ALTERNATIVE IRRIGATION SCHEDULING: COMPARING THE SMARTIRRIGATION™ APPLICATION FOR VEGETABLES TO CHECKBOOK AND SOIL MOISTURE BASED IRRIGATION METHODS

by

LUKE MILLER

(Under the Direction of Timothy Coolong)

ABSTRACT

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. To determine the efficacy of the new SmartIrrigation™ applications for watermelons and tomatoes, trials were conducted comparing them to automated soil-moisture based irrigation (tensiometers) and current recommendations based on traditional water-balance methods. Watermelon *(Citrullus lanatus*) 'Melody' and tomato (*Solanum lycopersicum*) 'Red Bounty' were planted into raised beds of black plastic mulch in spring 2016 and 2017 to determine the ability of the SmartIrrigation™ application to accurately schedule irrigation. Total water use, soil moisture at depths of 15, 25, and 36 cm, as well as yield, and internal quality parameters were recorded in both years of the study.

INDEX WORDS: Watermelon, Tomato, Irrigation, Water Use, Soil Moisture, SmartIrrigation™ App, Tensiometers

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LUKE MILLER

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LUKE MILLER

Major Professor: Timothy Coolong

Committee: George Vellidis
George Boyhan

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
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DEDICATION

This thesis is dedicated to my family for all of the love and support they have given me throughout this process, none of this would be possible without all of you.

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

Irrigation management information is crucial to increase economic and environmental benefits to tomato (*Solanum lycopersicum*) and watermelon (*Citrullus lanatus*) growers in Georgia. The total production value of Georgian watermelons is approximately $130 million with the majority of production in southern Georgia (Wolfe and Stubbs, 2016). Watermelon acreage accounts for 15% of vegetable acreage in Georgia, and irrigation management is essential to produce consistently high yields (Wolfe and Stubbs, 2016). Tomatoes are also economically important crops in Georgia with primary production focused in southwestern Georgia. Watermelons and tomatoes comprise nearly 20% of the farm gate value for vegetables generating over $200 million of revenue (Wolfe and Stubbs, 2016). Adoption of precision irrigation in the floriculture industry in Georgia has been estimated to result in annual savings in excess of $58 million (Wolfe and Stubbs, 2016). The economic importance of the vegetable industry would increase the impact of precise irrigation management practices as the vegetable industry, valued at over $1 billion, readily exceeds the floriculture industry in economic importance.

Estimated irrigated agricultural acreage of Georgia grew by over 700% between 1960 and 1995 and now exceeds 1.5 million acres (Litts et al., 2001). While vegetable production comprises roughly 12% of the total irrigated land in Georgia, a large portion of vegetables are irrigated heavily to ensure plant vigor, due to the high value of vegetable commodities compared to agronomic crops. Advancements in management practices will continue to result in enhanced yield, but may also increase overall water demand per unit area (Boyhan et al., 2017). Evapotranspiration (ET) based weather systems and soil moisture sensor systems (SMS) are irrigation scheduling tools that provide growers the ability to adequately water crops thus ensuring quality and yield while reducing inefficient water use.

The main objective of this research was to evaluate the efficacy of the Vegetable SmartIrrigation™ application (VegApp) and record differences in its performance as an irrigation scheduling tool in comparison to traditional methods and an SMS-based system. The study evaluated water use and water use efficiency of irrigation schedules generated by the VegApp in order to determine if current crop coefficient (K_c) values for watermelons and tomatoes were accurate in their estimation of crop water use. The study compared yields and quality of watermelons and tomatoes grown under different irrigation scheduling regimes. The study assessed regional watermelon K_c estimates used in northern Florida in order to aid in development of future localized K_c values for watermelon and tomato producers in southern Georgia. Soil water tension levels were monitored to evaluate the performance of the three treatments during the growing season.

Water balance (WB) based irrigation scheduling models vary in their ability to effectively adjust K_c. Two prominent plant maturity models are the days after planting model (DAP) and the growing degree day model (GDD). The GDD models allow for changing weather conditions to impact crop maturity predictions and therefore irrigation schedules. This flexibility is valuable since a crop may experience warmer than average weather conditions and will accelerate plant maturity while cooler weather will slow progression of plant maturity.

WATERMELON PRODUCTION

Seeded and seedless production

Watermelon is a member of the *Cucurbitaceae* family, which includes cucumber, cantaloupe, squash, pumpkin, and several other important horticultural crops. Watermelons require a relatively long production season lasting at least 85 days from transplant and grow well on sandy loam soils with good drainage (Boyhan et al., 2017). Watermelons grow well in warm soils, thus, it is desirable to grow plants on raised beds as they warm quickly and improve drainage. When planted on sandy soils windbreaks are advisable to prevent stunting of young plants or from spinning young plants, which can lead to crown damage (Shrefler et al., 2012).

Commercial watermelon production in Georgia is focused primarily on seedless fruit. Seedless watermelons are triploid hybrids, and must have a seeded variety interspersed throughout the field as a pollen source necessary for seedless fruit set (Boyhan et al., 2017). Pollinizers should be planted in a 3:1 ratio among seedless watermelons and pollen from the pollenizer must be available when the triploid seedless melon can accept pollen in order to initiate fruit set (Olson et al., 2005.) Several distinctions in optimal growth conditions between seedless and seeded watermelon production exist. Germination of seedless watermelon is limited under temperatures of 80^{0} F and should not be direct seeded into the field. Seed germination is inhibited by a thicker seedcoat in seedless watermelons, which will adhere to cotyledons and delay emergence (Boyhan et al., 2017).

Although watermelon is relatively drought tolerant, sufficient rainfall or irrigation application is necessary to produce adequate yields of marketable fruit. Critical periods of time for irrigation of watermelon are before seedling emergence, at early bloom and early fruit development (Shrefler et al., 2012). Irrigation should be limited when melons are near full maturity as excessive moisture may increase the incidence of hollow heart, reduce sugars and can result in fruit splitting (Shrefler et al., 2012). Soil-borne diseases such as *Phytophthora* blight caused by (*Phytophthora capsici*) are devastating diseases in Georgia. *Phytophthora* blight can lead to lesions on fruit, which quickly cause them to rot in the field or during transport. Overwatering plants can lead to poor drainage beneath the field, which contributes to the spread of *Phytophthora* blight and other diseases (Hausbeck and Lamour, 2004).

Water Relations and Watermelon Fruit Quality

Deficient and excessive irrigation disrupt carbon partitioning and quality of watermelon production. Reduced watering leading to mild water stress in plants may result in increased stomatal resistance and may decrease water and nutrient uptake from roots as well as reduce carbon assimilation during photosynthesis (Proietti et al., 2008). Reduced carbon allocation may reduce fruit size and quality parameters in watermelon. One such quality measurement that is known to be heavily impacted by watering regime is total soluble solids content (TSS). Drought stress may increase TSS levels when growers induce mild drought stress, late in fruit development (Rouphael et al., 2008). High levels of nitrogen fertilizer and overwatering have also been implicated as potential causes of hollow heart of melons (Proietti et al., 2008). Flesh coloration of watermelons, which can range from scarlet red to canary yellow, may also be impacted by irrigation timing and duration as fluxes in water stress affect lycopene production which gives watermelon its red flesh coloration (Leskovar et al., 2004). Similarly, decreasing water availability during fruit development has been shown to affect nutritional content by increasing plant polyamine, potassium and magnesium concentration (Proietti et al., 2008).

TOMATO PRODUCTION

Tomato is a member of the *Solanaceae* family, which includes eggplant (*Solanum melongena*), Irish potatoes (*Solanum tubersom*), peppers (*Capsicum annuum*) and tobacco (*Nicotiana tabacum*). Originating in western South America between modern-day Ecuador and Chile, the tomato was domesticated in Mexico (Jenkins, 1948). Although California is the leading producer of tomatoes for fresh markets and processing, Georgia is regarded as a significant producer of fresh market tomatoes with nearly 3,600 acres grown, valued at over $54 million (Wolfe and Stubbs, 2016). Tomatoes can be either determinate or indeterminate. Determinate varieties have a defined period of flowering and fruit development while indeterminate plants produce flowers and fruits throughout the growing season (Kelley and Boyhan, 2014). Tomatoes are commonly trellised and staked. This practice improves fruit quality, allows fruit to be harvested with less effort, and enhances spray coverage uniformity. In determinate varieties, pruning may be required to ensure adequate fruit size and quality (Kelley and Boyhan, 2014). Tomatoes grow best under average monthly temperatures of 70^0 F-75^0 F and grow well until daily average temperatures go below 55^0 F (Le Strange et al., 2000). Fresh market tomatoes are commonly grown in Georgia on plastic mulch with drip irrigation. Irrigation is most critical at the time of transplanting, first bloom, and early fruit development as this effects stand establishment and fruit quality characteristics (Machado et al., 2004).

Tomato Quality

Tomato yields may be affected by water availability; however tomato quality can also be affected. Key characteristics of tomato quality are color, consistency, soluble solid content, titratable acidity, and lycopene content. Consistency values as indexed by the Bostwick index and color parameters have been shown to be positively affected by elevated irrigation (Favati et al., 2009). Conversely, ascorbic acid is a key component in determining titratable acidity levels and has been shown to be increased in fruit grown with less frequent irrigation (Favati et al., 2009).

Pan evaporation-based irrigation treatments in tomato and partial root zone drying irrigation management have been shown to maximize irrigation water use efficiency (IWUE) while maintaining yield and quality (Kirda et al., 2004). Tomatoes require an adequate and consistent water supply to avoid reductions in fruit growth and size, reduce the incidence of blossom end rot, and prevent reductions in quality (Pill and Lambeth, 1980). Quality can also be impacted by excess water which may increase nitrogen leaching and susceptibility to cracking (Peet and Willits, 1995). Therefore, it is important to determine irrigation scheduling parameters that can achieve maximum quality as well as protect yields.

IRRIGATION SCHEDULING

Irrigation Scheduling Methods

Theoretical and empirical research of evapotranspiration is essential for estimating gross irrigation requirements during the production season and to produce optimal irrigation schedules. Irrigation scheduling allows growers to minimize fertilizer costs by controlling leaching, limits root zone salinity issues, and reduces water logging by reducing drainage requirements (Broner, 2005). A wide range of irrigation scheduling methods exist including: the water balance method, soil moisture monitoring, hand feel and soil appearance, and crop phenology observation. Water balance-based irrigation scheduling relies on evapotranspiration (ET_o) measurements to estimate water losses from a given area (Broner, 2005). However, there is limited information on the level of soil water deficit that should be maintained. Soil moisture-based sensor systems can be used to monitor soil water tension or soil water content, providing real time information to allow for adjusting irrigation events (Dursun and Ozden, 2011). Soil water content is the ratio of available water content over available water capacity, which is defined by water content at field capacity and permanent wilting point. Soil water content is also subject to two types of energy, kinetic and potential, potential energy moves water from where potential energy is higher to where it is lower (Allen et al., 1998).

Regulated deficit irrigation is another type of irrigation scheduling performed by imposing water deficits at different crop development stages (Fereres et al., 2003). Progressive or sustained deficit irrigation is the systematic application of water at a constant fraction of crop evapotranspiration (ET_c) throughout the season. Reducing irrigation based on deficit ET_c levels may not result in optimal or quality as reducing ET_c has been shown to result in a concomitant decrease in yield of most crops (Fereres et al., 2003). Irrigation scheduling can improve irrigation efficiency as well as water productivity. Focusing on improving water productivity or the ratio of yield to crop evapotranspiration, has been shown to lead to net water savings more consistently than other methods (Seckler, 1996).

A majority of vegetable growers use traditional methods of measuring soil moisture, by observing soil dryness through the look and feel of the soil itself. A small group of farmers use evapotranspiration based methods of irrigation scheduling and soil moisture sensor systems. As access to smartphone technology increases dispersal of precise irrigation scheduling methods is likely to increase.

Irrigation Scheduling Apps

Weather databases have been used to aid in the development of web-based irrigation scheduling. Recently, a web-based irrigation scheduling tool was designed for smartphones in order to allow growers greater accessibility in a field setting. These smartphone applications called SmartIrrigation™ Apps utilize real-time meteorological conditions gathered from the University of Georgia Automated Weather Network (UGAWN) (Migliaccio et al., 2016). The UGAWN is comprised of weather stations that monitor environmental conditions including: solar radiation, wind speed and direction, humidity, air temperature, rainfall, atmospheric pressure, soil moisture and soil temperature. The Penman-Monteith equation along with corresponding weather parameters are used to estimate reference evapotranspiration based on the water balance used by each app (Allen et al., 1998). Crop coefficients are then used to calculate ET_c and these coefficients are adjusted through the season using a days after planting model. The VegApp also is the only application that schedules irrigation for multiple crops including, tomato, cabbage, squash and watermelon.

Prior studies have reported that several crops have positively responded to use of the SmartIrrigation™ Apps including citrus, cotton, avocadoes and strawberries in Florida. SmartIrrigation™ Apps developed for turfgrass management evaluated in southern Florida were found to improve water savings up to 57% compared to traditional methods (Migliaccio et al., 2016). The Citrus SmartIrrigation™ Apps generated up to 37% water savings and was observed for several commercial growers in southern Florida (Migliaccio et al., 2016). The Cotton SmartIrrigation™ Apps was evaluated in Georgia at the University of Georgia's Stripling Irrigation Research Park and at the UGA Tifton Campus. Results indicated that water use could be reduced by 40%-75% compared to the University of Georgia Cooperative Extension recommendations based on the WB method (Vellidis et al., 2015). SmartIrrigation™ Apps have not been evaluated extensively due to their recent development and currently only the Cotton App has been evaluated in Georgia.

EVAPOTRANSPIRATION PROCESSES

Evaporation and Transpiration

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 (Shukla et al., 2007). Evapotranspiration defines the total loss of water from a specified region of plant material and soil surface to the atmosphere. While transpiration and evaporation occur simultaneously, evaporation is based on the availability of water in topsoil and the amount of solar radiation that reaches it (Pereira et al., 1999). Transpiration is a function of crop canopy density and soil water status. Evaporation accounts for the majority of ET_c during early stages of crop growth in bare ground plantings; transpiration contributes to nearly 90% of the ET_c for a mature crop (Allen et al., 1998.)

Evapotranspiration can be separated into ET_o and ET_c. Crop evapotranspiration is calculated from ET_o of a given area and the K_c of the crop being measured. Factors affecting ET_c include, extent of ground cover, crop canopy properties, and aerodynamic resistance (Shukla et al., 2007). Reference evapotranspiration 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 (Allen et al., 2011).

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 (Brown, 2000). Solar energy is the primary factor impacting water evaporation from soil as well as movement throughout the plant. Wind is an important factor as it transports moisture that builds up on moist vegetation and other surfaces and also transports heat from the soil surface (Pereira et al., 1999). Humidity and temperature work simultaneously to influence the moisture in the atmosphere, this is known as the vapor pressure deficit. The vapor pressure deficit measures the gradient in vapor pressure between moist vegetation and the atmosphere and is preferable to relative humidity which disregards temperature in calculating air moisture content (Allen et al., 1998). Temperature also affects ET_o by reducing the energy requirement of evaporation by warming or cooling vegetation, thereby allowing water to evaporate more quickly or slowly. Warm temperatures also increase the effectiveness of radiant energy and wind in evaporating water (Brown, 2000).

Crop Coefficients

Crop coefficients are an adjustable constant that defines the amount of transpiration occurring within a plant at a given stage of development. Crop coefficients are computed as the ratio of ET_o to ET_c. Environmental and physiological factors affecting K_c include crop type, crop growth stage, climate, and soil type (Allen et al., 1998). Plant developmental stage encompasses the relative activity of the plant whether dormant or actively growing. Plant size is also impacted by the crop development stage, thus affecting plant 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 crop coefficients. The K_c of watermelons and tomatoes is low during early development and increases until the plant produces reproductive structures and decreases after fruit matures. Climatic factors that significantly affect K_c are rainfall frequency, wind speed, temperature, and photoperiod (Allen et al., 1998). Soil profile characteristics that affect K_c development are water table depth and soil porosity. Therefore, regional K_c estimates from several seasons are essential to account for the variability in weather, irrigation, drainage and runoff (Rana and Katerji, 2000; Shukla et al., 2012).

Dual K_c predict the effects of specific wetting events on the value of K_c, separating K_c into two separate coefficients representing crop transpiration and soil evaporation (Allen et al 1998). The basal crop coefficient (K_{cb}) represents transpiration and is defined as the ratio of ET_c to ET_o when water is not limiting transpiration. The soil evaporation coefficient of ET_c is termed K_E, when soils are wet the evaporation is maximal while when it is dry it is minimal (Allen et al., 1998). Evaporation takes place primarily at the exposed portion of the soil and is limited by the energy available to this exposed portion. Evaporation from the exposed soil surface will take place in two stages: the energy limiting stage and the falling rate stage (Allen et al., 1998).

Growing Degree Days and Days after Planting Models

Water balance irrigation scheduling models vary in their ability to effectively adjust K_c, two prominent plant maturity models are the days after planting model (DAP) and the growing degree day model (GDD). Utilizing DAP to estimate the change in crop evapotranspiration is based on planting date and estimated growth based on average conditions from previous growing seasons. Days after planting models typically divide crop development into four crop development stages: initial growth, rapid growth, mid-season, and late season stages (Miller et al., 2001). Days after planting models are limited in their ability to adjust K_c based on abnormal conditions as an indicator of changing crop phenology and are therefore less reliable due to exclusion of varying climatic factors. However, GDD models utilize the daily maximum and minimum temperature experienced by a crop and a base temperature to determine accumulated heat units (Ojeda-Bustamante et al., 2004). Thus, GDD models allow for changing weather conditions to impact irrigation schedules as warmer than normal weather will advance plant maturity and insect populations while cooler weather slows their reproduction (Miller et al., 2001). A degree-day occurs when the average daily temperature is at least one degree above the lower developmental threshold. The base temperature for tomato is 50^0 F as growth is inhibited below this temperature while watermelon base temperatures are often calculated from 55^0 F. At each subsequent biofix date accumulated degree days should be reduced to zero for calculation purposes (Miller et al., 2001).

The GDD scale has been reported to improve transferability of K_c curves between locations and seasons (Slack et al., 1996). The GDD model's measure of maturity in cotton also reported stronger correlations between maximum lint yields and cumulative GDD heat units than DAP (Slack et al., 1996). Research has shown that regional crop coefficients developed in Texas and New Mexico were also more precise by utilizing GDD coefficients compared to the DAP method which overestimated crop water use due to the assumption of ideal conditions throughout the entire growing season (Allen et al., 1998). Differences between generic and locally developed Kc values have been reported for agronomic crops such as wheat, corn and potato and horticultural crops like watermelon, tomato and squash (Allen et al., 1998; Kashyap and Panda, 2001; Kang et al., 2003).

Water Balance Models

Several water balance methods exist to calculate ET_c rates such as the Priestley Taylor method and Hargreaves method. The Priestly Taylor equation is a refined alteration of the theoretical Penman Monteith equation by approximating parameters established by the Penman Monteith only solar radiation is required as an input to determine ET_o. Calculations at a research site in the humid southeastern United States found that Priestley Taylor overestimated ET_o and was less accurate than the Penman Monteith method for the region (Suleiman et al., 2007). Priestly Taylor has also overestimated the cumulative ET_c for the Georgia Coastal Plain area during months with significant rainfall, which corresponds to peak early summer vegetable production (Suleiman et al., 2007). Another method that has been successful in calculating ET_c has been the Hargreaves method. This equation is an empirical model that considers incoming solar energy, average amount of energy removed by evaporation, monthly maximum and minimum temperature and a temperature reduction coefficient (Kouwen, 2002). This method has high correlation with the PM model for estimates of average weekly ET_c in humid regions (Kouwen, 2002). These methods of calculating evapotranspiration are more basic than the Penman Monteith method; however, this reduced precision also can make them less accurate over the course of a season.

ET Irrigation Controllers

ET-based irrigation controllers are divided into three subgroups based on the collection of weather data used to generate an irrigation schedule. Signal-based ET_o controllers use data from remote weather stations via wireless technology that is updated daily (Dukes et al., 2009b). An advantage of signal based controllers is that weather stations update climatic information rapidly allowing ET_o measurements to be adjusted for real time conditions (Davis et al., 2007). However; weather stations may not have representative weather readings of a specific field due to spatial variability in weather conditions. Historical ET_o controllers use averages of climatic data from previous years to estimate ET_o and schedule irrigation. Historical ET_o controllers often do not account for abnormal growing conditions during the current season as it applies the average conditions from previous decades to the current growing season weather parameters (Dukes et al., 2009a). Onsite controllers collect weather data in intervals throughout the day and calculate ET_c from the data collected and crop information provided. The on-site calculation of rainfall is beneficial in Georgia because of the spatial variability of rainfall (Bosch et al., 1999).

INSTRUMENTATION

Tensiometers

Tensiometers measure the soil water tension of the soil profile and activate watering through measurements obtained by a built-in vacuum gauge. Before the tensiometer is buried in the soil, a hand pump is used to create a partial vacuum to adjust the tensiometer to similar wet soil conditions. When water exits the soil profile via transpiration or evaporation, water exits the tensiometer and the vacuum inside the tube increases (Goodwin, 2009). As water enters the field, the vacuum inside the tube pulls moisture from the soil and the vacuum decreases. Filling of the cylinder is required to maintain proper function of the instrument to prevent breaking the water column allowing air into the cylinder and causing the tensiometer to malfunction. Tensiometers are calibrated in kilopascals or centibars and measure on a scale of 0 kPa, to 100 kPa, however they only reliably measure soil moisture tensions up to 85 kPa (Goodwin, 2009). These devices can be combined with solenoids to control irrigation systems autonomously and when paired with transducers can be used with computerized irrigation systems.

Granular Matrix Sensors

Granular matrix sensors (GMS) are calibrated to measure soil water potential and can substitute for tensiometers in irrigation scheduling. Benefits of GMS are that they require less maintenance than tensiometers during the growing season (Munoz-Carpena et al., 2005). Data acquisition with GMS can be remote from the measurement site by use of electrical wires or radio, so the plants and soil at the measurement site remain relatively undisturbed. The active portion of the GMS sensor is the area along the sides of the cylinder with the perforated stainless steel screen (Eldredge et al., 1993). Two electrodes are connected by lead wires, around the electrodes is a fine granulated substance mixed with gypsum. When soil solution enters the sensor it reduces the electrical resistance between the electrodes and resistance is read by an ohmmeter (Eldredge et al., 1993).

Lysimeters

Lysimeters are used to measure the amount of weight lost due to water discharge into the atmosphere which can determine crop evapotranspiration. A lysimeter is a container that separates soil and water hydrologically from its environment (Shukla et al., 2007). Lysimeters are used to estimate the crop water use by utilizing the principle of the conservation of mass. Crop water use is quantified using the following water balance equation: $ET_c = K_c \times ET_o$. Accuracy of K_c and ET_c derived from lysimeter measurements is affected by lysimeter design, vegetation characteristics in the catch area and duration of lysimeter use (Farahani et al., 2007; Shukla et al., 2012). Lysimeter depth should be considered when accounting for groundwater exchanges and water table fluctuations. Tension lysimeters are commonly embedded in the ground as shallow lysimeters and tend to retain more water per unit depth than actual field conditions and thus are prone to overestimating ET_c (Shukla et al., 2012). Drainage lysimeters are used to measure all inflow and outflow of water from soils during a specific period of time to estimate crop evapotranspiration from the calculated volumetric water balance. Drainage lysimeters have been used to quantify ET_c in Florida for several crops including, citrus, pepper and watermelon (Shukla et al., 2006, 2012).

PREFERENTIAL WATER MOVEMENT

Watermelon production has moved to intensive cultivation methods including the use of plastic mulch. Plastic mulch research has primarily been focused on the impact of color, soil moisture retention, soil and air temperatures, and the effects on vegetable yields. Plastic mulches directly impact the microclimate around the plant by affecting absorptivity and reflectivity of soil surface and reducing water loss (Lamont, 2005). The color of a plastic mulch can also effect water movement as it influences the energy radiating behavior of the mulch, thus altering a plant's microclimate. Clear plastics have been shown to warm soil to the greatest amount compared to bare soil and are used to control diseases and weeds in regions with high solar radition, however fumigants are needed to control weeds and diseases in colder production areas of the US (Lamont, 2004).

Roughly 85-90% of the watermelon grown in Georgia is produced using plastic mulches (T. Coolong, personal communication). Approximately 60% of watermelons are grown with narrow-row plastic (less than 36 inches wide) with overhead center-pivot irrigation. The majority of the remainder is grown using raised beds and drip irrigation. A small percentage of watermelons grown on bare-soil use center pivot irrigation. Plastic mulch limits soil moisture losses due to evaporation and helps prevent leaching of plant nutrients from watermelon beds (Boyhan et al., 2017). However, little is known about the movement of water and nutrients underneath plastic mulch following rain events. Water movement is mainly directed by macropore flow, which is the result of soil forming factors such as non-capillary cracks or channels. Surface cracks and channels that bypass the root zone are also responsible for rapid transport of water through the soil profile (Goyal, 2015). Limited research has been conducted on water movement under plastic mulch with conventional watermelon and tomato production practices.

ECONOMIC SIGNIFICANCE

The cost of irrigation for watermelon producers is significant and the advent of proper scheduling would reduce production costs. In Georgia, the application of water in watermelon fields accounts for 14% of the overall budget of the operation per acre and 4% of the overall budget of tomatoes (Fosnah et al., 2009). Annual variable costs associated with irrigating via drip irrigation are higher than other irrigation systems and are estimated at $450/acre. Georgian producers recognize the importance of managing water efficiently from a profit basis and it has been suggested that a modest fee agricultural water may also reduce overall water demand (Mullen et al., 2009). Nonetheless, growers often view water inputs as a relatively small price to pay to ensure high yields, particularly given the high value of their crops.

WATER SCARCITY

Water is a dynamic resource that is replenished through the hydrologic cycle, however, water is becoming limited across large areas of the world. Water scarcity occurs when an individual does not have access to safe and affordable water to satisfy basic water needs. A majority of the southeastern United States is projected to have mild to severe water stress by 2030, including Georgia (Morrison et al., 2009). Water scarcity in the region will increase due to climate change, which will alter the intensity and pattern of rainfall in subtropical climates. The southeastern United States has a low water holding capacity and while it has many aquifers, these are heavily dependent on rainfall. Reservoirs in Georgia have lost storage capacity due to sedimentation as well (University of Georgia, 2010). Also these reservoirs are reliant on consistent seasonal rainfall and have been adversely affected by droughts in 2002, 2005 and 2007 (University of Georgia, 2010).

IRRIGATION PUBLIC POLICY

Drought and improper management of freshwater resources will have a continued impact in agricultural public policy. Historically, Georgian growers have responded to increased water demand by developing new supplies of water. However, the economic and environmental costs of water source development exceed the perceived benefits. Since 1994, Alabama, Georgia, and

Florida have had disputes over the allocation and use of freshwater resources of the Apalachicola, Chattahoochee and Flint River systems which cross state borders (Beaverstock, 1998) The Chattahoochee river system is largely impounded with reservoirs primarily for navigational, power and flood control purposes. Lake Lanier, the primary provider of fresh drinking water for Atlanta, lies along this river and is also used for recreational purposes. The Flint River is the most important of these three rivers for irrigation purposes although groundwater withdrawals in Southwest Georgia are mainly from the Floridian Aquifer (Ruhl, 2005).

Growers are also faced with the concern of limited accessibility to freshwater resources from aquifers or wells. In 2012, a moratorium placed on the opening of agricultural wells in the lower Flint and Chattahoochee rivers irrigation water withdrawals in southwestern Georgia has been initiated to limit irrigation withdrawals (Georgia Department of Natural Resources, 2012). This moratorium creates a higher risk of drought susceptibility for growers specializing in crops with high water requirements. The Flint River Drought Protection Act will also restrict irrigation withdrawals during severe drought, when crops are most vulnerable (Georgia Department of Natural Resources, 2012).

LITERATURE CITED

Allen, R.G., L.S. Pereira, T.A. Howell, and M.E. Jensen. 2011. Evapotranspiration information reporting: II. Recommended documentation. Agric. Water Manage. 98 (6):921–929.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: Proceedings of the Irrigation and Drainage Paper No. 56. Food and Agricultural Organization, United Nations, Rome, Italy.

Beaverstock, J.U. 1998. Learning to Get Along: Alabama, Georgia, Florida, and the Chattahoochee River Compact. 1-8.

Bosch, D. D., J. M. Sheridan, and F. M. Davis. 1999. Rainfall characteristics and spatial correlation for the Georgia Coastal Plain. Trans. ASAE 42 (6):1637−1644.

Boyhan, G., D.W. Granberry, and W.T. Kelley. 2017. Commercial watermelon production handbook. Univ. Georgia Coop. Ext. Bull. 996.

Broner, I. 2005. Irrigation Scheduling. Colorado State University Extension. Fort Collins, CO. Cooperative Ext. Bulletin. 4.708.

Brown, P. 2000. Basics of evaporation and transpiration. College of Agricultural and Life Sciences. University of Arizona. Tucson, AZ.

Davis, S., M.D. Dukes, S. Vyapari, and G.L. Miller. 2007. Evaluation and demonstration of evaporation-based irrigation controllers (Proc. ASCE EWRI World Environmental and Water Resources Congress, Tampa, FL, 15–19 May 2007.

Dukes, M.D., M.L. Shedd, and S.L. Davis. 2009a. Smart Irrigation Controllers: Operation of Evapotranspiration-Based Controllers. University of Florida Extension. Gainesville, FL.

Dukes, M.D., M.L. Shedd., and S.L. Davis. 2009b. Smart Irrigation Controllers: Programming Guidelines for Evapotranspiration-Based Irrigation Controllers. University of Florida Extension. Gainesville, FL.

Dukes, M. D., L. Zotarelli, and K. T. Morgan. 2010. Use of irrigation technologies for vegetable crops in Florida. Horttechnology, 20:133–142.

Dursun, M. and S. Ozden. 2011. A wireless application of drip irrigation automation supported by soil moisture sensors. Sci. Res. Essays. 6:1573–1582.

Eldredge, E.P., C.C. Shock, T.D. Stieber. 1993. Calibration of granular matrix sensors for irrigation management. Agron. J. 85:1228–1232.

Georgia Department of Natural Resources. 2012. Flint River Basin Plan Legislation and Guidelines. Environmental Protection Department. 39-45.

Goodwin, I. 2009. How to use tensiometers. Department of Environment and Primary Industries. Melbourne, Australia. Pub. AG0298.

Farahani, H., T. Howell, W. Shuttleworth and W.C. Bausch. 2007. Evapotranspiration: progress in measurement and modeling in agriculture. Trans Am Society Agricultural & Biological Engineers 50:1627–1638.

Favati, F., S. Lovelli, F. Galgano, V. Miccolis, T. Di Tommaso, and V. Candido. 2009. Processing tomato quality as affected by irrigation scheduling. Sci. Hortic. Amsterdam 122:562–571.

Fereres E, D.A. Goldhamer, L.R. Parsons. 2003. Irrigation water management of horticultural crops. Historical review compiled for the American Society of Horticultural Science's 100th Anniversary. HortScience 38:1036-1042.

Fosnah, E.G., A.N. Sparks, G.E. Boyhan., S. Culpepper, J.C. Diaz, P. Sumner, G. Kelley, and D. Langston. 2009. MALTAG Conventional Vegetables Planning Budgets. UGA Extension Athens, GA.

Goyal, M. 2015. Sustainable Practices in Surface and Subsurface Microirrigaton. Apple Academic Press. Toronto, New Jersey. 184-206.

Hausbeck, M.K. and K.H. Lamour. 2004. *Phytophthora capsici* on vegetable crops: research progress and management challenges. Plant Dis. 12:1292-1303.

Jenkins, J.A. 1948. The origin of the cultivated tomato. Econ. Bot. 2:379–392

Kang, S., B. Gu, T. Du, and J. Zhang. 2003. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. Agric. For. Meteorol. 59:239–254.

Kashyap, P.S., and R.K. Panda. 2001. Evaluation of evapotranspiration methods and development of crop-coefficients for potato crop in a sub-humid region. Agric. Water Manage. 50:9–25.

Kelley, W.T., and G.E. Boyhan. 2014. Commercial Tomato Production Handbook. University of Georgia Cooperative Extension. Bull. 1312.

Kirda C., M. Cetin, Y. Dasgan, S. Topcu, H. Kaman, B. Ekici, M.R. Derici, A.I. Ozguven. 2004 Yield response of greenhouse grown tomato to partial root drying and conventional deficit irrigation. Agric. Water Manage. 69:191–202.

Kouwen, N. 2002. Hargreaves Equations. WATFLOOD. Civil Engineering Department. University of Waterloo. Waterloo, ON, Canada.

Lamont, W. J. 2004. Plastic mulches. In: Lamont W (ed) Production of vegetables, strawberries, and cut flowers using plasticulture. Natural Resource, Agriculture, and Engineering Service (NRAES), Ithaca.

Lamont, W.J. 2005. Plastics: modifying the microclimate for the production of vegetable crops. HortTechnology 15:477–481.

Leskovar, D.I., H, Bang, K. Crosby, N. Maness, J.A. Franco, P. Perkins-Veazie, 2004. Lycopene, carbohydrates, ascorbic acid and yield components of diploid and triploid watermelon cultivars are affected by deficit irrigation. J. Hortic. Sci. Biotechnol. 79:75–81.

Le Strange M., W.L. Schrader, T.K. Hartz. 2000. Fresh Tomato Production in California. University of California Division of Agriculture and Natural Resources. Pub. 8017.

Litts, T., A. Thomas, and R. Welch. 2001. Mapping irrigated lands in southwest Georgia. Center for Remote Sensing and Mapping Science Department of Geography. The University of Georgia.

Machado, R.M.A., M. Rosario, G. Oliveira, C.M. Portas. 2003. Tomato root distribution, yield and fruit quality under subsurface drip irrigation. Plant and Soil 255:333–341.

Migliaccio, K.L., K.T. Morgan, G. Vellidis, L. Zotarelli,, C. Fraisse, D. Rowland., J.H. Andreis, and J.H. Crane. 2016. Smartphone apps for irrigation scheduling. Emerging Technologies for

Sustainable Irrigation: A joint ASABE / IA Irrigation Symposium, Long Beach, California, November 10 – 12, 2015.

Miller, P., W. Lenier, and Brandt, S. 2001. Using growing degree days to predict plant stages. Montana Guide Fact Sheet MT 200103 AG 7/2001. Montana State University Extension Service, Bozeman, Montana.

Morrison, J., M. Morkawa, M. Murphy, and P. Schulte. 2009. Water Scarcity and Climate Change: Growing Risks for Business and Investors, CERES, Boston, MA.

Mullen, J.D., Y. Yu, and G. Hoogenboom. 2009. Estimating the demand for irrigation water in a humid climate: A case study from the southeastern United States. Agric. Water Manage. 96:1421–1428.

Munoz-Carpena, R., M.D. Dukes, Y.C.C. Li., W. Klassen. 2005. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. HortTechnology 15:584–590.

Ojeda-Bustamante W, E. Sifuentes-Ibarra, D.C. Slack and M. Carrillo. 2004, Generalization of irrigation scheduling parameters using the growing degree days concept: Application to a potato crop. Irrigation and Drainage. 53:251-261.

Olson, S. M., E. H. Simonne, D. N. Maynard, G. J. Hochmuth, C. S. Vavrina, M. W. Stall, P. D. Roberts, S. E. Webb, T. G. Taylor, and S. A. Smith. 2005. Cucurbit production in Florida. pp. 81-85 *In* S. M. Olson and E. Simmone [eds.], Vegetable Production Handbook for Florida. University of Florida, IFAS Extension.

Peet, M.M. and D.H. Willits. 1995. Role of excess water in tomato fruit cracking. Hortic. Sci. 30: 65–68.

Pereira, L.S., Perrier, A., Allen, R.G., and Alves, I., 1999. Evapotranspiration: review of concepts and future trends. J. Irrig. Drain. Eng. 125 (2):45–51.

Pill, W.G. and V.N. Lambeth. 1980. Effects of soil water regime and nitrogen form on blossom-end rot, yield, water relations, and elemental composition of tomato. J. Am. Soc. Hortic. Sci. 105 (5): 730–734.

Proietti, S., Y. Rouphael, G. Colla, M. Cardarelli, M. De Agazio, M. Zacchini, S. Moscatello, and A. Battistelli. 2008. Fruit quality of mini-watermelon as affected by grafting and irrigation regimes. J. Sci. Food Agr. 88:1107-1114.

Rana. G. and N. Katerji. 2000. Measurements and estimation of actual evapotranspiration in the field under Mediterranean climate: a review, European Journal of Agronomy 13:25–153.

Rouphael, Y., M. Cardarelli, G. Colla, and E. Rea. 2008. Yield, mineral composition, water relations, and water use efficiency of grafted mini-watermelon plants under deficit irrigation. HortScience 43:730-736.

Ruhl, J. B. 2005. Water wars, eastern style: Divvying up the Apalachicola-Chattahoochee-Flint River Basin. J. Contemp. Water Res. Ed. 131: 47–54.

Seckler, D. 1996. The new era of water resources management: From 'dry' to 'wet' water savings. Res. Rpt. 1. Intl. Irr. Mgt. Inst., Colombo, Sri Lanka.

Shrefler, J., L. Brandenberger, E. Rebek, J. Damicone, and M. Taylor. 2012. Watermelon Production. Oklahoma State Cooperative Extension Service. Pub. HLA-6236. 1-7.

Shukla, S., F.H. Jaber, D. Goswami, and S. Srivastava. 2012. Evapotranspiration losses for pepper under plastic mulch and shallow water table conditions. Irrig. Sci., 31(3): 523-536.

Shukla S., F. Jaber, S. Srivastava, and J. Knowles 2007. Water Use and crop coefficient for watermelon in Southwest Florida. Agricultural and Biological Engineering Department.

Shukla, S., S. Srivastava, S., and J.D. Hardin. 2006. Design, construction, and installation of large drainage lysimeters for water quantity and quality studies. Appl. Eng. Agric. 22(4):529-540.

Slack, D.C., E.C. Martin, A.E. Sheta, F. Fox Jr., L.J. Clark, and R.O. Ashley. 1996. Crop coefficients normalized for climatic variability with growing-degree-days. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Evapotranspiration and Irrigation Scheduling. ASAE, St. Joseph, San Antonio, TX, 892–898.

Smajstrla, A.G. and S.J. Locascio. 1990. Irrigation scheduling of drip-irrigated tomato using tensiometers and pan evaporation. Proc. Fla. State Hort. Soc. 103:88-91.

Suleiman, A.A., and G. Hoogenboom. 2007. Comparison of Priestley–Taylor and FAO-56 Penman–Monteith for daily reference evapotranspiration estimation in Georgia, USA. Journal of Irrigation and Drainage Engineering 133:175–182.

University of Georgia. 2010. Southeastern U.S., with exception of Florida, likely to have serious water scarcity issues. ScienceDaily.

Vellidis, G., V. Liakos, C. Perry, P. Roberts, M. Tucker, and E. Barnes. 2015. Field evaluation of a smartphone app for scheduling irrigation in cotton. Proceedings of the 2015 Beltwide Cotton Conference, New Orleans, LA, National Cotton Council, Memphis, TN.

Wolfe, K., and K. Stubbs. 2016. 2015 Georgia Farm Gate Value Report. The Center for Agribusiness, & Economic Development, College of Agricultural & Environmental Sciences, University of Georgia.

CHAPTER 2

ALTERNATIVE IRRIGATION SCHEDULING: COMPARING THE SMARTIRRIGATION™ APPLICATION TO WATER-BALANCE, AND SOIL MOISTURE-BASED IRRIGATION METHODS FOR TOMATO

SUMMARY

A new smartphone application irrigation scheduling tool, the SmartIrrigation™ Vegetable App (VegApp), was compared to current irrigation scheduling recommendations, and soil-moisture sensor (SMS) based irrigation for growing tomatoes (*Solanum lycopersicum*) in southern Georgia during the spring of 2016 and 2017. Plants were grown using plastic mulch and drip irrigation following standard production practices for tomatoes in Georgia. The VegApp scheduled irrigation based on crop evapotranspiration (ET_c) values, which were calculated daily from meteorological data retrieved from nearby weather stations, while ET_c rates for current water-balance (WB) based recommendations were utilized from historical averages for the region and growing season. The SMS-based irrigation regime was automated using switching tensiometers and had on/off set points of -18 /-10 cbar. Water usage, soil moisture, fruit yield, quality, and foliar macronutrient content were measured. In 2016, plants grown using SMS-based irrigation utilized the least amount of water followed by the VegApp and WB-grown plants. In 2017, WB-treated plants received the least amount of water, followed by VegApp and SMS-grown plants. Total marketable yields were similar among treatments and years. Irrigation water use efficiency (IWUE) varied between year and irrigation regime, with SMS-grown plants having a significantly greater IWUE than the other treatments in 2016 and the VegApp having a greater IWUE than the SMS-irrigated plants in 2017. Much of the differences in IWUE were the

result of varying irrigation volumes and not changes in yield. Fruit total soluble solids (TSS) was not affected by treatment in either year, although fruit pH was impacted by treatment in 2017. Foliar nitrogen (N) concentrations were impacted by irrigation regime in 2017, with VegApp-grown plants having significantly greater concentrations of foliar N than other irrigation treatments. The results of this study suggest that the VegApp is a reliable tool that can be used by growers to produce yields comparable to currently accepted irrigation scheduling practices and reduce water use in some seasons.

INTRODUCTION

Georgia is regarded as a significant producer of fresh market tomatoes with more than 3,800 acres grown valued at over $56 million (Wolfe and Stubbs, 2016). Commercial fresh market tomatoes in Georgia are grown almost exclusively using plastic mulch with drip irrigation. In southwestern Georgia, where considerable commercial production of tomatoes occurs, ground water resources are relatively abundant and growers tend to over-irrigate. However, over-irrigating tomatoes, may lead to leaching of fertilizers and pesticides below the root zone (Tindall and Vencill, 1995), and may also negatively impact yields (Locascio, 2005).

Current recommendations for drip irrigated tomatoes in Georgia and Florida are based on variations of the WB method (Harrison, 2009). The WB method estimates daily crop water use based on historical theoretical evapotranspiration (ET_o) values for the region adjusted with a crop coefficient (Allen, 1998). Current recommendations utilize a range of crop coefficients based on five stages of tomato maturity (Simonne et al. 2010). 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_c. However, irrigating solely based on predicted ET_c values may be inaccurate due to changes in annual weather patterns as well as differences in production practices for which crop coefficients were developed (Amayreh and Al-Abed, 2005). Compared to historical ET_c, the experienced ET_c daily values may vary by up to 25% depending on current weather conditions experienced (Simonne et al., 2010).

In lieu of using the WB method, some growers may use a form of soil moisture-based irrigation. Personal observations by the author suggest that the most common soil moisture-based method utilized is the “feel method,” where irrigation is initiated when the soil “feels” dry. Other methods of soil moisture-based irrigation may utilize tensiometers, granular matrix, or resistance-based sensors to determine thresholds for irrigation management (Carhenas-Lailhacar and Dukes, 2010; Munoz-Carpena et al., 2005). While SMS-based irrigation has been shown to be more efficient than a time-based system (Zotarelli et al. 2009, 2011) proper placement of sensors to accurately reflect conditions experienced by the plant can be difficult (Dabach et al., 2015). Furthermore, placement of sensors within an irrigation zone can be problematic for growers with heterogeneous soil textures or topography within a field. In addition, determining an appropriate irrigation threshold for crops in order to initiate irrigation can be impacted by factors such as soil type and depth of drip tubing (Coolong, 2016).

The SmartIrrigation™ Vegetable App (VegApp) generates irrigation schedule recommendations based on real-time weather and short-term forecasted data for four different vegetables: cabbage (*brassica oleracea*), squash (*cucurbita moschata*), tomato (*solanum lycopersicum*), and watermelon (*citrullus lanatus*). The weather data are retrieved from the Florida Automated Weather Network (FAWN) or the University of Georgia Weather Network (UGAWN) and used to calculate ET_0 from temperature, solar radiation, wind speed, and relative humidity measurements using the Penman-Monteith equation (Migliaccio et al., 2016). New fields are registered in the VegApp to a self-designated weather station although the user has the option to select any of the other available weather stations. The VegApp used ET_o from the past five days to calculate an average ET_o Then ET_c is estimated using K_c curves developed by the University of Florida based on a days after planting model of crop maturity (Clark et al., 1993; Simonne et al., 2010.). The K_c curve for tomato is based on a weeks after planting model of crop maturity for a drip irrigated crop grown on plastic mulch (Clark et al., 1993; Simonne et al., 2010). This information is then used to project an irrigation schedule for the following week. Additional model variables used by the VegApp to develop the irrigation schedule include crop, row spacing, irrigation rate, irrigation system efficiency, and planting date. The VegApp's performance had not been evaluated in southern Georgia, the goal of this study was to determine the efficacy of the VegApp for tomato growers in Georgia. To meet this goal, water usage, yield, and quality of tomatoes grown using the VegApp were compared to water usage, yield, and quality of tomatoes grown using commonly accepted irrigation scheduling methods. Specifically, the VegApp was compared to a water balance (WB) method and a SMS-based irrigation regime.

MATERIALS AND METHODS

This study was conducted at The University of Georgia's Vegetable Park in Tifton, GA (lat. 31° 5' N, long. 83° 5' W) in 2016 and 2017. The soil was a Tifton loamy sand series (0%-2% slope). Tomato 'Red Bounty (HM Clause, Davis, CA) were grown by a local greenhouse producer (LTF Greenhouses, Tifton, GA) in 128-cell trays. Plants were grown on 6-inch tall by 32-inch wide raised beds spaced on 6-ft row centers covered with a 1.1-mil thick totally impermeable film plastic mulch (Vaporsafe RM, TIF, 60-inch; Raven Industries, Sioux Falls, SD). Soils were fumigated with chloropicrin (194 lb/acre) and 1, 3-dichloropropene (129 lb/acre) (Pic-Chlor 60; TriEst Ag. Group Inc, Tifton, GA) when plastic was laid. Irrigation was supplied with a single line of drip irrigation tubing (12-inch emitter spacing, 0.25 gal/min per 100 ft @ 10 psi, Chapin DLX, Jain USA Inc., Haines City, FL). Fumigation, plastic laying, and preplant fertility were applied using a raised bed plastic mulch layer with attached fumigation system and fertilizer hopper (SuperBedder, Kennco Mfg., Ruskin, FL). Preplant fertility consisted of 50 lb/acre N (5.0N-4.3P-14.5K; Rainbow Plant Food, Agrium, Tifton, GA) placed in the row immediately prior to laying plastic mulch. A row-middle herbicide mixture containing flumioxazin (0.12 lb/acre, Chateau; Valent USA, Walnut Creek, CA), S-metaloachlor (0.7 lb/acre, Dual Magnum; Syngenta, Greensboro, NC), ethalfluralin (0.38 lb/acre, Curbit 3 EC; Loveland Products, Loveland, CO), and glyphosate (0.84 lb/acre, RoundUp WeatherMax; Monsanto, St. Louis, MO) were applied between rows with a shielded sprayer prior to transplanting. Fungicides and insecticides were applied based on commercial recommendations for tomatoes grown in Georgia (Horton, 2016). Seedlings were transplanted on 28 Mar. and 4 Apr. in 2016 and 2017, respectively. A severe wind storm on 5-6 Apr. 2017 damaged many seedlings and all plants damaged plants were replaced on 12 Apr. 2017. Plants were watered equally for approximately 4 weeks after transplanting in 2016 and 3 weeks after transplanting in 2017 at which time irrigation treatments were implemented.

The VegApp used data from a UGAWN weather station located approximately 0.5 miles north of the Vegetable Park to calculate ET_0 from air temperature, solar radiation, wind speed, and relative humidity measurements using the Penman-Monteith equation (Migliaccio et al., 2016). Then, ET_0 was adjusted using a K_c based on a days after planting model of crop maturity for drip irrigated watermelon grown on plastic mulch (Simonne et al., 2010). Additional model variables entered into VegApp to adjust gross irrigation requirement calculations include: row spacing, irrigation rate (gal/100ft/hr), irrigation system efficiency, and planting date. The

VegApp then calculated average ET_0 over the previous five days and estimates ET_c based on the following equation: $ET_c=ET_0 \times K_c$. The projected daily irrigation run times recommended by the VegApp were then divided into two daily irrigation events.

Plots irrigated by the WB method were scheduled based on estimated crop water use determined by historical rates of ET_o adjusted by a K_c. Due to proximity to the research site, the ET_o rates attributed to northwest Florida were used (Simonne et al., 2010). Crop coefficients specific to tomatoes were incorporated in to the WB irrigation scheduling method (Simonne et al., 2010). Irrigation requirements were then determined using the following formula: *Irrigation =*ET_c*/System efficiency,* with system efficiency being determined to be 95%. ET_c was calculated using the following equation $ET_c = ET_o \times K_c$. Rainfall was also not included in the WB calculation due to the use of the plasticulture system. The irrigation requirement was then converted to an irrigation run time for one day and then divided into two daily irrigation events. Postharvest, irrigation water use efficiency (IWUE) was determined by the following formula IWUE = marketable yield weight (lbs/ac)/total seasonal irrigation applied (gal/ac).

The SMS-based irrigation regime was automated using paired-switching tensiometers (model RA 6-inch; Irrometer, Riverside, CA) (Coolong et al., 2011). One tensiometer functioned to turn on irrigation at the set point reflecting a higher (drier) soil moisture tension while the other turned it off at the set point indicating the lower (wetter) soil moisture tension. Tensiometers were placed approximately 6-inches from a drip emitter and a tomato plant at a depth of 6-inches from the bed surface. Irrigation treatments had set points of on/off: -18/-10 kPa. These set points were chosen to initiate irrigation at approximately 75% plant available water and terminate irrigation at approximately field capacity for a Tifton loamy sand soil. Plots receiving soil moisture-based irrigation were controlled independently. The frequency and duration of the automated irrigation events were recorded with data loggers (Hobo U9 State Data Logger; Onset, Cape Cod, MA). Average total water use for the season was recorded weekly using mechanical flow meters (DLJSJ50 Water Meter; Daniel L Jerman Co., Hackensack, NJ)

The treatments were arranged in a randomized complete block design with four replicates of each treatment in 2017 and five replicates of WB and VegApp plots in 2016. Each treatment plot contained approximately 30 and 20 plants each in 2016 and 2017, respectively. Tomatoes were harvested 6 times in 2016, beginning on 14 June and ending 11 July. In 2017, tomatoes were harvested 5 times beginning on 21 June and ending 21 July.

Soil moisture was measured continuously in all the plots with the University of Georgia Smart Sensor Array (UGA SSA). The UGA SSA consists of smart sensor nodes and a base station. The term sensor node refers to the combination of electronics and sensor probes installed within a field at a single location. The electronics include a circuit board for data acquisition and processing and a radio frequency (RF) transmitter. Each sensor probe integrates three Watermark® sensors (Irrometer, Riverside, CA) which measure soil matric potential. The UGA SSA converts matric potential to soil water tension and reports in units of cbar. Data from all nodes are routed to a centrally located base station at hourly intervals and the data are then transmitted to a server (Vellidis et al., 2013). For this study, the probes were fabricated so that the midpoints of the three Watermark® sensors were 6, 10, and 14-inch depths, respectively, when the probes were installed. Sensor probes were installed approximately 6-inches from drip irrigation tubing in each plot.

Tomato internal quality parameters were measured on five randomly selected extra-large, fully ripened fruit from each treatment replicate. Individual fruit dimensions and weight were then determined by calipers and a weigh scale, respectively. Total soluble solids (TSS) and pH were determined by slicing tomatoes longitudinally into 10 mm wide slices that weighed approximately 55 g. Two slices from each fruit were taken from the center of the fruit, placed in a 20 oz. blender (Blend N Go Blender, Oster, Boca Raton, FL) and processed into a liquid pulp. Approximately 5.0 µL of the pulp original sample was then tested using a refractometer (Brix Stick; Cole Parmer, Vernon IL) for TSS levels. A 45 ml subsample of the liquid pulp was placed into a 50 ml centrifuge tube and spun in a centrifuge (Allegra 25R; Beckmann-Coulter, Atlanta, GA) at 4100 rpm for 5-min at 28 ^{0}C and repeated twice. Then 15 ml of the supernatant was filtered through 50 grade cheesecloth (VeraTec Cheesecloth; Fiberweb, Old Hickory, TN). Internal pH was measured using 600 µl of the filtered supernatant, which was diluted with 39.4 ml of deionized water and transferred into a titrator (DL15; Mettler Toledo, Leicester, UK). A 0.1 M sodium hydroxide solution was used to bring the original pH of the solution recorded by the titrator to a value of 8.2 in order to measure titratable acidity.

Midday leaf water potential (Ψ_L) measurements were initiated on 4 June. 2016 and 15 June, 19 June and 26 June 2017. Measurements of Ψ_L were conducted within one and half hours of solar noon in both years of the study. Plant Ψ_L was measured using a pressure chamber (Model 615; PMS Instrument Company, Albany, OR) using fully expanded leaves exposed to full sunlight from plants near the center of each plot. After excising leaves for Ψ_L the plant material was wrapped in polyethylene bags, and measured within 1 min of sampling.

Tomato foliar macronutrient content was determined by taking the newest fully expanded leaf from 15 and 10 representative plants in the center of each plot in 2016 and 2017, respectively. Each sample was oven dried at 122 ^{0}F or a minimum of 10 d. Samples were analyzed by a commercial laboratory (Waters Agricultural Lab, Camilla, GA) for nutrient content.

Data were subjected to the GLM procedure and mean separation using Tukey's Honest Significant Difference test ($P \leq 0.05$) when appropriate with SAS statistical software (Version 9.3; SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

The total season ET_c was greater in 2016 than 2017. This was primarily due to a higher ET_c in May and June of 2016 compared to 2017 (Table 2.1). Average daily high air temperatures in June 2016 were 90.2 ^{0}F compared to 85.8 ^{0}F for the same period in 2017. Total rainfall levels were 0.96 inches greater in the 2016 growing season, but more than 50% of the rainfall was received in April 2016, with lower values during May, June, and July, when plant canopies were largest and ET_c were most impacted by weather conditions (Table 2.1).

During the 2016 growing season, the WB method of irrigation used 483,880 gal/acre of water for the season and averaged 5,760 gal/acre per day (Table 2.2). The VegApp and SMS irrigation methods used 353,440 and 206,850 gal/acre for the season, respectively. The SMS irrigation method used the least amount of water in 2016, which is similar to results obtained in other studies evaluating analyzing the impact of tensiometers on irrigation scheduling (Smajstrla and Locascio, 1990). The VegApp utilized less water than the WB method in 2016, suggesting that applying real-time ET_o values obtained by nearby UGAWN weather stations may be more efficient than historical ET_o values (Simonne et al 2010). Interestingly, irrigation volumes for the VegApp were lower than historical values early in the season, but increased to levels greater than historical values in late May and June of 2016 (*data not shown*). This suggests that the real-time weather data incorporated into the VegApp can ensure plants do not undergo water stress during periods of rapid increase in ET_c.

Irrigation volumes in 2017 were lower than 2016 levels for WB and VegApp methods. The WB irrigation method utilized 180,050 gal/acre irrigation water, while the VegApp and SMS irrigation treatments used 202,550 and 250,060 gal/acre water, respectively. There are 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 months of April and early May compared to the WB historical ET_o values. In addition, there were several significant rain events in June and July 2017, which resulted in scheduled irrigations in the VegApp and WB being discontinued for a period of several days. This was done to reflect grower practices where saturated soils would not be irrigated. The WB method generally applied more water than the VegApp treatment during these periods, discontinuing irrigation led to relatively less water being used by the WB method in 2017. Irrigation in the SMS-based treatments was allowed to remain on, to account for tensiometers detecting increased soil moisture and not initiating irrigation.

Soil water tension values showed differences among treatment and depth as measured by Watermark probes (Fig. 2.1a–f). The suspension and initiation of the irrigation schedule of the tomato plots are reflected in the wetting and drying cycles displayed by the probes' measurements (Fig. 2.1a-f). SMS irrigated plots were watered for shorter durations of time compared to the VegApp and WB methods which generated less drastic decrease in soil water tension. (Fig. 2.1c). The VegApp received higher volumes of water per application than the SMS treatment which resulted in greater variations of soil water tension in 2017 at all depths (Fig. 2.1b, 2.1d, 2.1f.). Based on the soil water tension data, the WB treatment may provide more favorable growth conditions immediately after irrigation applications due to prolonged saturated soil conditions compared to SMS treatments, potentially reducing water stress.

The increased water usage for the SMS-based irrigation suggests that despite saturated soils surrounding plots, rainfall did not significantly affect soil moisture levels within the planted beds, resulting in continued water use in SMS-based treatments. Based on soil water tension readings obtained from the UGA SSA also support that levels of soil moisture were not affected significantly affected by rainfall, thereby increasing water usage in SMS-based treatments compared to VegApp and WB based treatments. In addition, preliminary research conducted with a rainfall simulator suggested little impact of rainfall events on soil moisture levels under raised-bed plastic mulch (*unpublished data*).

When averaged over the two years of the study, the VegApp used 16% less water than the WB method. The SMS utilized 31% less water than the WB method. This suggests that the VegApp and SMS-based irrigation can reduce water use compared to methods relying on historical ET_c to manage irrigation. This may be expected as numerous studies have demonstrated the efficiencies of a SMS-based irrigation compared to microclimate and historical ET-based methods (De Pascale et al., 2011).

There was a significant treatment by year by depth interaction for soil moisture levels (Table 2.3). In April 2016, there was little plant canopy and soil moisture levels remained high at all depths (Table 2.3). Soil moisture levels remained highest in WB-treated plots in 2016, with the exception of the VegApp treated plots at a depth of 6-inches in July. Soil tension values overall were low in 2016 suggesting that overall the treatments were too wet, this is due to the crop coefficient being adjusted by a days after planting (DAP) model which over predicted crop water use during the season. On-farm trials in southwest Georgia with tomatoes and bell peppers have shown that growers typically maintain soil moisture levels between 0.5 and 5.0 cbar (*data not shown*) at soil depths of 6-inches to 12-inches. Interestingly, the SMS-treated plots had significantly higher soil water tension values at 6-inch depths in June and July 2016 compared to the VegApp treated plots, but there were no differences between the two treatments at 10 or 14-inch depths for the same time period. This may be due to the placement of the porous tip of the tensiometers, which may result in maintaining a shallower root system and greater water demand at shallower depths compared to the VegApp (Marouelli et al., 2004; Marouelli and Silva, 2007).

Analysis of main effects indicated that despite lower ET_c values in 2017, soil moisture tension increased in all treatments compared to 2016. However, it is possible that ET_c values used in the cooler and wetter 2017 growing season may have underestimated water use by the crop resulting in high moisture tension values. Significant differences in moisture levels among treatments in 2017 were primarily observed in May. The VegApp-treated plots utilized more irrigation water in May than WB-treated plots, due to higher ET_C values. However, despite using more water, the VegApp-treatments experienced higher moisture tension values than the WB treated plots at 6 inch and 10-inch depths (Table 2.3). Although these results may be unexpected, crop coefficients have been shown to vary significantly when used under a different set of climate conditions from which they were developed, particularly early in crop growth (Jagtop and Jones, 1989). The conditions for which the crop coefficients used in this trial were developed may have been more similar to conditions experienced in the warmer and drier 2016 growing season compared to 2017. In June and July 2017, there were no differences in soil moisture tension between irrigation treatments at any depth, although soil water tension values were generally higher in June and July of 2017 compared to the same period in 2016. Midday Ψ_L readings taken in June and July were no different among treatments or years suggesting that the differences observed in soil moisture tension between years or treatments were not indicative of plant moisture status (*data not shown*).

There was a significant year by treatment interaction for yield of large fruit (Table 2.4). There were no treatment by year interactions for total, extra-large, and medium fruit yields. When main effects were analyzed, there were no treatment effects on yield; however, year significantly affected yields of extra-large, large, and medium size-fruit (*data not shown*). Total marketable yields ranged from 43,520 lb/acre for the SMS-based treatment to 52,220 lb/acre in the Veg App-treated plots 2016 and 45,200 lb/acre in the WB-based treatments to 51,780 lb/acre in the VegApp-treated plots in 2017. The yield of extra-large fruit harvested increased in 2017 compared to 2016, while the yields of large fruit decreased concomitantly. The yield of medium fruit decreased in 2017 compared to 2016, but overall was a minor portion of the total fruit harvested. Average fruit weight was not affected by treatment or year and ranged from 237-264 g/fruit. The percentage of cull fruit was not affected by treatment, but was significantly affected by year (*data not shown*). Cull fruit ranged from 7.0% to 11.6% in the VegApp and SMS-based treatments, respectively in 2016 and from 28.7% to 30.6% in the SMS and VegApp-based treatments in 2017. Cull rates were primarily due to blossom end rot in 2016 and in 2017 due to misshapen fruit and some damage from green stink bug (*Chinavia hilaris*) and two spotted spider mites (*Tetranychus urticae*). Despite higher cull rates in 2017 compared to 2016, overall cull rates were similar to those found in nearby commercial tomato fields for the two seasons (*T. Coolong, personal observation*). Total marketable yields were comparable to those expected from a commercial tomato field in Georgia (Kelley and Boyhan, 2014)

There was a significant year by treatment interaction for IWUE. In 2016, plants grown using the SMS-based irrigation method had a significantly higher IWUE compared to those grown using the VegApp and WB-methods. While the yield of the SMS-managed plots was numerically lower than the other irrigation treatments in 2016, the SMS-plots used 41% and 57%

less water than the VegApp and WB-based plots, respectively, resulting in a significantly greater IWUE. In 2017, the VegApp had a significantly greater IWUE than the SMS-based irrigated plants. The WB-grown plants were not significantly different than any other irrigation treatment in 2017. The increased IWUE in 2017 for VegApp and WB-grown plants was due to the decrease in irrigation volume used (Table 2.2). During this study, the SMS-grown plants had the most consistent IWUE, with 0.21 lb/gal and 0.20 lb/gal in 2016 and 2017, respectively, which is similar to related research trials (Zotarelli et al., 2009). The IWUE of the other irrigation treatments were more variable. This variability was the result of changes in water used and not significant fluctuations in yield (Table 2.2). The difference in irrigation in the VegApp was primarily the result of variability in seasonal ET_c, while the large increase in rainfall in June and July 2017 led to limiting irrigation in the WB-based treatments during typical periods of relative high water demand. Prior studies with tomato suggested that maximum yields were consistently produced under irrigation ranges of between 50% and 100% ET_c in dry conditions (Locascio et al., 1989; Olson and Rhoads, 1992). Numerous reports using deficit irrigation have been shown to regularly reduce irrigation below 100% ET_c use while not impacting yield of plasticulture grown fresh market tomatoes (Favati et al., 2009; Ozbahce and Tari, 2010; Patanè and Cosentino, 2010). In future versions of the VegApp it may be possible to add an option to irrigate below 100% ET_c to save additional water without necessarily reducing yields.

When averaged over both study years, the relative IWUE of the VegApp and SMS-based irrigations were numerically similar. De Pascale et al. 2011 reported real-time microclimate-based irrigation to 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 has been shown to reduce water use while maintaining yields of tomato (Munoz-Carpena et al., 2005). Pulsed irrigation typically results in a shallower wetting front shortly after the irrigation event, increasing application efficiencies (Assouline and Ben-Hur., 2006; Coolong et al., 2011). The VegApp and WB-based irrigations were scheduled for two events per day to simulate optimal grower practices, suggesting that the twice-daily irrigations using the relatively easy to use VegApp tool may be as efficient in some years as a more complex soil-moisture based systems.

Fruit TSS and pH were not affected by a year by treatment interaction, but there were significant treatment and year effects for fruit pH (Table 2.5). Fruit TSS values ranged from 3.91% to 4.03% in the SMS and VegApp-treated plots, respectively. Fruit pH values were significantly higher in WB SMS-based plots compared to fruit grown using the VegApp. In addition, pH levels were affected by year, increasing from 3.41 in 2016 to 4.04 in 2017. Higher internal tomato pH levels have previously been reported to be impacted by irrigation management (Mitchell et al., 1991; Tuzel et al., 1994), while other studies have reported no impact of irrigation on fruit pH (Hanson et al., 2006). Regardless of treatment, pH values were lower than those deemed to be preferred (≤ 4.30) according to the reference scale of analytical parameters for tomato pulp, suggesting the harvested tomatoes grown in this trial may be slightly acidic (Patane and Consentio, 2010).

There was a significant year by treatment interaction for foliar N and Mg concentrations, but not for P, K, Ca or S (Table 2.6). Foliar N concentrations were not affected by irrigation regime in 2016, but the VegApp had significantly higher N levels than the WB and SMS-grown plants in 2017. In 2017, the VegApp had foliar N concentration of 5.56% compared to 5.04% and 4.61% in the WB and SMS-treated plants, respectively. It is notable that in May plants grown in the VegApp had higher moisture tension values at a 10-inch depth (Table 2.3) compared to other treatments, despite receiving more irrigation during this period. This suggests that there may have been increased root growth at this depth for VegApp-grown plants, potentially resulting in improved ability to accumulate N (Zotarelli et al., 2009). Foliar P concentrations were not affected by treatment, with concentrations ranged from 0.36% to 0.45% in VegApp-grown plants in 2016 and WB-grown plants in 2017, respectively. Potassium, a key nutrient for tomato fruit development ranged from 3.35% to 4.05% in VegApp and WB-treated plants, respectively in 2016. Foliar Ca concentrations displayed similar trends in 2016 and 2017 and the differences were not significant in either year. Foliar Mg concentrations were significantly greater in the VegApp treated plants compared to the other irrigation regimes in 2016. In 2017, the VegApp-grown plants had significantly greater Mg concentrations than SMS-treated plants. Foliar S concentrations were not affected by irrigation regime in either study year, but were significantly greater in 2017 (1.06%) compared to 2016 (0.80%). All macronutrient concentrations were within expected ranges for field-grown tomatoes (Bryson et al., 2014). While only N and Mg concentrations in the foliage were affected by irrigation regime, both were greater in VegApp-treated plants. The N fertilizer used in this study was nitrate-based. Utilizing the VegApp for scheduling irrigation may potentially reduce leaching through more judicious water use during fruit set (when plants were sampled) or potentially improving root growth early in the season and the ability of a crop to remove nutrients from the soil profile (Dukes et al., 2010).

CONCLUSIONS

Water usage results indicated that the WB method of irrigation conserved the least amount of water when averaging 2016 and 2017 data. The water use data indicate that the VegApp conserved more water in both years compared to the WB method of irrigation scheduling. When averaged over the two years of the study, the VegApp used 16% less water than the WB method. This suggests that applying real-time ET_o values obtained by UGAWN weather stations can be more efficient than using historical ET_o values to determine irrigation scheduling. SMS-grown plants had the most consistent IWUE between seasons, while the IWUE of the VegApp was greater than the WB treatment. This suggests that the VegApp and SMS-based irrigation can reduce water use and increase IWUE compared to methods relying on historically based ET_c to manage irrigation. The VegApp demonstrated a significantly greater IWUE than the SMS-based irrigated plants in 2017 and a numerically similar IWUE when both years are averaged. This suggests that the VegApp may be a suitable alternative to SMS irrigation as their performance in regards to IWUE was comparable. Yield was not significantly affected by irrigation scheduling, while fruit TSS and pH were not affected by a year by treatment interaction, but there were significant treatment and year effects for fruit pH.

LITERATURE CITED

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: Proceedings of the Irrigation and Drainage Paper No. 56. Food and Agricultural Organization, United Nations, Rome, Italy.

Amayreh, J. and N. Al-Abed. 2005. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum Mill.)* under drip irrigation with black plastic mulch. Agricultural Water Management. 73: 247–254.

Assouline, S. and M. Ben-Hur. 2006. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. Catena. 66:211–220.

Bryson, G.M., H.A. Mills, D.N. Sasseville, J.B. Jones, and A.V. Barker. 2014. Plant Analysis Handbook III. Micro Macro Publishing Inc., Athens, GA.

Cardenas-Lailhacar, B., M. D. Dukes, and G. L. Miller. 2010. Sensor-based automation of irrigation on bermudagrass, during dry weather conditions. J. Irrig. and Drain. Eng. 136:184-193.

Clark, G., C. Stanley, A.A. Csizinszky, A. G. Smajstrla, S. Zazueta and S. Fedro. 1993. Water Requirements and Crop Coefficients for Tomato Production in Southwest Florida. University of Florida, USA.

Coolong, T., S. Surendan, and R. Warner, 2011. Evaluation of irrigation threshold and duration for tomato grown in a silt loam soil: HortTechnology, 21:466-473.

Coolong T. 2016. Evaluation of shallow subsurface drip irrigation for the production of acorn squash. HortTechnology, 26(4):436-443.

Dabach, S., U. Shani, and N. Lazarovitch. 2015. Optimal tensiometer placement for high-frequency subsurface drip irrigation management in heterogeneous soils. Agric. Water Manage. 152:91–98.

De Pascale, S., D. Costa, S. Vallone, G. Barbieri, and A. Maggio. 2011. Increasing water use efficiency in vegetable crop production: From plant to irrigation systems efficiency. HortTechnology 21:301–308.

Dukes, M. D., L. Zotarelli, and K. T. Morgan. 2010. Use of irrigation technologies for vegetable crops in Florida. HortTechnology, 20:133–142.

Favati, F., S. Lovelli, F. Galgano, V. Miccolis, T. Di Tommaso, and V. Candido. 2009. Processing tomato quality as affected by irrigation scheduling. Sci. Hortic. Amsterdam 122:562–571.

Hanson, B.R., R.B. Hutmacher, and D.M. May. 2006. Drip irrigation of tomato and cotton under shallow saline ground water conditions. Irrig. Drain. Sys. 20:155–175.

Harrison, K. 2009. Irrigation Scheduling Methods. Univ. Ga. Coop. Ext. Serv. Athens, GA. Univ. Georgia Coop. Ext. Bull. 1312:1-5.

Horton, D. 2016. 2016 Georgia pest management handbook. Univ. Ga. Coop. Ext. Serv. Spec. Bul. 28.

Jagtop, S.S. and J.W. Jones. 1989. Stability of crop coefficients under different climate and irrigation management practices. Irr. Sci. 10:231-244.

Kelley, W.T., and G.E. Boyhan. 2014. Commercial Tomato Production Handbook. University of Georgia Cooperative Extension. Bull. 1312.

Locasio, S.J., S.M. Olson and F.M. Rhoads. 1989. Water quantity and time of N and K application for trickle-irrigated tomatoes. J. Amer. Soc. Hort. Sci. 114:265-268.

Locascio, S.J. 2005. Management of irrigation for vegetables: past, present, and future. HortTechnology 15:482–484.

Marouelli, W.A. and W.L.C. Silva. 2007. Water tension thresholds for processing tomatoes under drip irrigation in central Brazil. Irrig. Sci. 25:41–48.

Marouelli, W.A., W.L.C. Silva, and C.L. Moretti. 2004. Production: quality and water use efficiency of processing tomato as affected by the final irrigation timing. Hortic. Bras. 22:225–230.

Migliaccio, K.L., K.T. Morgan, G. Vellidis, L. Zotarelli,, C. Fraisse, D. Rowland., J.H. Andreis, and J.H. Crane. 2016. Smartphone apps for irrigation scheduling. Emerging Technologies for Sustainable Irrigation: A joint ASABE / IA Irrigation Symposium, Long Beach, California, November 10 – 12, 2015.

Mitchell, J.P., C. Shennan, S.R. Grattan, and D.M. May. 1991. Tomato fruit yield and quality under water deficit and salinity. J. Am. Soc. Horti. Sci. 116:215-221.

Munoz-Carpena, R., M.D. Dukes, Y.C.C. Li., W. Klassen. 2005. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. HortTechnology 15:584–590.

Olson, S.M. and F.M. Rhoads. 1992. Effect of water quantity on fall tomato production in north Florida. Proc. Fla. State Hort. Soc. 105:334-336.

Ozbahce, A. and F. A. Tari. 2010. Effects of different emitter space and water stress on yield and quality of processing tomato under semi-arid climate conditions. Agricultural Water Management, 97:1405-1410.

Patane, C. and S.L. Cosentino. 2010. Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. Agricultural Water Management 97:131–138.

Simonne, E.H., M.D. Dukes and L. Zotarelli. 2010. Principles and Practices of Irrigation Management for Vegetables. 17-26. In: S. M. Olson and E. Simonne. eds. Vegetable Production Handbook for Florida 2010-2011. IFAS, Gainesville, FL.

Smajstrla, A.G. and S.J. Locascio. 1990. Irrigation scheduling of drip-irrigated tomato using tensiometers and pan evaporation. Proc. Fla. State Hort. Soc. 103:88-91.

Tindall, J.A. and W.K. Vencill. 1995. Transport of atrazine, 2-4 D and dicamba through preferential flowpaths in an unsaturated claypan soil near Centralia, Missouri. J. Hydrol. (Amst.) 166:37–59.

Tuzel I.H., M.A. Ui and Y. Tuzel. 1994. Effects of different irrigation intervals and rates on spring season glasshouse production. II. Fruit quality. Acta Hort 366:389–396.

Vellidis, G., M. Tucker, C. Perry, D. Reckford, C. Butts, H. Henry, V. Liakos, W. R. Hill, and W. Edwards, 2013. A soil moisture sensor-based variable rate irrigation scheduling system. In J.V. Stafford (Ed.), Precision Agriculture 2013—Proceedings of the 9th European conference on precision agriculture (pp. 713–720). The Netherland: Wageningen Academic Publishers.

Wolfe, K., and K. Stubbs. 2016. 2015 Georgia Farm Gate Value Report. The Center for Agribusiness, & Economic Development, College of Agricultural & Environmental Sciences, University of Georgia.

Zotarelli, L., M.D. Dukes, J.M.S. Scholberg, K. Femminella, and R. Munoz-Carpena. 2011. Irrigation scheduling for green bell peppers using capacitance soil moisture sensors. J. Irrig. Drain. Eng., 137: 73-81

Zotarelli L., M.D. Dukes, J.M.S. Scholberg, R. Munoz-Carpena and J. Icerman. 2009. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agricultural Water Management 96:1247–1258.

Table 2.1. Accumulated rainfall, crop evapotranspiration (ET_c), and the average daily maximum (T_{max}) and minimum (T_{min}) temperatures during the study period for tomato grown in Tifton, GA in 2016 and 2017 obtained from UGAWN.

	(inches)^z			(°F)^z	
	Rainfall	ET_c^y	ET_0	T_{max}	T_{min}
		2016			
28-31 March	0.25	0.15	0.50	76.1	55.6
April	6.34	0.33	4.42	75.8	55.4
May	1.45	5.81	5.81	83.7	61.3
June	3.94	6.20	6.20	90.2	69.6
1-11 July	0.09	2.03	2.39	92.2	72.6
Season	12.07	17.52	19.32	83.9	62.9
		2017			
12-30 April	0.32	1.33	2.76	82.7	59.6
May	2.65	4.80	5.81	84.0	61.4
June	5.11	4.58	6.20	85.8	68.8
1-21 July	3.03	4.05	4.51	91.0	72.2
Season	11.11	14.76	19.28	85.7	65.5

^{z}(^{0}F - 32) ÷ 1.8 = ^{0}C, 1 inch = 2.54 cm.

^{y}*ETc = ET_0 x K_c*

Table 2.2. 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.

	Irrigation volume	Daily Water Use
Irrigation treatment	(gal/acre)[y]	(gal/acre per day)[y]
	2016	
VegApp	353,440	4,210
WB	483,880	5,760
SMS	206,850	2,460
	2017	
VegApp	202,550	3,120
WB	180,050	2,770
SMS	250,060	3,850

[z]1 gal/acre = 9.3540 $L \cdot ha^{-1}$, [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 2.3. Average monthly soil water tension at depths of 6, 10, and 14-inches in tomatoes grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

		Soil Moisture Tension (cbar)[z]													
		2016								2017					
Depth	Treatment	April		May		June		July		May		June		July	
6-inch	VegApp	0.13	a[y]	4.27	a	3.10	a	0.94	a	19.77	b	10.14	a	20.49	a
	WB	0.02	a	3.35	a	1.68	a	1.42	a	7.94	a	15.18	a	18.97	a
	SMS	0.65	a	3.92	a	9.99	b	7.07	b	14.12	ab	17.59	a	23.77	a
10-inch	VegApp	0.00	a	4.57	b	3.85	a	0.52	a	12.14	c	9.87	a	14.75	a
	WB	0.16	a	0.90	a	0.88	a	0.39	a	3.62	a	7.64	a	12.00	a
	SMS	0.16	a	3.32	b	3.13	a	2.43	a	7.47	b	11.30	a	9.50	a
14-inch	VegApp	0.00	a	5.04	b	5.59	b	1.67	a	11.34	a	11.31	a	15.45	a
	WB	0.00	a	0.22	a	0.50	a	0.11	a	8.41	ab	12.52	a	17.89	a
	SMS	0.00	a	3.37	b	3.14	b	2.34	a	6.00	b	10.50	a	7.48	a

[z] 1 cbar = 1.0 kPa, 1 inch = 2.54 cm.

[y] Values in the same column, depth 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 2.4. Marketable yields for total, extra-large, large and medium fruit as well as average fruit weight, cull percentage, 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.

	(lb/acre)[z]								(g)[z]		(%)[y]		(lb/gal)[z]	
Irrigation Treatment	Total		Extra-Large		Large		Medium		Fruit Weight		Cull		IWUE[x]	
2016														
VegApp	52,220	a	32,420	a	15,340	a	4,460	a	246	a	7.0	a	0.15	b[x]
WB	51,340	a	31,500	a	15,620	a	3,780	a	237	a	9.5	a	0.11	b
SMS	43,520	a	27,100	a	12,640	a	4,220	a	264	a	11.6	a	0.21	a
2017														
VegApp	51,780	a	45,650	a	4,960	a	1,170	a	245	a	30.6	a	0.26	a
WB	45,200	a	38,980	a	5,210	a	1,010	a	236	a	30.0	a	0.25	ab
SMS	48,740	a	41,400	a	6,220	a	1,120	a	245	a	28.7	a	0.20	b

[z] 1 lb/acre =1.1209 $kg\cdot ha^{-1}$, 1 g = 0.0353 oz, 1 lb/gal = 0.1198 $kg\cdot L^{-1}$.

[y]Cull percentage is based on weight of cull fruit divided by total weight of fruit harvested.

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

[w]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 2.5. Main effects of treatment and year for total soluble solids (TSS) and pH for tomato fruit grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

Irrigation treatment	TSS (%)		pH	
WB	3.93	a[z]	3.79	a
SMS	3.91	a	3.73	a
VegApp	4.03	a	3.62	b
2016	3.97	a	3.41	b
2017	3.95	a	4.04	a

[z]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 2.6. Foliar concentrations of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) for tomatoes grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

	(%) dry weight											
Irrigation Treatment	N		P		K		Ca		Mg		S	
2016												
VegApp	4.04	a[z]	0.36	a	3.45	a	2.99	a	0.48	a	0.73	a
WB	3.84	a	0.38	a	4.05	a	2.51	a	0.43	b	0.85	a
SMS	3.89	a	0.40	a	3.43	a	2.36	a	0.43	b	0.82	a
2017												
VegApp	5.56	a	0.41	a	3.35	a	2.55	a	0.57	a	1.12	a
WB	5.04	b	0.45	a	3.63	a	2.47	a	0.55	ab	1.05	a
SMS	4.61	b	0.42	a	3.44	a	2.24	a	0.50	b	1.00	a

[z]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.

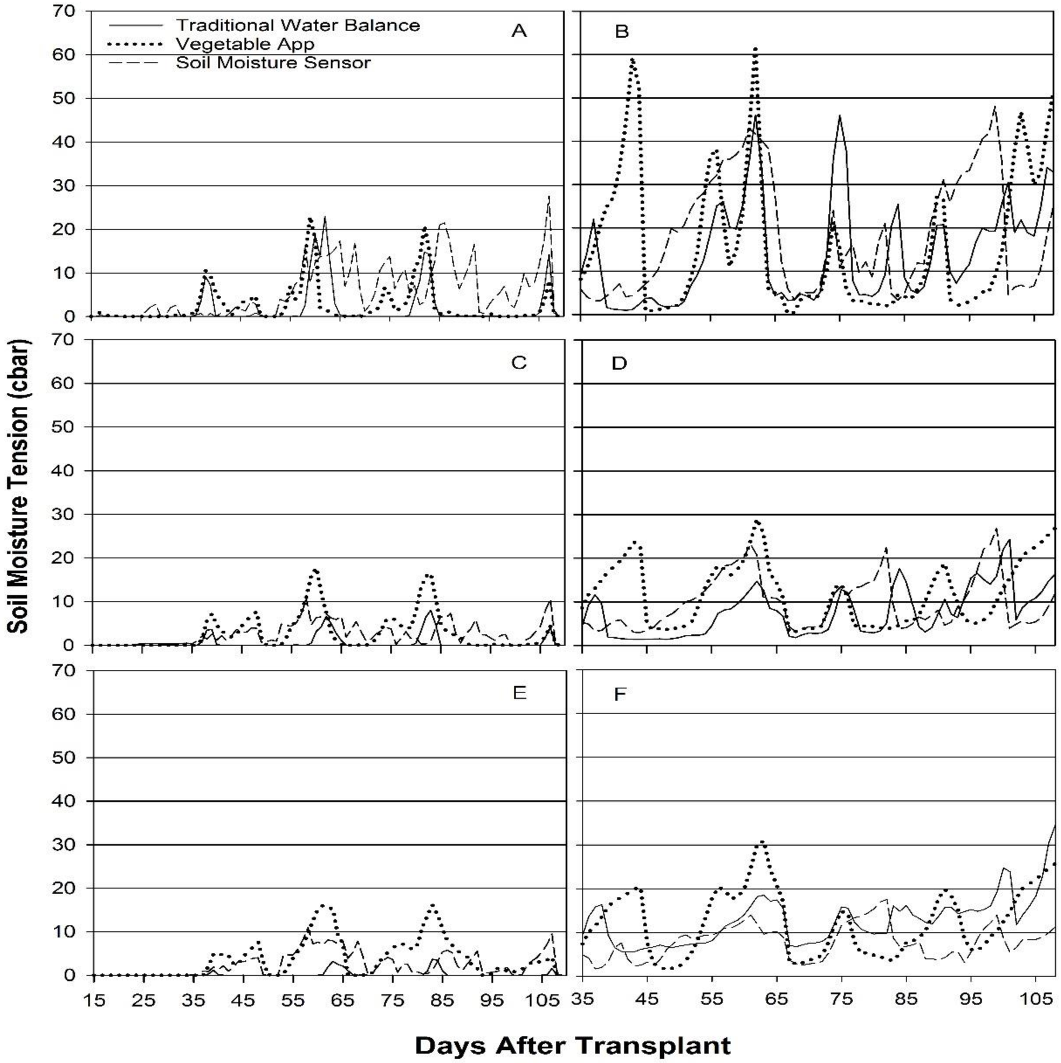

Figure 2.1. Average daily soil moisture tension measured in tomatoes grown in Tifton, GA.

Figure 2.1a. Soil moisture tension measured at depths of 6-inches in 2016

Figure 2.1b. Soil moisture tension measured at depths of 6-inches in 2017

Figure 2.1c. Soil moisture tension measured at depths of 10-inches in 2016

Figure 2.1d. Soil moisture tension measured at depths of 10-inches in 2017

Figure 2.1e. Soil moisture tension measured at depths of 14-inches in 2016

Figure 2.1f. Soil moisture tension measured at depths of 14-inches in 2017

CHAPTER 3

ALTERNATIVE IRRIGATION SCHEDULING: COMPARING THE SMARTIRRIGATION™ APP TO WATER-BALANCE, AND SOIL MOISTURE-BASED IRRIGATION METHODS FOR WATERMELON

SUMMARY

The SmartIrrigation™ Vegetable App (VegApp), was compared to current irrigation scheduling recommendations, which are based on the water balance (WB) method, and an automated soil moisture sensor (SMS) based irrigation system in southern Georgia during the spring of 2016 and 2017. Plants were grown using plastic mulch and drip irrigation following standard production practices for watermelon (*Citrullus lanatas)* in Georgia. The VegApp irrigation regime was based on evapotranspiration (ET_o) values calculated from real-time data collected from nearby weather stations, while ET_o rates for current recommendations were determined based on historic averages for the season. Water usage, soil water tension at 6, 10, and 14-inch depths, as well as yield and fruit quality were evaluated. In 2016 the SMS-based irrigation plots used the least water; however, in 2017 plants grown using the VegApp utilized the lowest water volume. Total marketable yields were not significantly affected by irrigation regime. However, although 45 count fruit is smaller than 36 count fruit, the of yield 45-count (ct) fruit yields were affected by irrigation in 2017, with plants grown using SMS-based irrigation having a significantly higher yield of 45-ct fruit (14-17 lb fruit) than those grown using the WB-method. Irrigation water use efficiency (IWUE) was affected by irrigation treatment an

year. The SMS-grown plants had an IWUE that was significantly better than the WB method, but was not significantly different from plants grown using the VegApp irrigation program. Internal quality parameters including firmness, hollow heart, and total soluble solids (TSS) were not significantly affected by irrigation scheduling during both study years. The study suggests that overall water use may be reduced and yields maintained when using the Smartirrigation™ Vegetable App compared to traditional WB methods of irrigation scheduling.

INTRODUCTION

The majority of watermelon production is in southern Georgia where soils are sandy and well drained. The proper scheduling of irrigation is vital as the incidence of foliar diseases including anthracnose (*Colletotrichum orbiculare*) as well as phytophthora fruit rot caused by *Phytophthora capsici* may be exacerbated by excessive irrigation (Hausbeck and Lamour, 2004; Hord and Ristaino, 1992; Zitter et al., 1996). Irrigation is typically limited when watermelons are near harvest as excess water has been reported to negatively impact watermelon internal quality (Shukla et al., 2013). Total soluble solids (TSS) content is often used as an indicator of total sugar concentration for watermelons has been negatively correlated with irrigation level late in fruit development (Rouphael, 2008). Overwatering during fruit development has also been associated with increased incidence of hollow heart (Proietti et al., 2008).

Drip irrigated watermelon in Georgia and Florida are currently irrigated based on variations of the WB method or by simpler methods of irrigation scheduling (Harrison, 2009). Typically the WB method determines irrigation values by calculating estimated crop water use based on historic ET_o values for the region adjusted with a crop coefficient (K_c) (Allen et al., 1998). Current recommendations utilize a range of K_c values associated with five stages of watermelon maturity correlated to a days after transplanting model (Simonne et al., 2010).

However, irrigating solely based on historic ET_o values may be subject to inaccuracies due to changes in annual weather patterns as well as differences in production practices for which crop coefficients were developed (Amayreh and Al-Abed, 2005; Bonachela et al., 2006.). Daily ET_o values may deviate from historical averages by up to 25% depending on the weather conditions experienced (Simonne et al., 2010). Therefore, the WB method may allow growers to estimate overall crop water requirements; however, accuracy in a given season may be limited. Soil moisture status may also be used to scheduled irrigation. While the simplest method of soil-moisture based irrigation may utilize the "feel" method, where growers simply touch the soil around plants to determine relative moisture content; other methods use sensors to determine soil moisture levels. In watermelon production, soil moisture sensor based irrigation may utilize tensiometers for irrigation management.

The VegApp which schedules irrigation in watermelon based on the same evapotranspiration model described for tomatoes represents an important step forward in reliable irrigation scheduling that is readily accessible to growers. It is free to download, relatively easy to use, and by making recommendations based on the incorporation of real-time weather data, should be more efficient than WB-based irrigation (De Pascale et al., 2011). The WB-method utilized in this study is identical to the method used for tomato production with exception to the K_c values attributed to each phase of development (Simonne et al., 2010). Similarly, the SMS method of irrigation scheduling used in this study is identical to the SMS method used in the tomato study in the previous chapter. The objective of this study was to compare water usage, yield, and quality of watermelons grown using the VegApp to current recommendations and a SMS-based irrigation regime to determine the appropriateness of the VegApp for watermelon producers in the region.

MATERIALS AND METHODS

This study was conducted at The University of Georgia, Tifton Vegetable Park in Tifton, GA (lat. 31^{o} 5' N, long. 83^{o} 5' W) in 2016 and 2017. The soil was a Tifton loamy sand series (0%-2% slope, fine-loamy, kaolinitic, thermic Plinthic Kandiudults). Seedless watermelon 'Melody' (Syngenta seeds, Woodland, CA) with the pollenizer 'Sp6' (Syngenta) were greenhouse grown for six weeks using a peat-based soilless mix (Pro-Mix BX; Premier Tech, Riviere-du-Loup, QC, Canada) using 200-cell trays. Seeded trays were placed in a germination chamber (85-90 ^{o}F, 90% relative humidity) for 48 h and then moved to a greenhouse for production. Temperature set points of 84/68 ^{o}F (day/night) were used. Plants were watered twice-daily as needed and fertilized three times weekly after germination with a 150 mg·L^{-1} nitrogen (N) solution (20N-4.4P-16.6K; Scotts, Marysville, OH).

Seedlings were transplanted by hand on 28 Mar. and 13 Apr. in 2016 and 2017, respectively. Plots consisted of two rows of plants spaced 6-ft apart on center with 42-inch in-row spacing (2074 plants/acre). Plots contained 30 and 20 plants each in 2016 and 2017, respectively. Pollenizer plants, 'Sp6', were planted equidistant between every third and fourth plants in a row. There were four replicates of each irrigation treatment and the study was arranged in a randomized complete block design. Plants were grown in 6-inch tall by 32-inch wide raised beds covered with a 1.1-mil thick impermeable film plastic mulch (Vaporsafe RM, TIF, 60-inch; Raven Industries, Sioux Falls, SD). Soils were fumigated with chloropicrin (194 lb/acre) and 1,3-dichloropropene (129 lb/acre) (Pic-Chlor 60; TriEst Ag. Group Inc, Tifton, GA) when plastic was laid. Irrigation was supplied with a single line of drip irrigation tubing (12-inch emitter spacing, 0.50 gal/min per 100 ft at 10 psi, Chapin DLX; Jain USA Inc., Haines City, FL). Fumigation, plastic laying, and preplant fertility were applied using a raised bed plastic mulch layer with attached fumigation system and fertilizer hopper (SuperBedder, Kennco Mfg., Ruskin, FL). Preplant fertility consisted of 50 lb/acre N (5.0N-4.3P-14.5K; Rainbow Plant Food, Agrium, Tifton, GA) placed in the row immediately prior to laying plastic mulch. Plants received an additional 130 lb/acre N in 2016 and 2017 for the growing seasons, respectively, through weekly applications of 13 lb N/acre (7N-0P-5.8K; Big Bend Agri-Services, Cairo, GA) for a season total of 180 lb/acre N.

A row-middle herbicide mixture containing flumioxazin (0.12 lb/acre, Chateau; Valent USA, Walnut Creek, CA), S-metaloachlor (0.7 lb/acre, Dual Magnum; Syngenta, Greensboro, NC), ethalfluralin (0.38 lb/acre, Curbit 3 EC; Loveland Products, Loveland, CO), and glyphosate (0.84 lb/acre, RoundUp WeatherMax; Monsanto, St. Louis, MO) were applied between rows with a shielded sprayer two weeks prior to transplanting. Fungicides and insecticides were applied weekly according to commercial recommendations for watermelon grown in Georgia (Horton, 2016). Plants were watered equally for approximately 4 weeks after transplanting in 2016 and 3 weeks after transplanting in 2017 at which time irrigation treatments were implemented.

The VegApp calculated crop evapotranspiration (ET_c) from weather data collected by University of Georgia Weather Network (UGAWN) weather station in Tifton. These data were used to calculate ET_o from air temperature, solar radiation, wind speed, and relative humidity measurements using the Penman-Monteith equation (Migliaccio et al., 2016). Then ET_o was adjusted using a K_c based on a days after planting model of crop maturity for drip irrigated watermelon grown on plastic mulch (Simonne et al., 2010). Additional model variables entered into VegApp include row spacing, irrigation rate (gal/100ft/hr), irrigation system efficiency, and planting date. The VegApp then calculates average ET_o over the previous five days and estimates ET_c based on the following equation: $ET_c = ET_o \times K_c$.

Irrigation schedules for WB-managed plots were calculated based on estimated watermelon crop water use determined by historic rates of ET_o adjusted with a K_c for watermelons. Historic ET_o was estimated from a 10-year monthly average of measured ET_o rates for several geographical regions of Florida (Simonne et al., 2010). Due to its proximity to the research site, the ET_o rates attributed to northwest Florida were used. Crop coefficients developed for plasticulture-grown watermelons in Florida were used (Simonne et al., 2010). Total ET_c was then divided by irrigation system efficiency, which was estimated to be 95% for this study, to determine total irrigation requirements. Total irrigation requirements were then divided into two equal daily irrigation events.

The SMS-based irrigation regime was automated using paired-switching tensiometers (model RA 6-inch; Irrometer, Riverside, CA) (Coolong et al., 2011; Coolong, 2016). One tensiometer functioned to turn on irrigation at the set point reflecting a higher (drier) soil moisture tension while the other turned it off at the set point indicating the lower (wetter) soil moisture tension. Tensiometers were placed approximately 6-inches from a drip emitter and a watermelon plant at a depth of 6-inches from the bed surface. Irrigation treatments had set points of on/off: -18/-10 kPa. Water usage in all treatments were recorded weekly using mechanical flow meters (DLJSJ50 Water Meter; Daniel L Jerman Co., Hackensack, NJ). Plots receiving SMS-based irrigation were controlled independently.

Watermelons were harvested three times in 2016 and 2017. Harvest periods ranged from 29 June to 13 July in 2016 and from 27 June to 12 July in 2017. All fruit were graded based on a combination of USDA grade standards for U.S. No. 1 watermelons as well as industry standards for size. All fruit were weighed individually and categorized into 60, 45, 36, and 30-ct fruit for those watermelons weighing 9.0-13.5 lb, 13.6 - 17.5 lb, 17.6 - 21.4 lb, and ≥ 21.5 lb, respectively (Schultheis and Thompson, 2014).

Watermelon internal quality parameters were measured on five randomly selected, fully ripened fruit from each treatment and replicate during each harvest. Firmness, TSS, and hollow heart incidence severity were determined by slicing watermelon longitudinally in half. Fruit TSS were measured on a composite sample of five fruit. A melon baller (5 ml) was used to remove flesh from the center of each fruit, which was then crushed using a hand-held lemon press. Approximately 0.5 ml of juice was then applied to a hand-held a refractometer for measurement of TSS. Flesh firmness was measured using a hand held pressure tester with an 11 mm probe (FDK 160; Wagner Instruments, Greenwich, CT). The probe was then inserted twice near the center of each halved fruit for a total of four firmness measurements per fruit. Hollow heart incidence was graded on a scale of 0-5, where 0 corresponded to no presence of hollow heart and 5 was a severe incidence of hollow heart (Coolong, 2017).

Foliar macronutrient concentrations were determined from plant material collected approximately two weeks prior to the first harvest. One of the newest fully expanded leaves each from 15 and 10 representative plants in the center of each plot in 2016 and 2017, respectively, were sampled and combined in paper bags. Each sample was oven dried at 50^{0}C for a minimum of 10 d. Samples were analyzed by a commercial laboratory (Waters Agricultural Lab, Camilla, GA) for nutrient content.

Soil moisture probes (Watermark; Irrometer, Riverside, CA) were utilized in combination with a smart sensor array (UGA SSA). The UGA SSA consists of smart sensor nodes and gateway sensor nodes (Vellidis et al. 2008). A UGA SSA node consists of a circuit board, a radio frequency transmitter as well as soil moisture and temperature sensors. Environmental data from the array was recorded every 5 min and transmitted to a server hourly (Vellidis et al., 2013). Probes were placed at depths of 6, 10, and 14-inches in each plot to monitor soil moisture levels. Sensors were placed into holes and filled with a mud slurry from soil removed from the hole. Sensors were placed approximately 6-inches from drip irrigation emitters in each plot.

Data were subjected to the GLM procedure and mean separation using Tukey's Honest Significant Difference test ($P \leq 0.05$) with SAS statistical software (Version 9.3; SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Total season ET_c was greater in 2016 than 2017, which was primarily due to a higher ET_c in May and June of 2016 compared to 2017 (Table 3.1). Average daily high air temperatures in June 2016 were 90.2 ^oF compared to 85.8 ^oF for the same period in 2017. The 2016 growing season had 2.36 inches more rainfall than the subsequent season, but more than 50% of the rainfall was received in April 2016, with lower values during May, June, and July, when plant canopies were largest and ET_c were most impacted by weather conditions (Table 3.1).

During the 2016 growing season, the WB method of irrigation used 323,390 gal/acre of water and averaged 2,970 gal/acre per day (Table 3.2). The VegApp and SMS irrigation methods used 309,130 and 213,540 gal/acre for the season, respectively. The SMS irrigation method used the least amount of water in 2016, which is similar to results obtained in a related study evaluating the impact of tensiometers on irrigation scheduling in other vegetable crops (Smajstrla and Locascio, 1990). The VegApp utilized less water than the WB method, suggesting that applying real-time ET_o values obtained by nearby UGAWN weather stations may be more efficient than historic ET_o values. Irrigation volumes in 2017 were lower than 2016 for all treatments. This is not unexpected as ET_c was 29% lower in 2017 than in 2016. The WB irrigation method utilized 221,000 gal/acre irrigation water, while the VegApp and SMS irrigation treatments used 153,720 and 173,120 gal/acre water, respectively.

In 2017, the VegApp accounted more appropriately for lower levels of ET_c in late May and June compared to the WB method using historic ET_o values. This resulted in a larger relative reduction in water use in the VegApp plots compared to plants grown using the WB method in 2017. In addition, due to several significant rain events in June and early July 2017, soils surrounding plots became saturated. To reduce the potential impact of diseases such as Phytophthora fruit rot, scheduled irrigations in VegApp and WB-treated plots were discontinued for several days during these rain events. Irrigation in the SMS-based treatments remained on to account for tensiometers detecting increased soil moisture and not initiating irrigation unless soil conditions became appropriately dry. The reduction in irrigation in the VegApp and WB-managed plots during this time period likely resulted in a relative increase in water usage among SMS plots compared to the others in 2017.

Currently, the contribution of rainfall for vegetable crops has not been incorporated into the VegApp due to limited information regarding the impact of rainfall on soil moisture levels under plastic mulches (Migliaccio et al, 2016). The increased water usage for the SMS-based irrigation suggests that despite saturated soils surrounding plots, soil moisture levels in the adjacent to the tensiometers did not change significantly due to rainfall. This resulted in continued water use in SMS-managed plots when the other treatments were not applying irrigation.

When averaged over the two 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. 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 compared to the SMS-based system was more variable over the two study years. Several studies have reported improved irrigation efficiencies using SMS-based or real-time ET_c data compared to historic ET_o-based methods (De Pascale et al., 2011, Munoz-Carpena and Dukes, 2005).

There were significant treatment by year by depth interactions for soil moisture levels (Table 3.3). In April 2016, there was little plant canopy and soil moisture levels remained high at all depths (Table 3.3). In May 2016, VegApp-treated plots retained the most soil moisture at all depths, while WB and SMS-based plots had similar moisture levels at 6 and 10-inch depths. At a depth of 14-inches, the WB-based plots had a greater moisture tension than the SMS-based plots. In June and July 2016, VegApp and WB-managed plots had similar soil moisture levels at 6 and 10-inch depths, while SMS-managed plots had significantly higher soil moisture tension values. This may be due to the placement of the porous tip of the tensiometers in the SMS treatments, which may result in maintaining greater water demand at shallower depths compared to the VegApp (Marouelli and Silva, 2007). Despite differences, soil moisture tension values were above or near field capacity for all treatments and depths in 2016, suggesting that plants were not subjected to drought stress.

In 2017, SMS-based plots had significantly higher soil moisture tension values than the VegApp and WB-managed plots for most depths and sampling periods (Table 3.3). Although the difference was relatively small in May and June, by July the differences in soil moisture tension between SMS-managed plots and other treatments were significant. Midday leaf water potential readings are important as they measure bulk leaf water potential which is a simple indicator of leaf water status; the more negative the value, the more dehydrated the leaf. Midday leaf water potential (Ψ_{L}) readings recorded in June and July in both study years were not significantly different among treatments and were overall low (*data not shown*). This suggests that the increased soil moisture tensions in the SMS-based treatment were not reflected in plant moisture status. During May and June 2017, the SMS-based plots maintained soil moisture tensions within the -18/-10 kPa on/off range of the tensiometers. The increase in recorded soil moisture tension in early July may have been due to differences in root growth of plants near the smart sensor probes compared to tensiometers, which may not have been notable until the end of the trial when plant canopies were largest. Furthermore, VegApp managed plots received 11% less water than SMS-based plots in 2017, while maintaining lower soil moisture tensions, suggesting that volume of water delivered may not have been the primary reason for the relatively higher moisture tensions in the SMS-managed plots.

Soil water tension values showed differences among treatment and depth as measured by Watermark probes (Fig. 3.1a–f). The suspension and initiation of the irrigation schedule of the watermelon plots are reflected in the wetting and drying cycles displayed by the probes' measurements (Fig. 3.1a-f). SMS irrigated plots were watered for shorter durations of time, which generated a smaller decrease in soil water tension compared to the other treatments. The shorter duration of irrigation application can potentially reduce percolation and thereby improve fertilizer use efficiency and nutrient retention (Dukes et al., 2010). Conversely, the VegApp and WB treatment received higher volumes of water per application than the SMS treatment as it was irrigated for a longer time period which resulted in greater variations of soil water tension in 2016 at all depths (Fig. 3.1a, 3.1c, 3.1e.). The VegApp and WB treatments may provide more favorable growth conditions closely after irrigation applications due to prolonged saturated soil conditions compared to SMS treatments, potentially reducing water stress. During 35-40 days after transplant (DATP) and 75-90 DATP duration of the 2017 season the SMS-controlled treatment plots may have experienced soil moisture deficits, potentially due to increased levels of ET_0 during May and increased root growth late in the season which increased soil water tension.

There was a significant year by treatment interaction for yield of 45-ct fruit (Table 3.4). There were no treatment by year interactions for total marketable yield or other size categories. When main effects were analyzed, there were no treatment effects on yield; however, year significantly affected yields of 45, 36, and 30-ct fruit (*data not shown*). Total marketable yields ranged from 43,390 lb/acre for the WB-based treatment to 49,680 lb/acre in the Veg App-treated plots in 2016 and 50,280 lb/acre in the VegApp-based treatments to 59,540 lb/acre in the WB-treated plots in 2017. The yield of 60-ct fruit was not impacted by treatment in either season, while yields of 45-ct fruit were not affected by treatment in 2016, but were greatest in the SMS and VegApp treatments in 2017. The yield of 45-ct fruit in WB-grown plants was significantly lower than SMS-managed plots in 2017. There were no differences in 36-ct fruit among treatments in either year. The yields of 30-ct fruit, which are less desirable than other sizes for wholesale markets, were not affected by treatment, though were significantly higher in 2017 compared to 2016.

The availability and timing of watermelon harvest can affect the price growers receive for their product in Georgia. Typically prices are highest in early June and fall until early July at which time the harvest moves to another location. Therefore, the impact of irrigation on timing of harvest could be important. In 2016, SMS-grown plants had a significantly lower first harvest yield than VegApp and WB-based treatments (Table 3.4). Despite maintaining a relatively low soil moisture tension, the reduction in water use in the SMS-grown plants in the warmer and drier 2016 compared to the other treatments may have resulted in a delay in fruit maturation. There were no differences in first harvest yields among treatments in 2017.

Average fruit weight was not affected by treatment in either year. In 2016 average fruit weight ranged from 14.8 lb/fruit to 15.5 lb/fruit in the SMS and WB-grown fruit, respectively. In 2017, average fruit weights ranged from 15.5 lb/fruit to 16.3 lb/fruit in the VegApp and WB-grown plants, respectively. Total marketable yields were comparable to those expected from commercial watermelon fields in Georgia (Boyhan et al., 2017). Our results suggest that the VegApp produced similar yields to recommended grower practices for watermelon production in Georgia.

There were no significant year by treatment interactions for IWUE. However, treatment and year individually affected IWUE (Table 3.5). The SMS-based treatment had the highest numerical IWUE, though it was not significantly different from VegApp-grown plants. Plants produced using the WB method had a significantly lower IWUE than SMS-irrigated plants. The IWUE ranged from 0.20 lb/gal in the WB-managed treatment to 0.28 lb/gal in the SMS-based plots. These IWUE values were nearly twice those obtained with mini watermelons grown using deficit irrigation (Rouphael et al., 2008) and consistent with IWUE values obtained from other watermelon trials (Xie et al., 2010). The SMS-based irrigation system was automated and watered on-demand. Therefore, SMS plots often received relatively high frequency and short duration irrigation events. This results in a shallower wetting front after irrigation events, increasing application efficiencies (Munoz-Carpena and Dukes, 2017). In the current study the twice-daily irrigations employed with the VegApp did not have a significantly different IWUE compared to the SMS-based system, suggesting that it may be as efficient in some seasons as a more complex soil-moisture based systems. Year also significantly affected IWUE. Plants grown in 2017 had a significantly greater IWUE than in 2016 (Table 3.5). This increase in IWUE was the result of a decrease in water use in 2017 compared to 2016, as yields were not significantly different between the two growing seasons.

There were no significant year by treatment interactions or treatment effects for fruit TSS, firmness, or hollow heart. However, year significantly impacted fruit TSS and firmness (Table 3.6). Fruit TSS values ranged from 10.4% to 10.6% in the WB and VegApp-treated plots, respectively. Fruit TSS values were significantly higher in 2016 compared to fruit grown in 2017 decreasing from 11.1% to 9.7%, respectively. Fruit flesh firmness ranged from 3.0 lbs in VegApp-treated plots to 3.1 lbs in fruit grown under the SMS regime. The firmness of the watermelon fruit was significantly higher in 2017 compared to fruit grown in 2016. Hollow heart incidence was unaffected by treatment or year. Research regarding irrigation management in watermelon has indicated that unless treatments are widely separated in there water use, they may not significantly affect fruit quality parameters such TSS or occurrence and severity of hollow heart (Clark et al., 1996).

There were no significant year by treatment interactions for foliar macronutrient concentrations. There was a significant treatment effect for foliar N but not for phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) or sulfur (S) (Table 3.7). Foliar N concentrations were significantly higher in the VegApp treated plots than the SMS-grown plants. This 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 those plants, which could reduce the ability to take up N from the soil. 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 (Dukes et al., 2010).

Foliar P concentrations were not affected by treatment, with concentrations ranged from 0.30% to 0.31% in VegApp-grown plants to WB-grown plants, respectively. Potassium, ranged from 2.03% to 2.35% in SMS-treated plants and WB-treated plants. Foliar Ca concentrations were greater than is typically reported for watermelon production among all treatments in both growing seasons, ranging from 4.33% to 4.15% but were not affected by treatment (Bryson et al., 2014). Foliar Mg and S concentrations ranged from 0.45% to 0.50% and 0.33% to 0.36%, respectively, and were not affected by treatment or year and were within typical levels for watermelon.

Study year significantly affected foliar N, P, K, and Ca concentrations (Table 3.7). Foliar N concentrations increased from 4.04% in 2016 to 4.65% in 2017. This may be expected due to lower volumes of water used in 2017 may have reduced potential leaching across all treatments. Foliar P and K concentrations also increased in 2017 compared to 2016. In contrast, foliar Ca concentrations decreased by 0.87% in 2017 compared to 2016. As stated previously, Ca concentrations were greater than is typically reported for watermelon foliage. This was unexpected as other research trials conducted in the vicinity of this study did not show elevated Ca levels (data not shown) and preplant soil Ca levels were typical for the region.

CONCLUSIONS

The WB irrigation regime, which was used as a current grower recommended method, used the most water when averaging 2016 and 2017 data. Our results suggest that the VegApp used less water compared to the WB method of irrigation scheduling; although, it was not as efficient as a SMS-based system. This suggests that applying real-time ET_o values obtained by UGAWN weather stations can be more efficient than using historic ET_o values to determine irrigation scheduling for watermelon. In addition, plants grown using the VegApp had an IWUE that was similar to the SMS-based irrigation regime. This suggests that the VegApp may be less complex but suitable alternative to SMS-based irrigation. Furthermore, yields in all treatments were commercially acceptable indicating that the VegApp is suitable for watermelon growers to use in southern Georgia.

LITERATURE CITED

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: Proceedings of the Irrigation and Drainage Paper No. 56. Food and Agricultural Organization, United Nations, Rome, Italy.

Amayreh, J. and N. Al-Abed. 2005. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum Mill.)* under drip irrigation with black plastic mulch. Agricultural Water Management. 73: 247–254.

Assouline, S. and M. Ben-Hur. 2006. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. Catena. 66:211–220.

Bonachela, S., A.M. Gonzales, and M.D. Fernandez. 2006. Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data. Irrigation Sci. 25:53–62.

Boyhan, G., D.W. Granberry, and W.T. Kelley. 2017. Commercial watermelon production handbook. Univ. Georgia Coop. Ext. Bull. 996.

Bryson, G.M., H.A. Mills, D.N. Sasseville, J.B. Jones, and A.V. Barker. 2014. Plant Analysis Handbook III.   Micro Macro Publishing Inc., Athens, GA.

Clark, G. A., D.N. Maynard, and C.D. Stanley. 1996. Drip-irrigation management for watermelon in a humid region. Appl. Eng. Agr. 12:335-340.

Coolong, T. 2017. Trial report: watermelon variety evaluation 2017. 21 Dec. 2017. <http://www.caes.uga.edu/extension-outreach/commodities/vegetables/trial-results/watermelon.html>

Coolong, T., S. Surendan, and R.Warner, 2011. Evaluation of irrigation threshold and duration for tomato grown in a silt loam soil: HortTechnology, 21:466-473.

Coolong T. 2016. Evaluation of shallow subsurface drip irrigation for the production of acorn squash. HortTechnology, 26(4):436-443.

De Pascale, S., D. Costa, S. Vallone, G. Barbieri, and A. Maggio. 2011. Increasing water use efficiency in vegetable crop production: From plant to irrigation systems efficiency. HortTechnology 21:301–308.

Dukes, M. D., L. Zotarelli, and K. T. Morgan. 2010. Use of irrigation technologies for vegetable crops in Florida. HortTechnology, 20:133–142.

Harrison, K. 2009. Irrigation Scheduling Methods. Univ. Ga. Coop. Ext. Serv. Athens, GA. Univ. Georgia Coop. Ext. Bull. 1312:1-5.

Hausbeck, M.K. and K.H. Lamour. 2004. *Phytophthora capsici* on vegetable crops: research progress and management challenges. Plant Dis. 12:1292-1303.

Hord, M. J. and J.B. Ristaino. 1992. Effect of the matric component of soil water potential on infection of pepper seedlings in soil infested with oospores of *Phytophthora capsici*. Phytopathology 82:792-798.

Horton, D. 2016. 2016 Georgia pest management handbook. Univ. Ga. Coop. Ext. Serv. Spec. Bul. 28.

Marouelli, W.A., W.L.C. Silva, and C.L. Moretti. 2004. Production: quality and water use efficiency of processing tomato as affected by the final irrigation timing. Hortic. Bras. 22:225–230.

Migliaccio, K.L., K.T. Morgan, G. Vellidis, L. Zotarelli,, C. Fraisse, D. Rowland., J.H. Andreis, and J.H. Crane. 2016. Smartphone apps for irrigation scheduling. Emerging Technologies for Sustainable Irrigation: A joint ASABE / IA Irrigation Symposium, Long Beach, California, November 10 – 12, 2015.

Munoz-Carpena, R., and M.D. Dukes. 2017. Automatic Irrigation Based on Soil Moisture for Vegetable Crops. Univ. Florida Inst. Food Agr. Sci. Bul. 354.

Munoz-Carpena, R., M.D. Dukes, Y.C.C. Li., W. Klassen. 2005. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. HortTechnology 15:584–590.

Proietti, S., Y. Rouphael, G. Colla, M. Cardarelli, M. De Agazio, M. Zacchini, S. Moscatello, and A. Battistelli. 2008. Fruit quality of mini-watermelon as affected by grafting and irrigation regimes. J. Sci. Food Agr. 88:1107-1114.

Rouphael, Y., M. Cardarelli, G. Colla, and E. Rea. 2008. Yield, mineral composition, water relations, and water use efficiency of grafted mini-watermelon plants under deficit irrigation. HortScience 43:730-736.

Schultheis, J.R., Thompson, W.B., 2014. 2014 North Carolina Watermelon Cultivar Trials. NC State University, Raleigh, NC. Hort. Series 210.

Shukla, S., F. Jaber, S. Srivastava, and J. Knowles. 2007. Water Use and crop coefficient for watermelon in Southwest Florida. Agricultural and Biological Engineering Department.

Simonne, E.H., M.D. Dukes and L. Zotarelli. 2010. Principles and Practices of Irrigation Management for Vegetables. 17-26. In: S. M. Olson and E. Simonne. eds. Vegetable Production Handbook for Florida 2010-2011. IFAS, Gainesville, FL.

Smajstrla, A.G. and S.J. Locascio. 1990. Irrigation scheduling of drip-irrigated tomato using tensiometers and pan evaporation. Proc. Fla. State Hort. Soc. 103:88-91.

Vellidis, G., M. Tucker, C. Perry, C. Kvien, and C. Bednarz, 2008. A real-time wireless smart sensor array for scheduling irrigation. Comput. Electron. Agric. 61:44–50.

Vellidis, G., M. Tucker, C. Perry, D. Reckford, C. Butts, H. Henry, V. Liakos, W. R. Hill, and W. Edwards, 2013. A soil moisture sensor-based variable rate irrigation scheduling system. In J.V. Stafford (Ed.), Precision Agriculture 2013—Proceedings of the 9th European conference on precision agriculture (pp. 713–720). The Netherland: Wageningen Academic Publishers.

Xie, Z., Y. Wang, G. Cheng, S. Malhi, C. Vera, Z. Guo, and Y. Zhang. 2010. Particle-size effects on soil temperature, evaporation, water use efficiency, and watermelon yield mulched with gravel and sand in semi-arid Loess Plateau of northwest China. Agr. Water Mgt. 97:917-923.

Zitter, T.A., D.L. Hopkins, and C.E. Thomas. 1996. Compendium of cucurbit diseases. APS Press, St. Paul, MN.

Table 3.1. Accumulated rainfall, crop evapotranspiration (ET_c), and the average daily maximum (T_{max}) and minimum (T_{min}) temperatures during the study period for watermelon grown in Tifton, GA in 2016 and 2017.

	(inches)[z]			(°F)[z]	
	Rainfall	ET_c[y]	ET_o	T_{max}	T_{min}
2016					
28-31 March	0.25	0.17	0.5	76.1	55.6
April	6.34	1.83	4.42	75.8	55.4
May	1.45	4.07	5.81	83.7	61.3
June	3.94	5.58	6.20	90.2	69.6
1-13 July	0.09	2.30	2.88	91.6	72.3
Season	12.07	13.95	19.81	84.5	63.5
2017					
13-30 April	0.32	0.95	3.17	82.7	59.6
May	2.65	3.54	5.57	84.0	61.4
June	5.11	3.36	4.58	85.8	68.8
1-12 July	1.63	2.01	2.51	91.3	72.3
Season	9.71	9.86	15.83	85.3	65.0

[z](°F - 32) ÷ 1.8 = °C, 1 inch = 2.54 cm.

[y]$ET_c = ET_o \times K_c$.

Table 3.2. 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.

Irrigation treatment	Irrigation volume (gal/acre)^z	Daily Water Use (gal/acre per day)^z
	2016	
VegApp	309,130	2,840
WB	323,290	2,970
SMS	213,540	1,960
	2017	
VegApp	153,720	1,710
WB	221,000	2,460
SMS	173,120	1,920

^{z}1 gal/acre = 9.3540 L·ha^{-1}.

Table 3.3. Soil moisture tension at depths of 6, 10, and 14-inches in watermelon grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

		Soil Moisture Tension (cbar)[z]													
		2016								2017					
Depth	Treatment	April		May		June		July		May		June		July	
6-inch	VegApp	0.05	a[y]	0.87	a	0.38	a	1.41	a	3.44	a	8.68	b	6.85	b
	WB	0.00	a	5.17	b	0.22	a	0.09	a	3.14	a	3.58	a	1.64	a
	SMS	0.19	a	4.22	b	3.23	b	5.82	b	14.66	b	11.87	b	41.82	c
10-inch	VegApp	0.16	a	0.51	a	0.14	a	0.00	a	1.15	a	6.33	b	1.26	a
	WB	0.16	a	7.06	b	0.48	a	0.00	a	1.38	a	1.25	a	0.61	a
	SMS	0.00	a	4.33	b	4.13	b	6.64	b	11.36	b	10.85	c	37.67	b
14-inch	VegApp	0.00	a	0.85	a	0.71	a	0.00	a	0.87	a	7.29	b	5.08	b
	WB	0.00	a	8.14	c	2.55	b	1.35	a	0.33	a	0.61	a	0.03	a
	SMS	0.00	a	5.03	b	8.33	c	10.50	b	11.11	b	15.61	c	58.23	c

[z] 1 cbar = 1.0 kPa, 1 inch = 2.54 cm.

[y] Values in the same column, depth 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 3.4. Total marketable yields, yield of 60, 45, 36, and 30-count (ct) watermelon fruit as well as average fruit weight for watermelons grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

	(lb/acre)[z]												(lb)[z]	
Irrigation Treatment	Total		60 ct[y]		45 ct		36 ct		30 ct		First Harvest		Fruit Weight	
	2016													
VegApp	49,680	a[x]	14,610	a	10,800	a	20,310	a	3,960	a	27,100	a	15.3	a
SMS	49,280	a	15,520	a	10,180	a	20,670	a	5,950	a	20,500	b	14.8	a
WB	43,390	a	11,130	a	7,130	a	19,010	a	3,070	a	28,560	a	15.5	a
	2017													
VegApp	50,280	a	13,760	a	21,190	ab	9,090	a	6,250	a	18,250	a	15.5	a
SMS	58,420	a	14,490	a	25,870	a	11,490	a	6,570	a	20,990	a	16.2	a
WB	59,450	a	18,640	a	14,930	b	14,310	a	11,560	a	21,220	a	16.3	a

[z] 1 lb/acre =1.1209 kg·ha^{-1}, 1 lb = 453.5924 g, 1 lb/gal = 0.1198 kg·L^{-1}.

[y]60 ct = 9 to 13.5 lb, 45 ct = 13.6 to 17.5 lb, 36 ct = 17.6 to 21.4 lb, and 30 ct ≥ 21.5 lb.

[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 3.5. Main effects of treatment and year for irrigation water use efficiency (IWUE) for watermelons grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

Irrigation treatment	IWUE[z] (lb/gal)[y]	
VegApp	0.24	ab[x]
SMS	0.28	a
WB	0.20	b
Year		
2016	0.17	b
2017	0.31	a

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

[y] 1 lb/gal = 0.1198 kg·L^{-1}.

[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 3.6. Main effects of treatment and year for total soluble solids (TSS) and pH for watermelon fruit grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

Irrigation treatment	TSS (%)		Firmness (lb)[z]		Hollow Heart (0-5)[y]	
WB	10.4	a[x]	3.03	a	0.35	a
SMS	10.5	a	3.10	a	0.23	a
VegApp	10.6	a	3.03	a	0.31	a
2016	11.1	a	2.8	b	0.35	a
2017	9.7	b	3.3	a	0.23	a

[z]1 lb = 453.5924 g

[y]Hollow heart graded on a 0-5 scale, with 0=no incidence, 2=0.25-0.5-inch cracking in center of fruit, 5= >1.5-inch cracking in center of fruit (1 inch = 2.54 cm).

[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 3.7. Foliar concentrations of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) for watermelons grown using the Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

	(%) dry weight											
Irrigation Treatment	N		P		K		Ca		Mg		S	
VegApp	4.54	a[z]	0.31	a	2.30	a	4.33	a	0.45	a	0.33	a
WB	4.30	ab	0.30	a	2.35	a	5.04	a	0.50	a	0.36	a
SMS	4.21	b	0.30	a	2.03	a	5.15	a	0.48	a	0.34	a
Year												
2016	4.04	b	0.28	b	2.04	b	5.30	a	0.49	a	0.31	a
2017	4.65	a	0.33	a	2.41	a	4.43	b	0.47	a	0.37	a

[z]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.

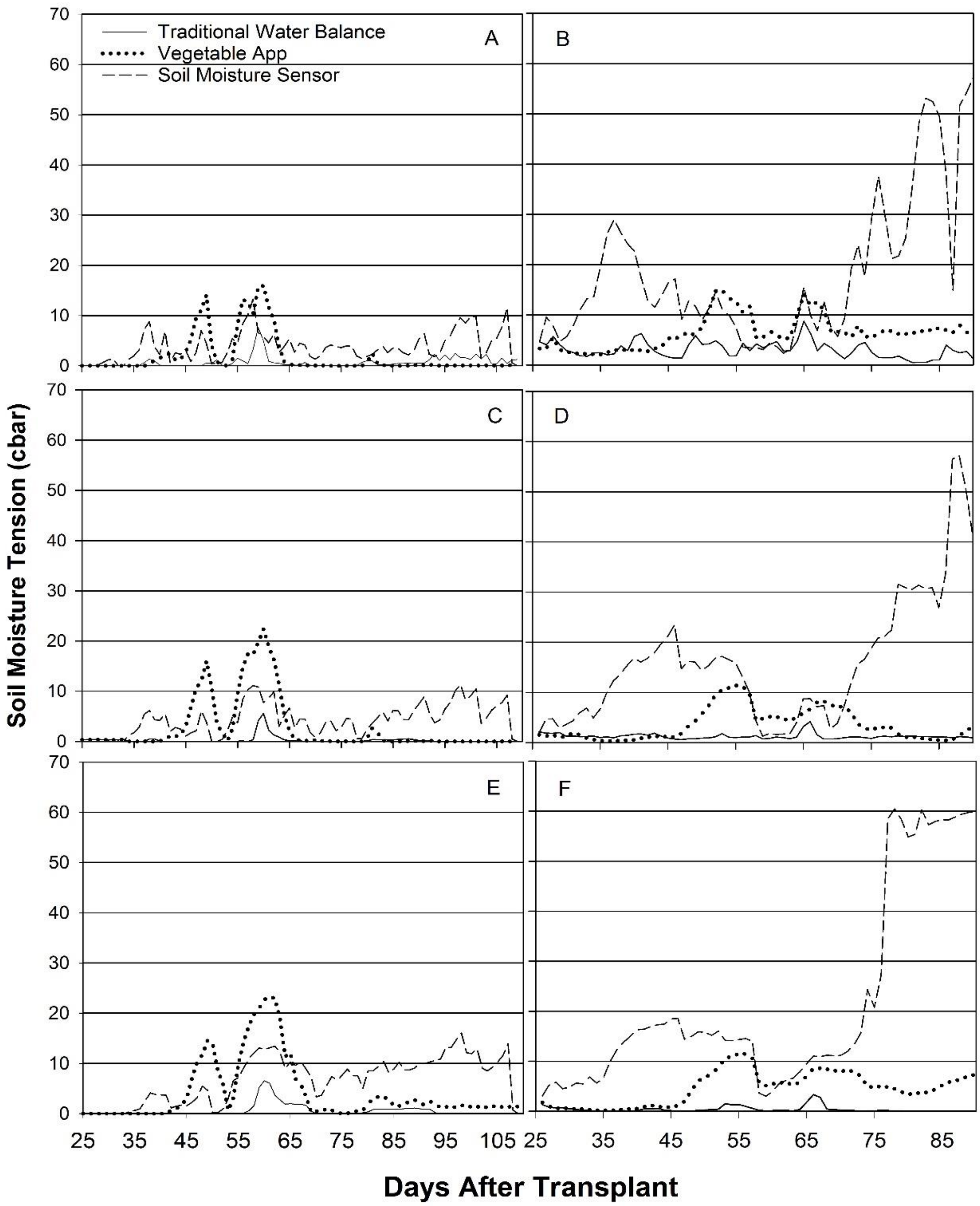

Figure 3.1 Average daily soil moisture tension measured in watermelon grown in Tifton, GA.

Figure 3.1a. Soil moisture tension at 6-inches in 2016.

Figure 3.1b. Soil moisture tension at 6-inches in 2017.

Figure 3.1c. Soil moisture tension at 10-inches in 2016.

Figure 3.1d. Soil moisture tension at 10-inches in 2017.

Figure 3.1e. Soil moisture tension at 14-inches in 2016.

Figure 3.1f. Soil moisture tension at 14-inches in 2017.

CHAPTER 4

EVALUATING PREDICTIVE CROP MATURITY MODELS IN COMBINATION WITH ALTERNATIVE IRRIGATION SCHEDULING METHODS

SUMMARY

An accurate irrigation scheduling methodology is necessary in crops with high water stress sensitivity and production costs. This involves the estimation of the scheduling parameters related to crop water requirements during different phenological stages. This study evaluates days after planting (DAP) models combined with the water balance (WB) and VegApp irrigation scheduling methods and assesses a potential growing degree days (GDD) model of crop maturity. The VegApp, utilize a DAP model for determining crop growth stage and a corresponding crop coefficient (K_c) used to determine irrigation volumes. However, dynamic seasonal changes in weather conditions can impact crop growth and development such that a DAP model may not acclimate to determine an accurate K_c curve in a given year. Instead, we propose that using GDD may be a more appropriate alternative to determining K_c curves in the VegApp. The VegApp was utilized to schedule irrigation in spring 2016 and 2017 in tomato (*Solanum lycopersicum*) and watermelon (*Citrullus lanatus*) in southern Georgia. The VegApp, was shown to be an alternative to current irrigation recommendations that more efficiently utilized irrigation water compared to current methods. However, differences in weather conditions between the 2016 and 2017 growing seasons resulted in changes to days required for first and last harvest. In tomato 2016, the first harvest occurred at 73 days after transplanting

(DAT), while it occurred at 70 DAT in 2017. Similarly, the first harvest for watermelon occurred at 93 DAT in 2016 and 75 DAT in 2017. This difference was due to differences in weather at planting and during key stages of plant growth development. Our data suggests that in 2016 the number of accumulated GDD accrued by watermelon crops between seasons differed substantially as to suggest its viability as a predictor of plant maturity. While in tomatoes GDD accumulation was similar and a predictive model based on environmental conditions may better adapted to the pace of maturity and development.

INTRODUCTION

Both the VegApp and WB methods require the availability of reliable ET_o reference evapotranspiration data and K_c crop coefficients, which define crop water use and water stress sensitivity (Ojeda-Bustamante et al., 2004). In addition, irrigation scheduling depends on multiple environmental factors as well as grower inputs such as soil water-holding capacity, irrigation method, duration of irrigation event and production system. Days after transplanting models are suitable when planting periods are short and weather conditions are not highly variable between growing seasons. However, when standardized planting dates or weather conditions frequently change between seasons, determining K_c as a function of cumulative GDD may be more accurate.

Growing degree days are determined by the integration of the ambient temperature between the maximum and minimum temperatures where crop growth occurs (Snyder et al., 1999). The crop's development will cease below the lower threshold of this range as defined by the base temperature.

Where GDD = growing degree days, T_H= average daily high temperature, T_L=Average daily low temperature and T_b= base temperature, the calculation of GDD is based on daily average air temperature using the following equation:

$$GDD= [(T_H\ {}^0\mathrm{F}+T_L\ {}^0\mathrm{F})/2]-T_b$$

Tomatoes and watermelons have fixed values of cumulative GDD to reach progressive stages of crop development, which therefore can be estimated based on accumulated GDD (Miller et al., 2001). The base temperature established for watermelon used in this study is 50^0 F, while the base temperature for tomato is 55^0 F. Certain crops may not be accurately modeled by this approach because of sensitivity to photoperiod or other external effects such as high moisture deficits, or pest and disease pressure, which can adversely affect plant growth and development.

Traditional WB-method recommendations for drip irrigated tomatoes and watermelon in Georgia and Florida are based on estimates of daily crop water use based on historic ET_o values for the region adjusted with a K_c (Allen et al., 1998). The WB method of calculating weekly ET_0 is based on the following equation: $ET_c = ET_0 \times K_c$. Generally the K_c increase over time until initial harvests are initiated, then decrease as the crop moves toward senescence. 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 and K_c. However, irrigating solely based on predicted ET_c and K_c values may be inaccurate due to changes in annual weather patterns.

MATERIALS AND METHODS

This study was conducted at The University of Georgia, Tifton Vegetable Park in Tifton, GA (lat. 31^0 5' N, long. 83^0 5' W) in 2016 and 2017. The soil was a Tifton loamy sand series

(0%-2% slope, fine-loamy, kaolinitic, thermic Plinthic Kandiudults). Seedless watermelon 'Melody' (Syngenta, Woodland, CA) with the pollenizer 'Sp6' (Syngenta) were used as well as the tomato 'Red Bounty' (HM Clause, Davis, CA).

Watermelon seedlings were transplanted by hand on 28 Mar. and 13 Apr. in 2016 and 2017, respectively. Plots consisted of two rows spaced 6-ft apart on center with 42-inch in-row spacing (2074 plants/acre). Pollenizer plants, 'Sp6', were planted equidistant between every third and fourth plants in a row. Tomato seedlings were transplanted on 28 Mar. and 12 Apr. in 2016 and 2017, respectively. Plants were watered equally for approximately 4 weeks after transplanting in 2016 and 3 weeks after transplanting in 2017 at which time irrigation treatments were implemented.

The VegApp calculated ET_c from weather data collected by University of Georgia Weather Network (UGAWN) weather station in Tifton. The VegApp calculated gross irrigation requirements as described in the watermelon and tomato studies in the previous two chapters. The ET_0 is adjusted using K_c based on a days after planting model of crop maturity for drip irrigated watermelons and tomatoes grown on plastic mulch (Simonne et al., 2010). The VegApp then calculated average ET_0 over the previous five days and estimated ET_c based on the following equation: $ET_c = ET_0 \times K_c$ (Migliaccio et al., 2016). Irrigation water use in the VegApp plots was compared to plots managed using the WB method. WB method irrigation schedules were calculated based on the method described in the watermelon and tomato studies. The gross irrigation requirement is based on estimated crop water determined by historical rates of ET_0 adjusted with K_c for watermelons or tomatoes. Historic ET_0 was comprised from a 10-year average of measured ET_0 rates during selected months in Northwest Florida. Crop coefficients developed for plasticulture-grown watermelons and tomatoes in Florida were used due to a lack of K_c developed for Georgia (Simonne et al., 2010).

RESULTS/DISCUSSION

Tomato Harvest

During the harvest period in tomato (after 73 DAT), the average maximum temperatures were 90.2 and 92.2^{0}F in June 2016 and July 2016 in tomato, respectively (Table 1). In 2016, tomato field production began 28 Mar. and ended 11 July for a cropping season of 115 days. During the 2016 season, the greatest amount of water was applied during the month of June which overlaps the small fruit stage and large fruit growth stage of the crop (Table 4.1). Similarly, in the 2017 season the greatest amount of water was applied during June and growth stage small fruit stage (Table 4.1). Average daily temperatures in June 2016 appeared to have limited negative effects on flower development as six harvests took place at 73 DAT, 81 DAT, 86 DAT, 91 DAT, 95 DAT and 99 DAT.

The 2017 tomatoes were grown from 12 Apr. to 21 July, with five harvests at 70, 83, 89, 94, and 100 DAT. Cumulative growing degree days experienced by tomatoes for the entirety of the growing season in both years were similar. In 2016, 1887 GDD were accumulated and in 2017, 1842 GDD were accumulated. Due to this, the harvest dates and progression of maturity in tomato were similar between years. In 2016, rainfall events occurred for 34 d (32% of growing season), resulting in a total rainfall of 12.07 inches. In 2017, rainfall events occurred for 26 d (31% of season) resulting in 11.12 inches of rain. There was a numerical correlation between increased K_c, increased water use, and increased growing degree days during the small fruit stage and large fruit stage of plant development (Table 4.1). This reflects the effects of crop growth, fruit initiation and development on ET_c described in related research and suggest that growing degree days has potential to accurately estimate increased K_c and crop water use (Allen et al., 1998).

Watermelon Harvest

In 2016, watermelon field production season lasted for 15 weeks with three harvests at 93 DAT, 100 DAT and 107 DAT. The 2017 growing season lasted 14 weeks with three harvests at 75 DAT, 83 DAT and 90 DAT. In 2016, 2479 GDD accumulated compared to 2336 were accumulated in 2017. In 2016, rainfall events occurred for 33 days (31% of growing season), resulting in a total rainfall of 12.07 inches. In 2017, rainfall events occurred for 25 days (28% of season), resulting in 9.71 inches of rain. Excessive rainfall during flowering potentially led to inhibited bee activity, delayed pollination or abortion of female flowers and fruit which may have contributed to along with other conditions to lesser yields in 2016 (Korkmaz and Dufault, 2001). In addition, rainfall earlier in the growing season, during flowering in 2016 may have delayed fruit set, therefore, delaying the first harvest in 2016 compared to 2017. The impact of increased temperatures and dry conditions during fruit enlargement in 2016 was supported by the significantly greater soluble solids content of the melons in 2016 compared to 2017. There was a numerical correlation between K_c and increased water use during the small fruit stage (Table 4.2), reflecting the effects of crop growth and development on ET_c (Allen et al., 1998). A slight increase of K_c was observed in the late season stage of crop development, which was correlated to increased water use (Table 4.2).

DAP Limitations

During the end of the 2017 season, using the VegApp became difficult as the DAP model inaccurately predicted harvest dates in tomatoes. The prediction for the end of the growing season can range from 70 to 115 days after transplant (Simonne et al., 2010). During the 2017 season, irrigation scheduling was not recommended during the week of final harvest, thus demonstrating a need to reevaluate the DAP model in combination with irrigation scheduling. Furthermore, in the 2017 season initial fruit set and initial harvest was not accurately predicted in watermelon production.

CONCLUSIONS

From this study we found that DAP harvests were sporadic between years in watermelon production. The pace of changing maturity in the tomato and watermelon crops were observed in both years pertaining to initial harvest and final harvest. The number of accumulated degree days accrued by both crops between seasons were numerically different and exhibited the changing conditions between seasons that ultimately affected crop phenology. Watermelon, as well as tomato maturity growth stages, were not precisely predicted by days after planting models and potentially could be more precisely accounted for by growing degree days.

LITERATURE CITED

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: Proceedings of the Irrigation and Drainage Paper No. 56. Food and Agricultural Organization, United Nations, Rome, Italy.

Korkmaz, A. and R.J. Dufault. 2001. Developmental consequences of cold temperature stress at transplanting on seedling and field growth and yield. J. Amer. Soc. Hort. Sci. 126:404-409.

Migliaccio, K.L., K.T. Morgan, G. Vellidis, L. Zotarelli,, C. Fraisse, D. Rowland., J.H. Andreis, and J.H. Crane. 2016. Smartphone apps for irrigation scheduling. Emerging Technologies for Sustainable Irrigation: A joint ASABE / IA Irrigation Symposium, Long Beach, California, November 10 – 12, 2015.

Miller, P, W. Lenier, and S. Brandt. 2001. Using growing degree days to predict plant stages. Montana Guide Fact Sheet MT 200103 AG 7/2001. Montanta State University Extension Service, Bozeman, Montana.

Ojeda-Bustamante, W., E. Sifuentes-Ibarra, D.C. Slack and M. Carrillo. 2004, Generalization of irrigation scheduling parameters using the growing degree days concept: Application to a potato crop. Irrigation and Drainage. 53:251-261.

Simonne, E.H., M.D. Dukes and L. Zotarelli. 2010. Principles and Practices of Irrigation Management for Vegetables. 17-26. In: S. M. Olson and E. Simonne. eds. Vegetable Production Handbook for Florida 2010-2011. IFAS, Gainesville, FL.

Snyder R.L., D. Spano, C. Cesaraccio, and P. Duce. 1999. Determining degree day thresholds from field observations. International Journal of Biometeorology 42:177–182.

Table 4.1. Accumulated rainfall, average daily maximum (T_{max}) and minimum (T_{min}) temperatures, growing degree days and treatment water use during the study period for tomato using GDD and days after planting models (DAP) in Tifton, GA in 2016 and 2017.

	(inches)[z]	(°F)[z]		(gal/ac/day)		
	Rainfall	T_{max}	T_{min}	GDD	VegApp DAP	WB DAP
			2016			
18-30 April	0.03	80.6	57.8	180	1380	1660
May	1.45	83.7	61.3	528	2940	4990
June	3.94	90.2	69.6	736	5230	5850
1-11 July	0.09	92.2	72.6	286	4570	4370
			2017			
17-31 May	2.65	86.5	65.6	308	4350	3580
June	5.11	85.8	68.8	624	3840	3410
1-21 July	3.03	91.0	72.2	523	860	1040

[z](°F - 32) ÷ 1.8 = °C, 1 inch = 2.54 cm.

Table 4.2. Accumulated rainfall, average daily maximum (T_{max}) and minimum (T_{min}) temperatures, growing degree days (GDD) and water use during the study period for GDD and days after planting models (DAP) for watermelon grown in Tifton, GA in 2016 and 2017.

	(inches)[z]	(°F)[z]			(gal/ac/day)	
	Rainfall	T_{max}	T_{min}	GDD	VegApp DAP	WB DAP
			2016			
18-30 April	0.03	80.6	57.8	245	1090	1380
May	1.45	83.7	61.3	683	2200	3010
June	3.94	90.2	69.6	886	3420	4060
1-13 July	0.09	91.6	72.3	402	3420	4050
			2017			
17-31 May	1.21	86.5	65.6	358	2790	3630
June	5.11	85.8	68.8	774	2240	3890
1-12 July	1.63	91.3	72.3	397	2710	3570

[z](°F - 32) ÷ 1.8 = °C, 1 inch = 2.54 cm.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

SUMMARY OF FINDINGS

The results of the tomato study demonstrated that the water balance (WB)-method of irrigation utilized the most water over both study years. The SmartIrrigation^{TM} Vegetable Application (VegApp) utilized 16% less water when averaged over both study years compared to the WB method of irrigation scheduling. Our data supports our hypothesis that applying real-time reference evapotranspiration (ET_0) values obtained by weather stations can potentially improve the efficiency of irrigation scheduling calculations. The irrigation water use efficiency (IWUE) was improved in the VegApp plots compared to the WB method. Based on this increase, we propose that VegApp has the ability to reduce water use and protect yields compared to methods relying on historic ET_0 to manage irrigation. The VegApp also generated significantly greater IWUE in 2017 when compared to soil moisture based (SMS)-based plots, which suggests that at times the VegApp may be a suitable alternative to SMS-based irrigation. Total tomato marketable yield and internal quality parameters were not heavily influenced by the irrigation scheduling treatments, suggesting that the VegApp does not adversely affect quality of tomatoes.

The watermelon trial demonstrated that the WB irrigation method utilized the most water over the course of the two-year study. Similar to tomatoes, results from the watermelon study also indicated real-time ET_0 values obtained by nearby weather stations can be more effective in determining crop water use than historic ET_0 values to create irrigation scheduling for watermelon. Additionally, VegApp-grown plants had an increased IWUE generated by the VegApp compared to the WB-grown plants. This suggests that the VegApp is an improved model for irrigation scheduling regarding water usage. Similar IWUE values were obtained between SMS and VegApp managed plants, suggesting that in watermelons, as with tomatoes, the VegApp may be a suitable alternative to SMS-based irrigation. Marketable yields of watermelon were equivalent to regional growers and quality of watermelon was not significantly altered by the VegApp treatment suggesting that the VegApp also safeguards yields and quality of watermelon crops.

The number of accumulated degree days accrued by watermelon crops varied between seasons, ultimately impacting crop development. Based on the days after planting (DAP) model used by the WB and the VegApp, the crop coefficients for tomato and watermelon (K_c) reached maximum values during the mid-season and first harvest, correlating to increased applications of water seen in the study. However, in our trials we found that watermelon and tomato maturity were not precisely predicted by DAP models and potentially could be accounted for in greater detail by growing degree days (GDD). The difference in experienced weather conditions between seasons highlighted disparities in crop water use calculated between a DAP and GDD model. In the 2017 growing season, cooler temperatures watermelon led to last harvest dates being at 107 DAP, while in the warmer and drier 2016 growing season, the last harvest was 93 DAP, suggesting that watermelon growth stages were not accurately predicted by the DAP schedule used currently by the VegApp and the WB method of scheduling irrigation.

CONCLUDING REMARKS

The VegApp compared to the currently recommended WB-method of irrigation scheduling conserved water and did not significantly affect total marketable yields in watermelons or tomatoes. This combined with the convenience of using the VegApp, compared to conducting time-consuming calculations required in the WB-method, makes it a viable alternative method of irrigation scheduling. The SMS treatment and the VegApp generated similar IWUE averaged over a two year period in watermelon and tomato plots. This indicates that the VegApp and SMS-based systems could produce similar yields while reducing water usage over currently accepted methods of irrigation. However, the VegApp may also reduce error that is inherent to SMS-based systems that are placed in heterogeneous soils. In our current study, we used independent SMS-based systems to control one or two rows of tomatoes or watermelons, respectively. Therefore, each SMS setup controlled irrigation for a small region of soil. To use this system on a large scale operation would likely create an increase in variability and potential error across the field as soil characteristics would vary from the region of sensor location. The alternative of increasing sensor numbers in fields would be costly and time consuming. Therefore, the added labor and financial expense associated with SMS systems compared to the VegApp, makes the VegApp a simpler and much more cost effective alternative to the SMS system. The VegApp is not an automated system, which allows the VegApp irrigation schedule to be applied with greater flexibility compared to the SMS method, which self-determines soil dryness and automatically triggers irrigation when necessary. The VegApp offers flexibility, simplicity and the ability to produce commercially acceptable yields, while reducing water use in watermelon and tomato production.

FUTURE RESEARCH

The importance of irrigation scheduling cannot be understated as the optimal amount and timing of water application reduces expenditures and increases water use efficiency. A key adjustment to irrigation scheduling recommendations regarding the SmartIrrigation™ App involves the potential of predictive crop maturity models. The days after planting model did not accurately predict several stages of growth during tomato and watermelon growth and may lead to improper application of water. In the future, the SmartIrrigation™ App could also employ deficit irrigation levels to be applied to the app to allow growers to adjust ET_c levels based on their perceived water needs of crops. The SmartIrrigation™ App should also incorporate soil data into the VegApp to optimize water use efficiency.

The irrigation schedule feature of the VegApp could be improved in several ways: alter number of days used to calculate ET_c, recommended number of days for irrigation scheduling, and allowing for an alternate water balance model that addresses bareground production systems. While many growers in southern Georgia use plastic mulch to grow vegetable crops, the VegApp does not provide an option for bareground growing production. Because the VegApp assumes that plastic mulch is being used, rainfall is not incorporated into irrigation recommendations. To develop a bareground production scenario, rainfall would also have to be incorporated into the VegApp. However, there are concerns of using rainfall data from a nearby weather station for predicting irrigation. Given the climate of southern Georgia and the volatile thunderstorms which bring intense rainfall in short durations of time, rainfall amounts tend to be very spatially variable.

The nature of rapidly changing weather conditions in southern Georgia also may lead to inaccurate representations of daily ET_c calculated by the VegApp as the VegApp averages a five day total, however, these five days may not reflect a significant change in weather between days sampled. This average is used for the crop water use and irrigation scheduling calculations, which could lead to inaccurate reflections of ET_c if there is significant variation in daily ET_c over the five day period. Based on the observation of the researcher, the utility of the VegApp could be improved by providing irrigation schedules with a shorter duration of recommended use than a two week period after the irrigation schedule is calculated. Changing weather conditions in the region may drastically change the evapotranspiration rate of a given crop within a two week period of time and thus adjustments to the irrigation schedule may be necessary.

Future research should also evaluate lateral water movement under plastic mulches with an emphasis on movement after intense rainfall. Rainfall was not used by either the VegApp or WB models, as the current assumption is that rainfall generally contributes little to soil moisture levels under raised beds with plastic mulches. To more accurately determine the impact of rainfall on soil moisture under raised beds with plastic mulches, soluble dyes could be used to track water movement underneath plastic mulch bed. This information could be used to refine irrigation scheduling calculations. Future applications, which would be easily incorporated into the VegApp may include peppers, eggplants and other plasticulture-grown vegetable crops.