cotton, peanut, strawberry, and vegetables). Irrigation schedules in the smartphone apps are based on evapotranspiration (ET) or a water balance methodology using real-time weather data from the Florida Automated Weather Network and the Georgia Environmental Monitoring Network. The FAO Penman-Monteith method is used for calculating reference ET, and crop coefficients (K_c) are applied based on time after planting, calendar month, or a crop's phenological stage. The functionality of each app was customized for each user group considering the most common irrigation systems used. Custom features include water conservation options, splitting irrigation events, spreadsheet output emails, and notifications. App inputs vary by crop (primarily due to the irrigation system used); however, all apps require root depth, irrigation rate, and soil type except the strawberry app. App outputs also vary and include estimated reference ET, days between irrigation events, irrigation depth and duration, accumulated rain for previous seven days, and growing degree days. National Weather Service forecast data are also provided in the apps. The apps are available in Android and iOS stores. A limitation to the app irrigation schedules is the spatial variation in rainfall, given the finite set of weather stations. Future efforts will focus on more accurate inclusion of rainfall into the irrigation schedules generated by the SmartIrrigation apps.*

Keywords. Avocado, Citrus, Cotton, Irrigation, Irrigation scheduling, Peanut, Strawberry, Turf, Vegetable.

Freshwater supply shortages are increasingly common worldwide. The demand on water supplies is expected to increase due to population growth, food demand needs, and changes in water availability (e.g., drought) (De Fraiture and Wichelns, 2010). Irrigation is a primary user of freshwater, with the Food and Agricultural Organization of the United Nations (FAO, 2014) reporting that 70% of freshwater in the world is used for irrigation purposes. Research has shown that irrigation volumes applied can be reduced without decreasing yield using science-based irrigation schedules, typically using evapotranspiration (ET) or soil water content (or tension) methodologies (e.g., Morgan et al., 2006; Zotarelli et al., 2009, 2011; Kiggundu et al., 2012; Dobbs et al., 2014).

Science-based scheduling can be achieved using on-site measuring equipment such as weather stations for ET or soil water sensors (SWS). These techniques measure on-site water demand (ET) or soil water content and translate this into an irrigation schedule, generally using an automated process. However, data exist that could be used to develop site-specific, real-time irrigation schedules without installing on-site equipment. National, regional, and state weather networks that provide environmental measurements (i.e., temperature, solar radiation, relative humidity, wind speed, and rainfall) are available and can be used to develop ET-based irrigation schedules (Coughlan and Huda, 2008; Pavan et al., 2011; Dukes, 2012).

Weather database resources have been used by some researchers to develop web-based irrigation scheduling tools (e.g., Morgan et al., 2010; Kelley and Miller, 2011; Scherer, 2014). However, the web-based tools that were previously developed had little user-tool interaction and depended largely on the user remembering to return to the website and engage. In addition, users typically accessed the web tool using a desktop computer or laptop. Another type of electronic communication that offers more flexibility and is more easily accessible is the smartphone/device app. The functionality of an app differs from a web tool, as apps are with the user at all times (via a smartphone) and readily accessible, and apps engage the user through notifications.

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Notifications, similar to text messages, prompt users to respond to critical events. Thus, notifications can be designed to achieve particular actions by the users. Furthermore, apps provide an ideal medium for irrigation scheduling because of the need for continual, repeated use and accessibility in field settings.

The growing use of smartphones and availability of weather data have resulted in an ideal situation for designing and implementing smartphone apps for irrigation scheduling. Using this concept, several SmartIrrigation apps were developed. Thus, this study's objectives were to (1) develop smartphone apps for scheduling irrigation using real-time and forecasted meteorological data and (2) provide users with an irrigation schedule for crops during different phases of phenological development based on soil and irrigation system characteristics and weather conditions.

METHODS

We designed SmartIrrigation apps using weather data, crop knowledge, and established smartphone app development protocols. These components were well established prior to the app development, ensuring the scientific integrity of the developed product. SmartIrrigation apps for avocado (*Persea Americana*), citrus (*Citrus* spp. L.), cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), strawberry (*Fragaria ananassa*), urban turf [e.g., St. Augustine grass (*Stenotaphrum secundatum*)], and vegetable [i.e., cabbage (*Brassica oleracea* var. capitata), squash (*Cucurbita pepo*), tomato (*Solanum lycopersicum* L.) and watermelon (*Citrullus lanatus*)] were developed and customized by crop type to accommodate for differences in water management practices and seasonal patterns of ET.

WEATHER DATA SOURCES AND ET

The smartphone apps use real-time meteorological data for calculating ET and for considering rainfall in irrigation schedules. Meteorological data were obtained from the Florida Automated Weather Network (FAWN) and the Georgia Automated Environmental Monitoring Network (GAEMN). FAWN (http://fawn.ifas.ufl.edu) began in 1997 with a legislative appropriation to University of Florida (UF) Institute of Food and Agricultural Sciences (IFAS). These funds and others have resulted in 42 sites available statewide. Most sites are located at UF IFAS research centers, USDA facilities, Florida Division of Forestry sites, state and county parks, and county extension offices. FAWN sites monitor air temperature at 60 cm and 10 m heights, relative humidity, atmospheric pressure, solar radiation, wind speed and direction, rainfall, and soil temperature at a 10 cm depth. Weather data are stored every 15 min. GAEMN (www.georgiaweather.net) was established in 1991 by the College of Agricultural and Environmental Sciences of the University of Georgia. The objective of GAEMN is to collect reliable weather information for agricultural and environmental applications. Each of the network's 82 stations monitor air temperature, relative humidity, rainfall, solar radiation, wind speed and direction, soil temperature at 5, 10, and 20 cm depths, atmospheric pressure, and soil moisture at 1 s intervals.

Weather data from FAWN and GAEMN are used by each app to calculate irrigation needs depending on the location of the irrigated property. Each new site or field identified in the app by a user is associated with a specific weather station using the closest proximity approach. Temperature, solar radiation, wind speed, and relative humidity time series are used to estimate evapotranspiration. All SmartIrrigation apps are currently available for Georgia and Florida except avocado and vegetable, which have been developed only for Florida thus far. This exception is due to funding sources for the different apps.

The Smartphone apps use a daily time step to calculate evapotranspiration (ET). The FAO Penman-Monteith equation and respective weather parameters are used to estimate reference ET (ET$_o$; Allen et al., 1998). Wind speed, temperature, and humidity measurements are standardized for a 2 m height. This value is adjusted for specific crops using a crop coefficient (K_c). Thus, crop ET (ET$_c$) is estimated using crop production system specific K_c values based on crop phenology and the reference ET (ET$_o$) (eq. 1):

$$K_c = \frac{ET_c}{ET_o} \qquad (1)$$

The crop coefficient (K_c) is widely used to estimate crop water use and to schedule irrigation. The concept of K_c was introduced by Jensen (1968) and further developed by other researchers (Doorenbos and Pruitt, 1975, 1977; Burman et al., 1980a, 1980b; Allen et al., 1998). The methodology was developed to provide a simple ET$_c$ estimate from ET$_o$.

Crop coefficients typically vary during the plant's life cycle. Different methods may be used to determine the plant stage and respective K_c value. Depending on the information available, one of three methods was used to assign K_c values in the apps: the growing degree day method (GDD), days after planting method, or calendar-based method. GDDs are calculated using equation 2:

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base} \qquad (2)$$

The GDD calculation for crops considers that T_{base} is equal to 15.5°C. Any temperature below T_{base} is equal to T_{base}, and consequently the GDD is equal to zero. Additionally, the cotton app considers daily average air temperatures higher than 37.7°C as equal to 37.7°C because growth is limited above this temperature for cotton. The peanut app has a similar limitation for temperatures higher than 35°C. The remaining apps with GDD calculations do not use the 37.7°C maximum threshold in the calculations. The specific GDDs required for each phenological stage of cotton and peanut are derived from Ritchie et al. (2004) and Rowland et al. (2006), respectively. The strawberry and vegetable apps do not associate GDD with crop phenological stage, as sufficient information is not currently available to make this correlation. Thus, strawberry and vegetable apps use days after planting to designate changes in K_c. The turf app uses a calendar-based method in which each month is associated with a different K_c.

Rainfall is included in the apps using a variety of methods due to the spatial variability of rainfall and the limited

Table 1. Irrigation system or water balance method and rainfall integration used by SmartIrrigation apps.

App	Irrigation System	Rainfall
Avocado	Microsprinkler, solid set under tree, or overhead.	Notifications of rainfall events or forecasted events.
Citrus	Microsprinkler.	Delay table based on selected rainfall amounts.
Cotton	Center pivot, lateral, sub-surface drip, or overhead.	Daily water balance uses rainfall from weather stations; can be user corrected.
Peanut	Center pivot, lateral, or overhead.	Delay table based on selected rainfall amounts.
Strawberry	Drip under plastic mulch.	Daily irrigation; no rainfall considerations.
Urban turf	Micro, spray, multi-stream spray, gear-driven rotors, and impact irrigation heads.	Notifications of rainfall events or forecasted events.
Vegetable	Drip under plastic mulch or buried in unmulched beds.	Daily irrigation; no rainfall considerations.

number of weather stations. The currently measured rainfall points provided by FAWN and GAEMN do not provide the resolution needed to accurately predict rainfall in app user fields located at a distance from a weather station. Thus, rainfall was incorporated into each app (except for strawberry and vegetable apps) considering this limitation and the user's needs (table 1). Some apps (i.e., vegetable and strawberry) exclude rainfall completely, as crops are typically irrigated daily and grown using plastic mulch. Other apps (i.e., citrus) use an approach in which growers can modify irrigation schedules based on local rainfall measurements using an irrigation delay chart developed for current weather conditions. The avocado and turf apps use notifications to alert users of potential rainfall events that might influence the need for irrigation.

Forecast data from the National Weather Service (NWS, 2014) were also integrated into the apps. The apps provide this information, which is continuously updated for the next eight hours as well as the next five days. Parameters include temperature, probability of rainfall, relative humidity, and wind speed.

CROP SYSTEM AND IRRIGATION SCHEDULE DETERMINATIONS

Apps were developed for commercially valuable seasonal crops (cotton, peanut, strawberry, and vegetables) and perennial crops (avocado, citrus, and turf grass). These plants were selected due to the potential for saving water with the SmartIrrigation app, the knowledge of the crop (i.e., phenological phases and available K_c values), and the interest of the clientele. The apps were developed considering the unique features of each plant in regard to production and irrigation. The apps are summarized in the following sections and in tables 1 through 3. All inputs in the apps are defined with specific ranges to help prevent input of incorrect values. For some apps, default values for inputs also are provided.

Avocado

Avocado is a perennial tree crop with approximately 63 different commercial varieties (20 primary varieties) in south Florida. Avocado has been grown commercially in Florida since the 1920s and is the tropical fruit crop with the greatest acreage in commercial production in Miami-Dade, south Florida (Crane et al., 2007). Avocado growth stages include flower bud development, flowering and fruit set, fruit growth, after harvest, and dormancy. Each stage is associated with a different crop coefficient, ranging from 0.6 at dormancy to 1.0 during fruit growth. To accommodate this variability, the app calculates irrigation needs based on user-set growth stages.

Table 2. Inputs for the SmartIrrigation apps provided by the user.

Inputs	Avocado	Citrus	Cotton	Peanut	Strawberry	Turf	Vegetable
Anticipated harvest date	-	-	-	X	X	-	-
Days to irrigate	X	-	-	X	-	X	-
Irrigated area	X	-	-	-	-	X	-
Irrigation rate	X	X	X	X	X	X	X
Irrigation system efficiency	X	X	-	-	X	-	X
Irrigation system type	X	X	X	-	X	X	X
Maximum duration of an irrigation event	-	-	-	-	-	-	X
Minutes to pressurize system	X	-	-	-	-	-	-
Number of trees or acreage	X	X	-	-	X	-	X
Pattern	X	X	-	-	X	-	X
Planting date	-	-	X	X	X	-	X
Root depth	X	X	-	X	-	X	X
Row spacing	-	-	-	-	X	-	X
Soil type	X	X	X	X	-	X	X
Spray diameter	X	X	-	-	X	-	X
Water conservation mode	X	-	-	-	-	X	-
Weather station selection	-	-	X	X	X	-	X

Table 3. Outputs provided by the SmartIrrigation apps to the user.

Outputs	Avocado	Citrus	Cotton	Peanut	Strawberry	Turf	Vegetable
Accumulated rain for previous seven days	X	-	-	X	-	-	-
Duration of irrigation events	X	X	-	-	X	X	X
Estimated ET_c	-	-	X	X	-	-	-
Growing degree days	-	-	X	X	X	-	X
Irrigation depth	X	-	X	X	-	X	-
Number of days between irrigation events	-	X	-	X	X	-	X
Phenological stage	-	-	X	-	-	-	-
Root zone soil water deficit	-	-	X	-	-	-	-
Water conservation state	-	-	-	-	-	X	-

Avocado is typically irrigated year round in Florida. Irrigation may be reduced during the rainy season (June to October) if sufficient rainfall occurs. The dry season generally coincides with the flower bud development and flowering stages of avocado, which are periods when water stress may occur if sufficient irrigation is not applied. The most common irrigation systems for avocado orchards are solid set sprinklers and microsprinklers. The app considers both systems. Avocado orchards may use solid set sprinklers for irrigation and cold protection. The avocado app does not provide cold protection irrigation scheduling. The irrigation depth needed is determined using input (table 2) with crop ET losses and soil water storage capacity. An irrigation schedule is provided for a 15-day period based on an average of the past five days' ET rates.

Citrus

Citrus is the largest horticultural commodity crop grown in Florida in terms of land area and production volume. The Florida citrus industry provides over 70% of the U.S. juice production. During the past ten years, a disease called Citrus Greening (*Candidatas* Liberibacter asiaticus) has weakened trees and reduced production levels. It has been determined that the water status of the trees leads to much of the reduced health and production of affected trees (Kadyampakeni et al., 2014a, 2014b). Likewise, tree health following mechanical harvesting of citrus has been found to be affected by irrigation before and after harvest (Morgan et al., 2014).

Citrus is typically produced on sandy soils with low water-holding capacity of 0.04 to 0.09 cm^3 cm^{-3} in Florida (Obreza et al., 1997). As with avocado, citrus production depends on an adequate supply of both irrigation water and fertilizer on an annual basis. Irrigation is supplied by microsprinklers providing between 2.5 and 7.5 mm h^{-1} at each tree. The key to plant water status is soil water availability (Morgan et al., 2006), and thus soil water content must be maintained within a relatively narrow range such that water availability to the crop does not limit growth or adversely impact yield or quality. The citrus microsprinkler irrigation app estimates the soil water balance in multiple soil areas and layers under a mature citrus tree using tree spacing and irrigation system information provided by the user (table 2; Jackson et al., 2008). An irrigation schedule is provided for a 15-day period based on an average of the past five days' ET rates.

Cotton

Cotton is grown in 17 states from Virginia to California, with annual production area ranging from 5.1 to 6.3 million ha. Cotton is an intensively managed crop that requires varying amounts of water during its phenological stages to maximize yield. Approximately 40% of U.S. cotton is currently produced under irrigated conditions. Most of the cotton grown in Georgia and Florida is irrigated with center-pivot or lateral-move irrigation systems. However, subsurface drip irrigation is gaining in popularity. The cotton app currently addresses overhead sprinkler irrigation and subsurface drip.

The cotton app is an interactive ET-based soil water balance model that estimates root zone soil water deficits in terms of inches of water and percentage of total. Unlike the other apps, the cotton app does not directly deliver irrigation recommendations. However, the app output can be used to make appropriate irrigation decisions. Changes in the model's crop coefficient values are driven by accumulated heat units, commonly referred to as growing degree days (GDDs). The model calculates ET_c to estimate the daily crop water use. ET_c, 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 water-holding capacity and current rooting depth. As the plant's rooting system grows, the soil depth from which the plants can extract water also increases. In the model, the initial rooting zone depth is 15.2 cm and increases by 0.7 cm d^{-1} until it reaches a maximum depth of 76.2 cm. At emergence, the soil profile from 0 to 76.2 cm is assumed to be at 85% of maximum plant-available soil water-holding capacity. The daily plant-available soil water is calculated by subtracting the previous day's ET_c from the previous day's plant-available soil water and adding any precipitation or irrigation events. 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. It uses an effectiveness factor of 95% for subsurface drip irrigation. The model assumes that 90% of measured precipitation reaches the soil to account for canopy interception and other possible losses.

Peanut

On average, there are 57,000 ha of peanut production in Florida, with peanut having the second largest land area devoted to production in comparison to other row crops in the state (FDACS, 2013; Beasley, 2013). Therefore, peanut is an important cash crop in Florida's overall farm economy. The Florida crop is also an important contributor to U.S. national peanut production. In 2012 and 2013, Florida tied for second in overall U.S. production among the peanut-producing states (USDA, 2014). Peanuts are grown primarily in the western and north central regions of the state and typically in rotation with cotton (*Gossypium hirsutum* L.). However, other row crops such as corn (*Zea mays* L.), sorghum (*Sorghum* L.), and soybeans (*Glycine max* L.) are also viable rotation options.

Over the last decade, the percentage of peanut production that is irrigated in the southeastern U.S. has reached nearly 50% in some regions, with irrigation infrastructure expanding dramatically in states such as Alabama in just the last five years. Irrigation is typically applied through center-pivot systems, which can range widely in efficiency. Irrigation scheduling options for peanut are limited, with the University of Georgia Cooperative Extension Service's Checkbook method (Beasley, 2007) and the Irrigator Pro method developed by the USDA National Peanut Research Laboratory (Lamb et al., 2004) as two or the primary scheduling options. The development of the University of Florida's PeanutFARM (Field Agronomic Resource Manager; http://agronomy.ifas.ufl.edu/peanutfarm) in 2013 provided the only web-based irrigation scheduling tool for southeastern peanut production to date.

PeanutFARM provides growers access to a suite of

tools, including a peanut maturity/harvest predictor, digital image analysis for peanut maturity, and an irrigation scheduling tool. The maturity/harvest predictor and the irrigation scheduling tools are based on an adjusted growing degree day (aGDD) model developed specifically for peanut (Rowland et al., 2006). The irrigation scheduling tool uses cumulative aGDDs and ET to estimate crop water use and provides daily irrigation recommendations. An irrigation recommendation is initiated by the program when 50% of the plant-available water (PAW) is depleted. The model determines PAW by using the available water capacity (AWC) for a specific soil texture and multiplying it by the peanut rooting depth (PAW = AWC × rooting depth). Losses of soil water are determined by multiplying the reference evapotranspiration (ET) by a dynamic K_c value relating percent canopy coverage (as determined by aGDD value) to water loss throughout the growing season. The peanut app in development is based on PeanutFARM.

Strawberry

The total value of strawberry production in the U.S. represents over $2 billion (USDA, 2013a). In 2012, the area planted with strawberry was 3560 ha, with a production of 1.367 million metric tons (USDA, 2013b). Florida is ranked second in the value of strawberry production in the U.S., with production concentrated in the west central region of the state. According to the Florida Strawberry Growers Association (FSGA), Florida's production represents 15% of the nation's strawberries and virtually all the strawberries grown during the winter. The high value of the strawberry crop often compels growers to use inputs intensively to ensure high yields and fruit quality. Sprinkler irrigation is normally used for 10 to 12 days to establish transplants in the field, followed by drip irrigation for the remainder of the season. Initial water requirements of strawberry transplants are low (20% to 40% of ET_o). As plants grow, mid-season water requirements approach 50% of ET_o, increasing to about 60% of ET_o during late season growth (Clark et al., 1992; Peres et al., 2007).

Planting and harvest dates are used to determine the percentage to date of the current crop season. Crop coefficients are then calculated for drip-irrigated strawberries on plastic mulch beds (Clark et al., 1992). The SmartIrrigation app uses this information along with the ET rate to estimate daily water use under the mulched row. An irrigation schedule is provided for a 15-day period based on an average of the past five days' ET rates. After the daily crop water use is determined in inches of water per day, the amount of water needed for daily irrigation is estimated based on the number of 100 ft rows in an acre as a function of the distance between rows and the amount of water applied per 100 ft of row per hour by the irrigation system.

Urban Turf

In 2005, U.S. turf grass was estimated to cover approximately 163,800 km^2, which is three times greater than any other irrigated crop in the country (Milesi et al., 2005). Urban irrigation turf systems vary widely but typically irrigate a warm season grass in Florida and Georgia. Warm season grass is the only crop currently available in the turf app. Turf is characterized with a crop coefficient that changes

on a monthly basis. Florida crop coefficients (K_c) for the north (Jia et al., 2009), central (Davis and Dukes, 2010), and south (Romero and Dukes, 2011) regions have been published and were used in the app. For Georgia, similar information was not available, so Irrigation Association values were used for the K_c (IA, 2008).

Users are provided with five sprinkler types for turf: micro, spray, multi-stream spray, gear-driven rotors, and impact. Turf is typically irrigated year round in south Florida, with this trend decreasing northward through Florida and Georgia due to cooler winters farther north. Irrigation needs vary widely due to ET_c demand and rainfall (wet versus dry season in Florida). The irrigation depth needed is determined using input (table 2) with crop ET losses and soil water storage capacity. An irrigation schedule is provided for a 15-day period based on an average of the past five days' ET rates.

Vegetable

Florida ranks second among all U.S. states in vegetable production, with 11.3% of planted area, and ranks first among all states in tomato area planted and harvested for the fresh market, with a total area planted of 14,170 ha and 13,765 ha harvested in 2013 (USDA, 2014). Other major vegetable crops are squash, cabbage, and watermelon. Vegetable production in Florida occurs mainly from September to May. An increasing proportion of vegetable area is now drip irrigated. The vegetable irrigation app was developed to provide daily drip irrigation schedules for selected vegetable crops grow in bedded fields with (e.g., squash, tomato, and watermelon) or without (watermelon) plastic mulch. When a specific crop is chosen, the app requires basic planting information (table 2) to generate an irrigation schedule.

Each crop is described using different K_c values. Experiments at the University of Florida resulted in development of K_c values for cabbage of 0.3 for 0 to 30 days after planting, 0.7 for 30 to 55 days after planting, and 1.05 for 55 days after planting until harvest. Crop coefficient values for squash and tomato are from Dukes et al. (2012), and watermelon K_c values are from Shukla et al. (2013).

APP DEVELOPMENT

The apps were developed using the official tools and programming languages provided by Apple (Objective C and iOS SDK) and Google (Java and Android SDK), which allowed the designing and coding of modern and responsive mobile applications for interaction and presentation of results from the models. The apps communicate with AgroClimate servers and databases via specific developed web services that return data in JavaScript Object Notation (JSON) format. AgroClimate (http://agroclimate.org/) is a web-based resource that provides tools for managing climate risk in agriculture. Code scripts are scheduled via the Crontab program of AgroClimate's UNIX-based server to retrieve, process, and store observed weather data from FAWN and GAEMN public application programing interfaces (APIs) to run the models needed for the water balance calculations that are made available to the users through the apps.

Critical information is sent to users via push notifications using Apple Push Notification Service (APNS) and Google Cloud Messaging (GCM) protocols. Examples of push notifications include irrigation schedule updates based on observed weather data and the water needs of different phenological stages; probability of rain for the next several hours, observed rain events, and recommendations to skip irrigation when appropriate; and the water savings achieved in the past months by following the recommendations delivered by the app.

RESULTS AND DISCUSSION

The SmartIrrigation apps have been released and are in different stages of field testing. The apps all provide an irrigation schedule or water balance using real-time weather data. All apps are currently in use by researchers and focus teams (composed of clientele). Smartphone apps are available in the respective app stores.

In developing the apps, special or unique features were added based on input from clientele groups. These features helped to improve the user experience. The ultimate goal of the apps is their use by irrigators such that water is applied using a science-based method, resulting in water conservation with no yield reduction or plant damage. Thus, the apps include notifications that are sent to promote irrigation scheduling changes that reflect plant water needs on a real-time basis. Features of each SmartIrrigation app are highlighted in the following sections to provide insight into their customization and application.

Avocado

The avocado app was designed to accommodate avocado's perennial nature and to remove pre-designated phenological periods due to the large variety differences in this crop. Thus, users have the ability to adjust the onset and ending of each stage (e.g., flowers and fruiting) (fig. 1). The app contains additional flexibility in that the user can start the crop at any growth stage when they initiate the app and input a field. The app then assigns other stages automatically with user-adjustable default time lengths (i.e., days).

Another option that was added to the avocado app was the ability to request emailed irrigation schedules. This was requested by the clientele focus group because some users manage many properties, and having to tap through the app for each property's irrigation schedule would become cumbersome. The Microsoft Excel output sheet of irrigation scheduling information allows the managers to use and share this information easily with others (table 4).

Citrus

Citrus is typically irrigated with low-volume microsprinklers that wet only the area under the tree canopy. Irrigation events are scheduled to replace crop ET in the wet-
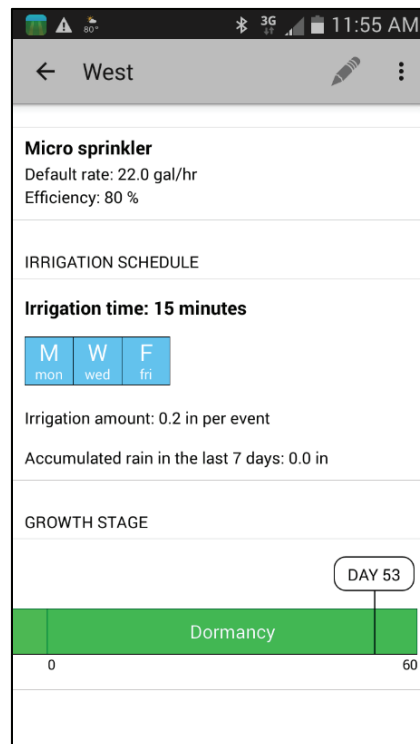

Figure 1. Screenshot of avocado app irrigation schedule with growth (phenological) stage shown.

ted area when the available soil moisture has been depleted by 25% to 33% from February to June and by 50% to 66% from July to January. Intervals between irrigation events range from every day during high crop ET period to as long as seven to ten days during the winter months. Rainfall also influences irrigation intervals; thus, a table with appropriate delays between irrigation events based on selected rainfall amounts is provided based on current reference ET. Few citrus growers irrigate with drip systems, and an option for daily irrigation schedules has also been provided.

In a three-year field evaluation of weather and soil water data, it was concluded that the web-based tool from which the citrus app was developed provides the accuracy needed for grower irrigation decisions. Furthermore, it was concluded that FAWN stations, rather than grove-sited weather stations, can provide reliable data for grower irrigation scheduling and, with the exception of rainfall data, do not require growers to maintain their own weather station.

Cotton

The cotton app provides a water deficit scale that is generated from a water balance (fig. 2). A unique feature of this app is the ability to input irrigation applied and rainfall received to more accurately tabulate an irrigation balance. The use of a deficit scale for irrigation also allows users to decide the level of deficit they prefer before initiating irrigation. To assess its performance, in 2013 the cotton app

Table 4. Example output generated by the avocado app and sent via email.

System	Zone	Irrigation Type	Irrigation Days	Irrigation Time		Irrigation Amount (in.)	Last 7 Days Rainfall (in.)
				(h)	(min)		
Trec Grove	West	Microsprinkler	Monday, Wednesday, Friday	0	15	0.2	0

Figure 2. Screenshot of the SmartIrrigation Cotton App indicating how users can view data from multiple fields or zones as well as from up to nine previous days. The root zone soil water deficit is displayed both graphically and numerically in the center of the screen.

was compared to three other scheduling methods at the University of Georgia's Stripling Irrigation Research Park (SIRP): the soil water tension-based Irrigator Pro model (requires sensors), the Crop Water Stress Index method (requires canopy temperatures), and the University of Georgia Cooperative Extension Service's Checkbook method. The Checkbook method does not take ET into account. It schedules irrigation by replacing the maximum expected weekly crop water use (a function of weeks after planting) minus measured precipitation and is thus a very conservative scheduling tool. Table 5 presents the yield and the amount of irrigation water used with each method. The 2013 growing season was unusually rainy, so even the rainfed treatments performed well. The cotton app performed well compared to the other scheduling methods. It resulted in the highest yield under conservation tillage and the second highest yield under conventional tillage, even though

Table 5. 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 November 2013, rainfall = 696 mm).

	Conservation Tillage		Conventional Tillage	
Method	Lint Yield (kg ha^{-1})	Water Applied (mm)	Lint Yield (kg ha^{-1})	Water Use (mm)
Checkbook	1513	323	1289	310
Cotton App	1664	76	1411	76
CWSI[a]	1603	127	1463	58
Irrigator Pro	1631	71	1345	109
Rainfed	1625	38[b]	-	-

[a] Crop water stress index.
[b] 38 mm was used to initiate germination and ensure a good stand after planting, as seeds were planted in dry soil. Irrigation ceased when the plants were established.

the current version of the cotton app does not differentiate between tillage methods. In addition, plots irrigated with the cotton app used similar amounts of water as the two sensor-based scheduling methods and used considerably less water than the Checkbook method.

Peanut

Similar to the cotton app, both irrigation and rainfall may be modified in the peanut app to reflect site events. These values are used in the soil water mass balance equation. The irrigation recommendation is communicated daily, with three possible automated messages: "adequate moisture" (indicating that no irrigation is needed), "check field" (indicating that an irrigation recommendation may be imminent and visual inspection of the crop and field would be beneficial), and "irrigate" (indicating that the PAW threshold had been reached and irrigation is recommended). Figure 3 is an example screenshot showing the irrigation recommendation.

PeanutFARM is in its early testing and validation phases, particularly for its irrigation scheduling tool. Validation trials are ongoing at research facilities where testing of cultivars and the incorporation of water conservation modifiers for the PeanutFARM recommendations are being evaluated.

Strawberry

The strawberry app requires users to input basic information regarding the irrigation system design, such as drip tube flow rate and distance between rows. Users must also indicate the planting and harvesting dates, as the system dynamically adjusts the K_c based on the current fraction of time (in days) between planting and harvesting. Irrigation

Figure 3. Screenshot of peanut app showing irrigation recommendations for various fields.

system efficiency and maximum duration of irrigation per day are also taken into consideration in generating the schedule. Growers can register fields in the system to avoid having to input the information every time a schedule is generated. A similar procedure is used in the citrus and vegetable apps. Registration requires selecting a weather station, normally the station closest to the field, to serve as a reference for the weather variables required to estimate daily reference evapotranspiration. At registration, growers can also select whether or not to receive notifications with updated schedules. Schedules may be generated in split applications based on a maximum irrigation run time supplied by the user.

Urban Turf

The urban turf app was designed to require limited user input while accommodating a range of user expertise. Users may select default values or enter specific information for the irrigation system. The urban turf app also includes a water conservation feature (fig. 4). This feature allows users to select a deficit irrigation schedule (75% of field capacity) on a seasonal basis (defined as when rainfall exceeds ET) or a year round basis. Users may also select no water conservation, which generates an irrigation schedule corresponding to 100% of field capacity. This option helps to reduce over-irrigation during the rainy season in Florida from June to October.

Vegetable

The vegetable app is the only SmartIrrigation app that includes multiple crops: cabbage, squash, tomato, and watermelon. Multiple crops were included due to their similar irrigation systems (i.e., drip irrigation) and seasonal planting schedules. In addition, many producers grow more than one type of vegetable, and thus they can access all irrigation scheduling tools with this one app.

In Florida, most vegetable crops are cultivated on sandy soils with low soil water retention capacity, which requires
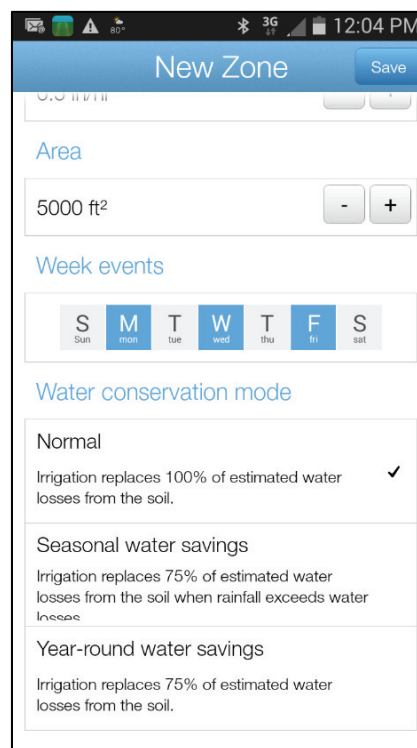

Figure 4. Screenshot of turf app water conservation mode options.

multiple irrigation events per day to minimize soil water percolation and nutrient leaching. With the selection of maximum duration of the irrigation event, the app indicates when the irrigation should be split into smaller applications instead of a single event. Figure 5 shows example information provided by the app for tomato, which includes the irrigation schedule and accumulated degree days.

EXPANSION AND FUTURE WORK
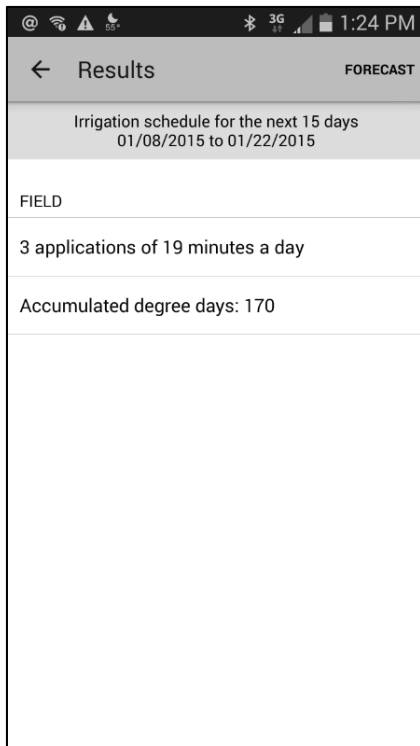
Each app presented here contains features specific to the

Figure 5. Screenshot of vegetable app output for tomato.

commodity and its respective users. While the apps currently only provide schedules for Florida and Georgia, they could be adapted for other states. However, some modifications would be needed. First, the app's functionality is based on real-time ET, and thus real-time weather data for the area of interest (e.g., state or region) would need to be incorporated into the app. The second modification would be inclusion of appropriate crop coefficients. The crop coefficients vary by crop, variety, management practices, and environmental conditions, and currently they are only applicable for Florida and Georgia. Crop coefficients can be assigned spatially in the app so that the user-selected location is associated with a particular set of crop coefficients. This approach is currently used in the turf app. The SmartIrrigation apps presented here also were customized for a target audience; for example, soil names were selected based on common terminology, and these customized features would likely need to be modified. This being said, the primary structure of the apps is viable for other locations, and we foresee expansion of these apps where similar crops are grown.

While the functionality behind the apps was designed and evaluated by scientists, the user interface was created by the app developer. The developer is a key component to the professional quality and continued integrity of the app, especially if iOS or Android products are created. These products require knowledge of the app approval process and continual software updates. App developers combine the science with accepted smartphone navigation protocols to provide users with easily accessible information. Thus, the app developer is essential to the process of making smartphone apps.

The SmartIrrigation apps described in this article are currently being validated through field tests in Florida and Georgia. These tests compare the app-generated schedules to other irrigation scheduling practices. In addition, most sites also measure rainfall and ET to compare the values measured at the study site to those of the nearest weather station used by the SmartIrrigation app. Preliminary testing of the apps has shown that while ET values may be fairly similar between the irrigation site and the weather station, difference in rainfall occur between the weather station and the irrigated field. The greater agreement between irrigation site and weather station ET could be attributed to the fact that 90% variations in minimum temperature, relative humidity, solar radiation, and evapotranspiration have been reported to require a spacing of about 30 km (Hubbard, 1994). Alternatively, Hubbard (1994) suggested that precipitation spacing should be 5 km to explain 90% or more of the variability in rainfall.

A more recent study using a network of 46 rain gauges in the southeastern U.S. concluded that the spatial variability of precipitation is season-dependent. Summer is characterized by a short, high-intensity, and localized precipitation pattern accompanied by high spatial variability. Winter is characterized by a widespread precipitation pattern with a relatively long duration and consistent storm behavior over the study area (Dzotsi et al., 2014). The researchers concluded that winter rainfall was more correlated at a mean distance of 54 km between locations, while summer rainfall was more correlated at a mean distance of 3 km. Thus, ET estimates using weather station data located throughout a region will likely be more accurate than rainfall estimates from the same stations when used to estimate weather conditions at an alternative location (>3 to 5 km in separation). While rainfall is integrated differently into each app, a better estimate of its value for scheduling is desired, and this is a limitation of the current apps. One option being explored is use of nationwide gridded datasets instead of less dense weather station records.

The limitation created by the spatial variability of rainfall and the ability to integrate this into an irrigation schedule may be reduced by considering the water conservation feature provided in the turf and avocado apps. These apps generate alternate irrigation schedules when seasonal (rainfall exceeds ET) or year round water saving features are selected. Water saving corresponds to irrigation schedules with a 25% deficit. The rainy and dry seasons that characterize weather conditions (especially in Florida) provide an environment in which such concepts would be viable. Preliminary evaluations show that the seasonal water saving feature would reduce irrigation during the rainy season, corresponding to the period when rainfall would most influence irrigation schedules.

Another potential modification being considered for future app development is to include an irrigation schedule that incorporates primed acclimation. Primed acclimation is the strategy of applying deficit amounts of water in the early season followed by full irrigation for the rest of the season. It has been shown to enhance crop production with reduced irrigation application (Rowland et al., 2012). Preliminary data resulting from implementing primed application with the cotton app during the 2014 growing season

indicate that the yield surpassed the yields of all other scheduling methods. During this evaluation, plots under primed acclimation were irrigated at 60% of normal irrigation whenever the app indicated irrigation was needed for the first 60 days after emergence.

CONCLUSION

Weather database resources were successfully used to develop smartphone apps for scheduling irrigation. The schedules are based on real-time ET data, ET data and rainfall, or a water balance. The method by which crop stage and corresponding K_c are assigned varies based on available research. The preferred approach would be to match crop stage with GDD or observed phonological stage instead of time after planting. Apps were developed for avocado, citrus, cotton, strawberry, urban turf, and vegetables for iOS and Android products. Each app was developed based on the user needs, irrigation system, and outputs desired for optimizing irrigation scheduling.

Future smartphone app development should include better rainfall information. The use of FAWN and GAEMN limits the application of rainfall in the irrigation schedule at locations where the app is applied due to the spatial variability of rainfall and the limited number of weather stations available. Possible alternative data sources include PRISM data from the Oregon State Climate Group and NOAA Real-Time Mesoscale Analysis (RTMA).

While the apps provide irrigation schedules that are designed to increase water use efficiency and water conservation, their ability to do so has not been assessed. Future evaluation of the SmartIrrigation apps in terms of their adoption and corresponding water savings is needed. While water savings per app is being evaluated in research studies, this does not provide information on adoption by growers. Future work will include assessment of the apps to determine the number of users, the area in which the apps are being applied for irrigation scheduling, and the estimated water savings.

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