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Scheduling Irrigation using an approach based on the Van Genuchten Model

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ABSTRACT

Crop irrigation which results in high water use efficiencies typically uses science-based irrigation scheduling tools to determine irrigation application timing and quantities. Although a large variety of sensors are available for measuring soil moisture status, there are a few easy-to-use irrigation scheduling tools which provide a yes/no irrigation decision or recommend how much water should be applied to return the soil profile to an optimal soil moisture condition. The work described here developed a method which uses soil water tension data from soil moisture sensors and the van Genuchten model to provide irrigation scheduling recommendations. The strength of the method is that it can use data readily available from USDA-NRCS soil surveys to predict soil water retention curves and calculate the volumetric water content and soil water tension of a soil at field capacity. Those parameters are then used to translate measured soil water tension into irrigation recommendations which are specific to the soil moisture status of the soil. The method was validated by comparing its results to other published methods and with continuous soil water tension data with multiple wetting and drying cycles from six fields in southern Georgia, USA. Finally, the model was incorporated into a web-based irrigation scheduling tool and used in conjunction with a wireless soil moisture sensing system to schedule irrigation in a large commercial field during 2015. By the van Genuchten model, we used about two thirds of the irrigation water and produced about the same yields as a commonly used yes/no irrigation decision tool. The presented method can be used to build resiliency to climate variability because it provides growers with data which they can use to make informed decisions about managing their water resources.

Key words: field capacity, permanent wilting point, volumetric water content, soil water tension

1. Introduction

Agricultural irrigation is vital to food production in many parts of the globe and a critical tool for ensuring food security. Irrigation not only serves to reduce risk of crop loss but also to build resiliency to climate variability and yield stability in food production systems. Irrigated agriculture provides 40% of the world's food while being used on only 18% of the cultivated land (FAO, 2015). The United Nations Food and Agricultural Organization estimates that the world currently consumes about 70% of available fresh water for irrigation (FAO, 2015). In the United States, irrigation withdrawals were estimated at 435 million m^3 per day in 2010 and accounted for 38% of total freshwater withdrawals (Maupin et al., 2014). In light of projected food needs of a growing world population, significant improvements in agricultural water use efficiency (WUE) leading to more crop per drop should be a high priority across multiple disciplines of science.

Irrigation which results in high WUE typically uses science-based irrigation scheduling tools to determine irrigation application timing and quantities. A large number of techniques and tools have been developed to assist growers to estimate when and how much water to apply to crops. Yet data recently released by the 2013 USDA National Agricultural Statistical Service Farm and Ranch Irrigation Survey indicated that more than 72% of irrigated farms still rely either on a fixed schedule or on visual symptoms of plant stress such as wilting. Only 28% use any type of science-based irrigation scheduling tools and even fewer (12%) use irrigation scheduling methods such as soil moisture sensors or web-based tools that address conditions specific to their farms (NASS, 2013).

Typically, farmers will apply a standard amount (for example, 25 mm or 1 in) at each irrigation event. As a result, both the timing and depths of irrigation may be inappropriate and may lead to yield, nutrient, and soil losses. The extent to which improper timing of irrigation can result in yield losses has been documented for many crops. For example, Vories et al. (2006) found that improper timing of irrigation in cotton can result in yield losses of USD 370 ha^{-1} to USD 1850 ha^{-1}. Sensors have been used to collect data for irrigation scheduling using several methods including sap flow, canopy temperature, and soil moisture measurements (Jones, 2004; O'Shaughnessy and Evett, 2010). In this paper we will focus on irrigation scheduling using soil water potential measurements.

1.1 Estimating Field Capacity

Knowing the range of plant available soil water content (AWC) is necessary to avoid crop water stress. The dry end of this range is at permanent willing point (PWP) and the wet end is at field capacity (FC). FC is generally described as the point at which gravitational water flow has ceased after rain or irrigation (Nemes et al., 2011) and is also defined as having a soil water potential in the range of -5 to -33 kPa (Tolk, 2003). PWP is generally defined as the soil water content at which plants irreversibly wilt and fail to recover and is also defined as having a soil water potentialof -1500 kPa (Tolk, 2003). Soil water tension (SWT) is equal to the modulus of the soil water potential (Shock et al., 2013) and for simplicity will be used throughout the remainder of this paper instead of soil water potential.

For agronomic crops, soil water depletion down to 35-65% of AWC is often used as the threshold for initiating irrigation and the exact threshold varies between soil types and crop species (Alan et al., 1998; Girona et al., 2002; Irmak et al., 2014). Frequently the goal of irrigation events is to return the soil profile to FC (Irmak et al., 2014; Zotarelli et al., 2009). For proper irrigation controlling, it is particularly important to have a good estimate of FC otherwise irrigation events may result in the under- or over-application of water.

FC is notoriously difficult to measure *in situ* and the results are often not repeatable. Field experiments (e.g., Brito et al., 2011; de Jong van Lier and Wendroth, 2016) using the method of fluxed-based estimation and simulation studies (e.g., Twarakavi et al., 2009) show that it may take several days for a saturated soil profile to reach FC. For example, Brito et al. (2011) observed that it took 52-205 hours to reach FC (defined as the soil water content at a flux rate of 0.01 mm d^{-1}) and that time was a function of soil texture and profile depth. In another study, drainage reached a flux rate of 0.01 mm d^{-1} after 83 h for sand and 303 h for clay (Twarakavi et al., 2009). Thus, *in situ* measurements are labor and time consuming. Lab measurements of FC usually determine the soil volumetric water content (VWC) at a SWT of 33 kPa (Majumdar, 2013; Rawls et al., 1982; Saxton and Rawls, 2006). However, this threshold is somewhat arbitrary and does not represent soils of different textures and with different horizons. FC should be defined for each specific soil and not by a universal SWT value (Nemes et al., 2011; Zacharias and Bohne, 2008) and its estimation should rather be flux- than SWT-based. For example, a SWT of 33 kPa is an underestimation of the *in situ* soil water content at FC in coarse-textured soils. FC is usually determined for the 12 USDA textural classes (Nemes et al., 2011; Twarakavi et al., 2009) overlooking some of the characteristics that individual soils within a certain textural class possess and their impact on FC. For instance, different percentages of silt and clay lead to variation in FC even within sandy soils (Zettl et al., 2011). It is thus imperative to further improve approaches to estimate soil-specific FC and SWT at FC.

1.2 Soil Water Retention Curves

The transpiration requirements of plants result in tension being transmitted to the roots to extract water from the soil (Muñoz-Carpena et al., 2005; Shock et al., 2013), also known as the soil-plant-atmosphere continuum. As a measure of the energy status of soil water, SWT has been widely used in irrigation management and irrigation scheduling thresholds are often suggested in terms of SWT rather than VWC.

Soil matric sensors measure directly the tension required by plants to extract water from the soil (Thompson et al., 2007; Vellidis et al., 2008; Shock et al., 2013; Irmak et al., 2014). For effective irrigation scheduling, SWT thresholds must be converted to soil-specific irrigation volumes which replenish soil moisture but do not add excessive irrigation water which would result in water moving below the root zone causing leaching of nutrients and other crop inputs. To estimate this optimal irrigation amount, it is necessary to convert measured SWT to VWC and to also know the VWC of the soil at FC and PWP.

Soil water retention curves (SWRC) characterize the relationship between SWT and VWC and by those curves it is possible to describe the respective amounts of recharge and depletion of soil water between FC and PWP. SWRC can be utilized to translate SWT into VWC but the curves are difficult and time consuming to create experimentally and consequently generic curves found in the literature are frequently used (Fredlund and Xing, 1994; Rajkai et al., 2004; Ghanbarian-Alavijeh et al., 2010). A prerequisite for their use is to evaluate their accuracy in describing the changes in soil water status observed under field conditions.

1.3 Objectives

The goal of this study was to develop techniques for using SWRC to estimate optimal irrigation amounts from measured soil water tension by applying the van Genuchten (1980) model. The specific objectives of this research were to: 1) propose a new method of calculating FC using the van Genuchten model; 2) evaluate the accuracy of the van Genuchten model in converting SWT into VWC under field conditions; and 3) develop irrigation scheduling recommendations from the calculated VWCs.

2. Methods

2.1 The van Genuchten model

The van Genuchten model has been widely used to describe water retention behavior of soils. The model describes this relationship in a continuous function. Through the capillary rise equation SWT can be converted to an equivalent pore diameter, and the first derivative of SWRC reflects the pore size distribution of a soil. In the transition from saturated to increasingly unsaturated conditions, at first, the larger pores and subsequently pores with decreasing equivalent diameter are drained. The water in the larger pores is only weakly held by capillary forces, and with decreasing pore diameter, the water is retained with increasing SWT. Therefore, given the same cross sectional area of water-filled pore space, water in large pores flows much faster than in a bundle of smaller pores, we may conceptually link the segments of the SWRC to different rates of water transport. Large soil pores that are known to drain rapidly after long rain periods cover the range between water saturation and an inflection point of the SWRC. This range is also known for relatively small SWT changes with decreasing VWC. Between the inflection point and the PWP, soil water is held in smaller pores. In this range, SWT changes increasingly rapidly with each unit of soil water content decrease. The inflection point of SWRC segregates “structural” soil pores (i.e., draining at SWT lower than the inflection point) and “textural” pores (i.e., emptying at SWT higher than the inflection point) (Dexter, 2004; Reynolds et al., 2009). The slope of the line tangent to the inflection point reflects soil physical quality, including relative field capacity (the proportion of soil

VWC at FC over saturation), plant-available water capacity, air capacity, and macroporosity (Reynolds et al., 2009). The “textural” pores determine FC (Aschonitis et al., 2013). In the range between FC and PWP, soil water is barely draining but available for plant water uptake (Brady and Weil, 2008), even if it becomes increasingly difficult for plant roots to extract water from these smaller pores. Soil water content at the inflection point of the van Genuchten model is strongly affected by soil texture (Reynolds et al., 2009). The inflection point between the rapid and slow drainage can be used to identify FC (Zotarelli et al., 2009). The intersection of lines tangent to the inflection point and the PWP identifies the soil’s FC, VWC and SWT at that point (Fig. 1).

The equation below is used by the van Genuchten model to describe the relationship between VWC and SWT:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^{1-\frac{1}{n}}} \tag{1}$$

where θ is soil VWC (cm^3 cm^{-3}), h is the pressure head (cm); θ_s and θ_r are the saturated and residual VWC (cm^3 cm^{-3}), respectively; α is an empirical parameter which is often referred to as the inverse of the air entry point (cm^{-1}); and n is an empirical constant affecting the shape of the curve (van Genuchten, 1980). Pressure head (h) reported in centimeters is converted to SWT in units of kPa by using

$$SWT = \frac{h \times 9.8}{100} \tag{2}$$

For convenience, we will hereafter refer to h as SWT.

The inflection point of the model is obtained by setting its second derivative to zero. The first derivative of the model is:

$$\frac{d\theta}{dh} = \alpha^n(1-n)(\theta_s-\theta_r)\frac{h^{n-1}}{[1+(\alpha h)^n]^{2-\frac{1}{n}}} \quad (3)$$

The second derivative of the model is:

$$\frac{d^2\theta}{dh^2} = \alpha^n(1-n)(\theta_s-\theta_r)\{(n-1)h^{n-2}[1+(\alpha h)^n]^{\frac{1}{n}-2} - h^{2n-2}\alpha^n(2n-1)[1+(\alpha h)^n]^{\frac{1}{n}-3}\} \quad (4)$$

At the inflection point: $\frac{d\theta^2}{dh^2} = 0$

Therefore, the SWT (*h*h_i) and soil VWC (θ_i) at the inflection point are:

$$h_i = \frac{1}{\alpha}\left(\frac{n-1}{n}\right)^{\frac{1}{n}} \text{ and } \theta_i = \theta(h_i).$$

The equation of the line tangent to the inflection point (h_i, θ_i) is $\theta - \theta_i = S_i(h-h_i)$ or $\theta = S_i(h-h_i)+\theta_i$. Its slope ($S_i$) is the first derivative of the equation which is defined as $S_i = \theta'(h_i)$. Similarly, the equation of the line tangent to the PWP (h_{PWP}, θ_{PWP}) is $\theta - \theta_{PWP} = S_{PWP}(h-h_{PWP})$ or $\theta = S_{PWP}(h-h_{PWP}) + \theta_{PWP}$. Its slope ($S_{PWP}$) is defined as $S_{PWP} = \theta'(h_{PWP})$. The parameter h_{PWP} has been assigned a value of 15310 cm which is equivalent to a SWT of 1500 kPa (Tolk, 2003). The corresponding VWC is $\theta_{PWP} = \theta(15310)$.

The intersection of the two tangent lines is defined as

$$S_i(h-h_i)+\theta_i = S_{PWP}(h-h_{PWP}) + \theta_{PWP} \quad (5)$$

The SWT at the intersection is

$$h_{inter} = \frac{\theta_{PWP}+S_ih_i-S_{PWP}h_{PWP}-\theta_i}{S_i-S_{PWP}} \quad (6)$$

and the soil VWC at the intersection (or FC) is $\theta_{FC} = \theta(h_{inter})$ ($\theta_{PWP} < \theta < \theta_i$ and $h_i < h < h_{PWP}$).

Plant available water content (AWC) at FC is calculated as $\theta_{AWC} = \theta_{FC} - \theta_{PWP}$. Available water quantity (AWQ) in a certain soil profile is calculated as $\theta_{AWQ} = \theta_{AWC} \times D$, and the soil profile depth (D) was either 0.38 or 0.76 m in the current study.

2.2 Generating soil water status parameters using the van Genuchten model

Nine agricultural soils ranging from sands to sandy clay loams commonly found in southern Georgia, USA, were selected. Soil texture and dry bulk density were assumed to be homogeneous throughout the respective soil profiles (Table 1). Particle distribution of sand, silt, and clay, and bulk density at depths of 0-0.38 m and 0-0.76 m were averaged in a depth-weighted way across horizons (Perkins et al., 1986). The soil profiles of 0-0.38 and 0-0.76 m (0-15 and 0-30 in) were selected for shallow- and deep-rooted crops. Soil physical parameters (i.e., particle size distribution and bulk density) (Table 1) were entered into the RETC software (RETC, 2009), and parameters of the van Genuchten model (θs, θr, n, and α) were generated based on the H1 model of the ROSETTA pedo transfer function (Schaap et al., 2001) (Table 2). FC, SWT at FC, PWP, and AWC at FC of the nine soils were calculated following the method described in Section 2.1.

2.3 Comparing FC and AWC from the van Genuchten model with other methods

The calculated FC was compared to the FC generated from 1-dimensional simulations of internal drainage in soil profiles. For these simulations, the HYDRUS-1D software (HYDRUS-1D, 2012) was used. HYDRUS-1D is widely used to analyze soil water flow and solute transport. For the simulations, the profile depth was set to 0-0.38 and 0-0.76 m. The initial soil water conditions were set at saturation. The upper boundary condition was constant flux at zero, and the lower boundary condition was free drainage. Field capacity can be defined as the soil water content when the drainage flux decreases from the initial saturation to a predefined negligibly small value, such as 0.001, 0.01, and 0.1 cm d^{-1} (Twarakavi et al., 2009). Drainage flux rates of 0.01 and 0.1 cm d^{-1} at the bottom of the profile (0.38 or 0.76 m) were selected in this study. The flux rate 0.01 cm d^{-1} was found more accurate to estimate FC across a range of soils evaluated by Twarakavi et al. (2009). Since the drainage process is more rapid in coarse-textured compared to fine-textured soils, a higher flux rate (i.e., 0.1 cm d^{-1}) was also selected in the current study. In order to compare the van Genuchten model approach with the simulated drainage, linear regression was performed between both methods. Linear regression was performed in SigmaPlot (ver. 13.0 Systat Software Inc. San Jose, CA) (the same as below).

AWC at FC and PWP obtained from the van Genuchten model was also compared to that measured at a SWT of 33 and 1500 kPa, respectively. Measured AWC and PWP values were obtained from Perkins et al. (1986) who had performed these measurements for the same soil series as shown in Table 1. Linear regressions between AWC calculated from the van Genuchten model and measured at 33 kPa, and between PWP from the van Genuchten model and measured at 1500 kPa were employed for comparing these approaches as well.

2.4 Validating the van Genuchten model under field conditions

Before utilizing the van Genuchten model in irrigation scheduling, its accuracy in converting SWT into VWC was evaluated under field conditions. Six cotton fields in southern Georgia were selected for this evaluation (Table 3). The University of Georgia Smart Sensor Array (UGA SSA) was used for collecting continuous SWT from these fields for the entire growing season. The UGA SSA is a wireless SWT sensing system which allows for a high density of sensor nodes – a feature needed to account for soil variability in fields. The term sensor node refers to the combination of electronics and sensor probes installed within a field. Each sensor probe includes three Watermark® (Irrometer, Riverside, California, USA) soil moisture sensors and up to two thermocouples for measuring soil and canopy temperature (Vellidis et al., 2013; Liakos et al., 2015).

In this study, the three Watermark® sensors were integrated into the probes at depths of 0.20, 0.41, and 0.61 m (8, 16, and 24 inches) as shown in Fig. 2 to measure SWT. UGA SSA nodes were installed in each of the fields soon after planting in the spring of 2014. The number of sensor nodes installed in each field is shown in Table 3. SWT data from the nodes were collected hourly and transmitted wirelessly to a web server where the data were stored and visualized (Fig. 3). The data from the three sensors in each probe were combined into a weighted average. A weighted average rather than a simple average was used because we assumed that more soil water extraction took place in the shallower portions of the soil profile. The SWT weighting function was:

$$h = \frac{1}{2}h_{0.20\,m} + \frac{1}{3}h_{0.41\,m} + \frac{1}{6}h_{0.61\,m}\text{ , and } h = SWT \quad (7)$$

SWRC were generated based on the van Genuchten model for the soils given in Table 3 using soil physical properties from the USDA NRCS Web Soil Survey (USDA-NRCS, 2013) and following the procedure described in Section 2.2. The van Genuchten model was used to calculate VWC between dry and wet SWT values observed in the field. A dry SWT (h_1) value from the weighted SWT field data (Eq. 7) was entered into the van Genuchten model. After rainfall or irrigation occurred in this field, SWT decreased to a lower (wetter) value (h_2). The soil VWC difference between the two SWT values was calculated as $\Delta\theta = \theta(h_2) - \theta(h_1)$. $\Delta\theta$ is reported in terms of cm^3 cm^{-3}. The amount of irrigation water that must be applied to bring the soil profile from SWT (h_1) to SWT (h_2) was calculated as $\Delta\Theta = \Delta\theta \times D$. $\Delta\Theta$ is reported in mm, and D is the soil profile depth, which is 0.61 m, the largest depth of the sensors.

$\Delta\Theta$ was compared to the change in soil water storage calculated using a simple soil water balance equation

$$\Delta S = P + I - ET - D - R \quad (8)$$

where ΔS is the change in soil water storage and P, I, ET, D and R represent precipitation, irrigation, evapotranspiration, drainage, and runoff, respectively. It was assumed that no runoff or drainage occurred. Precipitation was measured using tipping bucket rain gauges installed in the field or precipitation data were retrieved from adjacent meteorological stations. Irrigation quantities and application dates were recorded. Because of inherent difficulties, fixed amounts of water are applied at irrigation events without taking into account the exact amount of water required to bring the soil profile moisture content back to an optimal condition. *ET* was calculated on a daily basis using reference *ET* and cotton crop coefficients developed for southern Georgia (Vellidis et al., 2014).

Several rainfall and irrigation events which resulted in observable changes of SWT during the growing season were selected from each of the fields for analysis. Both the van Genuchten model and the water balance equation were used to calculate changes in soil water content ($\Delta\Theta$ and ΔS, respectively). To be consistent with the field observations, the van Genuchten model was used to calculate the soil water changes during the recharge stage (i.e., SWT from dry to wet values). Linear regression was performed between the soil water storage values calculated from the van Genuchten model and the water balance equation.

2.5 Irrigation scheduling development

For each soil series in Table 1, irrigation depths required to bring the soil water status from 10, 20, 30, 40, 50, 60, 80, 100, 150, and 200 kPa back to FC were calculated using the van Genuchten model in soil profiles of 0-0.38 m (0-15 in) and 0-0.76 m (0-30 in). The values of FC and AWQ at FC used in the irrigation scheduling were generated from the van Genuchten model as described in Section 2.1 and 2.2.

During the 2015 growing season, the method we developed, based on the van Genuchten model, was used to schedule irrigation in a study evaluating the efficacy of variable rate irrigation (VRI) (Liakos et al., 2016). The method was incorporated into the web-based user interface of the UGA SSA and used to automatically generate irrigation scheduling recommendations in a 93-ha peanut field located in southwestern Georgia. The field had high variability in soils and according to the USDA NRCS soil survey contained eight different soil types. The majority soils were Red Bay sandy loam (53.4%), Rains loamy sand (14.5%), and Goldsboro loamy sand (10.1%). The field was irrigated with a VRI-enabled center pivot irrigation system.

3. Results

3.1 Estimating soil water parameters with the van Genuchten model

Calculated from the van Genuchten model, FC ranged from 0.12 to 0.14 cm^3 cm^{-3} for sand, 0.14 to 0.23 cm^3 cm^{-3} for loamy sand, 0.16 to 0.23 cm^3 cm^{-3} for sandy loam, and 0.20 to 0.26 cm^3 cm^{-3} for sandy clay loam (Table 4). SWT at FC ranged from 5 to 6 kPa for sand, 6 to 15 kPa for loamy sand, 9 to 15 kPa for sandy loam, and 13 to 17 kPa for sandy clay loam (Table 4). PWP ranged from 0.04 to 0.05 cm^3 cm^{-3} for sand, 0.04 to 0.08 cm^3 cm^{-3} for loamy sand, 0.05 to 0.09 cm^3 cm^{-3} for sandy loam, and 0.07 to 0.13 cm^3 cm^{-3} for sandy clay loam (Table 4). PWP was close to parameter θ_r in the van Genuchten model in sand and loamy sand soils (Tables 2 and 4). AWC at FC ranged from 0.07 to 0.10 cm^3 cm^{-3} for sand, 0.10 to 0.13 cm^3 cm^{-3} for loamy sand, 0.12 to 0.14 cm^3 cm^{-3} for sandy loam, and 0.12 to 0.13 cm^3 cm^{-3} for sandy clay loam (Table 4).

3.2 Comparison to other methods

FC values estimated using HYDRUS-1D at drainage flux rates of 0.01 and 0.1 cm d^{-1}, were close to those calculated with the van Genuchten model and were linearly correlated (Fig. 4). Values of AWC calculated from the van Genuchten model were higher than those based on SWT measured between 33 and 1500 kPa, even though they were linearly correlated (Fig. 5). Compared to FC, values of PWP from the van Genuchten model was very close to those based on SWT measured at 1500 kPa, indicated as the slope of the linear regression was close to 1 (0.928) (Fig. 5). Thus, FC should be the cause of the variation in AWC. Changes in soil water content calculated with the van

Genuchten model were similar to those calculated with the water balance equation and they were linearly correlated (Fig. 6).

3.2 Irrigation scheduling tables

The above results indicated that the van Genuchten model was translating SWT into VWC well enough to be used for making irrigation scheduling decisions. Using the model, an example irrigation scheduling table was developed providing the depth of irrigation water needed to bring a range of soils back to FC (Table 5). For soil series of sand, soil water depletion was relatively rapid; and even at 20 kPa, irrigation quantity was more than 50% of its AWQ at FC. When the soil texture became finer (i.e., sandy clay loam), soil water depletion was slowed down; and the irrigation requirement of 50% AWQ at FC occurred at 50 kPa.

3.3 Field evaluation of the presented method

The 93 ha field in which the method was evaluated was divided into alternating conventional irrigation and VRI strips with each strip 120 rows wide. The VRI strips contained 13 different irrigation management zones (IMZ) (Fig. 7) which were irrigated individually based on the van Genuchten model estimates. The conventional strips were irrigated uniformly using Irrigator Pro (Davidson et al., 2000). Irrigator Pro is a public domain irrigation scheduling tool developed by USDA which utilizes soil temperature, ambient temperature, and precipitation to provide yes/no irrigation decisions for peanuts.

A UGA SSA sensor node was installed in each IMZ (Fig 7). Data were transmitted hourly from the field to the user interface where SWT data from the three individual sensors at each node were used to calculate a weighted mean SWT (Eq. 7). This value was then used to automatically calculate the depth of irrigation needed to bring the soil profile back to 75% of FC (Fig 7). Because peanut is a shallow-rooted crop, the 0-0.38 m (0-15 in) irrigation recommendations were used. Seventy five percent of FC rather than 100% of FC was selected as the soil water replenishment goal was to allow for rainfall and minimize the risk of over irrigation. Summer rainfall is common in southwestern Georgia but because of sandy soils, supplemental irrigation is widely used.

A 50 kPa weighted mean SWT was used to trigger irrigation. Over the entire growing season, the dynamic VRI system (sensors + van Genuchten model + VRI) recommended an average irrigation amount of 77 mm compared to 109 mm by Irrigator Pro with approximately the same yields for both methods. The average yield for the dynamic VRI system strips was 5543 kg ha^{-1} while the average yield for Irrigator Pro was 5552 kg ha^{-1}. The 2015 growing season was wetter than average and the dynamic VRI system greatly outperformed Irrigator Pro in yield by 8.4% in the wetter areas of the field which were mostly areas of lower topographical relief. In contrast, Irrigator Pro outperformed dynamic VRI yields in sandy areas with higher elevations by 9.6% indicating that the 50 kPa irrigation trigger may have been too dry for these areas (Liakos et al., 2016). In this field, approximately 72 hours were required for the center pivot irrigation system to circle the field. Because plant AWC is very small above 50 kPa in sandy soils, any delay in irrigation results in the SWT increasing rapidly and the crop experiencing water stress. In retrospect, it appears that the threshold for these areas should have been lower to account for time to irrigation.

4. Discussion

Using benchmark pressure heads (i.e., 33 kPa) to estimate FC from SWRC is an inaccurate method (Twarakavi et al., 2009) because it does not consider soil texture and is particularly inaccurate for sandy soils and strongly aggregated soils. By developing SWRC, Obreza et al. (1998) found that in two Florida sandy soils, SWT at FC ranged from 5 to 8 kPa. Jabro et al. (2009) calculated FC to be 18 kPa for a sandy loam and 27 kPa for a clay loam by developing the regression between SWT and elapsed time following cessation of infiltration. When the percentage of sand was higher than 80% Twarakavi et al. (2009) found that SWT at FC was lower than 12 kPa when simulated at a drainage flux rate of 0.01 cm d^{-1}. These findings match the results calculated with the van Genuchten model in this study (Table 4 and Fig. 4). It is therefore inaccurate to use a universal benchmark of SWT to estimate FC in all types of soils as such a benchmark might underestimate soil water content and lead to inappropriate irrigation scheduling decisions. Because laboratory and field studies to measure FC are difficult and time consuming, SWRC models can also be used to provide theoretical references of FC.

4.1 Limitations of the presented method

The effects of soil organic matter on soil water status were not considered in this study. However, VWC is positively correlated to organic matter content and each percent increase of soil carbon content can result in an increase of 0.5% in VWC in sandy soils (Saxton and Rawls, 2006; Teepe et al., 2003; Wall and Heiskanen, 2003). The results from this study were not greatly affected by organic matter because the common agricultural soils in southern Georgia are very poor in organic matter which generally measures below 2%. The use of the van Genuchten model and Rosetta for calculating FC and developing irrigation schedules in soils with moderate to high levels of organic matter should be evaluated carefully.

In this study, we assumed homogeneous soil particle distribution which ignored the interactive effects of soil layering on soil water status (Zettl et al., 2011). The capillary break resulting from differences in the hydraulic properties of adjacent layers may hinder soil water redistribution in the soil profile leading to an increase of *in situ* FC (McCoy and McCoy, 2009; Zettl et al., 2011). Therefore, the VWC at FCs calculated in this study are assumed to be the baseline and actual VWC at FCs may be higher with the additional effects of soil organic matter and textural breaks.

4.2 Applying the van Genuchten model to irrigation scheduling

The example irrigation scheduling table developed in the current study (Table 5) is calculated after an irrigation scheduling table developed by Irmak et al. (2014) for irrigation scheduling in Nebraska. The Nebraska table contains soil water depletion and available water capacity for sand, loamy sand, and sandy loam soils of that state. In that work, the values of SWT and VWC was measured experimentally for each soil and measured SWT was converted to VWC for irrigation scheduling. As discussed earlier, it is expensive and time consuming to experimentally develop SWRC for multiple soils across large areas and SWRC models offer the advantage of creating these types of tables more easily as long as the pedo transfer function used provides valid results.

For the method developed here to be implemented successfully for irrigation scheduling, SWT should be available from SWT sensors. Online irrigation scheduling tools using the van Genuchten model method which are linked to soil moisture sensing system and VRI-enabled irrigation systems have the potential to improve agricultural WUE by applying irrigation water in the amounts needed to maintain soil moisture at optimal levels.

4.3 Improving resiliency

A dynamic VRI system consisting of the van Genuchten model method in conjunction with soil moisture sensors can be used to enhance resiliency to climate variability because it provides growers with data which they can use to make informed decisions about irrigation. In times of drought and reduced access to water resources, a dynamic VRI system can be used to implement deficit irrigation – a strategy which maintains the soil profile in a drier condition – across many individual IMZ. During wet periods, improper timing of irrigation has been shown to significantly suppress yields (Vellidis et al., 2016). A dynamic VRI system can be used to apply irrigation amounts that maintain the soil profile within desirable SWT ranges rather than repeatedly saturating the soil profile.

5. Conclusions

A method was developed in this study to use soil water tension data from soil sensors and the van Genuchten model to provide irrigation scheduling recommendations. The method uses data readily available from USDA-NRCS soil surveys to construct soil water retention curves and calculate the volumetric water content and soil water tension for calculating an amount of water to be irrigated. The parameters (i.e., volumetric water content and soil water tension at field capacity, permanent wilting point, and available water content) calculated based on the van Genuchten model were consistent with the results from other methods. This model can thus be used to provide theoretical references of field capacity of specific soils rather than soil textural classes. Our results, obtained using a pedotransfer function based on soil texture information, also indicated the inaccuracy to use a universal benchmark of soil water tension (i.e., 33 kPa) to estimate field capacity in all types of soil.

Those parameters calculated from the van Genuchten model are then used to translate measured soil water tension into irrigation recommendations which are specific to the soil moisture status of the soil. In this study, the van Genuchten method offers the superiorities of creating irrigation recommendations over experimental development of soil water retention curves for irrigation scheduling. The method was validated for six fields in southern Georgia, USA comparing its results with continuous soil water tension data with multiple wetting and drying cycles.

The presented model was incorporated into a web-based irrigation scheduling tool and used in conjunction with a wireless soil moisture sensing system to schedule variable rate irrigation in a large commercial field during 2015. The use of the van Genuchten model based irrigation scheduling allowed us to apply about two thirds of the irrigation water that provided about the same peanut yields as a commonly used yes/no irrigation decision tool. The developed irrigation management system thus has the potential to improve the water use efficiency in crop production, and enhance the resilience to climate variability by making informed irrigation decisions in the evaluated areas.

Acknowledgements

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REFERENCES

Alan, R.G., Pereira, L.S., Raes, D., Smith, M, 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations.

Aschonitis, V.G., Antonopoulos, V.Z., Lekakis, E.H., Litskas, V.D., Kotsopoulos, S.A., Karamouzis, D.N. 2013. Estimation of field capacity for aggregated soils using changes of the water retention curve under the effects of compaction. Eur. J. Soil Sci. 64, 688-698.

Brady, N.C., Weil, R.R, 2008. Soil water: Characteristics and behavior, in: The nature and properties of soils, 14th ed. Pearson Prentice Hall, New Jersey and Ohio, pp. 173-217.

Brito, A.d.S., Libardi, P.L., Anunciato Mota, J.C., Moraes, S.O., 2011. Field capacity estimation based on retention curve and soil water flux density. Rev. Bras. Cienc. Solo 35, 1939-1948.

Davidson Jr., J.I., Lamb, M.C., Sternitzke, D.A., 2000. Farm suite-Irrigator Pro (Peanut irrigation software, and user's guide), The Peanut Foundation, Alexandria, VA.

Dexter, A.R. 2004. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201-214.

de Jong van Lier, Q., Wendroth, O., 2016. Reexamination of the field capacity concept in a Brazilian Oxisol. Soil Sci. Soc. Am. J. (in press).

FAO. 2015. Food and Agriculture Organization of the United Nations, Aquastat website. Rome, Italy: United Nations. www.fao.org/nr/water/aquastat/water_use/index.stm.

Fredlund, D.G., Xing, A. 1994. Equations for the soil-water characteristic curve. Can. Geotech. J. 31, 521-532.

Ghanbarian-Alavijeh, B., Liaghat, A., Huang, G., van Genuchten, M.Th. 2010. Estimation of the van Genuchten soil water retention properties from soil textural data. Pedosphere 4, 456-465.

Girona, J., Mata, M., Fereres, E., Goldhamer, D.A., Cohen, M., 2002. Evapotranspiration and soil water dynamics of peach trees under water deficits. Agric. Water Manage. 54, 107-122.

HYDRUS-1D. 2012. HYDRUS-1D version 4.15. http://www.pc-progress.com/en/Default.aspx?H1d-downloads

Irmak, S., Payero, J.O., Van DeWalle, B., Rees, J.M., Zoubek, G.L., 2014. Principles and operational characteristics of Watermark granular matrix sensor to measure soil water status and its practical applications for irrigation management in various soil textures. University of Nebraska-Lincoln Extension Circular EC783.

Jabro, J.D., Evans, R.G., Kim, Y., Iversen, W.M., 2009. Estimating in situ soil-water retention and field water capacity in two contrasting soil textures. Irrig. Sci. 27, 223-229.

Jones, H.G., 2004 Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Exp. Bot. 55, 2427-2436.

Liakos, V., Porter, W., Tucker, M., Liang, X., Vellidis, G., 2016. Dynamic variable rate irrigation scheduling with University of Georgia Smart Sensor Array (UGA SSA). In S. Boyd, M. Huffman and B. Robertson (eds) Proceedings of the 2016 Beltwide Cotton Conference, New Orleans, LA, National Cotton Council, Memphis, TN (paper 16778) (in press).

Liakos, V., Vellidis, G., Tucker, M., Lowrance, C., Liang, X., 2015. A decision support tool for managing precision irrigation with center pivots. In: J.V. Stafford (Ed.), Precision Agriculture '15 - Papers Presented the 10th European Conference on Precision Agriculture (10ECPA), Tel Aviv, Israel, p677-683, doi:10.3920/978-90-8686-814-8.

Majumdar, D.K., 2013. Soil-water relationship, in Irrigation water management principles and practice. 2nd ed. PHI Learning Pvt. Ltd., New Delhi, India. pp. 67-114.

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., Linsey, K.S., 2014. Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, pp. 56.

McCoy, E.L., McCoy, K.R., 2009. Simulation of putting-green soil water dynamics: Implications for turfgrass water use. Agric. Water Manage. 96, 405-414.

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

NASS. 2013. 2012 Census of Agriculture Farm and Ranch Irrigation Survey (2013). National Agricultural Statistics Service, United States Department of Agriculture. http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/

Nemes, A., Pachepsky, Y.A., Timlin, D.J., 2011. Toward improving global estimates of field soil water capacity. Soil Sci. Soc. Am. J. 75, 807-812.

Obreza, T.A., Pitts, D.J., Parsons, L.R., Wheaton, T.A., Morgan, K.T., 1998. Soil water-holding characteristic affects citrus irrigation scheduling strategy. Proc. Fla. State Hort. Soc. 110, 36-39.

O'Shaughnessy, S.A., Evett, S.R., 2010. Canopy temperature based system effectively schedules and controls center pivot irrigation of cotton. Agric. Water Manage. 98, 1310-1316.

Perkins, H.F., Hook, J.E., Barbour, N.W., 1986. Soil characteristics of selected areas of the coastal plain experiment station and ABAC research farms. [Athens, GA.]: Georgia Agricultural Experiment Stations, College of Agriculture, University of Georgia.

Rajkai, K., Kabos, S., van Genuchten, M.Th. 2004. Estimating the water retention curve from soil properties: comparison of linear, nonlinear and concomitant variable methods. Soil Tillage Res. 79, 145-152.

Rawls, W.J., Brakensiek, D.L., Saxton, K.E., 1982. Estimation of soil water properties. Trans. ASAE 25, 1316-1328.

RETC. 2009. RETC model version 6.02. http://www.pc-progress.com/en/default.aspx?retc

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C.A., Yang, X.M., 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152, 252-263.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristics estimates by texture and organic matter for hydrologic solution. Soil Sci. Soc. Am. J. 70, 1569-1578.

Schaap, M.G., Leij, F.J., van Genuchten, M.Th., 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251, 163-176.

Shock, C.C., Wang, F.X., Flock, R., Feibert, E., Shock, C.A., Pereira, A., 2013. Irrigation monitoring using soil water tension. Oregon State University - Malheur Extension Office: EM 8900.

Teepe, R., Dilling, H., Beese, F., 2003. Estimating water retention curves of forest soils from soil texture and bulk density. J. Plant Nutr. Soil Sci. -Z. Pflanzenernahr. Bodenkd. 166, 111-119.

Thompson, R.B., Gallardo, M., Valdez, L.C., Fernández, M.D., 2007. Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors. Agric. Water Manage. 88, 147-158.

Tolk, J.A. 2003. Soils, permanent wilting points, in Stewart, B.A., Howell, T.A. (Eds.), Encyclopedia of water secience. Dekker Press, New York, USA, pp. 927-929.

Twarakavi, N.K.C., Sakai, M., Simunek, J., 2009. An objective analysis of the dynamic nature of field capacity. Water Resour. Res. 45, W10410.

USDA-NRCS, 2013. Web soil survey. http://websoilsurvey.sc.egov.usda.gov/app/HomePage.htm

van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892-898.

Vellidis, G., Liakos, V., Perry, C., Porter, W., Tucker, M., 2016. Irrigation scheduling for cotton using soil moisture sensors, smartphone apps, and traditional methods. In S. Boyd, M. Huffman and B. Robertson (eds) Proceedings of the 2016 Beltwide Cotton Conference, New Orleans, LA, National Cotton Council, Memphis, TN (paper 16779), (in press).

Vellidis, G., Liakos, V., Perry, C., Tucker, M., Collins, G., Snider, J., Andreis, J., Migliaccio, K., Fraisse, C., Morgan, K., Rowland, D., Barnes, E., 2014. A smartphone app for scheduling irrigation on cotton. In S. Boyd, M. Huffman and B. Robertson (eds) Proceedings of the 2014 Beltwide Cotton Conference, New Orleans, LA, National Cotton Council, Memphis, TN (paper 15551), p.175-186.

Vellidis, G., Tucker, M., Perry, C., Reckford, D, Butts, C., Henry, H., Liakos, V., Hill, R.W., Edwards, W., 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 (9ECPA), Lleida, Spain, p.713-720. doi: 10.3920/978-90-8686-778-3

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

Vories, E.D., Teague, T., Greene, J., Stewart, J., Clawson, E., Pringle, L., Phipps, B., 2006. Determining the optimum timing for the final irrigation on mid-south cotton. In. Proceedings National Cotton Council Beltwide Cotton Conference, January 3-6, 2006, San Antonio, Texas. 516-521, 2006 CDROM.

Wall, A., J. Heiskanen. 2003. Water-retention characteristics and related physical properties of soil on afforested agricultural land in Finland. For. Ecol. Manage. 186, 21-32.

Zacharias, S., Bohne, K., 2008. Attempt of a flux-based evaluation of field capacity. J. Plant Nutr. Soil Sci. 171, 399-408.

Zettl, J.D., Barbour, S.L., Huang, M., Si, B.C., Leskiw, L.A., 2011. Influence of textural layering on field capacity of coarse soils. Can. J. Soil Sci. 91, 133-147.

Zotarelli, L., Dukes, M.D., Morgan, K.T., 2009. Interpretation of soil moisture content to determine soil field capacity and avoid over-irrigating sandy soils using soil moisture sensors. Rep. AE460. Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Flori

Figure Captions

Fig. 1. The van Genuchten model with lines tangent to inflection point (h_i, θ_i) and permanent wilting point (PWP (h_{PWP}, θ_{PWP})) to identify the intersection (or field capacity (h_{FC}, θ_{FC})) (gray solid lines).

Fig. 2. The University of Georgia Smart Sensor Array (UGA SSA) is a wireless soil moisture sensing system which allows for a high density of sensor nodes. A sensor node consists of electronics and a sensor probe (left) installed within a field (right). Each sensor probe includes three Watermark® soil moisture sensors. In this study, the three Watermark® sensors were integrated into the probes at depths of 0.20, 0.41, and 0.61 m (8, 16, and 24 inches).

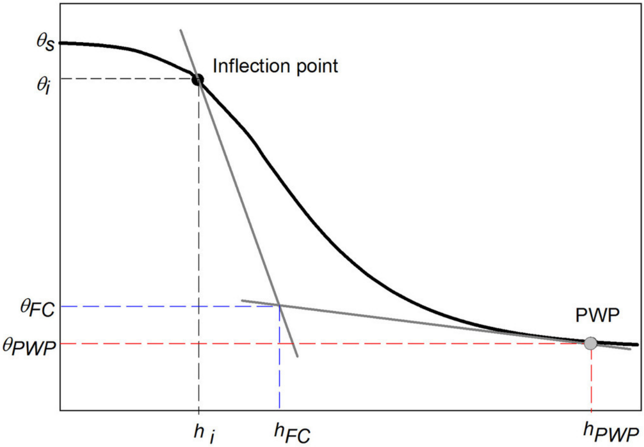
Fig. 3. Soil water tension (SWT) graphs from two locations in Field 8 (Table 3). Each line on the graphs represents SWT from 15 June to 15 September 2014 for sensors at 0.20, 0.41, and 0.61 m (8, 16, and 24 inches). Drops in SWT are caused by irrigation or precipitation events. The graphs clearly show why it is important to customize irrigation applications in response to localized soil moisture conditions.

Fig. 4. Comparing field capacity from the van Genuchten model (FC_{vG}) and HYDRUS-1D (FC_H) at drainage flux rates of 0.1 cm d^{-1} (left) and 0.01 cm d^{-1} (right).

Fig. 5. Comparison of plant available water content at field capacity and permanent wilting point calculated from the van Genuchten model (AWC_{vG} and PWP_{vG}) and measured at SWT of 33 and 1500 kPa ($AWC_{\theta(33kPa)-\theta(1500kPa)}$ and $PWP_{\theta(1500kPa)}$) (Perkins et al., 1986).

Fig. 6. Comparison of the change of soil water content derived from the van Genuchten model ($\Delta\Theta$) and water balance equation (ΔS).

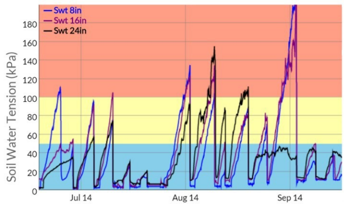
Fig.7. A 93 ha field was divided into alternating conventional irrigation and variable rate irrigation (VRI) strips with each strip 120 rows wide. The VRI strips contained 13 different irrigation management zones (IMZ) which were irrigated based on the van Genuchten model recommendations. The gages indicate the location of UGA SSA sensor nodes (left). Irrigation recommendations for a soil profile depth of 0-0.38 m (0-15 in) were used to irrigate the peanuts in the VRI IMZs (right).

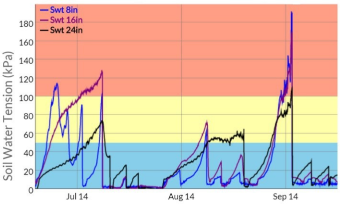

θ_S
θ_i
Inflection point
θ_{FC}
PWP
θ_{PWP}
h_i
h_{FC}
h_{PWP}

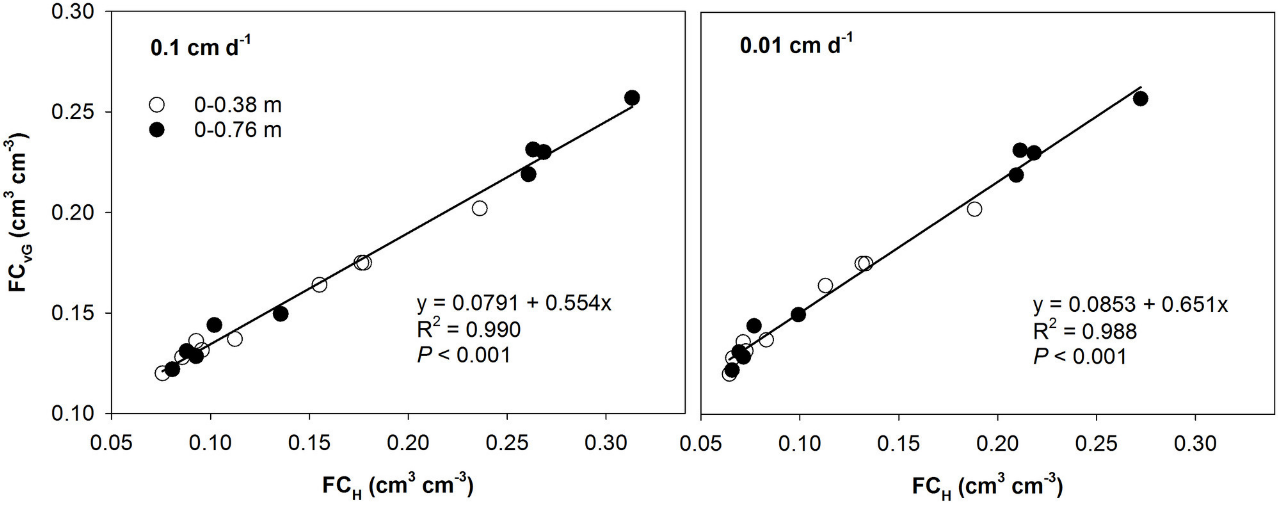
electronics

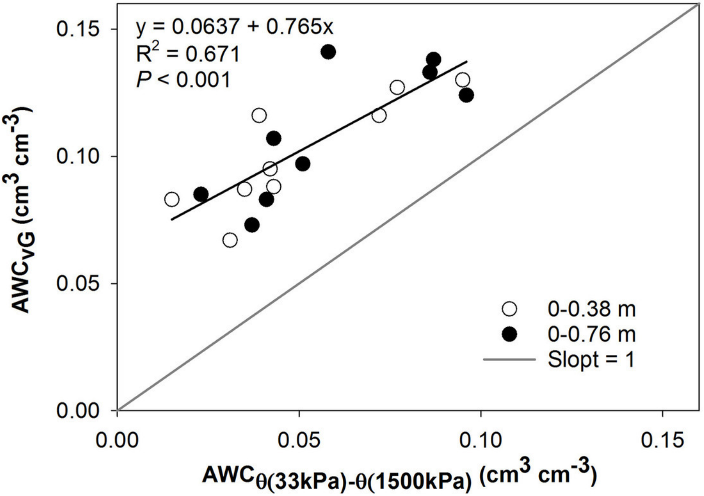
3 Watermark® sensors

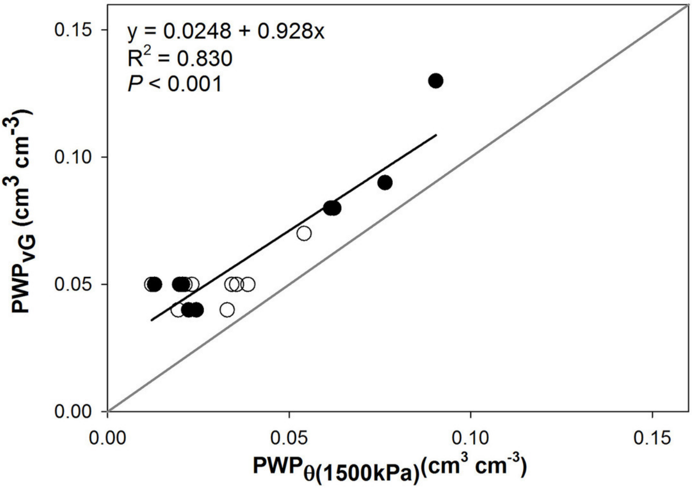
04/16/13

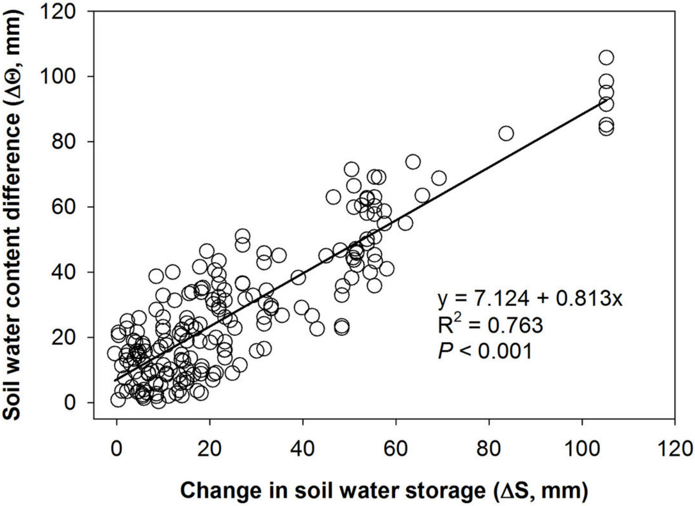

Swt 8in
Swt 16in
Swt 24in
Soil Water Tension (kPa)
0
20
40
60
80
100
120
140
160
180
Jul 14
Aug 14
Sep 14

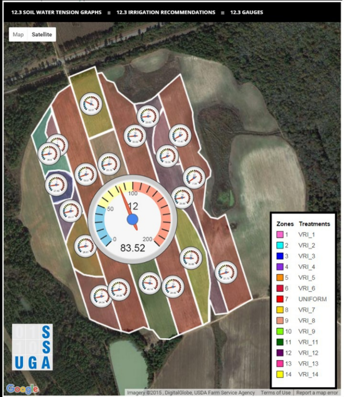

Swt 8in
Swt 16in
Swt 24in
Soil Water Tension (kPa)
0
20
40
60
80
100
120
140
160
180
Jul 14
Aug 14
Sep 14


0.1 cm d⁻¹
○ 0-0.38 m
● 0-0.76 m
y = 0.0791 + 0.554x
R² = 0.990
P < 0.001
0.01 cm d⁻¹
y = 0.0853 + 0.651x
R² = 0.988
P < 0.001
FCvG (cm³ cm⁻³)
FCH (cm³ cm⁻³)
FCH (cm³ cm⁻³)
0.30
0.25
0.20
0.15
0.10
0.05
0.10
0.15
0.20
0.25
0.30

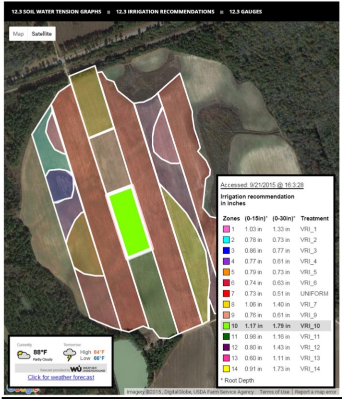

y = 0.0637 + 0.765x
R^2 = 0.671
P < 0.001
0-0.38 m
0-0.76 m
Slopt = 1
$\mathbf{AWC_{vG}}$ (cm^3 cm^{-3})
$\mathbf{AWC_{\theta(33kPa)-\theta(1500kPa)}}$ (cm^3 cm^{-3})
0.00
0.05
0.10
0.15
0.00
0.05
0.10
0.15


y = 0.0248 + 0.928x
R^2 = 0.830
P < 0.001
$\mathbf{PWP_{vG}}$ (cm^3 cm^{-3})
$\mathbf{PWP_{\theta(1500kPa)}}$(cm^3 cm^{-3})
0.00
0.05
0.10
0.15
0.00
0.05
0.10
0.15


Soil water content difference (ΔΘ, mm)
Change in soil water storage (ΔS, mm)
0
20
40
60
80
100
120
0
20
40
60
80
100
120
y = 7.124 + 0.813x
R2 = 0.763
P < 0.001



Zones		Treatments
■	1	VRI_1
■	2	VRI_2
■	3	VRI_3
■	4	VRI_4
■	5	VRI_5
■	6	VRI_6
■	7	UNIFORM
■	8	VRI_7
■	9	VRI_8
■	10	VRI_9
■	11	VRI_11
■	12	VRI_12
■	13	VRI_13
■	14	VRI_14



Accessed: 9/21/2015 @ 16:3:28

Irrigation recommendation in inches

Zones		(0-15in)*	(0-30in)*	Treatment
■	1	1.03 in	1.33 in	VRI_1
■	2	0.78 in	0.73 in	VRI_2
■	3	0.86 in	0.77 in	VRI_3
■	4	0.77 in	0.61 in	VRI_4
■	5	0.79 in	0.73 in	VRI_5
■	6	0.74 in	0.63 in	VRI_6
■	7	0.73 in	0.51 in	UNIFORM
■	8	1.06 in	1.40 in	VRI_7
■	9	0.76 in	0.61 in	VRI_9
■	**10**	**1.17 in**	**1.79 in**	**VRI_10**
■	11	0.98 in	1.16 in	VRI_11
■	12	0.80 in	1.43 in	VRI_12
■	13	0.60 in	1.11 in	VRI_13
■	14	0.91 in	1.73 in	VRI_14

* Root Depth

Currently
88°F
Partly Cloudy
Tomorrow
High 84°F
Low 66°F
forecast provided by WEATHER UNDERGROUND
Click for weather forecast

Table 1 Weighted average of soil particle distribution into sand, silt and clay, and bulk density (BD) of common agricultural soils in southern Georgia in soil profiles of 0-0.38/0-0.76 m (0-15/0-30 in).

Soil type	Sand				Loamy sand		Sandy loam		Sandy clay loam
Soil series	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
Sand (%)	96/93	90/88	91/91	88/89	85/83	81/73	78/70	82/71	76/65
Silt (%)	1.6/4.7	7.0/8.3	7.0/7.0	9.3/8.3	11/13	9.8/9.7	14/14	9.6/10	8.6/9.0
Clay (%)	2.4/2.3	2.8/3.4	1.6/2.2	2.5/2.6	3.3/4.5	9.2/18	7.8/16	7.9/19	15/26
BD (g cm^{-3})	1.6/1.6	1.5/1.5	---	1.6/1.6	1.6/1.6	1.7/1.6	1.6/1.6	1.6/1.6	1.7/1.7

Table 2 Parameters of van Genuchten model of common agricultural soils in southern Georgia in soil profiles of 0-0.38/0-0.76 m

	Sand				Loamy sand		Sandy loam		Sandy clay loam
Parm	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
α (cm^{-1})	.03/.03	.04/.04	.04/.04	.04/.04	.04/.04	.04/.03	.04/.03	.04/.03	.03/.03
n	3.6/3.1	2.7/2.4	2.9/2.8	2.5/2.6	2.2/1.9	1.7/1.4	1.6/1.4	1.8/1.4	1.4/1.2
θ_s (cm^3 cm^{-3})	.37/.36	.39/.40	.38/.38	.36/.36	.34/.35	.35/.36	.36/.36	.37/.37	.34/.35
θ_r (cm^3 cm^{-3})	.05/.05	.05/.05	.05/.05	.04/.04	.04/.04	.05/.05	.04/.05	.05/.06	.05/.06

Table 3 Locations, numbers of sensors installed, and soil series for the van Genuchten model evaluation in southern Georgia

Location	Number of sensors	Soil series
SIRP	18	Lucy loamy sand,
NESPAL	8	Tifton loamy sand
Field 8	10	Tifton sandy loam, Norfolk loamy sand, Goldsboro sandy loam
Field 9	10	Tifton sandy loam, Norfolk loamy sand, Goldsboro sandy loam, Orangeburg loamy sand
Field 10	4	Tifton sandy loam, Norfolk loamy sand, Orangeburg loamy sand
Field 11	12	Tifton sandy loam, Norfolk loamy sand, Goldsboro sandy loam, Grady soils

Table 4 Field capacity (FC), soil water tension (SWT) at FC, permanent wilting point (PWP), and available water content (AWC) at FC generated from the van Genuchten model for profiles of 0-0.38/0-0.76 m (0-15/0-30 in) of common agricultural soils in southern Georgia.

Parameter	Sand				Loamy Sand		Sandy Loam		Sandy Clay Loam
	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
FC ($cm^3 cm^{-3}$)	0.12/0.12	0.14/0.14	0.13/0.13	0.13/0.13	0.14/0.15	0.18/0.23	0.18/0.22	0.16/0.23	0.20/0.26
SWT at FC (kPa)	5/5	6/6	5/5	6/5.5	6.5/6.5	10/15	9/14	8/15	13/17
PWP ($cm^3 cm^{-3}$)	0.05/0.05	0.05/0.05	0.05/0.05	0.04/0.04	0.04/0.04	0.05/0.08	0.05/0.08	0.05/0.09	0.07/0.13
AWC at FC ($cm^3 cm^{-3}$)	0.07/0.07	0.09/0.10	0.08/0.08	0.09/0.08	0.10/0.11	0.12/0.13	0.13/0.14	0.12/0.14	0.13/0.12

Table 5 Irrigation required (mm) to bring soils back to field capacity (FC) and available water quantities (AWQ) at FC for profiles of 0-0.38 and 0-0.76 m (0-15 and 0-30 in) of common agricultural soils in southern Georgia.

SWT (kPa)	Irrigation required (mm) to bring soil water status back to FC for profiles of 0-0.38/0-0.76 m (0-15/0-30 in)								
	Sand				Loamy sand		Sandy loam		Sandy clay loam
	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
0	0	0	0	0	0	0	0	0	0
10	20/38	20/36	20/41	18/36	15/23	3/0	3/0	5/0	0
20	25/51	30/61	28/58	28/53	25/48	15/10	20/15	23/10	10/5
30	25/53	30/66	30/61	3058	30/58	20/25	28/30	30/28	15/15
40	25/56	33/69	30/64	30/61	30/64	25/33	30/41	30/38	20/25
50	25/56	33/69	30/64	30/61	33/66	28/41	33/48	33/46	25/30
60	25/56	33/71	30/64	33/61	33/69	28/46	36/53	36/51	25/36
80	25/56	33/71	30/64	33/61	33/71	30/53	38/61	38/58	30/43
100	25/56	33/71	30/64	33/64	36/74	33/58	41/66	38/64	33/48
150	25/56	33/74	30/64	33/64	36/76	36/66	43/74	41/74	36/56
200	25/56	33/74	30/64	33/64	36/76	38/71	43/79	41/79	38/64
AWQ at FC	25/56	33/74	30/64	33/64	36/81	43/102	48/104	43/107	51/94