Chapter 4

Using Smartphone Technologies to Manage Irrigation

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77304

Abstract

Numerous tools have been developed with the aim of improving irrigation scheduling. Some methods involve using soil moisture sensors and irrigating based on soil moisture thresholds. Others may be based on evapotranspiration models. More novel techniques include irrigating based on the water status within the target crop. However, growers have been reluctant to adopt many of these irrigation scheduling methods because they may be too cumbersome to use, require specialized equipment, or are perceived as too risky compared to traditional methods. Recently, smartphone applications have been developed that schedule irrigation based on crop coefficients and real-time weather data. Called the SmartIrrigation™ application (smartirrigationapps.org), these tools have the potential to aid farmers in conserving water and nutrients, while maintaining crop yields. These applications were developed by the University of Florida and include such crops as citrus (*Citrus spp*.), cotton (*Gossypium hirsutum*), turfgrass, blueberries (*Vaccinium darrowii*), and several vegetables. These applications can be downloaded for free by the public and utilize real-time data from nearby weather stations in Georgia and Florida. To determine the efficacy of the new SmartIrrigation™ applications for watermelons and tomatoes, trials were conducted over 2 years in southern Georgia, USA.

Keywords: drip irrigation, plasticulture, soil moisture sensor, evapotranspiration

1. Introduction

Fruit and vegetable farmers in the USA rely on irrigation to produce high-value crops. Though drip irrigation is perceived to be efficient compared to other forms of irrigation, mismanagement can result in excessive water applications with water migrating through macropores (worm holes, cracks, root channels) to below the root zone. Previous experiments have demonstrated that water used for irrigation can be detected in a pan lysimeter within 20 min of drip irrigation initiation on tomatoes [1]. When the water used for irrigation migrates below the root zone, there may be associated leaching of fertilizer and pesticides [2]. Efficient irrigation scheduling requires that farmers manage the timing and duration of irrigation in a manner that maintains yield and quality, while efficiently using water. Many irrigation scheduling methods exist including: the water balance (WB) method, soil moisture monitoring, hand feel and soil appearance, and crop phenology observations. Water balance-based irrigation scheduling relies on reference (ET_o) measurements to estimate water losses from a given area [3].

A majority of vegetable growers use traditional methods of measuring soil moisture, by observing soil dryness and through feeling the soil itself. Recent surveys conducted in Georgia (US) found that this method accounts for over 40% of the irrigation scheduling occurring on farms. In addition, an estimated 88% of growers in Georgia may allow crops to be visibly stressed before watering [4]. Other methods of soil moisture-based irrigation may utilize tensiometers, granular matrix probes, or resistance-based sensors to determine thresholds for irrigation management [5, 6]. While soil moisture sensor (SMS)-based irrigation has been shown to be more efficient than a time-based system [7–9], proper placement of sensors to accurately reflect conditions experienced by the plant can be challenging [10]. Furthermore, placement of sensors within an irrigation zone can be problematic for growers with heterogeneous soils or topography within a field. Irrigation thresholds may also be impacted by factors such as soil type and depth of drip tubing [11].

2. Determining irrigation scheduling

2.1. Evapotranspiration

Evaporation and transpiration are two important processes involved in the removal of water from soil and plants into the atmosphere. These processes occur simultaneously and are inherently connected to each other [12]. While transpiration and evaporation occur simultaneously, evaporation is based on the availability of water in topsoil and the amount of solar radiation reaching the soil surface [13]. Transpiration is a function of crop canopy density and soil water status. Evaporation accounts for the majority of crop evapotranspiration (ET_c) during early stages of crop growth in bare-ground plantings, while transpiration contributes to nearly 90% of the ET_c for a mature crop [14].

Evapotranspiration can be separated into ET_o and ET_c. Crop evapotranspiration is calculated from ET_o of a given area and the crop coefficient (K_c) of the crop being measured. Factors affecting ET_c include extent of ground cover, crop canopy properties, and aerodynamic resistance [12]. Reference ET_o is the amount of water exiting the soil at any time from a reference surface covered by grass at a 0.12 m height that is adequately watered, actively growing, and with a fixed surface resistance [14]. Weather conditions are also important to quantify as they affect the amount of energy available for ET_o to occur. The four most important conditions to measure are solar radiation, wind speed, temperature, and humidity, with the most important factor being solar radiation [15].

http://dx.doi.org/10.5772/intechopen.77304

Crop coefficients are an adjustable constant that define the amount of transpiration occurring within a plant at a given stage of development. Crop coefficients are computed as the ratio ET_o:ET_c. Environmental and physiological factors affecting K_c include crop type, crop growth stage, climate, and soil type [14]. Plant developmental stage encompasses the relative activity of the plant. Plant size is also impacted by the crop development stage, thus affecting leaf area and canopy density, which in turn impacts transpiration. Accounting for environmental and management factors that influence the rate of canopy development is also important in calculating K_c. Climatic factors that significantly affect K_c are rainfall frequency, wind speed, temperature, and photoperiod [14]. Soil profile characteristics that affect K_c development are water table depth and soil porosity. Therefore, regional K_c estimates from several seasons are important to account for the variability in weather, irrigation, drainage, and runoff [16, 17].

Several WB-based methods exist to calculate ET_o rate, such as the Priestley-Taylor method and Hargreaves method. The Priestly-Taylor equation is a modification of the Penman-Monteith equation that approximates parameters established by the Penman-Monteith, using solar radiation to determine ET_o. However, calculations at a research site in the humid Southeastern USA found that Priestley-Taylor could overestimate ET_o for the region [18]. Priestly-Taylor has also been reported to overestimate the cumulative ET_o for the Georgian Coastal Plain area during months with significant rainfall, corresponding to peak early summer vegetable production [18]. Another method that has been used to estimate ET_o has been the Hargreaves method. This equation is an empirical model that considers incoming solar energy, evaporation, monthly maximum and minimum temperature, and a temperature coefficient [19]. This method has a high correlation with the Penman-Monteith model for estimates of average weekly ET_o in humid regions [19]. These methods of calculating evapotranspiration are easier to use than the Penman-Monteith method; however, this can also result in reduced precision over the course of a season.

2.2. Current recommendations

Current recommendations for drip-irrigated tomatoes in Georgia and Florida are based on variations of the WB method [20]. The WB method estimates daily crop water use based on historical theoretical ET_o values for the region adjusted with a K_c [14]. An advantage of using the WB method is that it allows growers to anticipate crop water requirements at certain times during the growing season and plan irrigation based on anticipated ET_o. However, irrigating solely based on predicted ET_o values may be inaccurate due to changes in annual weather patterns as well as differences in production practices for which crop coefficients were developed [21].

Regulated deficit irrigation is another method of irrigation management performed by imposing water deficits only at certain crop development stages [22]. Progressive or sustained deficit irrigation is the systematic application of water at a constant fraction of ET_c throughout the season. Reducing irrigation based on deficit ET_c levels may not result in optimal yields or quality in some crops as reducing ET_c has been shown to result in a concomitant decrease in yield of many crops [22].

2.3. Smartphone irrigation technologies

Recently, a suite of smartphone-based irrigation scheduling tools, which use real-time ET_o data from statewide weather station networks, were developed [24]. Called SmartIrrigation™ Apps [24], these tools use meteorological parameters to determine irrigation schedules based on ET_c calculated using K_c and ET_o in the following relationship: $ET_c = ET_o \times K_c$. The suite includes applications for avocado (*Persea americana*), citrus, strawberry (*Fragaria × ananassa*), cotton, turfgrass, and several vegetables. Prior studies have reported that the applications have performed well for citrus in Florida and cotton in Georgia [23, 25]. Migliaccio et al. [25] reported up to a 37% reduction in water use for growers using the SmartIrrigation™ Citrus App. in Southern Florida. SmartIrrigation™ applications developed for turfgrass management evaluated in Southern Florida were found to improve water savings of up to 57% compared to traditional methods [26]. The use of SmartIrrigation™ Cotton App resulted in the reduction of water used for irrigation by 40–75% with concomitant 10–25% increases in yield in Georgia when compared to the WB-based method recommended for cotton by the University of Georgia Cooperative Extension Service. The SmartIrrigation™ Cotton App also performed well when compared to SMS-based methods [25].

The SmartIrrigation™ Vegetable App (VegApp) generates irrigation recommendations based on real-time weather for vegetables. The VegApp currently can be used to schedule irrigation for multiple crops including tomato (*Solanum lycopersicum*), cabbage (*Brassica oleracea var. capitata*), squash (*Cucurbita pepo*), and watermelon (*Citrullus lanatus*). The weather data are retrieved from the Florida Automated Weather Network or the University of Georgia Automated Environmental Monitoring Network and are used to calculate ET_o from air temperature, solar radiation, wind speed, and relative humidity measurements using the FAO Penman-Monteith Equation [23]. Each new field registered in the VegApp by a user is automatically associated with the closest weather station; however, the user has the option to select any of the other available weather stations. The VegApp uses ET_o from the prior 5 d to calculate an average ET_o. Then ET_c is estimated using K_c curves developed by The University of Florida based on a weeks-after-planting model of crop maturity [27, 28]. The K_c curve for tomato is based on a drip-irrigated crop grown on plastic mulch [27, 28]. The VegApp may then provide an irrigation schedule for the subsequent 2 weeks. The user can recalculate requirements at any time to devise a weekly or even daily irrigation schedule. The irrigation schedule is provided to the user as an irrigation run time per day. Additional model variables used by the VegApp to schedule irrigation include crop, row spacing, irrigation rate, irrigation system efficiency, and planting date. The VegApp differs from other applications in the SmartIrrigation™ suite, in that it does not account for precipitation or soil type as it is designed for use with vegetables grown in a drip irrigation and raised-bed plastic mulch production system [23].

3. Evaluating the SmartIrrigation™ vegetable application in tomatoes and watermelons

3.1. SmartIrrigation™ vegetable application performance in tomatoes

Studies conducted during the 2016 and 2017 spring growing seasons in Georgia compared the new VegApp to currently recommend WB-based methods as well as an SMS-based system.

Total water use, yield, irrigation water use efficiency (IWUE), soil moisture status, and plant macronutrient content in tomato "Red Bounty" (HM Clause, Davis, CA) were measured.

Results of studies conducted with tomatoes in Georgia over 2 years suggested that the weather conditions during the growing season can influence the relative performance of the VegApp. Results from the 2016 growing season showed that the WB-based method of irrigation used the most water, followed by plants grown using the VegApp and SMS-based irrigation (**Table 1**). The SMS irrigation method used the least amount of water in 2016, which was similar to results obtained in other studies evaluating the impact of tensiometers for irrigation scheduling [29]. In 2016, plants grown with the VegApp utilized less water than the WB method, suggesting that applying real-time ET_o values obtained by nearby weather stations may be more efficient than using historic ET_o values [28] in some seasons. Irrigation volumes in the second year of the study were lower than the first year levels for WB and VegApp-based irrigations. There were two likely causes for the increase in water use for the SMS-based and VegApp methods relative to the WB method in 2017. In 2017, the VegApp accounted for higher levels of ET_c in the earlier growing season than historic ET_o values. In addition, there were several significant rain events late in the 2017 growing season, which resulted in irrigations in the VegApp and WB being discontinued for a period of several days. During the time period when irrigation was turned off, the WB method would have called for more water than the VegApp based on historic ET_o values.

Discontinuing irrigation led to relatively less water being used by the WB method in 2017. The contribution of rainfall has not been incorporated into the VegApp due to limited information regarding the impact of rain on soil moisture levels under raised beds covered with plastic mulches and the potential for significant spatial variability in precipitation [23]. Soil water tension readings (data not shown) suggested that levels of soil moisture were not significantly affected by rainfall. This suggests that the assumption that the VegApp does not incorporate rainfall into irrigation recommendations for crops grown on raised beds with plastic mulch is appropriate.

Irrigation treatment	**Irrigation volume**	**Daily water use**
	($L \cdot ha^{-1}$)	**($L \cdot ha^{-1} \cdot d^{-1}$)**
	2016	
VegApp	3306,000[z]	39,380
WB	4,526,000	53,880
SMS	1,935,000	23,010
	2017	
VegApp	1,895,000	29,180
WB	1,684,000	25,910
SMS	2,339,000	36,010

[z]Mean separation could not be performed between treatments as water meters were not replicated in individual treatments.

Table 1. Season irrigation volume and daily water use for tomatoes grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

When averaged over the two study years, the VegApp used 16% less water than the WB method, though much of this was due to the 2016 growing season. The SMS-managed plots utilized 31% less water than the WB method. This suggests that the VegApp and SMS-based irrigation can reduce water use when compared to methods relying on historic ET_o to manage irrigation. This may be expected as numerous studies have demonstrated the efficiencies of a microclimate and SMS-based irrigation when compared to historical ET-based methods [30].

While tomatoes grown using the VegApp utilized less water than the currently recommended WB irrigation method, yields were comparable among the three treatments (**Table 2**). In both study years, plants grown using the VegApp had the highest numerical total yield, but this was not significantly different than the other treatments.

In 2016, plants grown using the SMS-based irrigation method had a significantly higher IWUE when compared to those grown using the VegApp and WB-based methods (**Table 2**). While the yield of the SMS-managed plots was numerically lower than the other irrigation treatments in 2016, the SMS plots used substantially less water than the VegApp and WB-based plots, resulting in a significantly greater IWUE. In 2017, the VegApp had a significantly greater IWUE than the SMS-based irrigated plants. The increased IWUE in 2017 for VegApp and WB-grown plants was due to the decrease in irrigation volume used (**Table 1**). During this study, the SMS-grown plants had the most consistent IWUE, with 25.2 $g \cdot L^{-1}$ and 24.0 $g \cdot L^{-1}$ in 2016 and 2017, respectively, which were similar to those reported for fresh market tomato in North Florida [7]. The IWUE of the other irrigation treatments were more variable. This variability was the result of fluctuations in water used with no significant difference in yield (**Table 2**). However, when averaged over both study years, the IWUE of the VegApp and SMS-based irrigations were numerically similar. DePascale et al. [30] reported real-time microclimate-based irrigation to

Irrigation treatment	**($kg \cdot ha^{-1}$)**			**($g \cdot L^{-1}$)**
	Total	**Extra large**	**Large**	**IWUE[z]**
	2016			
VegApp	58,490a[y]	36,310a	17,180a	18.0b
WB	57,500a	35,280a	17,490a	13.2b
SMS	48,740a	30,350a	14,160a	25.2a
	2017			
VegApp	57,990a	51,130a	5560a	31.1a
WB	50,620a	43,660a	5840a	30.0ab
SMS	54,590a	46,370a	6970a	24.0b

[z] IWUE = total marketable yield divided by seasonal irrigation volume.

[y] Values in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Table 2. Marketable yields of total, extra-large, and large fruit and irrigation water use efficiency (IWUE) for tomatoes grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

be slightly more efficient than tensiometer-based irrigation scheduling. The automated SMS-based system has the ability to deliver water at a high frequency with short-duration (pulsed) irrigation events, which have been shown to reduce water use while maintaining yields of tomato [31]. Pulsed irrigation typically results in a shallower wetting front shortly after the irrigation event, increasing application efficiencies [32, 33]. The VegApp and WB-based irrigations were scheduled for two events per day to simulate optimal grower practices, suggesting that the twice-daily irrigations with the VegApp tool may be as efficient in some years as a more complex SMS-based system.

Foliar concentrations of macronutrients were measured during this 2-year trial. While there were no significant differences among treatments for most macronutrients in either study year, plants grown with the VegApp had significantly higher nitrogen (N) levels than the WB- and SMS-grown plants in 2017 (**Figure 1**). In 2017, the VegApp had foliar N concentrations of 5.56% when compared to 5.04% and 4.61% in the WB and SMS-treated plants, respectively. In 2017, less water was applied to WB-grown plants, yet these plants had lower leaf N concentrations. However, during periods of sampling (fruit formation), the historic ET_o values used in the WB-based irrigation methods were higher than those generated using the VegApp. This additional application of water during the sampling period may have resulted in leaching of some fertilizer during fruit formation.

3.2. SmartIrrigation vegetable application performance in watermelon

Watermelons were also grown in order to evaluate the performance of the VegApp when compared to WB-based and SMS-managed irrigation regimes. Water usage, fruit yield, quality, and nutrient content were measured in plasticulture-grown "Melody" seedless watermelons over 2 study years. Results in the watermelon trial were similar to those of the tomatoes.

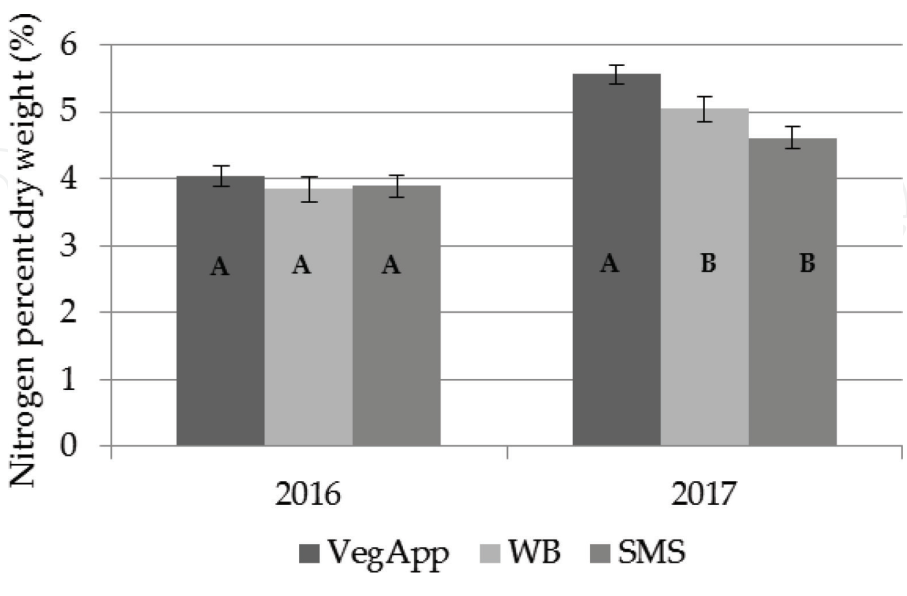

Figure 1. Comparison of foliar nitrogen levels between tomato plants grown using Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

The SMS irrigation method used the least amount of water in 2016, which was similar to results found in tomatoes in 2016 (**Table 3**). Likewise, irrigation volumes in 2017 were lower than 2016 in watermelons. This is not unexpected as ET_c was 29% lower in 2017 than in 2016. As with tomatoes, in 2017, the VegApp accounted more appropriately for lower levels of ET_c in late May and June for watermelons when compared to the WB method using historic ET_o values. This resulted in a larger relative reduction in water use in the VegApp plots when compared to plants grown using the WB method in 2017.

When averaged over the 2 years of the study, the VegApp used 15% less water than the WB method, and the SMS-based regime utilized 29% less water than the WB method. Unlike tomatoes, the VegApp used less water than the WB-grown plants in both study years. The cumulative water use data suggests that the VegApp was more conservative in scheduling water than the current recommended WB method.

The performance of the VegApp when compared to the SMS-based system was more variable over the 2 study years. Several studies have reported improved irrigation efficiencies using SMS-based or real-time ET_c data when compared to historic ET_o-based methods [30, 31]. Nonetheless, in both study years, the VegApp utilized less water than the WB method, again suggesting that applying real-time ET_o values obtained by nearby weather stations may be more efficient than historic ET_o values.

As with tomatoes, total yields of watermelon were not impacted by irrigation treatment in either study year (**Table 4**). There were differences between first harvest yields in 2016, with plants grown using the SMS-based irrigation regime having a significantly lower first harvest than the other treatments. This may be due to the lower irrigation volume used by the SMS-grown plants in the hot and dry 2016 growing season. In 2017, there were differences in yields of 45-ct fruit among the treatments, with WB-grown plants having the lowest yields of this size category of melon.

Irrigation treatment	**Irrigation volume**	**Daily water use**
	(L·ha^{-1})	**(L·ha^{-1}·d^{-1})**
	2016	
VegApp	2892,000[z]	26,570
WB	3,024,000	27,780
SMS	1,997,000	18,330
	2017	
VegApp	1,438,000	16,000
WB	2,067,000	23,010
SMS	1,629,000	17,960

[z]Mean separation could not be performed between treatments as water meters were not replicated in individual treatments.

Table 3. Season irrigation volume and daily water use for watermelon grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

http://dx.doi.org/10.5772/intechopen.77304

Irrigation treatment	(kg·ha^{-1})			
	Total	45 ct[z]	36 ct	First harvest
	2016			
VegApp	55,640a[x]	12,100a	22,750a	30,350a
SMS	55,190a	11,400a	23,150a	22,960b
WB	48,600a	7990a	21,290a	31,990a
	2017			
VegApp	56,310a	23,730ab	10,180a	20,440a
SMS	65,430a	28,970a	12,870a	23,510a
WB	66,580a	16,720b	16,020a	23,770a

[z] 45 ct = 6.2 to 7.9 kg, 36 ct = 8.0 to 9.7 kg.

[x] Values in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Table 4. Total marketable yields, first harvest yields, and yield of 45 and 36 count (ct) fruit for watermelons grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

Similar to tomatoes, there were differences in IWUE among treatments and study years. However, there were no interactions between the study year and the treatment. Analysis of main effects indicated that IWUE in the VegApp was not significantly different than either the SMS or WB irrigation systems (**Table 5**). In addition, results of foliar nutrient analysis in the watermelons were similar to those in tomatoes. Foliar N concentrations were significantly higher in the VegApp-treated plots than the SMS-grown plants (**Table 5**). In this instance, the increase in foliar N levels in VegApp-grown plants compared to SMS-managed plants may not be due to differences in leaching, as the SMS-grown plants utilized less water than those managed using the VegApp. A shallower wetting front that may be associated with pulsed-type irrigations in the SMS system may have resulted in a shallower root system in

	IWUE[z]	N
Irrigation treatment	(g·L^{-1})	(%)
VegApp	28.8ab[y]	4.54a
SMS	33.6a	4.21b
WB	24.0b	4.30ab

[z] IWUE = season irrigation volume divided by total marketable yield.

[y] Values in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Table 5. Effects of treatment for irrigation water use efficiency (IWUE) and foliar nitrogen (N) concentrations for watermelons grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

those plants reducing nitrogen uptake by those plants. Alternatively, the VegApp, through improved early-season irrigation management, may improve root growth and the ability for crops to remove nutrients from the soil profile [34].

4. Conclusions

The rapid incorporation of smartphones into the daily lives of individuals has opened new avenues for data delivery. A 2015 survey indicated that 69% of farmers owned smartphones, and this number was expected to increase to 87% by 2016 [35]. As access to smartphone technology increases, dispersal of precise irrigation scheduling methods may also increase. Using real-time weather data to schedule irrigation is not a new concept; however, previously, it would have involved directly downloading data from a weather station or, more recently, accessing data from the Internet-based site and entering it into a fairly complicated equation to develop irrigation recommendations. This process was generally too time-consuming for growers who may be managing dozens if not hundreds of irrigation zones. By linking to nearby weather stations and generating automated recommendations that are sent directly to a smartphone in the field, these new SmartIrrigation™ applications bypass the cumbersome data transfer and calculations previously required for scheduling irrigation. Our data suggest that the VegApp is more efficient in terms of water use than a well-managed irrigation program developed from historic Et_o data and, in most cases, just as efficient as a relatively complicated SMS-based system, while maintaining similar yields. In addition, our data suggest that some of the assumptions incorporated into the VegApp (e.g., rainfall not accounted for when using raised beds covered with plastic mulch) are indeed appropriate. Because these trials were conducted on a loamy sand soil, we could not confirm how soil type would affect the efficiency of the VegApp. Nonetheless, our findings suggest that the SmartIrrigation™ applications represent an easily accessible tool that growers and managers can use to produce vegetables by an efficient irrigation management system.

Acknowledgements

We would like to thank the Georgia Department of Agriculture for funding this research through a Specialty Crop Block Grant titled: *SmartPhone Apps for Scheduling Irrigation in Six Specialty Crops*. We would also like to thank the University of Florida for developing the SmartIrrigation™ used in these experiments.

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