

DECISION SUPPORT TOOLS FOR IRRIGATION SCHEDULING IN PEANUT

by

IOANNIS GALLIOS

(Under the Direction of George Vellidis)

ABSTRACT

Two peanut irrigation scheduling decision support tools (DSTs) were developed and evaluated. The first involved modifying Irrigator Pro, a public-domain DST developed by the USDA-ARS National Peanut Research Laboratory, so that it is compatible with soil moisture sensors that measure volumetric water content. The new version offers automated data entry and provides hourly or daily irrigation decisions. The second tool involved developing an evapotranspiration (ET) -based DST that was incorporated into the existing SmartIrrigation CropFit App. The DST includes a localized growing degree day (GDD) -based crop coefficient (Kc) curve. Both tools were compared to other advanced irrigation scheduling tools in replicated plot studies at two southern Georgia, USA, locations. The results showed that both tools performed at least as well as well as the other scheduling tools in terms of yield and in some cases, outperformed them in terms of irrigation water use efficiency. The two DSTs were released for public use in April 2023 and will continue to be evaluated in the upcoming seasons with on-farm trials.

INDEX WORDS: Irrigator Pro, Soil moisture sensors, Volumetric Water Content, SmartIrrigation Apps, Evapotranspiration, Georgia, Field study

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

The peanut, or groundnut (*Arachis hypogaea*), is a low-growing crop which produces its fruit underground. It is native to South America but is widely grown around the world and is a critical source of protein and income. In 2021, world peanut production was 49.8 million metric tons (Mg). China is the world's largest peanut producer with 18.3 million Mg produced in 2021. The USA was ranked fourth with 2.5 million Mg (US Department of Agriculture 2023). In the USA, peanuts are grown primarily in the southeastern states (Figure 1.1.).

The state of Georgia grows the most peanuts in the USA. In 2022, Georgia produced 52% of the country's crop or 0.66 million Mg on 275,200 ha with a mean yield of 4,770 kg ha⁻¹ (Georgia Peanut Commission 2022; "USDA/NASS Georgia Agriculture Overview" 2022). Mean yields in Georgia ranged from 4,682 to 4,929 kg ha⁻¹ between 2018 and 2022 (Table 1.1.). Peanuts are grown in 77 counties in Georgia by approximately 4000 farmers, resulting in a USD2.2 billion industry in the state (Georgia Peanut Commission 2022). Between 45 and 55% of the peanut acreage is irrigated (UGA Extension System 2022). The U.S. Geological Survey (USGS) estimates that three-quarters of the state's freshwater withdrawals are used for irrigation (Dieter et al. 2018; USGS 2015).

1.2. Literature Review

1.2.1. Irrigation Scheduling in Peanut

Peanut is moderately adaptive to water-deficit conditions and its water demands are lower than many crops (Reddy, Reddy, and Anbumozhi 2003). However, it benefits significantly from irrigation during dry years with irrigated yields generally exceeding rainfed yields by 2000-3000 kg ha⁻¹ (Soler 2007; University of Georgia, CRSS 2022). This is because water stress during the crop's reproductive stage when water use by the crop is highest, results in yield losses. However, (Kottapalli et al. 2009). Porter (2016), Wright, Hubick, and Farquhar (1991), and Lamb et al. (2007) have all shown that overirrigation in peanuts suppresses yield.

Irrigation scheduling research on peanuts has been conducted in most peanut-growing states. In Mississippi, irrigation scheduling thresholds were evaluated in 2015 and 2016 with a study conducted at the Delta Research and Extension Center in Stoneville. Soil matric potential thresholds of -50 kPa, -75 kPa, -100 kPa, and the FAO-56 were used to schedule irrigation (Leininger et al. 2019). The results showed that using the -50 kPa as an irrigation threshold increased peanut yield by at least 12.7% relative to FAO-56-based based irrigation (Allen et al. 1998) or non-irrigated fields while in some cases it also improved the peanut quality.

Jackson et al. (1981); Alderfasi and Nielsen (2001) developed a method to calculate a Crop Water Stress Index (CWSI) using canopy temperature stress that can be used as an early indicator of stress and irrigation requirements. Porter et al (2015) conducted a study focusing on how Smart Crop sensors (SmartField, TX, USA) which are thermal infrared thermometers can predict crop water stress by measuring the canopy temperature. Six irrigation scheduling treatments were compared in this study including potentiometric sensors, SmartCrop sensors, an extension checkbook method, the University of Georgia EasyPan, and rainfed as a control. Due to the lack

of rainfall in that year, the rainfed plots produced only 521 kg ha⁻¹, while the most productive irrigated treatment yielded 6783 kg ha⁻¹. The CSWI-based irrigation treatment yielded 6323 kg ha⁻¹, the third highest yield while using the least amount of water (163 mm). The study provided positive feedback on scheduling irrigation using a CSWI (Porter et al. 2015).

1.2.2. Evapotranspiration and Irrigation Scheduling

Water loss through evaporation from the soil surface combined with plant transpiration is defined as evapotranspiration (ET) (Allen 2005). The method known as ET-based irrigation scheduling (ETIS) allows uses crop-specific water use characteristics and meteorological data to determine the crop's daily water requirements (Allen and FAO 1998). By tracking daily water requirements, growers can use ETIS methods to decide when and how much to irrigate.

The parameters that affect ET are divided into three major categories: meteorological conditions, crop physiology, and management parameters. The first include solar radiation, relative humidity, air temperature, and wind speed. Crop factors which affect ET include the crop and cultivar, planting density, and phenological growth stage (Allen and FAO 1998). The third group of conditions which can impact ET are soil type, fertility, salinity, and the grower's soil management.

The United Nations Food and Agricultural Organization (FAO) developed a sequence of ET-based irrigation scheduling protocols (Jensen et al. 1990) most recently summarized in a document known as FAO-56 (Allen and FAO 1998). In the FAO-56 method, daily crop water use is estimated as shown in Eqn. (1.1.).

$$ET_c = ET_o \times K_c \quad (1.1.)$$

where,

E_{Tc} = daily crop water use (mm day^{-1}),

E_{To} = reference ET (mm day^{-1}) calculated using the Penman- Monteith equation, and

K_c = a crop coefficient (unitless).

E_{To} can be calculated using meteorological data which in general are readily available for the southeastern U.S. from a variety of sources including state weather station networks. To calculate E_{Tc} , a K_c that applies to that day is needed. For annual crops, K_c changes with the phenological stage. K_c typically begins with small values after emergence and increases to 1.0 or above when the crop has the greatest water demand. This typically occurs during the reproductive stage. K_c decreases as crops reach maturity and begin to senesce. Over the years FAO developed K_c values for the phenological stages of many crops and published them as tables (Jensen et al. 1990). Table 1.2. shows FAO recommended K_c values for three peanut phenological stages while Table 1.3. shows the expected length of those periods in different geographic regions. Since FAO-56 did not include crop coefficient values for the southeastern United States, Figure 1.2. demonstrates the K_c curve through the season on a daily interval for West African climates. The horizontal axis depicts the Days After Planting (DAP) according to Table 1.3., while the vertical axis depicts the values of K_c through the season according to Table 1.2.. Since there is no specific K_c value during peanut development, this stage has been estimated as the daily increase in water needs for a development period of 35 days.

These tables were the first step to developing ET-based irrigation scheduling tools for peanut. However, these K_c values were single values for entire phenological stages and did not accurately represent the progression of K_c during plant growth. Consequently, agronomists began

experimentally developing Kc curves that capture daily changes in the Kc (Allen and FAO 1998).

Figure 1.3. shows a continuous Kc curve developed for peanuts and compared to FAO-56 and FAO-33 estimated Kc values for each phenological stage (Bandyopadhyay, Mallick, and Rana 2005). The figure also includes FAO-33 (Allen et al. 1996) and FAO-56 (Allen et al. 1998) estimates of Kc for different phenological stages. For the first 1-2 weeks the $K_{c_{init}}$ is close to 0, but as the first vegetative stage comes to an end and the plant is in its developing period, water needs are increasing. The Kc curve reaches its highest value of $K_{c_{mid}} = 1.15$ a few days after fruit initiation begins (Allen and FAO 1998). Knowing the Fruit Initiation Day (FID) is important for irrigation scheduling because water demands reach their maximum values after this threshold and water stress during this stage can adversely affect crop yield. Lately, new tools have been developed to better identify phenological transitions, so that growers can plan their irrigation accordingly (Jensen et al. 2016). During pod development, daily water use (DWU) can reach values of 5 to 7.5 mm day⁻¹ (0.21 to 0.29 inches day⁻¹). During pod maturation, DWU is 1.5 – 3 mm day⁻¹ (0.07-0.14 inches day⁻¹) (Sorensen and Butts 2014). This decrease in DWU is reflected in the Kc curve. The FAO-56 $K_{c_{end}}$ value is close to 0.6 (Figure 1.2.) as the crop reaches maturity and harvest (Shavkat Kenjabaev et al. 2020).

A study conducted in eastern India showed that the peanut Kc curve published by FAO must be modified to account for regional climate and soils. They found that the best irrigation scheduling resulted when the Kc curve was associated with accumulated heat units commonly referred to as growing degree days (GDDs) and leaf area index (LAI) (Bandyopadhyay, Mallick, and Rana 2005).

University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) released a full guide for southeastern peanut growers within which they provide irrigation scheduling guidelines

(Wright et al. 2020). The guidelines include a growing season water use curve that was developed from several years of studies. UF/IFAS also developed an online irrigation scheduling tool called PeanutFARM (Rowland et al 2015; Migliaccio, T Morgan, et al. 2015). This tool uses the FAO-56 method and accumulated GDDs to determine crop growth stage and estimate crop water needs based on the water use curve developed by (Wright et al. 2020). ETo is calculated with data from the closest meteorological station.

1.2.3. Decision Support Tools (DSTs) for Irrigation Scheduling

DSTs for peanut irrigation scheduling have been available since the late 1980s. In a study that compared MOISNUT, a peanut irrigation scheduling tool developed at Auburn University (Tyson and Curtis 1989; 1990), and EXNUT, a peanut irrigation scheduling tool developed by the USDA Agricultural Research Service (ARS) National Peanut Research Laboratory (NPRL) (Davidson et al. 1995), the results showed that during dryer years there was a significant difference between irrigated and non-irrigated fields, but a difference between EXNUT and MOISNUT was not found for any year or field location (Davidson et al. 1995). Another study that used both DSTs showed a profit of USD1098 ha⁻¹ and USD1011 ha⁻¹ for peanuts irrigated on sandy soil and medium-textured soil, respectively, when compared to rainfed peanuts over three years. In addition, aflatoxin was consistently below 10 ppb in the edible kernels of irrigated peanuts and the market grade was higher than that of the non-irrigated ones. Meteorological conditions were significantly different between years and therefore irrigation needs also differed. Overall, the DSTs resulted in 16-23% higher yields (Davidson et al. 1998).

Davidson et al. (1995); Davidson, Lamb, and Sternitzke (2000); Butts, Sorensen, and Lamb (2020) described a rule-based DST which used crop history, yield potential, soil type, irrigation/precipitation, and soil temperature data to determine the available water content in the

soil profile that progressed from EXNUT to the current irrigation scheduling DST known as Irrigator Pro (Davidson et al. 1995; Davidson, Lamb, and Sternitzke 2000; Lamb et al. 2007; Butts, Sorensen, and Lamb 2020). Further research led to additional improvements to Irrigator Pro that made it more accurate (Bauer and Stone, 2008; Stone et al. 2015; Liakos et al. 2017). Irrigator Pro is described in detail further below.

In 2005, researchers in Texas improved the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) which was first developed in 1990 (Wanjura, Upchurch, and Mahan 1990). BIOTIC uses two thresholds to trigger irrigation, canopy temperature, and time thresholds as well as a limiting relative humidity criterion. The tool was mainly tested in Texas, Mississippi, and California and has been proven effective in both semi-arid and humid environments. However, the many methods of determining the time and temperature thresholds for BIOTIC have made its use complicated for growers and consultants.

During the same period, researchers from the University of Georgia were testing Cropping System Models (CSM) as a way to schedule irrigation in peanuts and cotton (Soler 2007). CROPGRO-Peanut, a CSM for peanut crops, was tested in four rainout shelters at Griffin, GA under a 2-year study. The irrigation thresholds (IT) that were tested during that study were 30%, 40%, 60%, and 90% of the AWC, and the soil moisture levels were monitored using capacitance type sensors that measure volumetric water content (VWC). The results showed a significant difference in yield among all IT with 90% achieving the highest pod yield, 4899 kg ha⁻¹. The 90% IT outperformed the rest of the treatments in pod number while the final biomass appeared no significant difference except the 30% threshold. These results concluded that peanut growth and development were affected by different irrigation scheduling thresholds and assumed that CSMs could quantify the effects of ITs on peanut growth, development, and yield.

In Australia, a similar irrigation scheduling tool was developed that incorporated two older models into a new one called AQUAMAN (Chauhan et al. 2013). This tool uses the FAO-56 method (Allen et al. 1998) in combination with the APSIM model which is described in (Keating et al. 2003) to estimate the crop water use and provide a decision for irrigation. AQUAMAN uses a series of equations to calculate daily crop evapotranspiration (ET). The results showed that the tool reduced the amount of irrigation by 50 % in some years while increasing the yield even by 38% and in some cases improving the quality of the seeds as well (Chauhan et al. 2013)

The University of Florida (UF) developed PeanutFARM (Rowland et al 2015; Wright et al. 2020)), an irrigation scheduling DST that uses adjusted growing degree days (aGDD) to determine the crop's phenological stage and the FAO-56 method (Allen et al. 1998) and meteorological data exclusively from weather station networks to provide the user with irrigation scheduling decisions. The DST has been commercialized and is now used primarily to forecast peanut maturity.

Irrigator Pro

Irrigator Pro is a public domain irrigation scheduling DST developed by the NPRL. The original version of the tool utilizes min/max soil temperature, and precipitation to provide yes/no irrigation decisions for peanuts. It is hereafter referred to as Irrigator Pro (Temp). During the course of the season, the user records field data including rainfall, irrigation, and the maximum and minimum soil temperature as part of regular field scouting. When entering the rainfall data, the user must estimate the effective amount of rainfall by determining the portion that infiltrated into the soil, based on their knowledge of the time over which the rainfall occurred. If the rainfall event is less than 3 mm, it is disregarded as having little effect on the water status. The installation of maximum and minimum recording thermometers typically occurs around 30 days after planting to ensure that the selected site is representative of the field. The max/min soil thermometers are

installed in the peanut row at a depth of 50 mm under the canopy to monitor and record the temperature. If there are variations in soil conditions throughout the field, it is recommended to install at least two thermometers. It is essential to reset the maximum and minimum temperature recordings within 24 h of a rainfall or irrigation event exceeding 3 mm. The model also requires that users describe their soil type as sandy, medium/heavy, or heavy soil. To simplify this requirement, Jerry Pilkinton, a retired USDA-NRCS soil scientist, contributed to classifying soil series in areas in which peanuts are grown in the USA as sandy (I), medium/heavy (II), and (III) heavy (Butts, Sorensen, and Lamb 2020). Based on the precipitation and soil temperature readings, the model provides a decision for irrigation. That decision is based on the assumption that as the plant's demand for water exceeds the rate at which it is released from the soil, the peanut leaves fold allowing sunlight to penetrate the canopy, thus warming the soil. Irrigation is recommended when the maximum soil temperature exceeds the 29.5° C for three consecutive days without a precipitation event of more than 3mm. After irrigation or a rainfall, the thermometers are reset and start new measurements until soil temperature exceeds the thresholds again or rainfall occurs.

One of the model's strengths is that irrigation decisions are also a function of crop phenology and not only of soil condition. For example, because peanut is an indeterminate crop, it continues to flower and set fruit while environmental conditions remain favorable. Irrigator Pro withholds irrigation for two weeks after the midpoint of the growing season to terminate flowering and promote seed filling. Irrigator Pro has been evaluated by growers and crop consultants and consistently produces high yields(Lamb et al. 2007). Because of this, it has been used by crop consultants in Alabama and Georgia even though the model requires manual data collection and entry at least three times per week

More recently scientists at NPRL developed a sensor-based soil water balance model version

of Irrigator Pro that automates the data collection process. This version allows either manual data entry or automated entry of soil matric potential data from sensors located at 0.1, 0.2, and 0.4 m and was designed to work with the UGA Smart Sensor Array (UGA SSA) – a wireless soil moisture sensor system (G. Vellidis et al. 2008). Soil matric potential, also referred to as soil water tension (SWT), is essentially a measure of the energy required by plants to extract soil water from the soil matrix and is measured in units of centibars (cb) or kiloPascals (kPa). There are generally accepted SWT values for field capacity and permanent wilting point that hold true regardless of soil type. What varies by soil type is the plant available water at any given SWT. The UGA SSA reports soil moisture in terms of SWT and Irrigator Pro uses SWT measurements at the three depths to estimate the plant available soil water in the soil profile by converting SWT into volumetric water content (VWC) using the following empirical equation developed by NPRL scientists. VWC is estimated using observed SWT (kPa) at each depth (i) by:

$$VWC_i = \alpha_i + b_i \ln(kPa_i) \quad (1.2.)$$

Coefficients α and b vary depending on the soil categories previously described. The VWC irrigation trigger level was calculated to be the equivalent of 40 kPa. The total available water content (AWC) is defined as the difference between the current VWC_i and the minimum VWC for that specific soil type. VWC is then used to calculate the soil water balance within the root zone (Butts, Sorensen, and Lamb 2020; Davidson et al. 1998). This version of Irrigator Pro is hereafter referred to as Irrigator Pro (SWT).

Trellis, a Georgia-based start-up company modified and commercialized a soil moisture sensing system similar to the UGA SSA. A partnership between NPRL, UGA, and Flint River Soil and Water Conservation District (FRSWCD) where Irrigator Pro users are concentrated allowed the collaborative team to modify Irrigator Pro so that it now also uses SWT data from the Trellis

soil moisture sensing system. This version of the model is hereafter referred to as Irrigator Pro (SWT). Trellis is one of few matric potential-based soil moisture sensing systems commercially available to growers. This limits the flexibility and adoption of the sensor-based version of Irrigator Pro as most commercially available soil moisture sensing systems use capacitance-type sensors and measure soil moisture in terms of VWC.

The early temperature-driven versions of Irrigator Pro (Temp) software were manually distributed on floppy disks during conferences and symposiums across the Southeast (Butts, Sorensen, and Lamb 2020). Later on, the code was downloadable from the NPRL website. The first internet-based version became available for public use in 2017. In 2018, both Irrigator Pro (Temp) and Irrigator Pro (SWT) were made available through a new web platform (<https://irrigatorpro.org/>) and as a smartphone app ([Google Play](#), [Apple Store](#)) through the partnership between NPRL, UGA, and the FRSWCD. The web-based platform and the smartphone app platform mirror each other so users can utilize them interchangeably.

These platforms have 1,200 active users in Georgia, Alabama, North and South Carolina, and Florida. Over the past 5 years, 25-30% of the users schedule their irrigation using the automated data entry options while the rest either prefer the manual daily input or their sensors are incompatible with the current versions of Irrigator Pro (Irrigator Pro Stats 2023). Lastly, between 35-40% of users utilize the temperature version of the model. Further automating temperature entry will therefore also likely increase the useability of the model.

Despite the availability of DSTs like Irrigator Pro, most peanut growers in Georgia use the UGA Extension Checkbook method for irrigation scheduling. The method which is described in the University of Georgia's Peanut Production Guide (UGA Extension System 2022; Porter et al 2022) recommends weekly irrigation application amounts based on weeks after planting (Figure

1.4.). In Georgia's growing environment, peanut reaches peak water requirement about 10 weeks after planting. The weekly estimates were determined by using historical meteorological data to calculate weekly evapotranspiration (ET). The weekly irrigation needed is calculated by subtracting precipitation received from weekly demand. The weakness of the Checkbook method is that it does not account for current environmental conditions, and it is left to the user to estimate how current conditions may affect the crop's water needs. In irrigation scheduling studies in which it is compared to more responsive irrigation scheduling tools, the Checkbook method generally applies the most water and does not produce the highest yields. In a 3-year study conducted in Georgia, Vellidis et al. (2023) showed that the Checkbook method used 57% more water and resulted in 7% lower yields than scheduling irrigation with soil moisture sensors (Vellidis 2023).

SmartIrrigation Apps for Irrigation Scheduling

Beginning in 2012, a group of UGA and University of Florida (UF) researchers began developing a suite of irrigation scheduling apps for a variety of crops. The suite was called SmartIrrigation Apps for Scheduling Irrigation (SI Apps) and includes horticultural and agronomic crops (Migliaccio, T Morgan, et al. 2015; Vellidis et al. 2016; Migliaccio, Morgan, et al. 2015; Miller et al. 2018; Miller, Vellidis, and Coolong 2018; Ayankojo et al. 2018). The apps all estimate daily crop water use (ET_c) using the FAO 56 method described earlier. The SI Apps pull meteorological data from national data sets, state-operated mesonets, and on-farm automated rain gauges. The UGA team under the leadership of Dr. George Vellidis developed the cotton and soybean SI Apps and co-developed the Corn SI App. Plot studies have demonstrated that scheduling irrigation with the agronomic SI Apps results in irrigation water use efficiency (IWUE) gains of up to 50% and yield gains of up to 15% when compared to standard checkbook scheduling methods most often used by growers in the Southeast (Migliaccio, Morgan, et al. 2015). A grant

from the 2019 USDA NIFA AFRI program provided funding to develop the algorithms for a peanut ET-based scheduling model and integrate the peanut algorithms along with the existing Corn, Cotton, and Soybean SI Apps into a new CropFIT SI App. The Corn, Cotton, and Soybean Apps were recently consolidated into the SI CropFit App which was publicly released in 2023. The SI CropFit App includes several new features including using USDA-NRCS SSURGO data to extract soil water holding capacity for individual fields (Vellidis et al. 2021).

The models that drive the SI Apps use meteorological data to calculate daily ETo. The models then apply the appropriate Kc to estimate daily ETc. Figure 1.5. presents the Kc curve used for the Cotton App (Vellidis et al.,2016). For all the agronomic crops in the SmartIrrigation suite (corn, cotton, soybean), changes in phenology and associated changes in Kc are driven by accumulated heat units commonly referred to as growing degree days (GDDs). GDDs are calculated using Eqn. 1.3. In cotton, for example, Tbase is 60°F. Any temperature below Tbase is set to Tbase before calculating the average.

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base} \quad (1.3.)$$

The SI Apps take two different approaches to scheduling irrigation. The specialty crop apps (avocado, blueberry, citrus, strawberry, and vegetable) provide the user with the frequency and duration of irrigation events needed to replace accumulated weekly ETc. In contrast, the agronomic crop apps use a soil water balance model. The model uses daily ETc, soil parameters, precipitation, and irrigation applications to estimate a daily root zone soil water deficit (RZSWD) in terms of percent and inches of plant available soil water and provides these two pieces of information to the user. Plant available soil water is defined as the water held by the soil matrix between field

capacity and the wilting point. A 50% RZSWD or depletion of 50% of plant available soil water is a commonly accepted irrigation threshold for agronomic crops.

In the models, plant available soil water is a function of the soil's plant available water holding capacity and current rooting depth. As the plant rooting system grows, the depth of the profile from which the plant can extract water also increases. In the Cotton App, for example, the initial rooting zone depth is 0.15 m (6 in) and increases by 7.5 mm day⁻¹ (0.3 in day⁻¹) until it reaches a maximum depth of 0.75m (30 in). At emergence, the soil profile from 0 to 0.75 m is assumed to be at 85% of the maximum plant available soil water holding capacity.

In the model, today's plant available soil water is calculated by subtracting yesterday's ETC from yesterday's plant available soil water and adding any precipitation or irrigation measured. A maximum of 25 mm and a minimum of 4 mm in daily precipitation is used in soil water balance calculations. The maximum is used because even if the RZSWD is greater than 25 mm, it is unlikely that more than that amount will infiltrate into the soil profile during a 24 h period. The minimum is used because less than 4 mm of precipitation in a 24 h period does not have an appreciable effect on soil moisture. All these parameters are used to calculate RZSWD in inches and % RZSWD.

Despite the obvious advantages offered by using DST for irrigation scheduling and their availability on easy-to-use platforms such as Irrigator Pro and the SI Apps, the adoption of DSTs among growers has been relatively low. Adoption barriers include knowledge gaps and perception of complexity (Irmak et al. 2013). Another obstacle is the need to use different scheduling tools for different crops making the process unnecessarily cumbersome and complex.

1.3. Objectives

The overall goal of this research project was to make DSTs for irrigation scheduling in peanut easier to use and more adoptable by peanut growers. The specific objectives of the research were to:

1. Incorporate VWC (capacitance) sensors as an automated data entry solution for Irrigator Pro.

The deliverable of this objective was to release a new version of Irrigator Pro that uses VWC data directly from capacitance probes.

2. Develop an ET-based irrigation scheduling tool for peanut similar to that of the agronomic SI Apps. The deliverable of this objective was to integrate the new peanut tool into the SI CropFit App.

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1.5. Tables and Figures

Table 1.1. Georgia Statewide Variety Testing program yields for Georgia-06G from 2018-2022.

Year	Irrigated Tifton, GA (kg ha ⁻¹)	Rainfed Tifton, GA (kg ha ⁻¹)	Irrigated Plains, GA (kg ha ⁻¹)	Rainfed Plains, GA (kg ha ⁻¹)	Statewide Average* (kg ha ⁻¹)
2022	7110	6278	3963	3351	4764
2021	7922	6351	5843	4631	4988
2020	3805	4334	-	-	4618
2019	7528	6672	5642	5249	4674
2018	6930	6056	5208	5207	4921

* Includes irrigated and rainfed.

Table 1.2. FAO recommended Kc values for peanuts (Allen 2005).

Groundnut (Peanut) <i>Arachis hypogea</i>	Phenological Stage		
	Initial	Middle	End
Kc Value	0.4	1.15	0.6

Table 1.3. FAO estimated growth stage length for different geographic regions.

Groundnut (Peanut) <i>Arachis hypogea</i>	Phenological Stage				Total	Location
	Initial	Development	Middle	Late		
	25	35	45	25	130	West Africa
Duration (Days)	35	35	35	35	140	High Altitudes
	35	45	35	25	149	Mediterranean

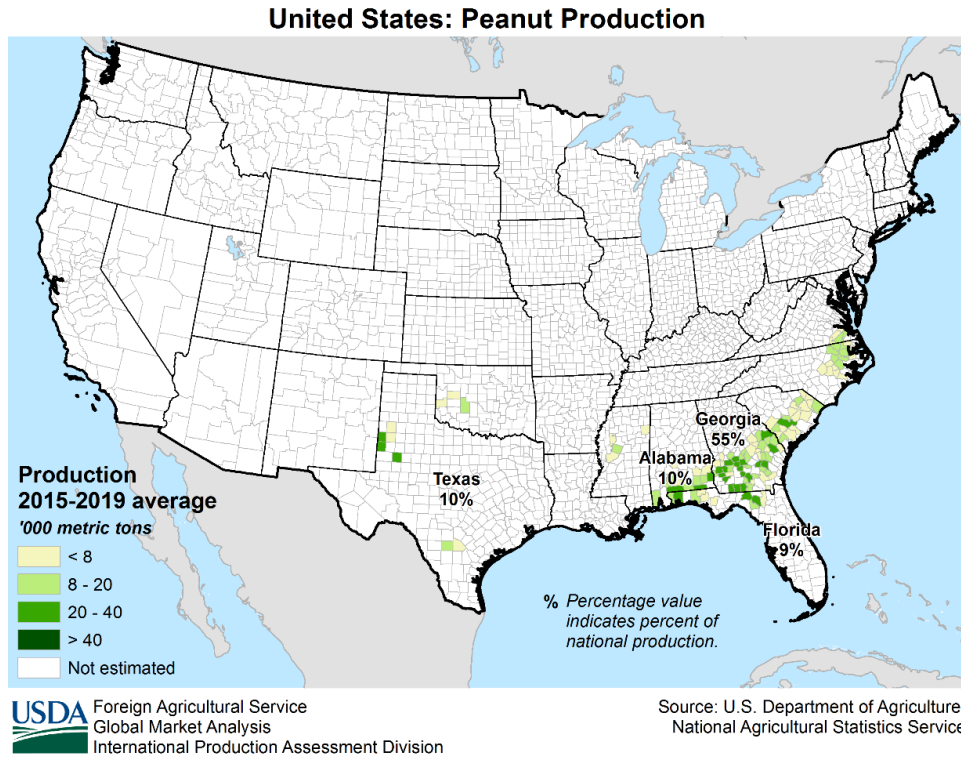


Figure 1.1. 2015-2019 average peanut production in the US on a county level. The percentage value indicates the percent of the national production (U.S. Department of Agriculture, National Agricultural Statistics Service, 2020).

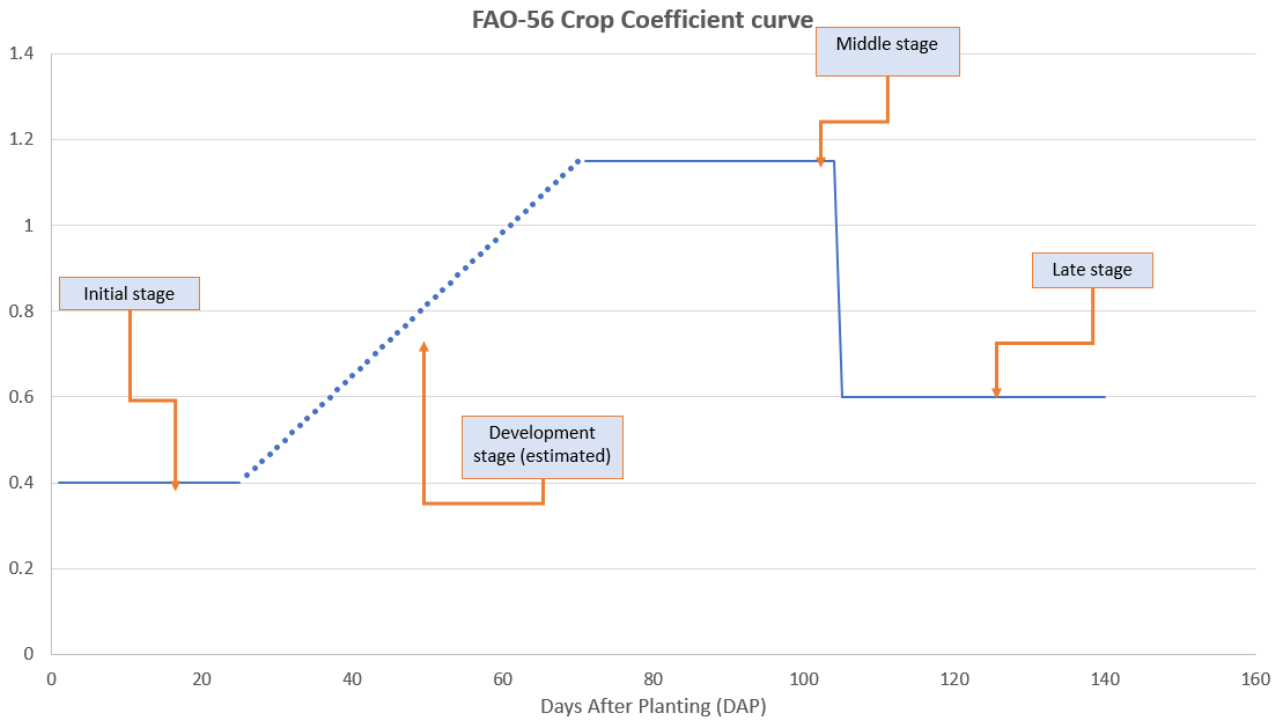


Figure 1.2. Crop coefficient (Kc) curve for peanut grown in western Africa climates according to FAO-56 guidance (Allen et al. 1998).

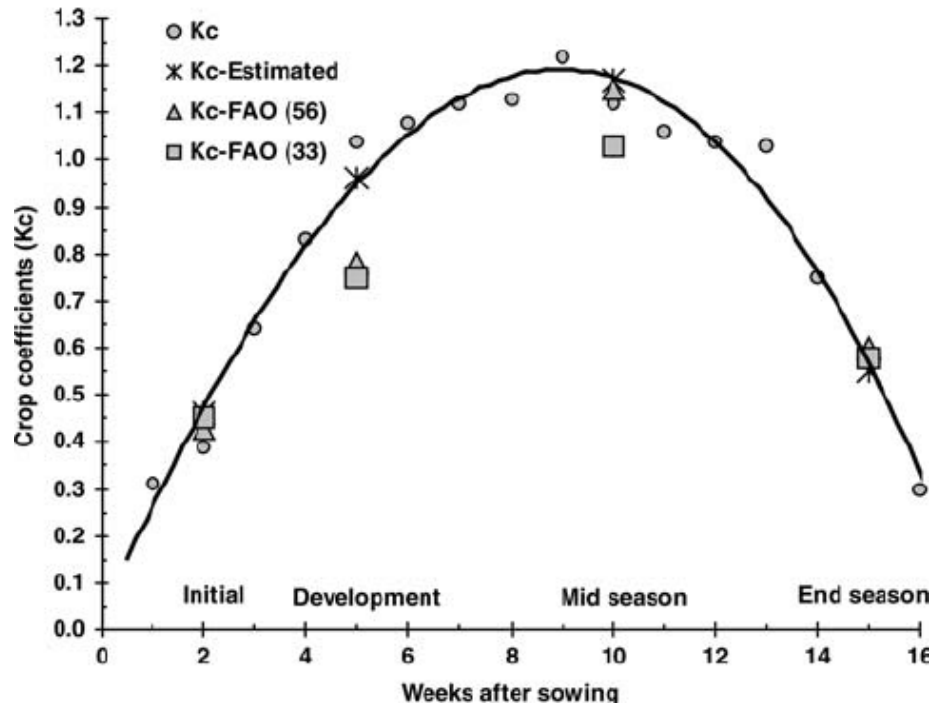


Figure 1.3. Kc curve for peanuts created compared to FAO 56 and FAO 33 estimated Kc values for specific phenological stages.

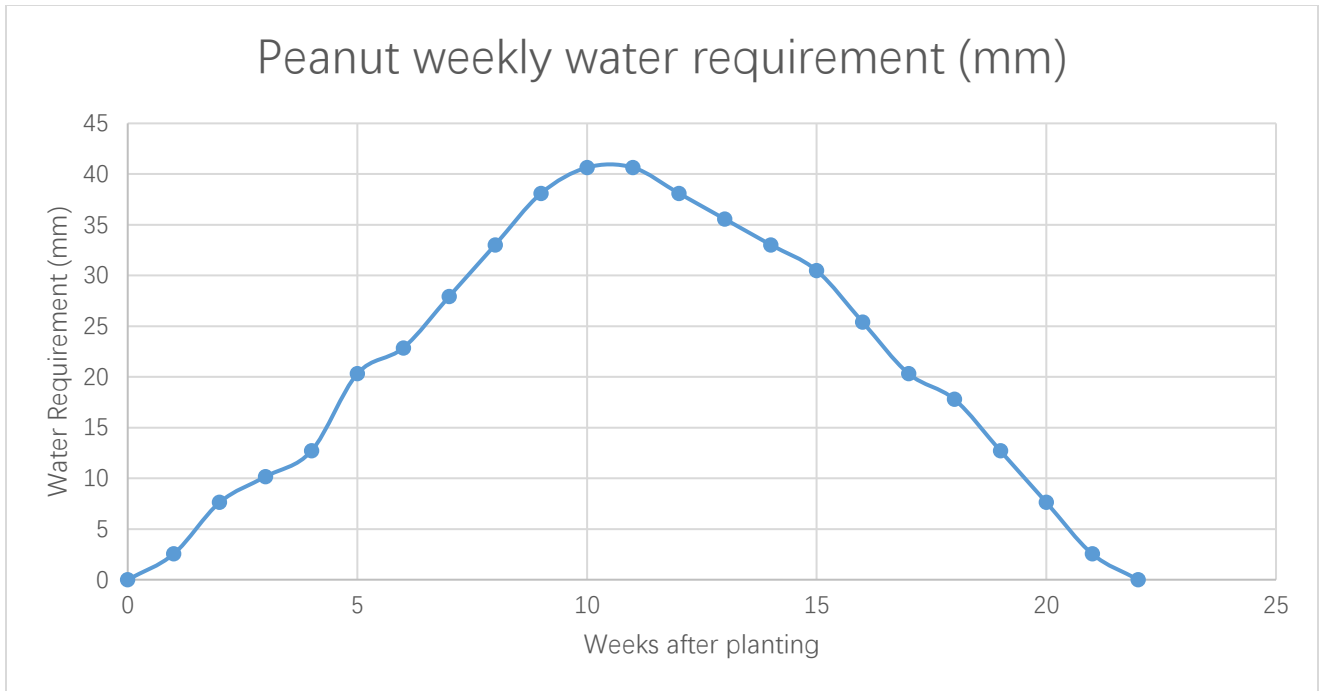


Figure 1.4. Estimation of peanut water needs throughout the growing season (Porter et al 2022).

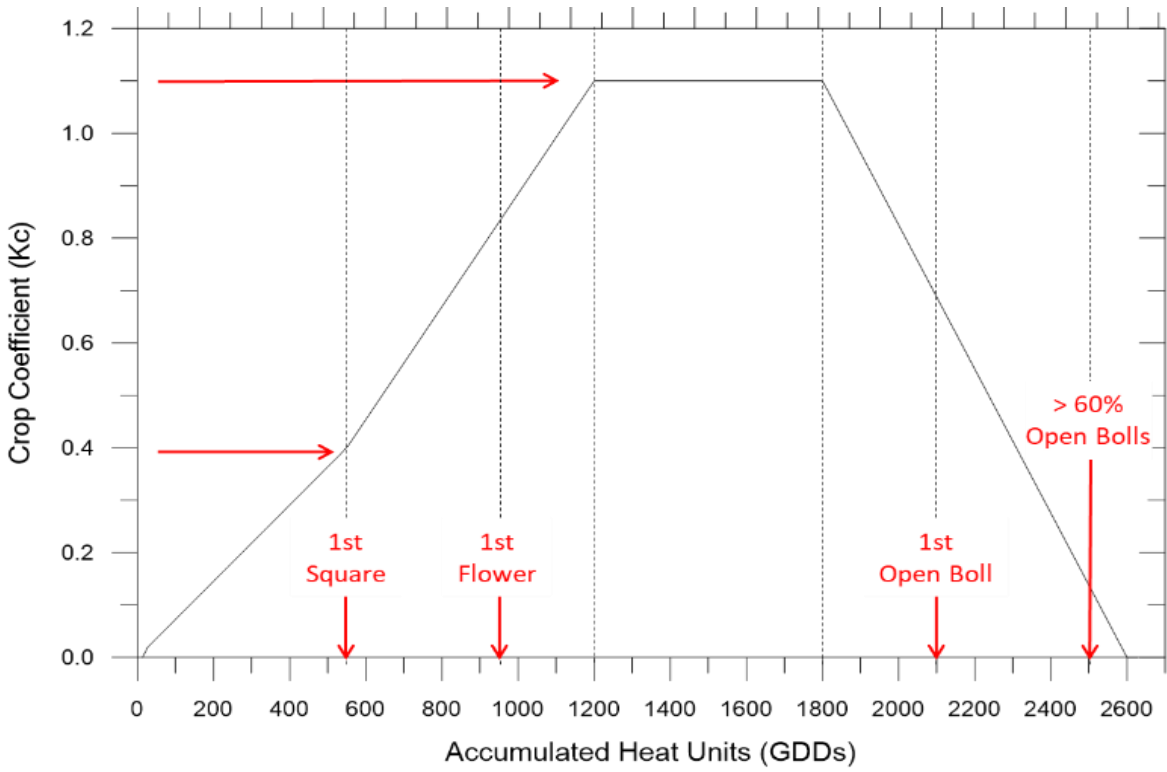


Figure 1.5. Crop coefficient (Kc) curve used by the SmartIrrigation Cotton App. Phenological stages are driven by GDDs (Migliaccio et al., 2016)

¹CHAPTER 2

INCORPORATING VOLUMETRIC WATER CONTENT (CAPACITANCE) SENSORS AS AN AUTOMATED DATA ENTRY SOLUTION FOR IRRIGATOR PRO¹

¹Gallios, I., Butts, C., Perry, C., Gruver, M., and Vellidis, G. To be submitted to the *Journal of the American Society of Agricultural and Biological Engineers*.

Abstract

Irrigator Pro (IP) is a public domain irrigation scheduling decision support tool (DST) developed by the USDA-ARS National Peanut Research Laboratory which is widely used by peanut growers and consultants in the southeastern U.S. The original version of the DST utilizes min/max soil temperature and precipitation to provide yes/no irrigation decisions for peanuts. More recently scientists at NPRL developed a sensor-based soil water balance model version of Irrigator Pro that automates the data collection process. This version allows either manual data entry or automated entry of soil matric potential data from sensors located at 0.1, 0.2, and 0.4 m. To make Irrigator Pro more accessible to growers and consultants, the work described here focused on incorporating volumetric water content (VWC) also known as capacitance sensors as an automated data entry solution for Irrigator Pro. The deliverable of this project was to release a new version of Irrigator Pro that uses VWC data directly from capacitance probes.

During the 2021 growing seasons, the VWC version of Irrigator Pro was developed and tested at two field sites in southern Georgia, USA, using replicated plot studies that compared the VWC version to the other versions of the Irrigator Pro and to other advanced irrigation scheduling tools. The results indicate that the VWC version performs at least as well as the temperature and matric potential versions in terms of irrigation application and crop yields. In light of these positive outcomes, the VWC version of Irrigator Pro was integrated into the Irrigator Platform in early 2023 and made available for public use in April 2023. Ongoing evaluation of the model will continue in subsequent growing seasons through plot studies and on-farm trials.

2.1. Introduction.

Peanut, or groundnut (*Arachis hypogaea*), is a low-growing crop which produces its fruit underground. It is native to South America but is widely grown around the world and is a critical source of protein and income. In 2021, world peanut production was 49.8 million metric tons (Mg). China is the world's largest peanut producer with 18.3 million Mg produced in 2021. The USA was ranked fourth with 2.5 million Mg (US Department of Agriculture 2023). In the USA, peanuts are grown primarily in the southeastern states (Figure 2.1.).

The state of Georgia grows the most peanuts in the USA. In 2022, Georgia produced 52% of the country's crop or 0.66 million Mg on 275,200 ha with a mean yield of 4,770 kg ha⁻¹ (Georgia Peanut Commission 2022; "USDA/NASS Georgia Agriculture Overview" 2022). Mean yields in Georgia ranged from 4,682 to 4,929 kg ha⁻¹ between 2018 and 2022 (Table 2.1.). Peanuts are grown in 77 counties in Georgia (Figure 2.2.) by approximately 4000 farmers, resulting in a USD2.2 billion industry in the state (Georgia Peanut Commission 2022). Between 45 and 55% of the peanut acreage is irrigated (UGA Extension System 2022). The U.S. Geological Survey (USGS) estimates that three-quarters of the state's freshwater withdrawals are used for irrigation (Dieter et al. 2018; USGS 2015).

2.2. Literature Review

2.2.1. Irrigation Scheduling in Peanut

Peanut is moderately adaptive to water-deficit conditions and its water demands are lower than many crops (Reddy, Reddy, and Anbumozhi 2003). However, it benefits significantly from irrigation during dry years with irrigated yields generally exceeding rainfed yields by 2000-3000 kg ha⁻¹ (Soler 2007; University of Georgia, CRSS 2022). This is because water deficit stress during the crop's reproductive stage when water use by the crop is highest, results in yield losses.

However, Kottapalli et al. (2009), Porter (2016), Wright, Hubick, and Farquhar (1991), and Lamb et al. (2007) have all shown that overirrigation in peanut suppresses yield.

Irrigation scheduling research on peanuts has been conducted in most peanut-growing states. In Mississippi, irrigation scheduling thresholds were evaluated in 2015 and 2016 with a study conducted at the Delta Research and Extension Center in Stoneville. Soil matric potential thresholds of -50 kPa, -75 kPa, -100 kPa, and the FAO-56 were used to schedule irrigation (Leininger et al. 2019). The results showed that using the -50 kPa as an irrigation threshold increased peanut yield by at least 12.7% relative to FAO-56-based irrigation (Allen et al. 1998) or non-irrigated fields while in some cases it also improved the peanut quality.

Jackson et al (1981) and Alderfasi and Nielsen (2001) developed a method to calculate a Crop Water Stress Index (CWSI) using canopy temperature stress that can be used as an early indicator of stress and irrigation requirements. Porter et al (2015) conducted a study focusing on how Smart Crop sensors (SmartField, TX, USA) which are thermal infrared thermometers can predict crop water stress by measuring the canopy temperature. Six irrigation scheduling treatments were compared in this study including potentiometric sensors, SmartCrop sensors, an extension checkbook method, the University of Georgia EasyPan, and rainfed as a control. Due to the lack of rainfall in that year, the rainfed plots produced only 521 kg ha⁻¹, while the most productive irrigated treatment yielded 6,783 kg ha⁻¹. The CSWI-based irrigation treatment yielded 6,323 kg ha⁻¹, the third highest yield while using the least amount of water (163 mm). The study provided positive feedback on scheduling irrigation using a CSWI (Porter et al. 2015).

2.2.2. Decision Support Tools (DSTs) for Irrigation Scheduling

DSTs for peanut irrigation scheduling have been available since the late 1980s. In a study that compared MOISNUT, a peanut irrigation scheduling tool developed at Auburn University (Tyson

and Curtis 1989; 1990), and EXNUT, a peanut irrigation scheduling tool developed by the USDA Agricultural Research Service (ARS) National Peanut Research Laboratory (NPRL) (Davidson et al. 1995), the results showed that during drier years there was a significant difference between irrigated and non-irrigated fields, but a difference between EXNUT and MOISNUT was not found for any year or field location (Davidson et al. 1995). Another study that used both DSTs showed a profit of USD1098 ha⁻¹ and USD1011 ha⁻¹ for peanuts irrigated on sandy soil and medium-textured soil, respectively, when compared to rainfed peanuts over three years. In addition, aflatoxin was consistently below 10 ppb in the edible kernels of irrigated peanuts and the market grade was higher than that of the non-irrigated ones. Meteorological conditions were significantly different between years and therefore irrigation needs also differed. Overall, the DSTs resulted in 16-23% higher yields (Davidson et al. 1998).

Davidson et al. (1995); Davidson, Lamb, and Sternitzke (2000); Butts, Sorensen, and Lamb (2020) described a rule-based DST which used crop history, yield potential, soil type, irrigation/precipitation, and soil temperature data to determine the available water content in the soil profile that progressed from EXNUT to the current irrigation scheduling DST known as Irrigator Pro (Davidson et al. 1995; Davidson, Lamb, and Sternitzke 2000; Lamb et al. 2007; Butts, Sorensen, and Lamb 2020). Further research led to additional improvements to Irrigator Pro that made it more accurate (Bauer and Stone, 2008; Stone et al. 2015; Liakos et al. 2017). Irrigator Pro is described in detail further below.

In 2005, researchers in Texas improved the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) which was first developed in 1990 (Wanjura, Upchurch, and Mahan 1990). BIOTIC uses two factors to trigger irrigation, a canopy temperature threshold, and a time-based one. In addition, it uses a limiting relative humidity criterion to adjust the thresholds to

humidity conditions. The tool was mainly tested in Texas, Mississippi, and California and has been proven effective in both semi-arid and humid environments. However, the many methods of determining the time and temperature thresholds for BIONIC have made its use complicated for growers and consultants.

During the same period, researchers from the University of Georgia were testing Cropping System Models (CSM) as a way to schedule irrigation in peanuts and cotton (Soler 2007). CROPGRO-Peanut, a CSM for peanut crops, was tested in four rainout shelters at Griffin, GA under a 2-year study. The irrigation thresholds (IT) that were tested during that study were 30%, 40%, 60%, and 90% of the AWC, and the soil moisture levels were monitored using capacitance type sensors that measure volumetric water content (VWC). The results showed a significant difference in yield among all IT with 90% achieving the highest pod yield, 4899 kg ha⁻¹. The 90% IT outperformed the other treatments in pod number while the final biomass was not significant different among the treatments, except for the 30% threshold. These results concluded that peanut growth and development were affected by different irrigation scheduling thresholds and assumed that CSMs could quantify the effects of ITs on peanut growth, development, and yield.

In Australia, a similar irrigation scheduling tool was developed that incorporated two older models into a new one called AQUAMAN (Chauhan et al. 2013). This tool used the FAO-56 method in combination with the APSIM model which is described in Keating et al. (2003) to estimate the crop water use and provide a decision for irrigation. AQUAMAN uses a series of equations to calculate daily crop evapotranspiration (ET). The results showed that the tool reduced the amount of irrigation by 50% in some years while increasing the yield even by 38% and in some cases improving the quality of the seeds as well (Chauhan et al. 2013; Keating et al. 2003)

The University of Florida (UF) developed PeanutFARM (Rowland et al 2015; Wright et al.

2020)), an irrigation scheduling DST that uses adjusted growing degree days (aGDD) to determine the crop's phenological stage and the FAO-56 method (Allen et al. 1998) and meteorological data exclusively from weather station networks to provide the user with irrigation scheduling decisions. The DST has been commercialized and is now used primarily to forecast peanut maturity.

Irrigator Pro

Irrigator Pro is a public domain irrigation scheduling DST developed by the NPRL. The original version of the tool utilizes min/max soil temperature, ambient temperature, and precipitation to provide yes/no irrigation decisions for peanuts. It is hereafter referred to as Irrigator Pro (Temp). During the course of the season, the user records field data including rainfall, irrigation, and the maximum and minimum soil temperature as part of regular field scouting. When entering the rainfall data, the user must estimate the effective amount of rainfall by determining the portion that infiltrated into the soil, based on their knowledge of the time over which the rainfall occurred. If the rainfall event is less than 3 mm, it is disregarded as having little effect on the water status. The installation of maximum and minimum recording thermometers typically occurs around 30 days after planting to ensure that the selected site is representative of the field. The max/min soil thermometers are installed in the peanut row at a depth of 50 mm under the canopy to monitor and record the temperature. If there are variations in soil conditions throughout the field, it is recommended to install at least two thermometers. It is essential to reset the maximum and minimum temperature recordings within 24 h of a rainfall or irrigation event exceeding 3 mm. The model also requires that users describe their soil type as sandy, medium/heavy, or heavy soil. To simplify this requirement, Jerry Pilkinton, a retired USDA-NRCS soil scientist, contributed to classifying soil series in areas in which peanuts are grown in the USA as sandy (I), medium/heavy (II), and (III) heavy (Butts, Sorensen, and Lamb 2020). Based on the precipitation and soil

temperature readings, the model provides a decision for irrigation. That decision is based on the assumption that soil moisture reduces soil temperature. Irrigation is recommended when the maximum soil temperature exceeds the 29.5° C for three consecutive days without a precipitation event of more than 3mm. After irrigation or a rainfall, the thermometers are reset manually and start new measurements until soil temperature exceeds the thresholds again or rainfall occurs.

One of the model's strengths is that irrigation decisions are also a function of crop phenology and not only of soil condition. For example, because peanut is an indeterminate crop, it continues to flower and set fruit while environmental conditions remain favorable. Irrigator Pro withholds irrigation for two weeks after the midpoint of the growing season to terminate flowering and promote seed filling. During that period the water needs in the model reduce for a short period before reaching their maximum values during the middle stage where the seed filling takes place. Irrigator Pro has been evaluated by growers and crop consultants and consistently produces high yields (Lamb et al. 2007). Because of this, it has been used by crop consultants in Alabama and Georgia even though the model requires manual on-field data collection and entry at least three times per week.

More recently scientists at NPRL developed a sensor-based soil water balance model version of Irrigator Pro that automates the data collection process. This version allows either manual data entry or automated entry of soil matric potential data from sensors located at 0.1, 0.2, and 0.4 m and was designed to work with the UGA Smart Sensor Array (UGA SSA) – a wireless soil moisture sensor system (G. Vellidis et al. 2008). Soil matric potential, also referred to as soil water tension (SWT), is essentially a measure of the energy required by plants to extract soil water from the soil matrix and is measured in units of centibars (cb) or kiloPascals (kPa). There are generally accepted SWT values that growers and consultants use as irrigation thresholds for each crop. What varies

by soil type is the plant available water at any given SWT. The UGA SSA reports soil moisture in terms of SWT and Irrigator Pro uses SWT measurements at the three depths to estimate the plant available soil water in the soil profile by converting SWT into volumetric water content (VWC) using the following empirical equation developed by NPRL scientists. VWC is estimated using observed SWT (kPa) at each depth (i) by:

$$VWC_i = \alpha_i + b_i \ln(kPa_i) \quad (2.1.)$$

Coefficients α and b vary depending on the soil categories previously described. The VWC irrigation trigger level was calculated to be the equivalent of 40 kPa. The total available water content (AWC) is defined as the difference between the current VWC_i and the minimum VWC for that specific soil type. VWC is then used to calculate the soil water balance within the root zone (Butts, Sorensen, and Lamb 2020; Davidson et al. 1998). This version of Irrigator Pro is hereafter referred to as Irrigator Pro (SWT).

Trellis, a Georgia-based start-up company modified and commercialized a soil moisture sensing system similar to the UGA SSA. A partnership between NPRL, UGA, and Flint River Soil and Water Conservation District (FRSWCD, <http://flintriverswcd.org/>) where Irrigator Pro users are concentrated allowed the collaborative team to modify Irrigator Pro so that it now also uses SWT data from the Trellis soil moisture sensing system. This version of the model is hereafter referred to as Irrigator Pro (SWT). Trellis is one of few matric potential-based soil moisture sensing systems commercially available to growers. This limits the flexibility and adoption of the sensor-based version of Irrigator Pro as most commercially available soil moisture sensing systems use capacitance-type sensors and measure soil moisture in terms of VWC.

Irrigator Pro Usage

The early temperature-driven versions of Irrigator Pro (Temp) software were manually distributed on floppy disks during conferences and symposiums across the Southeast (Butts, Sorensen, and Lamb 2020). Later on, the code was downloadable from the NPRL website. The first internet-based version became available for public use in 2017. In 2018, both Irrigator Pro (Temp) and Irrigator Pro (SWT) were made available through a new web platform (<https://irrigatorpro.org/>) and as a smartphone app ([Google Play](#), [Apple Store](#)) through the partnership between NPRL, UGA, and the FRSWCD. The web-based platform and the smartphone app platform mirror each other so users can utilize them interchangeably.

These platforms have 1,200 active users in Georgia, Alabama, North and South Carolina, and Florida. Over the past 5 years, 25-30% of the users schedule their irrigation using the automated data entry options while the rest either prefer the manual daily input or their sensors are incompatible with the current versions of Irrigator Pro (Irrigator Pro Stats 2023). Lastly, between 35-40% of users utilize the temperature version of the model. Further automating temperature entry will therefore also likely increase the usability of the model.

Despite the availability of DSTs like Irrigator Pro, most peanut growers in Georgia use the UGA Extension Checkbook method for irrigation scheduling. The method which is described in the University of Georgia's Peanut Production Guide (UGA Extension System 2022; Porter et al 2022) recommends weekly irrigation application amounts based on weeks after planting (Figure 2.3.). In Georgia's growing environment, peanut reaches peak water requirement about 10 weeks after planting. The weekly estimates were determined by using historical meteorological data to calculate weekly evapotranspiration (ET). The weekly irrigation needed is calculated by subtracting precipitation received from weekly demand. The weakness of the Checkbook method is that it does not account for current environmental conditions, and it is left to the user to estimate

how current conditions may affect the crop's water needs. In irrigation scheduling studies in which it is compared to more responsive irrigation scheduling tools, the Checkbook method generally applies the most water and does not produce the highest yields. In a 3-year study conducted in Georgia showed that the Checkbook method used 57% more water and resulted in 7% lower yields than scheduling irrigation with soil moisture sensors (Vellidis 2023).

2.3. Objectives

The overall goal of this project was to make Irrigator Pro an easier-to-use irrigation scheduling tool by providing users with several options for automated data entry. The specific objective of the work reported here was to incorporate VWC (capacitance) sensors as an automated data entry solution for Irrigator Pro. The deliverable of this work was to release a new version of Irrigator Pro that uses VWC data directly from capacitance probes.

2.4. Materials and Methods

The project consisted of a data collection and data analysis/model development component. Data collection consisted of field and laboratory work. The field work was conducted at UGA's C.M. Stripling Irrigation Research Park (SIRP) located near Camilla, GA and the USDA-ARS National Peanut Research Laboratory's Hooks-Hanner Environmental Resource Center (HHERC) near Sasser, GA during the 2021 and 2022 growing seasons. The laboratory and data analysis/model development components were conducted at the UGA Tifton campus.

2.4.1. *SIRP Field Work*

The fieldwork at SIRP was conducted in a 4 ha. research field known as the Newton Lateral (31°16'46.24"N, 84°17'59.59" W). The field was divided into three blocks (North, Middle, and South) with each block containing 27 plots (Figure 2.4.). The Georgia-06G cultivar was planted and harvested on May 19th and October 5th, respectively, in 2021 and May 10th and September 26th

in 2022.

The plots were each 14.5×14.5 m (48×48 ft or 48 ft long \times 16 rows wide). The eight middle rows in each plot were used for data collection and the four rows on either side of the middle eight serve as buffers. The soil in the Newton Lateral field is classified as a Lucy Loamy Sand with available water holding capacity (WHC) of 0.08 cm cm^{-1} with 0 to 5% slope. Soil texture varies slightly across the field with 83% Sand, 10% Silt, and 7% Clay in the South block to 86% Sand, 8% Silt, and 6% Clay in the North block. The field is irrigated with a variable-rate-enabled lateral irrigation system which can apply a unique water application rate to each of the 81 plots.

A cotton-peanut-corn rotation is maintained with crops rotating from north to south each year. All crops were planted into a rye cover crop using strip tillage following burndown with glyphosate. During Year 1 of the project, peanuts were in the Middle Block, and during Year 2 in the South Block.

Soil Moisture Sensors

Two types of soil moisture sensor systems were used in the study – the UGA SSA and Sentek (Sentek Sensor Technologies, Australia) probes. The UGA SSA is an automated wireless soil moisture sensing system developed at the University of Georgia that measures soil moisture in terms of SWT (the absolute value of matric potential) in units of kPa (G. Vellidis et al. 2008; Liakos et al. 2017). A UGA SSA node consists of a probe with Watermark (Irrrometer, Riverside California, USA) sensors at depths of 0.10, 0.20, and 0.40 m (4, 8, 16 in), a thermocouple that measures soil temperature at 0.10 m (4 in), and an electronics package that transmits that data to a cloud server. UGA SSA nodes were installed in all 27 plots for monitoring purposes. Only those installed in the SWT (UGA SSA) and Irrigator Pro (SWT) treatment plots were used for irrigation scheduling.

VWC was measured with Sentek 0.6m (24 in) probes with sensors at depths of 0.1, 0.2, 0.3, 0.4,

0.5, and 0.6 m (4, 8, 12, 16, 20, 24 in) at 30 minute intervals and data were transmitted to a cloud server using AgSense telemetry ([AgSense](#), Huron, SD). Sentek probes were installed in the treatment in which irrigation scheduling was triggered by VWC. Sentek probes measure temperature at all six depths. Figure 2.5. shows a plot at SIRP with both UGA SSA and Sentek probes installed. Irrigation was triggered separately for each treatment and the plots were irrigated accordingly by the VRI-enabled lateral. Approximately 19mm (0.75in) of water was applied with each irrigation event.

Irrigation Scheduling Treatments

The experimental design was a randomized complete block design (Figure 2.6.). The 27 plots in each block were divided into nine treatments with three replicates each. Five irrigation scheduling treatments and a rainfed treatment were evaluated. The five scheduling treatments were: SWT (UGA SSA), Irrigator Pro (VWC), Irrigator Pro (Temp), Irrigator Pro (SWT), evapotranspiration (ET)-based, and rainfed. Tables 2.2. and 2.3. show the treatments assigned to each plot for 2021 and 2022, respectively. Because six treatments were evaluated and nine treatment areas were available, the Irrigator Pro (VWC), Irrigator Pro (SWT), and ET-based treatments were each assigned two treatment areas allowing for 6 replicates of those treatments.

Treatment 1 – SWT (UGA SSA). SWT thresholds applied using the Porter method were used to trigger irrigation (Porter et al. 2015). This method uses SWT data measured at 3 depths with UGA SSA probes to estimate the water availability in the soil profile using Eqn. 2.2. A weighting factor (α , β and γ) was applied to sensor readings based on sensor depth to represent the distribution of the rooting system of the peanut crop at that phenological stage. Days after planting date were used to estimate the crop growth stage and adjust the weighting factors based on past research. Table 2.4. shows the distribution of weighting factors as a function of DAPs for the growing season. The

weighted SWT values from each plot at 07:00 each morning were averaged and that average SWT was used to determine if irrigation was needed for the treatment. The irrigation threshold was set at 45 kPa (Porter et al. 2015).

$$\textit{Weighted Average SWT} = \alpha * \textit{SWT}_{0.1\text{m}} + \beta * \textit{SWT}_{0.2\text{m}} + \gamma * \textit{SWT}_{0.4\text{m}} \quad (2.2.)$$

Treatment 2 – Irrigator Pro (VWC). During Year 1 of the study, VWC thresholds of 10%, 12%, and 14% were established for triggering irrigation in sandy, medium, and clay soils, respectively. These thresholds were selected to reflect VWC at 45 kPa for each of the soil types based on the experience of the project team. The thresholds were modified prior to Year 2 to 11.5%, 13.5%, and 15.5% for sandy, medium, and clay soils, respectively, based on soil moisture release curves developed from soil samples collected from the plots as described further below. The new thresholds were increased by almost 10% to avoid moisture stress in case of soil variability within the field. Because the soil at the study site was sandy, the 11.5% threshold was used to trigger irrigation. Sentek probes were used to measure VWC. The threshold was the weighted average VWC of the sensors at the six depths as described for SWT. The weighting factors were developed by observing the VWC curves and determining when roots began extracting soil water at each of the six depths. The crop growth stages, which were linked to the accumulated DAP, were aligned with the Growing Degree Days based on observations conducted throughout the 2021 growing season. These observations were compared with the findings of Boote (1982) and the distribution of crop water requirements as reported by Porter et al. (2015). Table 2.5. provides the weighting factors used for this treatment. The difference in VWC between two consecutive days provided an estimate of the daily water use (DWU) and provided an estimate of anticipated DWU. When

anticipated DWU subtracted from VWC exceeded the VWC threshold, irrigation was triggered. During Year 2, the threshold was incorporated into a spreadsheet version of Irrigator Pro which is described in more detail below. The spreadsheet model was used to trigger irrigation. This model uses the soil-type irrigation thresholds mentioned above.

Treatment 3 – Irrigator Pro (Temp). Treatment 3 applied the traditional Irrigator Pro scheduling method that uses soil temperature to trigger the irrigation (Butts, Sorensen, and Lamb 2020). In this study, temperature data were acquired from the thermocouple on the UGA SSA probes. Irrigation was triggered when the maximum soil temperature measured at 0.1m depth exceeded 29.5°C (85°F) for 3 consecutive days (Davidson, Lamb, and Sternitzke 2000).

Treatment 4 – Irrigator Pro (SWT). The sensor-based soil water balance model version of Irrigator Pro uses SWT measurements at three depths to estimate the plant available soil water in the soil profile by converting SWT into VWC data using an empirical equation (Eqn. 2.1.) developed by NPRL scientists (Davidson, Lamb, and Sternitzke 2000). VWC is calculated using observed SWT (kPa) readings at each depth.

Coefficients α and b are a function of the soil types described previously. The irrigation trigger threshold was set at 40 kPa and the corresponding VWC value was calculated using Eqn. 2.1. This is set as the minimum allowable VWC. The total available water content (AWC) is defined as the difference between the current VWC_i and the minimum VWC for that specific soil type. VWC is then used to calculate the soil water balance within the root zone (Butts, Sorensen, and Lamb 2020; Davidson et al. 1998).

Treatment 5 – ET-based. This scheduling method is an ET-based model for irrigation scheduling in peanuts that is currently under development. It uses the FAO-56 method for estimating daily crop water use (ETc) (Allen et al. 1998). The method maintains a soil water balance by subtracting

ETc from a rootzone soil water reservoir and adding any precipitation and irrigation. Irrigation is triggered at a preestablished soil water balance. This treatment was only used during Year 2 (Table 2.3.).

Treatment 6 – Rainfed. This treatment served as the control. Irrigation was applied only to promote germination and to activate herbicides during the first days after planting.

2.4.2. *HHERC Field Work*

HHERC is located between Dawson and Sasser, GA (31°43'54.5"N 84°23'39.3" W) and is managed by the USDA-ARS NPRL. The field that was used in this study is divided into 3 blocks of 4 plots each (3 irrigated and 1 rainfed) (Figure 2.7.). The crops are planted into a rye cover crop using strip tillage following burndown with glyphosate. During Year 1 of the project, peanuts were in the Middle Block, and during Year 2 in the Eastern Block. The AU-NPRL-17cultivar was planted and harvested on May 4th and harvested on September 24th, respectively, in 2021 and April 28th and September 15th in 2022.

The soil of the field is classified as a Greenville sandy loam with available water holding capacity of 0.23 cm cm⁻¹ with 0 to 2% slope. Soil texture is homogeneous across the field with around 45% sand, 12% silt, and 43% clay. The field is irrigated with a variable rate-enabled lateral irrigation system which can apply a unique water application rate to each of the 9 plots. As in SIRP, a cotton-peanut-corn rotation is maintained with crops rotating from west to east each year. The experimental design utilized a randomized complete block design. The Irrigator Pro (Temp), Irrigator Pro (SWT), Irrigator Pro (VWC) and rainfed treatment were evaluated with three replicates of each.

As at SIRP, soil moisture was monitored continuously in all plots using both UGA SSA probes and Sentek probes with AgSense telemetry. Irrigation was triggered separately for each treatment

and the plots were irrigated accordingly by the VRI-enabled lateral. Because the heavier soils at HHERC had lower infiltration rates, irrigation (approximately 19mm or 0.75in) was applied in two passes to reduce runoff.

2.4.3. Soil Moisture Release Curves

To accurately convert between SWT and VWC, soil moisture release curves were developed from soil samples collected at six depths in each of the plots using Meter Hyprop 2 (Meter Group, WA, USA) equipment (Shokrana and Ghane 2020) and applying a method described by López-Urrea et al. (2006). The depths corresponded to the depths of the sensors in the Sentek probes [0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m (4, 8, 12, 16, 20, 24 in)]. The transformation was made using the Van Genuchten model's simplified version as described (Lipovetsky et al. 2020). Figure 2.8. depicts the collected data points for the loamy sand soil in SIRP field during the curve fitting process. Following that, the lower irrigation threshold of 45 kPa for peanut irrigation (Butts, Sorensen, and Lamb 2020; Porter et al. 2015) was translated into VWC for the three major soil type categories (sandy, medium, and medium-heavy) leading to 11.5%, 13.5%, and 15.5% respectively. The SIRP field is classified as sandy while the HHERC location belongs to the medium-heavy class. Since both trial fields were either from the first or third class, the medium category was calculated using the average of the other two classes. These values were later implemented into the Irrigator Pro (VWC) database where all the available soil types have been categorized according to their soil properties.

2.4.4. Beta Version of Irrigator Pro (VWC)

During Year 2, a beta version of the Irrigator Pro model that utilizes data from VWC soil moisture sensors was developed and tested. The beta version used an application programming

interface (API) provided by AgSense ([AgSense](#), Huron, SD) to automatically retrieve Sentek probe data from the cloud server and input them to the Irrigator Pro server. An algorithm was developed in Python to rapidly clean the data and prepare them for input to the model. As described earlier, the Sentek probes provide VWC and temperature data at six depths every 30 minutes, but Irrigator Pro operates with either daily or hourly data collection. The incoming VWC data are in units of soil moisture % that were converted to units of the depth of water (mm) to fit the model using Eqn. 2.3.

$$DWU = \frac{(-VWC_i + VWC_{i-1}) * 609.6 \text{ (mm)}}{100} + IR(\text{mm}) + PR(\text{mm}) \quad (2.3.)$$

where:

DWU = daily water use in mm

VWC_i = volumetric water content on the day of the calculations in %.

VWC_{i-1} = volumetric water content the day before the calculations in %.

IR = Amount of irrigation that has been applied during the last 24 h in mm.

PR = Amount of precipitation that has occurred during the last 24 h in mm.

Once the model calculates the amount of water that is needed for one day, it extrapolates DWU and estimates when AWC will be depleted below the established threshold and provides a “when to irrigate” recommendation to the user. The user is also advised to adjust the recommendation based on to the short-term weather forecast. To make Irrigator Pro compatible with more VWC sensors and thus increase the adoption of the model by growers, APIs were later implemented for [Prospera Ag](#) (Omaha, Nebraska, USA) and [Trellis, Inc.](#) (Atlanta, Georgia, USA).

2.4.5. Yield and Statistical Analyses

Yields were measured by harvesting the center four rows of each plot using a bagging combine. Bags were weighed in the field. A subsample from each bag was collected and taken to a nearby peanut buying point where kernel moisture content and percent foreign material were measured. The mass of peanut in each bag was adjusted for percent foreign material and further adjusted to a common moisture content of 10%. Adjusted mass was divided by harvested area and yield reported in terms of kg ha^{-1} . Irrigation water use efficiency (IWUE) was calculated by dividing yield by irrigation applied and reported in units of $\text{kg ha}^{-1} \text{mm}^{-1}$. Irrigation applied was the difference between total irrigation water applied minus water applied to activate herbicides and promote germination after seeding which all treatments received. Yield results from the 2021 HHERC plots were not included in statistical analyses because several adjustments were made to the VWC thresholds during the growing season in that field. A one-way Analysis of Variance (ANOVA) was performed to check the effects of the treatments using R studio 2022.12.0 and the Tukey's Honestly Significant Difference (HSD) test was used to compare the means with a 0.05 significance level.

2.5. Results and Discussion

2.5.1. Soil Moisture Release Curves

Soil moisture release curves were developed for the six depths corresponding to the depths of the sensors in the Sentek probe [0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m (4, 8, 12, 16, 20, 24 in)]. The results of the curve fitting process for the 0.2 m samples at both sites are presented in Figure 2.9. Curves for all depths from each site are presented in Appendix A. These curves were utilized to determine the irrigation thresholds in VWC (%) for each depth based on the predefined SWT thresholds for sandy, medium, and medium-heavy soils in the Irrigator Pro system (Butts, Sorensen, and Lamb 2020). The VWC irrigation threshold at 0.2 m at SIRP (sandy) was 11.5%

while at HERC it was 15.5%. Subsequently, the threshold values were averaged across all six depths, resulting in a single value for each soil profile class (11.5%, 13.5%, or 15.5%).

2.5.2. *SIRP*

In 2021, the growing season precipitation at SIRP was 681 mm, distributed throughout the season and irrigation was triggered only few times for each treatment (Figure 2.10.). Because peanut typically requires approximately 457 mm of water during the growing season (Porter et al 2022) there were no statistically significant differences in treatment yields (Table 2.6., Figure 2.11.). Although there was less precipitation during the 2022 growing season (525 mm), there were regular precipitation events during the reproductive stage of the crop (Figure 2.10.), and again there were no statistically significant differences in treatment yields although yields were much lower than in 2021 for all treatments (Table 2.6., Figure 2.12.). Because of the plentiful precipitation, it is not feasible to assess the effectiveness of the irrigation scheduling treatments using yields with the data collected at SIRP in 2021 and 2022. However, Irrigator Pro (VWC) scheduled similar amounts of irrigation as the other scheduling treatments (Table 2.2.) providing some level of confidence that the model performed at least as well as the other treatments.

In contrast to yield, there were statistically significant differences in IWUE among all treatments in 2021 as the amount of irrigation water applied varied from 55 mm to 131 mm. The highest IWUE was achieved by the Irrigator Pro (VWC) treatment ($340 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and the lowest by the Irrigator Pro (Temp) treatment ($68 \text{ kg ha}^{-1} \text{ mm}^{-1}$) (Table 2.6.). Because 2022 yields and amount of irrigation water applied were similar for all treatments, there were no statistically significant differences in IWUE.

2.5.3. *HHERC*

As described earlier, results from *HHERC* are presented only for the 2022 growing season. Much less precipitation was measured at *HHERC* (405 mm) than at *SIRP* (525 mm) in 2022 with two 10-day periods without precipitation increasing the number of times where irrigation needed to be applied (Figure 2.13.). Consequently, there were statistically significant differences in yield between the irrigated and rainfed treatments (Table 2.7., Figure 2.14.). There were no statistically significant differences between irrigation scheduling treatments indicating that the Irrigator Pro (VWC) treatment performed as well as the other irrigation scheduling treatments. In addition, the Irrigator Pro (VWC) treatment's IWUE was statistically higher than that of the Irrigator Pro (SWT) treatment, while it was statistically similar to the ET-based treatment.

2.6. Conclusions and Next Steps

The yield results of 2021 and 2022 at *SIRP* and 2021 at *HERC* where rainfed treatment yielded as well as the irrigated treatments show that even our best available irrigation scheduling tools need improvement during growing seasons when precipitation meets or exceeds crop needs. More research is needed to understand the dynamics between soil moisture availability and peanut physiology and what levels of water stress are critical at different phenological stages. Irrigator Pro and the other irrigation scheduling tools significantly out-yield rainfed treatments when growing precipitation does not meet or exceed crop needs.

The results from the 2022 field studies indicate that the VWC version of Irrigator Pro performs at least as well as the temperature and SWT versions of the model in terms of irrigation applied (*SIRP* and *HERC*) and yields (*HHERC*). Because of this, the VWC version of Irrigator Pro was incorporated into the Irrigator Platform in early 2023 and released for public use in April 2023. Links to the smartphone applications for iOS and Android are available on the web-based platform

(<https://irrigatorpro.org/>). Tutorials are also available. The model will continue to be evaluated in upcoming growing seasons with plot studies at SIRP and HERC and with on-farm trials. Improvements will be incorporated as necessary.

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2.8. Tables and Figures

Table 2.1. Georgia Statewide Variety Testing program yields for Georgia-06G from 2018-2022.

Year	Irrigated Tifton, GA (kg ha ⁻¹)	Rainfed Tifton, GA (kg ha ⁻¹)	Irrigated Plains, GA (kg ha ⁻¹)	Rainfed Plains, GA (kg ha ⁻¹)	Statewide Average* (kg ha ⁻¹)
2022	7110	6278	3963	3351	4764
2021	7922	6351	5843	4631	4988
2020	3805	4334	-	-	4618
2019	7528	6672	5642	5249	4674
2018	6930	6056	5208	5207	4921

* Includes irrigated and rainfed.

Table 2.2. Plots assigned to each treatment during the 2021 season at SIRP.

Treatment	Treatment ID		Plots	
SWT (UGA SSA)	1	212-1	224-1	239-1
Irrigator Pro (VWC)	2	211-2	228-2	238-2
Irrigator Pro (Temp)	3	217-3	225-3	231-3
Irrigator Pro (SWT)	4	219-4	226-4	233-4
SWT (UGA SSA)	5	215-5	227-5	235-5
Irrigator Pro (VWC)	6	216-6	222-6	237-6
Irrigator Pro (Temp)	7	214-7	229-7	234-7
Irrigator Pro (SWT)	8	218-8	223-8	236-8
Rainfed	9	213-9	221-9	232-9

Table 2.3. Plots assigned to each treatment during the 2022 season at SIRP.

Treatment	Treatment ID	Plots		
ET-based	1	312-1	324-1	339-1
Irrigator Pro (Temp)	2	311-2	328-2	338-2
Rainfed	3	317-3	325-3	331-3
Irrigator Pro (SWT)	4	319-4	326-4	333-4
Irrigator Pro (VWC)	5	315-5	327-5	335-5
ET-based	6	316-6	322-6	337-6
Irrigator Pro (VWC)	7	314-7	329-7	334-7
SWT (UGA SSA)	8	318-8	323-8	336-8
Irrigator Pro (SWT)	9	313-9	321-9	332-9

Table 2.4. Weighting factors used for the SWT values from the Watermark sensors incorporated into UGA SSA probes in the SWT (UGA SSA) treatment during the 2021 and 2022 seasons at SIRP (Porter et al, 2015).

Days After Planting (DAP)	Weight at 0.1m	Weight at 0.2m	Weight at 0.4m
0-13	0.8	0.2	0
14-24	0.6	0.3	0.1
25-31	0.5	0.3	0.2
32-40	0.5	0.25	0.25
40-Harvest	0.4	0.3	0.3

Table 2.5. Weighting factors used for the Irrigator Pro VWC model during the 2022 season.

GDDs	DAP	Weighting Factor at Given Depth					
		0.1 m	0.2m	0.3 m	0.4 m	0.5 m	0.6 m
0-299	0-13	0.8	0.2	0	0	0	0
300-549	14-24	0.6	0.3	0.05	0.05	0	0
550-699	25-31	0.5	0.3	0.1	0.1	0	0
700-999	32-40	0.5	0.2	0.15	0.15	0	0
1000+	40-Harvest	0.17	0.17	0.17	0.16	0.16	0.16

Table 2.6. Yield, irrigation applied, and IWUE for the treatments used during the 2021 and 2022 growing seasons at SIRP. Irrigation applied to each treatment includes amount applied at seeding to promote germination and activate herbicides. Tukey’s HSD test was used for comparison of means by treatment ($\alpha = 0.05$).

Treatment	Year (Precipitation)					
	2021 (681 mm)			2022 (525 mm)		
	Yield (kg ha ⁻¹)	Irrigation (mm)	IWUE* (kg ha ⁻¹ mm ⁻¹)	Yield (kg ha ⁻¹)	Irrigation (mm)	IWUE (kg ha ⁻¹ mm ⁻¹)
ET-based	-	-	-	5410 ^a	119	51 ^a
Irrigator Pro (Temp)	6445 ^a	131	68 ^d	5154 ^a	137	41 ^b
SWT (UGA SSA)	6605 ^a	74	173 ^b	4967 ^a	137	40 ^b
Irrigator Pro (SWT)	6510 ^a	112	85 ^c	5453 ^a	137	44 ^b
Irrigator Pro (VWC)	6480 ^a	55	340 ^a	5467 ^a	155	38 ^b
Rainfed	6780 ^a	36	-	5267 ^a	13	-

*IWUE = irrigation water use efficiency

Table 2.7. Yield, irrigation applied, and IWUE for the treatments used during the 2022 and growing season at HHERC. Tukey’s HSD test was used for comparison of means by treatment ($\alpha = 0.05$).

Treatment	Year (Precipitation)		
	2022 (405mm)		
	Yield (kg ha ⁻¹)	Irrigation (mm)	IWUE* (kg ha ⁻¹ mm ⁻¹)
ET-based	4144 ^a	142	33 ^a
Irrigator Pro (SWT)	3808 ^a	160	26 ^b
Irrigator Pro (VWC)	3997 ^a	124	36 ^a
Rainfed	1937 ^b	-	-

*IWUE= Irrigation Water Use Efficiency

United States: Peanut Production

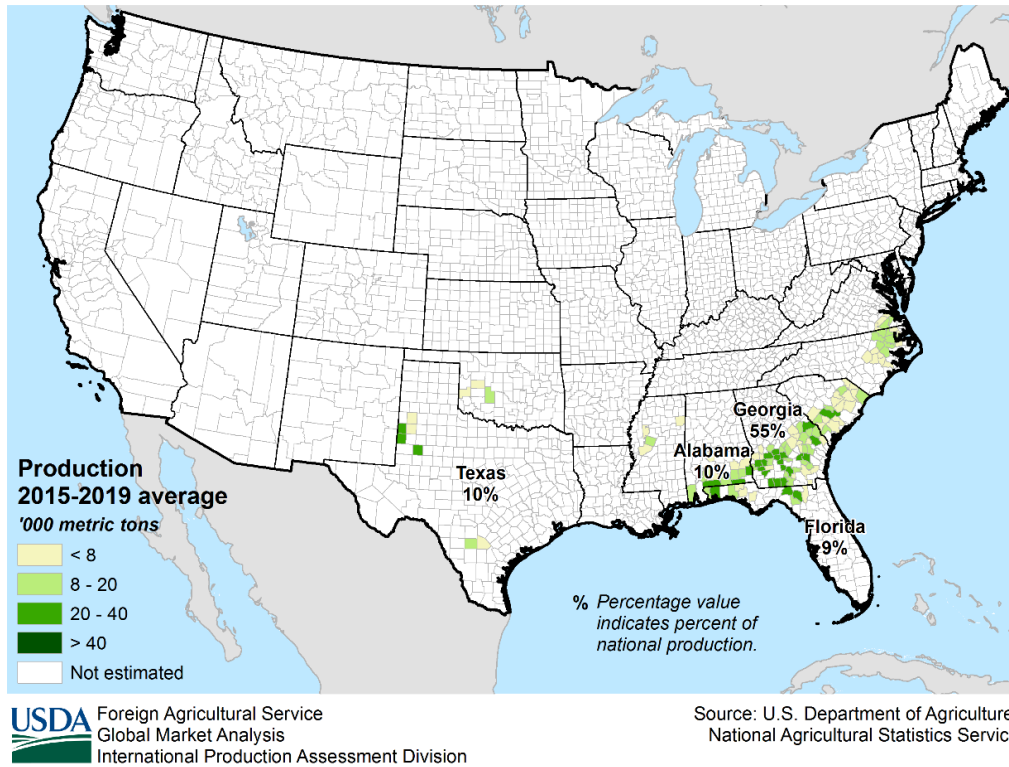


Figure 2.1. 2015-2019 average peanut production in the USA on a county level. The percentage value indicates the percent of the national production (U.S. Department of Agriculture, National Agricultural Statistics Service, 2020).



Figure 2.2. State of Georgia, USA, and counties with highest peanut production during 2022.

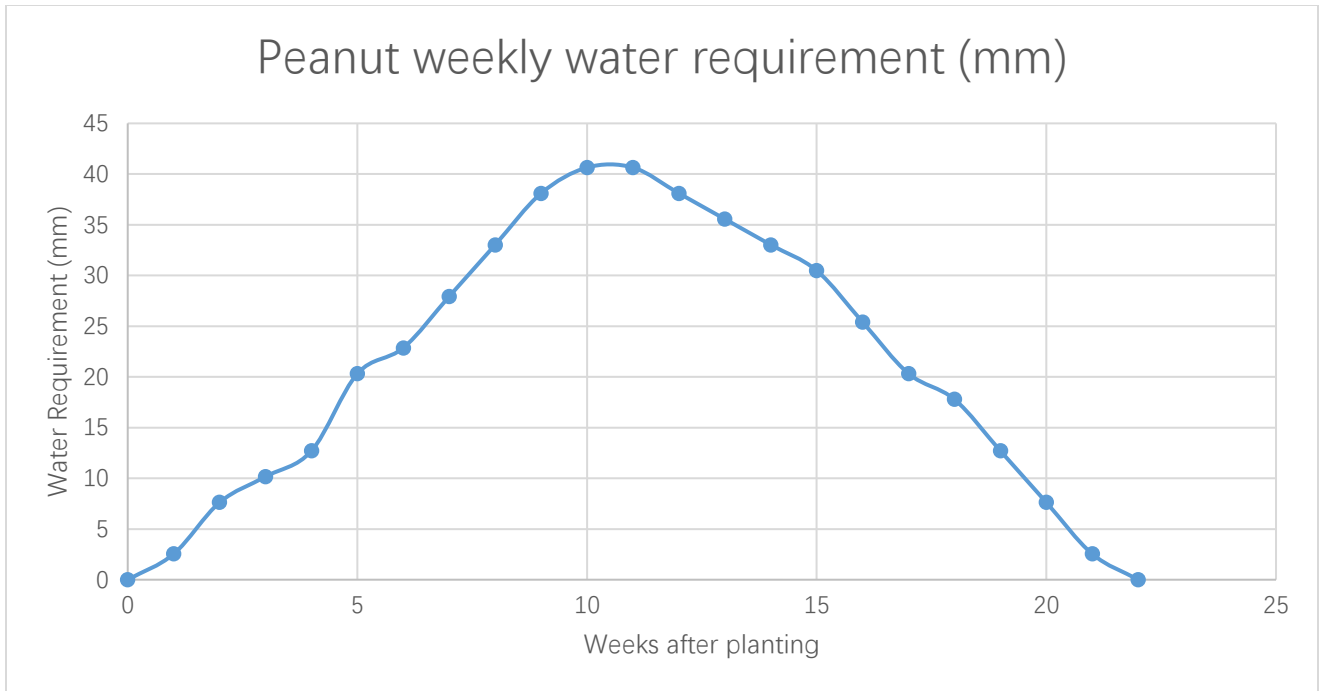


Figure 2.3. Estimation of peanut water needs throughout the growing season (Porter et al 2022).



Figure 2.4. Satellite image of the Newton Lateral field at SIRP depicting the 3 blocks (North, Middle, South).



Figure 2.5. Plot 228-2 at the SIRP field during Year 1, where both Sentek probes with AGsense telemetry loggers (right) and UGA SSA sensors (right) were installed.

Newton Lateral Plot Plan											
North					Middle					South	
xxx-x = Plot Number - Treatment											
VRI Zones	9	////	////	////	////	////	////	////	////	////	////
		111-5	112-9	113-7	211-2	212-1	213-9	311-1	312-8	313-9	////
		////	////	////	////	////	////	////	////	////	////
	8	114-3	115-8	116-1	214-7	215-5	216-6	314-2	315-5	316-4	////
		////	////	////	////	////	////	////	////	////	////
	7	117-6	118-2	119-4	217-3	218-8	219-4	317-6	318-7	319-3	////
		////	////	////	////	////	////	////	////	////	////
	6	121-8	122-4	123-9	221-9	222-6	223-8	321-6	322-5	323-1	////
		////	Alley	////	////	Alley	////	Alley	////	Alley	////
	5	124-2	125-9	126-6	224-1	225-3	226-4	324-3	325-2	326-8	////
	////	////	////	////	////	////	////	////	////	////	
4	127-7	128-3	129-5	227-5	228-2	229-7	327-7	328-9	329-4	////	
	////	////	////	////	////	////	////	////	////	////	
3	131-2	132-8	133-7	231-3	232-9	233-4	331-3	332-1	333-7	////	
	////	////	////	////	////	////	////	////	////	////	
2	134-1	135-4	136-6	234-7	235-5	236-8	334-4	335-2	336-9	////	
	////	////	////	////	////	////	////	////	////	////	
1	137-5	138-1	139-3	237-6	238-2	239-1	337-5	338-8	339-6	////	
	////	////	////	////	////	////	////	////	////	////	
	48 ft	60 ft	48 ft	60 ft	48 ft	60 ft	48 ft	60 ft	48 ft	60 ft	
					////	Buffer					

Figure 2.6. Plot layout of the Newton Lateral field at SIRP. In 2021 (Year 1) peanuts were planted in the Middle block and in 2022 (Year 2) they were planted in the South block. The three-digit number of each plot indicates the plot number. The number following the dash indicates the treatment number. For example, 111-5 identifies that treatment 5 is assigned to plot 111. Identifiers beginning with 1, 2, and 3 are assigned to the north, middle, and south blocks, respectively.

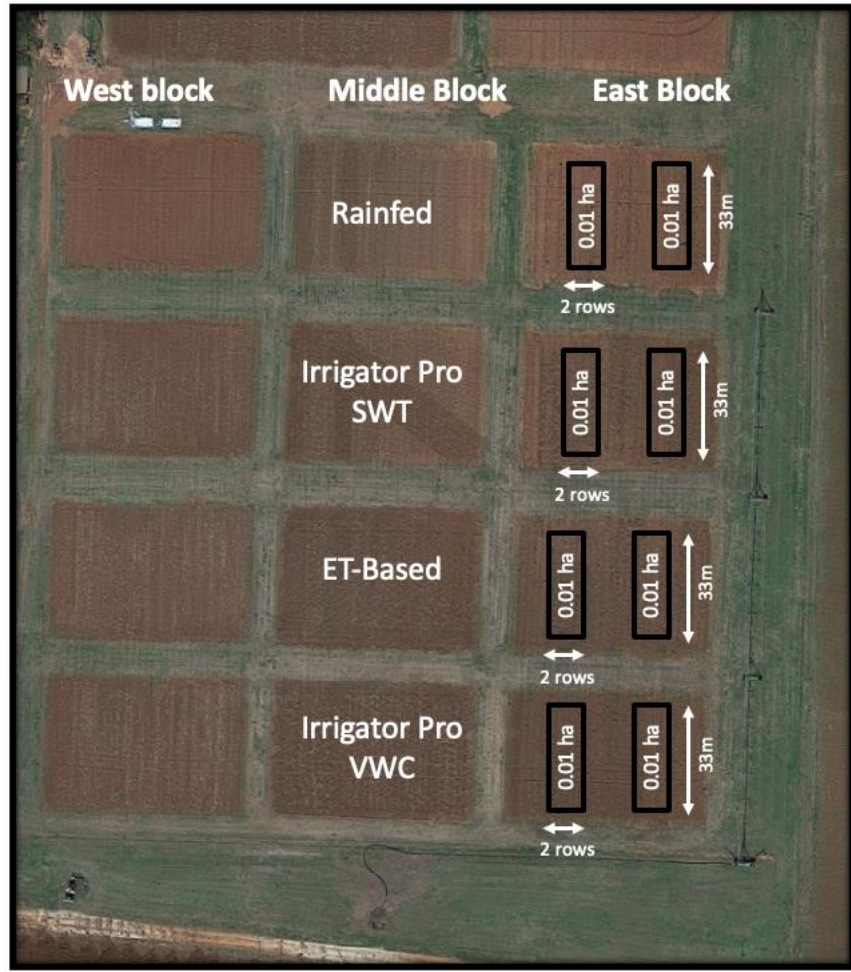


Figure 2.7. Satellite image of the HHERC field depicting the 3 blocks going from west to east. Each block consists of 4 plots. The figure shows the configuration of plots used during Year 2 in the East Block. The configuration was similar in the Middle block during Year 1.

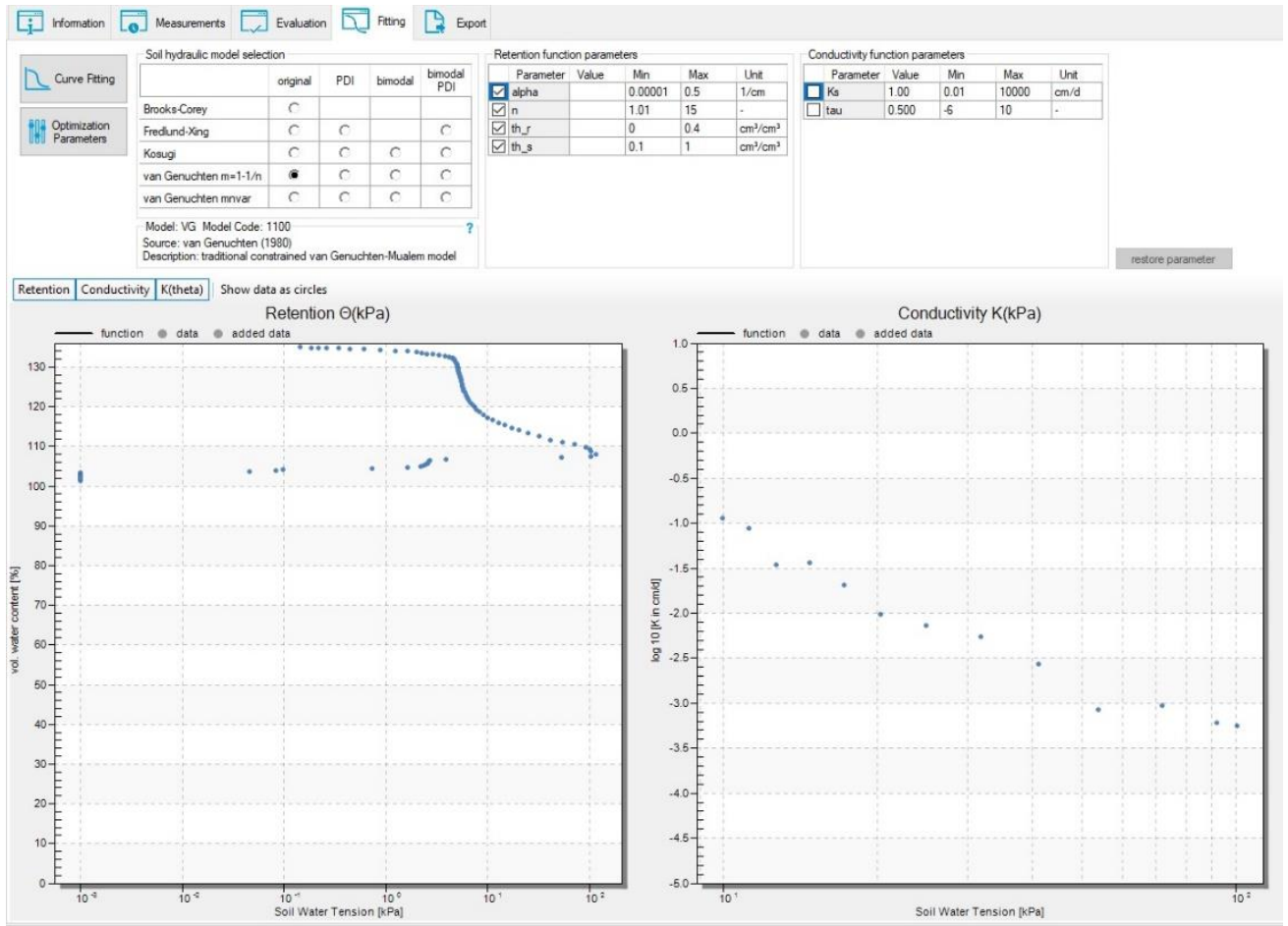


Figure 2.8. Hyprop 2 (Meter Group, WA, USA) interface during water release curve development and curve fitting using the simplified version of the Van Genuchten model.

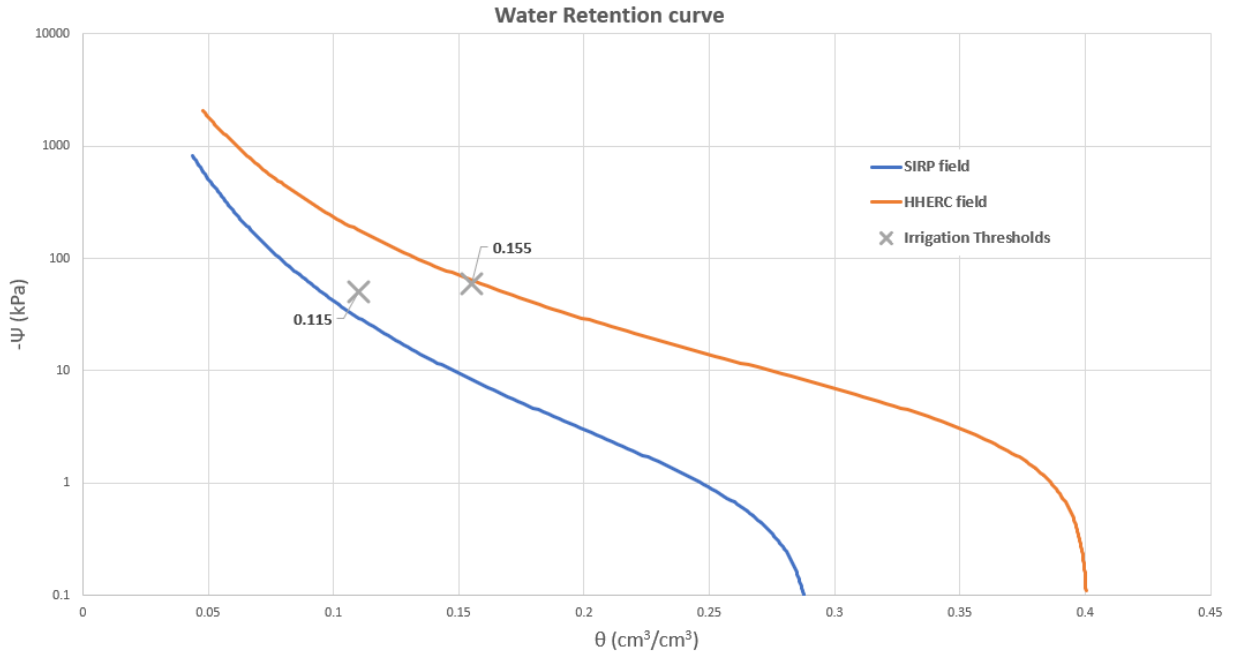


Figure 2.9. Fully developed soil moisture curves for SIRP and HHERC sites from samples at 0.2m depth. The average irrigation threshold for SIRP and HERC soil types was 11.5% and 15.5%, respectively.

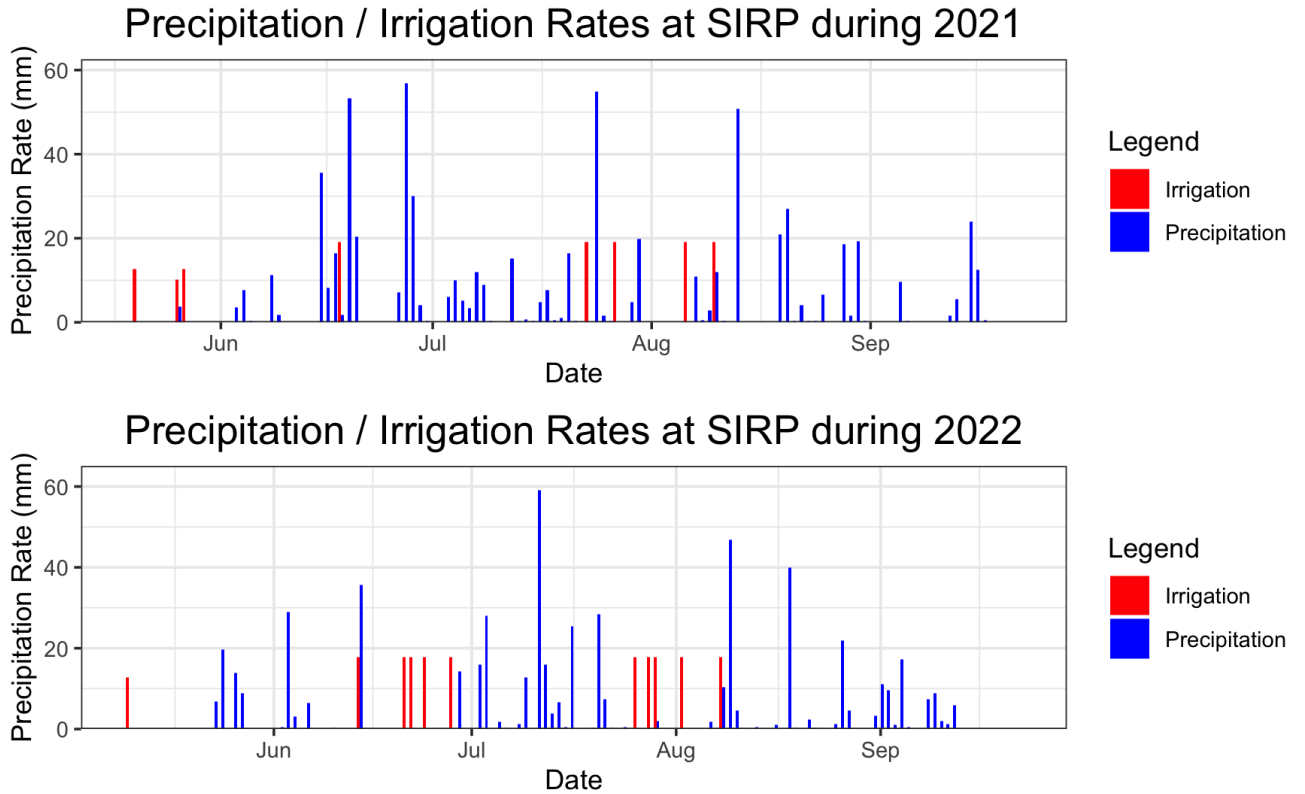


Figure 2.10. Precipitation and irrigation at SIRP during the 2021 (top) and 2022 (bottom) growing seasons. Red bars depict the days when at least one treatment was irrigated. The initial irrigation event (13mm) was used to activate herbicides and promote germination. All other irrigation events were 19mm.

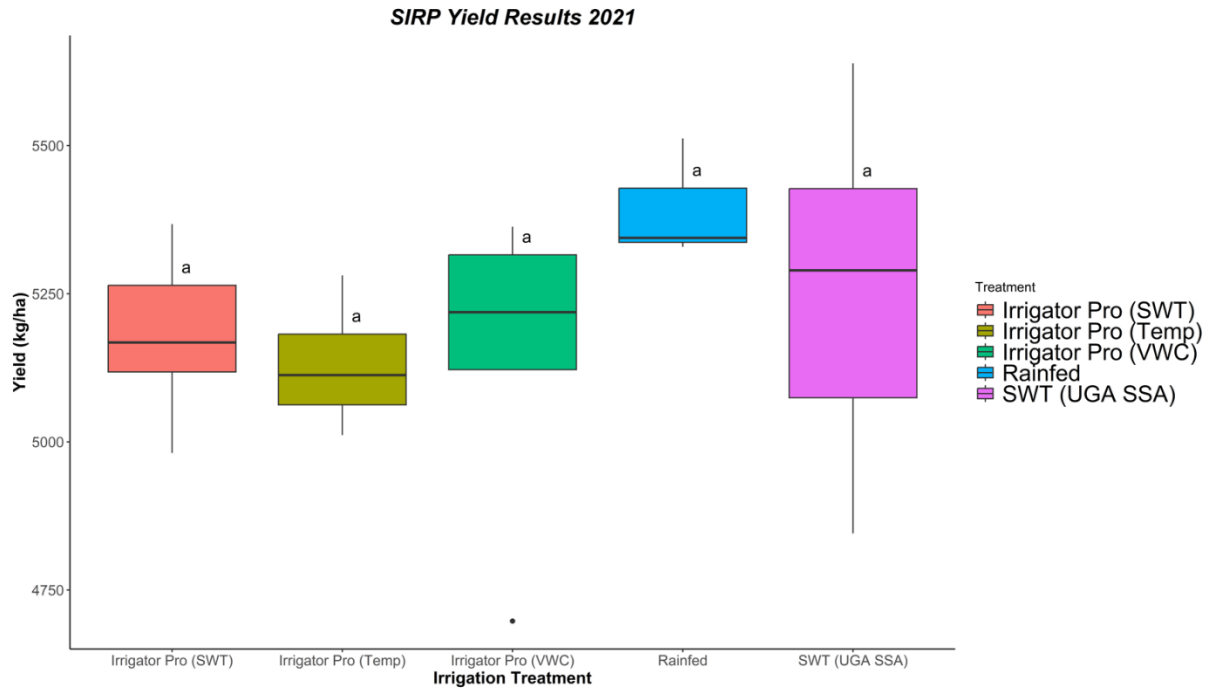


Figure 2.11. Yield results of the 2021 study at SIRP. Tukey’s HSD test was used for comparison of means by treatment ($\alpha = 0.05$).

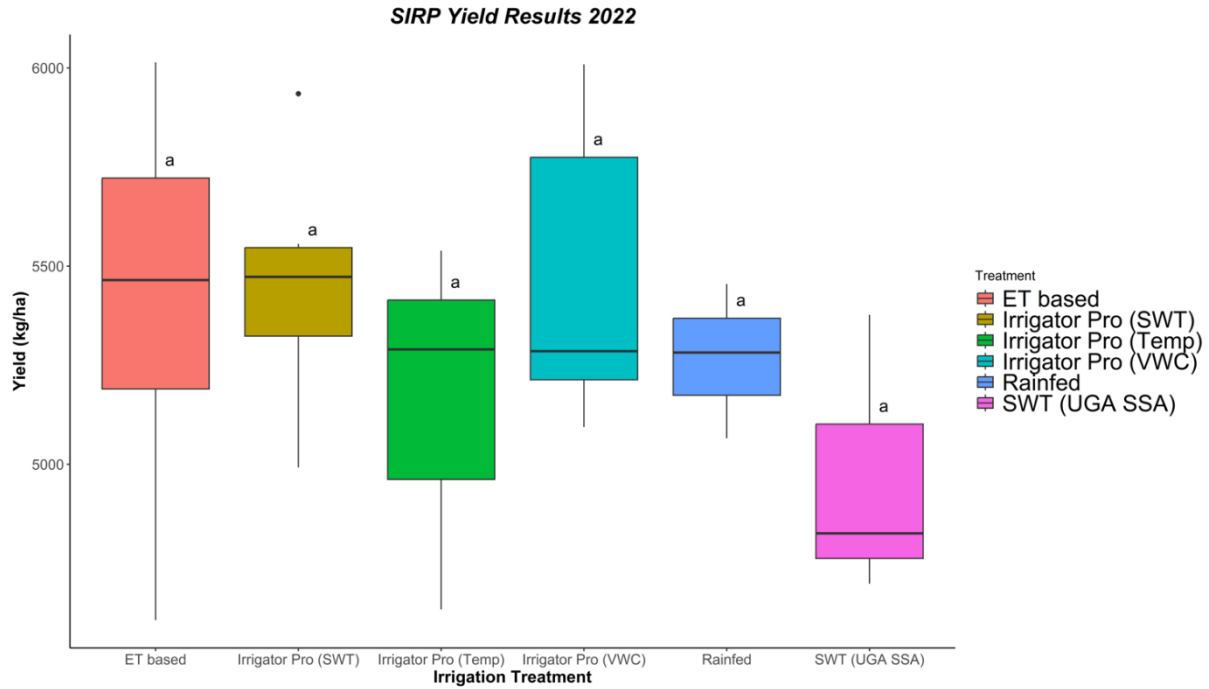


Figure 2.12. Yield results of the 2022 study at SIRP. Tukey’s HSD test was used for comparison of means by treatment ($\alpha = 0.05$).

Precipitation / Irrigation Rates at HHERC during 2022

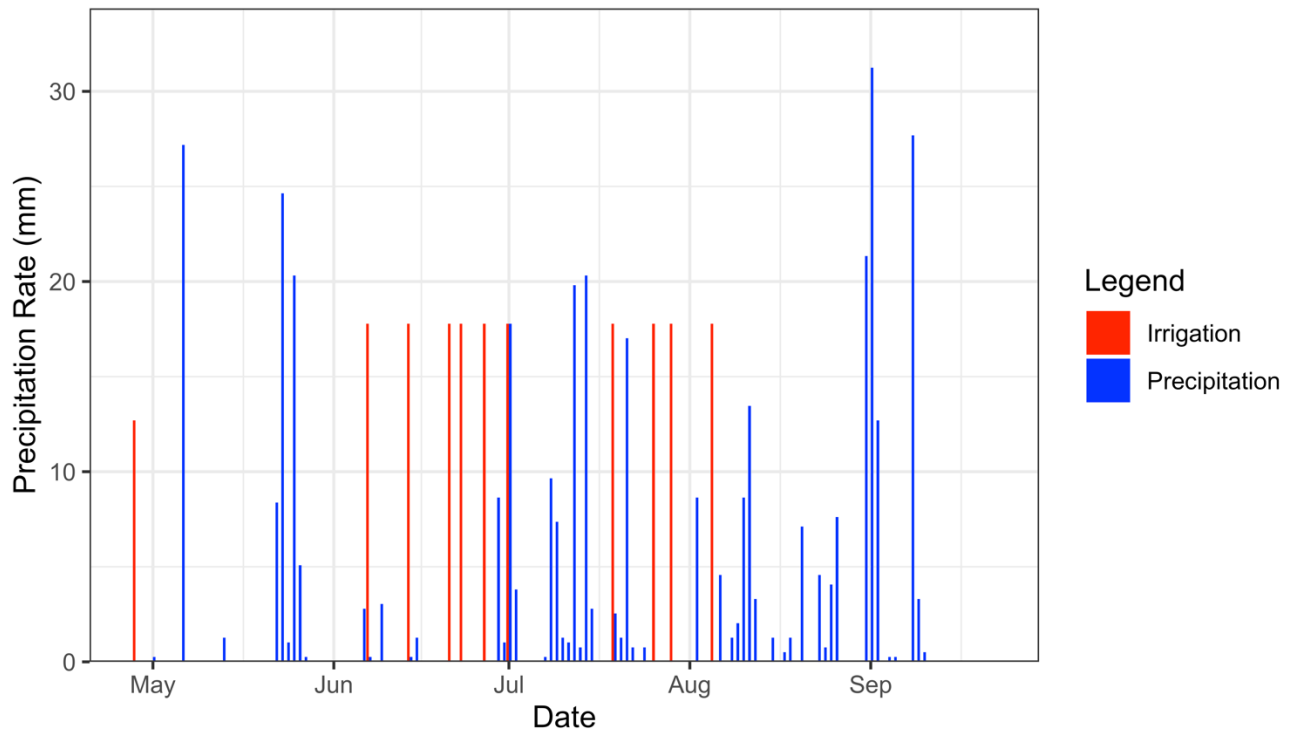


Figure 2.13. Precipitation and irrigation at HHERC during the 2022 growing season. Red bars depict the days when at least one treatment was irrigated. The initial irrigation event (13mm) was used to activate herbicides and promote germination. All other irrigation events were 19mm.

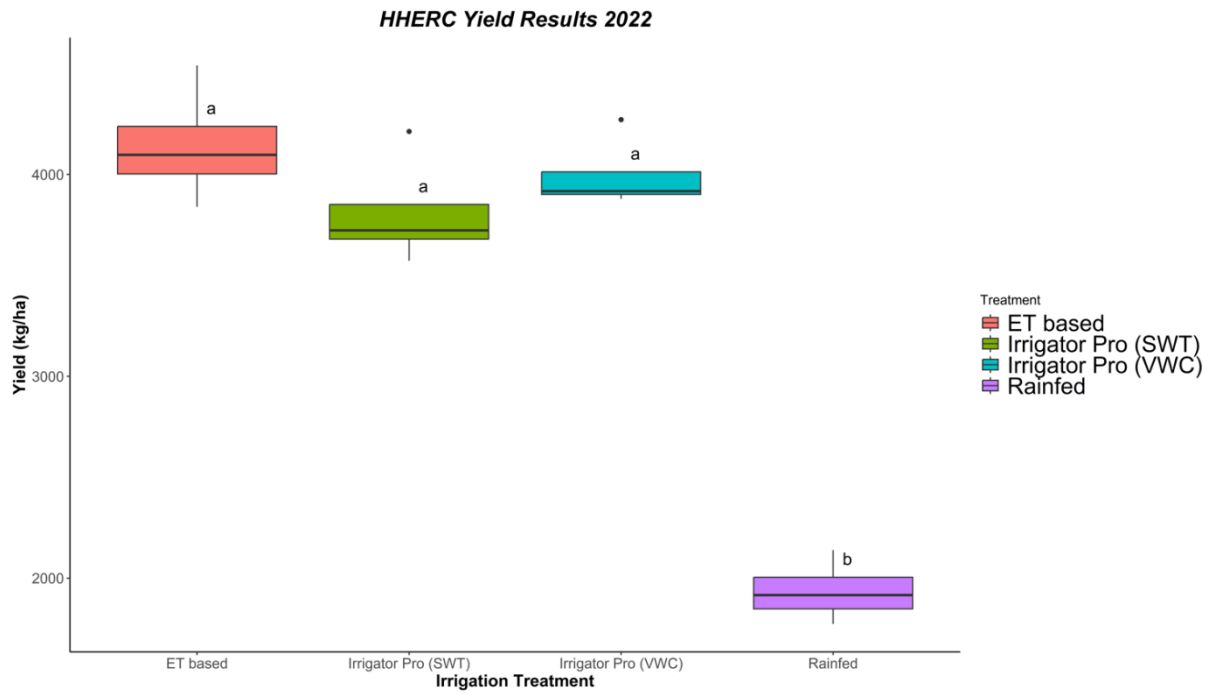


Figure 2.14. Yield results of the 2022 study at HERC. Tukey's HSD test was used for the comparison of means by treatment ($\alpha = 0.05$).

²CHAPTER 3

AN EVAPOTRANSPIRATION-BASED MODEL FOR SCHEDULING IRRIGATION IN PEANUT²

² Gallios, I., Butts, C., Porter, W., Perry, C., Pilon, C., and Vellidis, G. To be submitted to *Smart Agricultural Technology*

Abstract

The suite was of SmartIrrigation Apps for Scheduling Irrigation (SI Apps) is a group of models that estimate daily crop water use (ET_c) using the FAO-56 method and provide notifications to users when irrigation is needed. The work reported here developed an ET_c-based peanut model (SI Peanut) that was incorporated into the existing SmartIrrigation CropFit App. The model includes a localized growing degree day (GDD) -based crop coefficient (K_c) curve and operates on a daily basis. It utilizes meteorological data from a variety of sources to calculate ET_c and determine daily precipitation and to estimate crop phenology. These are then used as inputs to a daily root zone soil water balance calculation. Data from irrigation scheduling field trials conducted at two locations in southern Georgia, USA, in 2021 were used to develop the K_c curve. SI Peanut was then compared to other advanced irrigation scheduling tools at both locations during 2022. The results from these trials indicated that SI Peanut performed at least as well as sensor-based irrigation scheduling methods. However, this assessment is based on one year of data and additional testing at the plot and field scale is needed to confirm these findings. Based on the 2022 results, there was enough confidence in the performance of the SI Peanut model that it was incorporated into a beta-testing version of the SI CropFit App and made available to select growers and researchers for evaluation during the 2023 growing season.

3.1. Introduction

Peanut (*Arachis hypogaea*) production is a crucial industry in the southeastern United States (Sharon P. Kane 2023) and Georgia is the largest peanut-producing state. In 2022, Georgia produced 52% of the country's crop or 0.66 million Mg on 275,200 ha with a combined statewide rainfed and irrigated mean yield of 4,770 kg ha⁻¹. Between 2018 and 2022, mean yields ranged from 4,682 to 4,929 kg ha⁻¹ (Georgia Peanut Commission 2022; "USDA/NASS Georgia Agriculture Overview" 2022). Peanuts are grown in 77 counties in Georgia resulting in a USD2.2 billion industry in the state (Georgia Peanut Commission 2022). Between 45 and 55% of the peanut acreage is irrigated (UGA Extension System 2022). The U.S. Geological Survey (USGS) estimates that three-quarters of the state's freshwater withdrawals are used for irrigation (Dieter et al. 2018; USGS 2015).

Although peanut appears to be moderately adaptive to water-deficit conditions and has lower water requirements than many crops (Reddy, Reddy, and Anbumozhi 2003), it benefits greatly from irrigation, with irrigated yields typically outpacing rainfed pod yields in Georgia during dry years by 2000–3000 kg ha⁻¹ (Soler 2007). This is because water stress during the crop's reproductive stage when water use by the crop is highest, results in yield losses. However, Kottapalli et al. (2009); Porter (2016); Wright, Hubick, and Farquhar (1991), and Lamb et al. (2007) have all shown that overirrigation in peanuts suppresses yield as well.

More frequent droughts during the growing season (Kottapalli et al. 2009) are pushing growers in Georgia to steadily invest in irrigation systems with irrigated acreage increasing from 287,700 ha in 2003 to 470,700 ha in 2018 according to the latest irrigation survey ("USDA/NASS Georgia Agriculture Overview" 2022). Escalating water demands for competing uses and steady declines in some aquifers used for irrigation in Georgia make a compelling case for more efficient irrigation scheduling strategies.

3.2. Literature Review

3.2.1. *Evapotranspiration and Irrigation Scheduling*

Water loss through evaporation from the soil surface combined with plant transpiration is defined as evapotranspiration (ET) (Allen 2005). The method known as ET-based irrigation scheduling (ETIS) employs crop-specific water use characteristics and meteorological data to determine the crop's daily water requirements (Allen and FAO 1998). By tracking daily water requirements, growers can use ETIS methods to decide when and how much to irrigate.

The parameters that affect ET are divided into three major categories: meteorological conditions, crop physiology, and management parameters. The first include solar radiation, relative humidity, air temperature, and wind speed. Crop factors which affect ET include the crop and cultivar, planting density, and phenological growth stage (Allen and FAO 1998). The third group of conditions which can impact ET are soil type, fertility, salinity, and the grower's soil management.

The United Nations Food and Agricultural Organization (FAO) developed a sequence of ET-based irrigation scheduling protocols (Jensen et al. 1990) most recently summarized in a document known as FAO-56 (Allen and FAO 1998). In the FAO-56 method, daily crop water use is estimated as shown in Eqn. (3.1.).

$$ET_c = E_{To} \times K_c \quad (3.1.)$$

Where,

E_{Tc} = daily crop water use (mm day^{-1}),

E_{To} = reference ET (mm day^{-1}) calculated using the Penman- Monteith equation, and

K_c = a crop coefficient (unitless).

E_{To} can be calculated using meteorological data which in general are readily available for the

southeastern U.S. from a variety of sources including state weather station networks. To calculate ET_c , a K_c that applies to that day is needed. For annual crops, K_c changes with the phenological stage. K_c typically begins with small values after emergence and increases to 1.0 or above when the crop has the greatest water demand. This typically occurs during the reproductive stage. K_c decreases as crops reach maturity and begin to senesce. Over the years FAO developed K_c values for the phenological stages of many crops and published them as tables (Jensen et al. 1990). Table 3.1. shows FAO recommended K_c values for three peanut phenological stages while Table 3.2. shows the expected length of those periods in different geographic regions. Since FAO-56 does not include crop coefficient values for the southeastern United States, Figure 3.1. demonstrates the K_c curve through the season on a daily interval for West African climates. The horizontal axis depicts the Days After Planting (DAP) according to Table 3.2., while the vertical axis depicts the values of K_c through the season according to Table 3.1. Since there is no specific K_c value during peanut development, this stage has been estimated as the daily increase in water needs for a development period of 35 days.

These tables were the first step to developing ET-based irrigation scheduling tools for peanut. However, these K_c values were single values for entire phenological stages and did not accurately represent the progression of K_c during plant growth. Consequently, agronomists began experimentally developing K_c curves that capture daily changes in the K_c (Allen and FAO 1998).

Figure 3.2. shows a continuous K_c curve developed for peanuts and compared to FAO-56 and FAO-33 estimated K_c values for each phenological stage (Bandyopadhyay, Mallick, and Rana 2005). The figure also includes FAO-33 (Allen et al. 1996; 1998) and FAO-56 (Allen et al. 1996; 1998) estimates of K_c for different phenological stages. For the first 1-2 weeks the $K_{c_{init}}$ is close to 0, but as the first vegetative stage comes to an end and the plant is in its developing period,

water needs are increasing. The K_c curve reaches its highest value of $K_{c_{mid}} = 1.15$ a few days after fruit initiation begins (Allen and FAO 1998). Knowing the Fruit Initiation Day (FID) is important for irrigation scheduling because water demands reach their maximum values after this threshold and water stress during this stage can adversely affect crop yield. Lately, new tools have been developed to better identify phenological transitions, so that growers can plan their irrigation accordingly (Jensen et al. 2016). During pod development, daily water use (DWU) can reach values of 5 to 7.5 mm day⁻¹ (0.21 to 0.29 inches day⁻¹). During pod maturation, DWU is 1.5 – 3 mm day⁻¹ (0.07-0.14 inches day⁻¹) (Sorensen and Butts 2014). This decrease in DWU is reflected in the K_c curve. The FAO-56 $K_{c_{end}}$ value is close to 0.6 (Figure 3.1.) as the crop reaches maturity and harvest (Shavkat Kenjabaev et al. 2020).

A study conducted in eastern India showed that the peanut K_c curve published by FAO must be modified to account for regional climate and soils. They found that the best irrigation scheduling resulted when the K_c curve was associated with accumulated heat units commonly referred to as growing degree days (GDDs) and leaf area index (LAI) (Bandyopadhyay, Mallick, and Rana 2005).

University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) released a full guide for southeastern peanut growers within which they provide irrigation scheduling guidelines (Wright et al. 2020). The guidelines include a growing season water use curve that was developed from several years of studies. UF/IFAS also developed an online irrigation scheduling tool called PeanutFARM (Rowland et al 2015; Migliaccio, T Morgan, et al. 2015). This tool uses the FAO-56 method and accumulated GDDs to determine crop growth stage and estimate crop water needs based on the water use curve developed by Wright et al. (2020). ETo is calculated with data from the closest meteorological station. PeanutFARM has been commercialized and is now primarily

used to manage peanut development and maturity by tracking adjusted growing degree days (aGDD).

3.2.2. SmartIrrigation Apps for Irrigation Scheduling

Beginning in 2012, a group of University of Georgia (UGA) and University of Florida (UF) researchers began developing a suite of irrigation scheduling apps for a variety of crops. The suite was called [SmartIrrigation Apps for Scheduling Irrigation](#) (SI Apps) and includes horticultural and agronomic crops (Migliaccio et al. 2015; Vellidis et al. 2016; Migliaccio et al. 2015; Miller et al. 2018; Ayankojo et al. 2018). The apps all estimate daily crop water use (ET_c) using the FAO-56 method described earlier. The SI Apps pull meteorological data from national data sets, state-operated weather station networks, and on-farm automated rain gauges. The UGA team developed the Cotton and Soybean SI Apps and co-developed the Corn SI App. Plot studies have demonstrated that scheduling irrigation with the agronomic SI Apps results in irrigation water use efficiency (IWUE) gains of up to 50% and yield gains of up to 15% when compared to standard checkbook scheduling methods most often used by growers in the Southeast (Migliaccio, Morgan, et al. 2015).

The agronomic crop apps use a soil water balance model. The model uses daily ET_c, soil parameters, precipitation, and irrigation applications to estimate a daily root zone soil water deficit (RZSWD) in terms of percent and inches of plant available soil water and provides these two pieces of information to the user. Plant available soil water is defined as the water held by the soil matrix between field capacity and the wilting point. A 50% RZSWD or depletion of 50% of plant available soil water is a commonly accepted irrigation threshold for agronomic crops.

For all the agronomic crops in the SmartIrrigation suite, changes in phenology and associated changes in K_c are driven by GDDs. In the models, plant available soil water is a function of the

soil's plant available water holding capacity and current rooting depth. As the plant rooting system grows, the depth of the profile from which the plant can extract water also increases. In the Cotton App, for example, the initial rooting zone depth is 0.15 m (6 in) and increases by 7.5 mm day⁻¹ (0.3 in day⁻¹) until it reaches a maximum depth of 0.75 m (30 in). At emergence, the soil profile from 0 to 0.75 m is assumed to be at 85% of the maximum plant available soil water holding capacity. In the model, today's plant available soil water is calculated by subtracting yesterday's ETc from yesterday's plant available soil water and adding any precipitation or irrigation measured. All these parameters are used to calculate RZSWD in inches and % RZSWD.

The Corn, Cotton, and Soybean Apps were recently consolidated into the SI CropFit App which was publicly released in 2023. The SI CropFit App includes several new features including using USDA-NRCS SSURGO data to extract soil water holding capacity for individual fields (Vellidis et al. 2021).

Despite the obvious advantages offered by using ETIS for irrigation scheduling and its availability on easy-to-use platforms such as the SI Apps, the adoption of ETIS among growers has been relatively low. Adoption barriers include knowledge gaps and perception of complexity (Irmak et al. 2013). Another obstacle is the need to use different scheduling tools for different crops making the process unnecessarily cumbersome and complex.

3.3. Objectives

The overall goal of this research project was to develop easy-to-use irrigation scheduling tools for peanut. The specific objective of the work reported here was to develop an ET-based irrigation scheduling tool for peanut similar to that of the agronomic SI Apps and to integrate the new peanut tool into the SI CropFit App.

3.4. Materials and Methods

The project consisted of a data collection, data analysis/model development component, and field verification. Data collection consisted of field and laboratory work. The laboratory and data analysis/model development components were conducted at the UGA Tifton campus.

The field work was conducted at UGA's C.M. Stripling Irrigation Research Park (SIRP) located near Camilla, GA (31.279345, -84.299799) and the USDA-ARS National Peanut Research Laboratory's Hooks-Hanner Environmental Resource Center (HHERC) near Sasser, GA (31.733409, -84.394847) during the 2021 and 2022 growing seasons. These two sites were selected because they were both in the heart of Georgia's peanut production region and represented two major soil types on which peanuts are grown in Georgia (Figure 3.3.).

In 2021, the field work consisted of leveraging an ongoing peanut irrigation scheduling study with five irrigation scheduling treatments at SIRP to collect data on DWU of peanut in the growing environment of southern Georgia. The ongoing study at SIRP was supplemented by a scaled-down version of the study conducted at HHERC. DWU values were then used to modify the peanut FAO-56 Kc curve shown in Figure 3.1. Prior to the 2022 growing season, the modified Kc curve was integrated into a spreadsheet version of the agronomic SI Apps that is hereafter referred to as SI Peanut. The irrigation scheduling study was repeated in 2022 at SIRP and HHERC and the performance of SI Peanut was evaluated as an additional irrigation scheduling treatment.

3.4.1. Soil Moisture Sensors

Two brands of soil moisture sensor systems were used in the study to trigger irrigation and to estimate DWU – the UGA Smart Sensor Array (UGA SSA) and Sentek (Sentek Sensor Technologies, Australia). The UGA SSA is an automated wireless soil moisture sensing system developed at UGA that measures soil moisture in terms of SWT (the absolute value of matric

potential) in units of kPa (Vellidis et al. 2008; Liakos et al. 2017). A UGA SSA node consists of a probe with Watermark (Irrometer, Riverside California, USA) sensors at depths of 0.10, 0.20, and 0.40 m (4, 8, 16 in), a thermocouple that measured soil temperature at 0.10 m (4 in), and an electronics package that transmitted that data to a cloud server. UGA SSA nodes were installed in all 27 plots for monitoring purposes. Only those installed in the plots of two of the treatment described below were used for irrigation scheduling.

Volumetric water content (VWC) was measured with Sentek 0.6 m (24 in) probes with sensors at depths of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m (4, 8, 12, 16, 20, 24 in) at 30 minute intervals and data were transmitted to a cloud server using AgSense telemetry (AgSense, Huron, SD). Sentek probes were installed in the treatment in which irrigation scheduling was triggered by VWC. Sentek probes measure temperature at all six depths.

3.4.2. Irrigation Scheduling Treatments

Five irrigation scheduling treatments and a rainfed treatment were used in this study. All five scheduling treatments [SWT (UGA SSA), Irrigator Pro (VWC), Irrigator Pro (Temp), Irrigator Pro (SWT), SI Peanut] were used at SIRP while three were used at HHERC due to less available area [Irrigator Pro (VWC), Irrigator Pro (SWT), SI Peanut]. SI Peanut was used only in 2022. The following paragraphs briefly describe the treatments.

SWT (UGA SSA) The irrigation triggering process involved the application of SWT (Soil Water Tension) thresholds based on the Porter method, as described by Porter et al. (2015). This method utilizes SWT data obtained from UGA SSA loggers, which measure soil water tension at three different depths. Equation 3.2. is employed to estimate the availability of water in the soil profile based on these SWT measurements. To account for the spatial distribution of the peanut crop's rooting system at different phenological stages, a weighting factor (α , β , and γ) is applied to the

sensor readings, with the magnitude determined by the depth of the sensor. The weighting factors are adjusted based on the accumulated heat units or growing degree days (GDDs) to accurately reflect the crop's growth stage. Each morning at 07:00, the average weighted SWT values from each plot are calculated, and this average SWT value is compared to the irrigation threshold of 45 kPa to determine if irrigation is required for the treatment (Porter et al. 2015).

$$\textit{Weighted Average SWT} = \alpha * \textit{SWT}_{0.1\text{m}} + \beta * \textit{SWT}_{0.2\text{m}} + \gamma * \textit{SWT}_{0.4\text{m}} \quad (3.2.)$$

Irrigator Pro (Temp). Irrigator Pro is a public domain irrigation scheduling tool developed by USDA Agricultural Research Service (ARS) National Peanut Research Laboratory (NPRL) beginning in the 1990s (Lamb et al. 2007). The original version of the tool utilizes min/max soil temperature, ambient temperature, and precipitation to provide yes/no irrigation decisions for peanuts. It is hereafter referred to as Irrigator Pro (Temp). In this study, temperature data were acquired from the thermocouple on the UGA SSA probes. Irrigation was triggered when the maximum soil temperature measured at 0.1m depth exceeded 29.5° C (85° F) for 3 consecutive days (Davidson, Lamb, and Sternitzke 2000). Irrigator Pro includes a Fruit Initiation Day (FID) tool, which employs on-field phenological observations to determine the crop growth stage. The user inputs the number of reproductive units and the model estimates the FID and the current maturation stage of the plants.

Irrigator Pro (SWT) More recently scientists at NPRL developed a sensor-based version of Irrigator Pro that automates the data collection process. This version allows either manual data entry or automated entry of SWT data from sensors installed at three depths. In this study, data from UGA SSA were collected from on-field sensors and were automatically used to populate

Irrigator Pro in order to provide irrigation decisions.

Irrigator Pro (VWC). Gallios et al. (2023) developed another version of Irrigator Pro that incorporated VWC (capacitance) sensors as an automated data entry solution for the tool. In this study, data from Sentek probes were used to populate Irrigator Pro.

Rainfed. This treatment served as the control. Irrigation was applied only to promote germination and to activate herbicides.

SI Peanut. Data collected during 2021 from SIRP and HHERC using the treatments described above were used to experimentally modify the FAO peanut Kc curve into a GDD-based Kc curve for the growing conditions of southern Georgia. During 2022, the new Kc curve was integrated into a spreadsheet version of the agronomic SI Apps hereafter referred to as SI Peanut and used to schedule irrigation at SIRP and HHERC.

3.4.3. SI Peanut Development

Data collection and wrangling

Following the 2021 growing season, VWC data from six plots at SIRP and 2 plots at HERC irrigated using VWC thresholds [Irrigator Pro (VWC)] were used to calculate DWU. These data were visualized in form of time-series graphs of VWC (Figure 3.4.) and temperature. The daily change in VWC (Δ VWC) was estimated by subtracting today's VWC from yesterday's VWC during the drying cycle of the graphs. Sentek probes come from the factory calibrated for a generic, medium-range soil. Because of this, they do not accurately measure field capacity or wilting point unless calibrated with site-specific values. However, the embedded VWC sensors are very precise and thus difference between individual VWC measurements is accurate. Consequently, it was not necessary to calibrate each probe for local soil texture. Instead, the factory calibration was used, which makes it easier for the end user to use generic type sensors that can operate to every soil

type and avoid extra time and possibly cost.

The ΔVWC calculation was performed for sections of the time-series graphs with optimal conditions for these calculations. When VWC is increasing rapidly because of irrigation or precipitation, it is difficult to estimate ΔVWC resulting from crop water use. Optimal conditions for estimating ΔVWC occur when VWC is decreasing due to extraction by the roots and the soil moisture is between field capacity and the wilting point. As soil moisture decreases and approaches the wilting point, ΔVWC begins to decrease because soil water availability becomes limiting. The rationale for this is that this is the period during which daily crop water use is at its maximum because of the availability of water in the soil profile to be used by the plant roots. When the slope of the graph begins to decrease, this indicates that daily crop water use is declining because the remaining soil water is strongly attached to soil particles, and consequently becomes less available to the plants' roots. Identifying the beginning and the end of these optimal periods is typically done by using lines tangential to the VWC curves to identify the critical inflection points. To simplify the processes of identifying the optimal periods, in this study, VWC data from within an 18 h window following precipitation events exceeding 10 mm or any amount of irrigation were not used. For the remaining data record, DWU calculations were performed over 24 h periods (Figures 3.5., 3.6.). A model was developed using Python to rapidly wrangle the data and estimate DWU for each of the six sensors in the Sentek probe. Each sensor was assigned a soil depth of 101.6 mm (4 in) that corresponded to the soil profile interval between sensors. The total soil depth used was 609.6 mm (24 in). The model then calculated daily ET_c using Eqn. 3.3. VWC data were in units of % that were converted to units of depth of water (mm).

$$ET_c(\text{mm}) = DWU = \frac{\sum_i \{(-VWC_i + VWC_{i+1}) * 101.6 \text{ (mm)}\}}{100} + IR(\text{mm}) + PR(\text{mm}) \quad (3.3.)$$

where:

ETc = daily crop Evapotranspiration in mm.

VWC_i = volumetric water content on the day of the calculations in % for each depth.

VWC_{i-1} = volumetric water content the day before the calculations in % for each depth.

IR = Amount of irrigation that has been applied during the last 24 h in mm.

PR = Amount of precipitation that has occurred during the last 24 h in mm.

Because of the 18 h filter, ETc values were not available for every day of the growing season. Once ETc values were calculated, the model used an Application Programming Interface (API) to access meteorological data (minimum and maximum temperature, solar radiation, precipitation, wind speed) from Georgia Weather Network weather stations located at SIRP and HERC. These data were used to calculate corresponding ETo values. The final step of this model used Eqn. 3.1. to calculate the crop coefficient (Kc) value for each day in the growing season for which ETc values were available.

Crop coefficient curve development

Daily Kc values from SIRP and HERC were combined to develop a preliminary localized Kc curve for peanut using Days After Planting (DAP) as the independent variable (x-axis) (Figure 3.7.) that was similar to the experimentally derived FAO-33 and FAO-56 Kc curves shown in Figure 3.2. A biquadratic equation (Eqn. 3.4.) was fitted to the data with a coefficient of determination (R-squared, R²) value of 0.9809.

$$y = 6E-08x^4 - 2E-05x^3 + 0.0015x^2 - 0.0298x + 0.5359 \quad (3.4.)$$

The Kc curve was simplified into a trapezoidal-shaped curve with linear segments (Figure 3.8.) to

match the Kc curves used in the other SI Apps and those generally used in ETIS models (Migliaccio, T Morgan, et al. 2015; Vellidis et al. 2016; Migliaccio, Morgan, et al. 2015; Miller et al. 2018; Miller, Vellidis, and Coolong 2018; Ayankojo et al. 2018). The trapezoidal curve matched the general shape of the curve proposed by Allen in the FAO-56 guidance (Figure 3.1.).

The final step in the Kc curve development was to replace DAP with GDDs as the independent variable. This made Kc dependent on the crop's phenological development rather than the checkbook and better accounted for environmental conditions affecting crop development.

The *degdays* package in R Studio (Posit, Boston, MA, USA) was used to calculate accumulated GDDs from meteorological data using the single sine method with a horizontal cutoff (Roltsch et al. 1999). This method utilizes the daily low and high temperatures to generate a sine wave by assuming that the minimum and maximum temperatures that occur within 24 hours represent the lowest and highest points of that wave respectively. Additionally, temperatures that surpass the upper threshold are reduced to the threshold value. The area below the curve and above the low threshold represents accumulated GDDs. Calculated GDDs were then paired with the corresponding DAPs to create the final version of the Kc curve shown in Figure 3.9. Crop growth stages were associated with accumulated GDDs and were paired to DAP based on phenological observations (number of pins, pegs, pods, and distance till lapping) made during the 2021 growing season and compared to those made by (Boote 1982) and to the distribution of crop water requirements reported by (Porter et al. 2015). Table 3.3. presents the developed relationships between, GDDs, Kc, and DAP. It should be noted that the relationship for DAP is valid only for the 2021 growing season and is shown for comparison purposes, along with the corresponding GDD thresholds for each crop growth stage. The GDD – Kc relationships shown in Table 3.3. were then integrated into the SI Peanut app.

SI Peanut coding

Prior to the 2022 growing season, the Kc curve is incorporated into a spreadsheet version of the soil water balance model of the agronomic SI Apps described earlier. The spreadsheet was automated so that it pulled daily meteorological data from the Georgia Weather Network's API to calculate ETo, and record measured precipitation, calculate daily ETc and perform the water balance and RZSWD calculations. Figure 3.10. presents a flowchart of SI Peanut's processes and the necessary input information that is needed for the model to run. The spreadsheet version was used to schedule irrigation for the SI Peanut treatment at SIRP and HERC during the 2022 growing season. Following the 2022 growing season, the SI Peanut algorithms were coded into the peanut module of the existing SI CropFit App and released to selected users for beta testing during 2023 growing season.

Another valuable tool that was integrated into the peanut module of CropFit is the Fruit Initiation Date (FID) estimator, which refers to the date when the initial burst of blooms occurs. These result in the formation of fruiting structures with at least 10 blooms per plant (Davidson et al. 1998). This tool has been widely utilized by growers and researchers to estimate the maturity of peanuts and determine the optimal harvest time. Butts et al. (2020) incorporated this estimator into the Irrigator Pro as a benchmarking feature, enabling the tracking of accumulated Growing Degree Days (GDDs) in both the field and the app. By assessing the number of reproductive components such as pins, pegs, and pods, the estimator can accurately determine the current growth stage of the crop. It is important to note that for an accurate assessment of fruit initiation, the total count of these reproductive components should exceed six. By utilizing the FID calculator, the peanut module of SI CropFit will compare the accumulated GDDs in the model with the on-farm conditions, employing simple phenological measurements that do not require specialized knowledge or extensive time investment.

Figure 3.11. presents screen captures of the peanut module of SI CropFit, showcasing various stages of operation, including the decision-making screen and examples of notifications that users receive from the application.

3.4.4. *SIRP Field Work*

The fieldwork at SIRP was conducted in a 4 ha. research field known as the Newton Lateral (31°16'46.24"N, 84°17'59.59" W). The field was divided into three blocks (North, Middle, and South) with each block containing 27 plots (Figure 3.12.). The plots are each 14.5 × 14.5 m (48 × 48ft or 48ft long × 16 rows wide). The eight middle rows in each plot are used for data collection and the four rows on either side of the middle eight serve as buffers. The Georgia-06G cultivar was planted and harvested on May 19th and October 5th, respectively, in 2021 and May 10th and September 26th in 2022.

The soil in the Newton Lateral field is classified as a Lucy Loamy Sand with available water holding capacity (WHC) of 0.08 cm cm⁻¹ with 0 to 5% slope. Soil texture varies slightly across the field with 83% Sand, 10% Silt, and 7% Clay in the South block to 86% Sand, 8% Silt, and 6% Clay in the North block. The field is irrigated with a variable-rate-enabled lateral irrigation system which can apply a unique water application rate to each of the 81 plots. A cotton-peanut-corn rotation is maintained with crops rotating from north to south each year. All crops were planted into a rye cover crop using strip tillage following burndown with glyphosate. During Year 1 of the project, peanuts were in the Middle Block, and during Year 2 in the South Block.

The experimental design utilized a randomized complete block design (Figure 3.13.). The 27 plots in each block were divided into nine treatments with three replicates each. Five irrigation scheduling treatments and a rainfed treatment were evaluated. Table 3.4. shows the treatments assigned to each plot for 2022. Because six treatments were evaluated and nine treatment areas

were available, the Irrigator Pro (VWC), Irrigator Pro (SWT), and SI peanut treatments were each assigned two treatment areas allowing for 6 replicates of those treatments. Irrigation was triggered separately for each treatment and the plots were irrigated accordingly by the VRI-enabled lateral. Approximately 19 mm (0.75 in) of water was applied with each irrigation event.

3.4.5. HHERC Field Work

Hooks Hanner Environmental Resource Center (HHERC or HERC) is located near Sasser, GA (31°43'54.5"N 84°23'39.3" W) and is administered by the USDA Agricultural Research Service (ARS) National Peanut Research Laboratory. The field that was utilized in this research is separated into three blocks comprising four plots each, three of which are irrigated, and one is rainfed (Figure 3.14.). Strip tillage was employed to plant crops into a rye cover crop after burndown with glyphosate. During the Year 1 of the study (2021), peanuts were grown in the Middle Block, and during Year 2 (2022) in the Eastern Block. The AU-NPRL-17cultivar was planted and harvested on May 4th and harvested on September 24th, respectively, in 2021 and April 28th and September 15th in 2022.

The soil in this field is classified as Greenville sandy clay, with a water holding capacity of 0.23 cm cm⁻¹ and a slope of 0-2%. The texture of the soil is consistent across the field, with approximately 45% sand, 12% silt, and 43% clay. A variable rate-enabled lateral irrigation system was used to irrigate the field, allowing for a unique water application rate to be applied to each of the nine plots. Similar to SIRP, a cotton-peanut-corn rotation is maintained with crops rotating from west to east every year. A randomized complete block design was employed for the experiment. The Irrigator Pro (SWT), Irrigator Pro (VWC), SI Peanut, and rainfed treatments were assessed with two replications each. As at SIRP, UGA SSA probes were employed to continuously monitor soil moisture in all plots. The Irrigator Pro (VWC) plots were fitted with Sentek probes

equipped with AgSense telemetry. Irrigation was triggered separately for each treatment, and the plots were irrigated accordingly by the VRI-enabled lateral. Because the heavier soils at HHERC had lower infiltration rates, irrigation (approximately 19mm or 0.75in) was applied in two passes to reduce runoff.

3.4.6. Yield and Statistical Analyses

The assessment of peanut yield involved the use of a bagging combine to harvest the center four rows of each plot, which were then weighed in the field. A subsample from each bag was taken to a nearby peanut buying point where measurements were taken for kernel moisture content and % foreign material. Measured mass was adjusted for % foreign material and to a common moisture content of 10%. The adjusted mass was then divided by harvested area to report yield in terms of kg ha^{-1} . To determine the effects of the treatments, a one-way Analysis of Variance (ANOVA) was conducted using R studio 2022.12.0, and Tukey's range test was employed to compare the means at a 0.05 significance level. Irrigation Water Use Efficiency (IWUE) was determined by dividing the yield by irrigation applied, and the results were reported in units of $\text{kg ha}^{-1} \text{mm}^{-1}$. Irrigation applied was the difference between total irrigation applied to the treatment minus irrigation applied at the beginning of the growing season to activate herbicides which was applied uniformly across all plots including the rainfed plots.

3.5. Results and Discussion

3.5.1. SIRP

During the 2022 growing season, SIRP received 525 mm of precipitation and irrigation was not needed except very few times (Figure 3.15.) which exceeded the approximately 457 mm of water required by a peanut crop in southern Georgia during the growing season (Porter et al 2022).

Nonetheless, there were specific time intervals in June, July, and August characterized by 10 or more consecutive days with little to no precipitation, prompting irrigation for all irrigation scheduling treatments. Interestingly, despite the recommendations from most DSTs to irrigate during these periods, the subsequent yield outcomes indicated that irrigation may not have been necessary after all. It is crucial to acknowledge that in the Southeast, irrigation serves as a supplementary source of water, and these brief periods of drought offer valuable insights into whether they can potentially result in yield losses and how to identify the crops' most vulnerable stages. Ultimately, there were no statistically significant differences in treatment yields (Figure 3.16.) including that of the rainfed treatment. This result is not unusual in southern Georgia when growing season rainfall exceeds crop demand and indicates that additional research is needed to understand the physiological response of peanut to periods without precipitation.

SI Peanut used less irrigation water than all the other irrigation treatments (Table 3.5.) and this resulted in an IWUE of $51 \text{ kg ha}^{-1} \text{ mm}^{-1}$ which was significantly higher than the other irrigation scheduling treatments. This indicates that the SI Peanut model is at least as effective as the other irrigation scheduling methods used in the study.

3.5.2. *HHERC*

HHERC received less precipitation (405 mm) in 2022, with two 10-day periods without precipitation during which irrigation was applied (Figure 3.17.). Hence, there were statistically significant differences in yield between the irrigated and rainfed treatments but not among the irrigation scheduling treatments (Table 3.6., Figure 3.18.). SI Peanut applied an intermediate amount of irrigation water (142 mm) that resulted in the second highest IWUE at this site. There were statistically significant differences in IWUE with SI Peanut and Irrigator Pro (VWC) having statistically higher IWUEs.

3.6. Conclusion and next Steps

Figure 3.19. compares the SI Peanut Kc curve to the FAO-56 guidance curve (Allen et al. 1998) to demonstrate the importance of experimentally adjusting Kc curves for local / regional environments and for using GDDs to initiate changes in Kc. The FAO-56 curve uses the DAP (top) axis while the SI Peanut curve uses the GDD (bottom) axis. The SI Peanut curve shows that in the Georgia growing environment, peanut water use increases earlier and more sharply than the FAO-56 curve, reaches a higher plateau earlier in the season, and begins to decrease earlier. However, initial and final baselines are the same.

An additional aspect to take into account is the range of applicability of the developed crop coefficient (Kc) curve. According to the guidelines provided by FAO-56, factors such as soil properties and localized microclimatic conditions can influence Kc values by up to 5%. In the context of southeastern states, the newly-developed curve exhibits an earlier increase during the development stage, while the remainder follows a similar pattern. It is important to note that this generic curve may not fully capture the variations in water requirements among different cultivars. Instead, it adopts a more generalized approach that aligns with the water needs of commonly used cultivars in the Southeastern region.

The results from the 2022 trials indicate that the SI Peanut ET-based model performs at least as well as sensor-based irrigation scheduling methods. However, this assessment is based on one year of data and additional testing at the plot and field scale is needed to confirm these findings. Based on the 2022 results, there was enough confidence in the performance of the SI Peanut model that it was incorporated into a beta-testing version of the SI CropFit App and made available to select growers and researchers for evaluation during the 2023 growing season. The SI CropFit App has significant advantages compared to sensor-based irrigation scheduling because no sensors are required to be installed after sowing and prior to harvest reducing capital and labor investments. It

also allows growers to run multiple versions of the App for the same field to account for soil differences. However, the App requires accurate precipitation data for the soil water balance model to accurately calculate RZSWDs. Precipitation data from weather stations that are not adjacent to fields or estimates from national meteorological data sets are not reliable in an environment like southern Georgia in which growing season precipitation is driven by localized convective thunderstorms. For the CropFit App to accurately calculate RZSWDs, on-farm precipitation data are needed. Because of this, the App includes options for using precipitation data from grower-owned automated rain gages (Figure 3.11c).

The goal of this project is to make the SI Peanut model with the SI CropFit App publicly available prior to the 2024 growing season. However, the SI Peanut model will continue to be evaluated and improved during upcoming growing seasons in Georgia and surrounding states. Additional internal features like the Fruit Initiation Date estimator will continue to be improved as well.

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3.8. Tables and Figures

Table 3.1. FAO recommended Kc values for peanuts (Allen 2005).

Groundnut (Peanut) Arachis hypogaea	Phenological Stage		
	Initial	Middle	End
Kc Value	0.4	1.15	0.6

Table 3.2. FAO estimated growth stage length for different geographic regions.

Groundnut (Peanut) <i>Arachis hypogea</i>	Phenological Stage				Total	Location
	Initial	Development	Middle	Late		
Duration (Days)	25	35	45	25	130	West Africa
	35	35	35	35	140	High Altitudes
	35	45	35	25	149	Mediterranean

Table 3.3. Necessary calculations for SI Peanut Kc-GDD curve where GDD_i are the accumulated GDD on the day of the calculations.

GDDs	Crop coefficient (Kc)	Estimated DAP
0-449	0.4	1
450-1449	$Kc=0.4+(0.774*(GDD_i-450)/1000)$	17-23
1450-2199	1.174	55-60
2200-2449	$Kc=1.174-(0.574*(GDD_i-2200)/250)$	95-100
2450-	0.6	120-125
	Harvest	135-145

Table 3.4. Plots assigned to each treatment during 2022 season at SIRP.

Treatment	Treatment ID	Plots			
SI Peanut	1	312-1	324-1	339-1	
Irrigator Pro (Temp)	2	311-2	328-2	338-2	
Rainfed	3	317-3	325-3	331-3	
Irrigator Pro (SWT)	4	319-4	326-4	333-4	
Irrigator Pro (VWC)	5	315-5	327-5	335-5	
SI Peanut	6	316-6	322-6	337-6	
Irrigator Pro (VWC)	7	314-7	329-7	334-7	
SWT (UGA SSA)	8	318-8	323-8	336-8	
Irrigator Pro (SWT)	9	313-9	321-9	332-9	

Table 3.5. Total yield, irrigation, and IWUE per treatment during the 2022 season at the SIRP field.

Treatment	Year (Precipitation)		
	2022 (525 mm)		
	Yield (kg ha ⁻¹)	Irrigation (mm)	IWUE (kg ha ⁻¹ mm ⁻¹)
SI peanut	5410 ^a	119	51 ^a
Irrigator Pro (Temp)	5154 ^a	137	41 ^b
SWT (UGA SSA)	4967 ^a	137	40 ^b
Irrigator Pro (SWT)	5453 ^a	137	44 ^b
Irrigator Pro (VWC)	5467 ^a	155	38 ^b
Rainfed	5267 ^a	13	-

Table 3.6. Total yield, irrigation, and IWUE per treatment during the 2022 season at the HHERC field.

Treatment	Year (Precipitation)		
	2022 (405mm)		
	Yield (kg ha ⁻¹)	Irrigation (mm)	IWUE* (kg ha ⁻¹ mm ⁻¹)
SI Peanut	4144 ^a	142	33 ^a
Irrigator Pro (SWT)	3808 ^a	160	26 ^b
Irrigator Pro (VWC)	3997 ^a	124	36 ^a
Rainfed	1937 ^b	-	-

*IWUE= Irrigation Water Use Efficiency

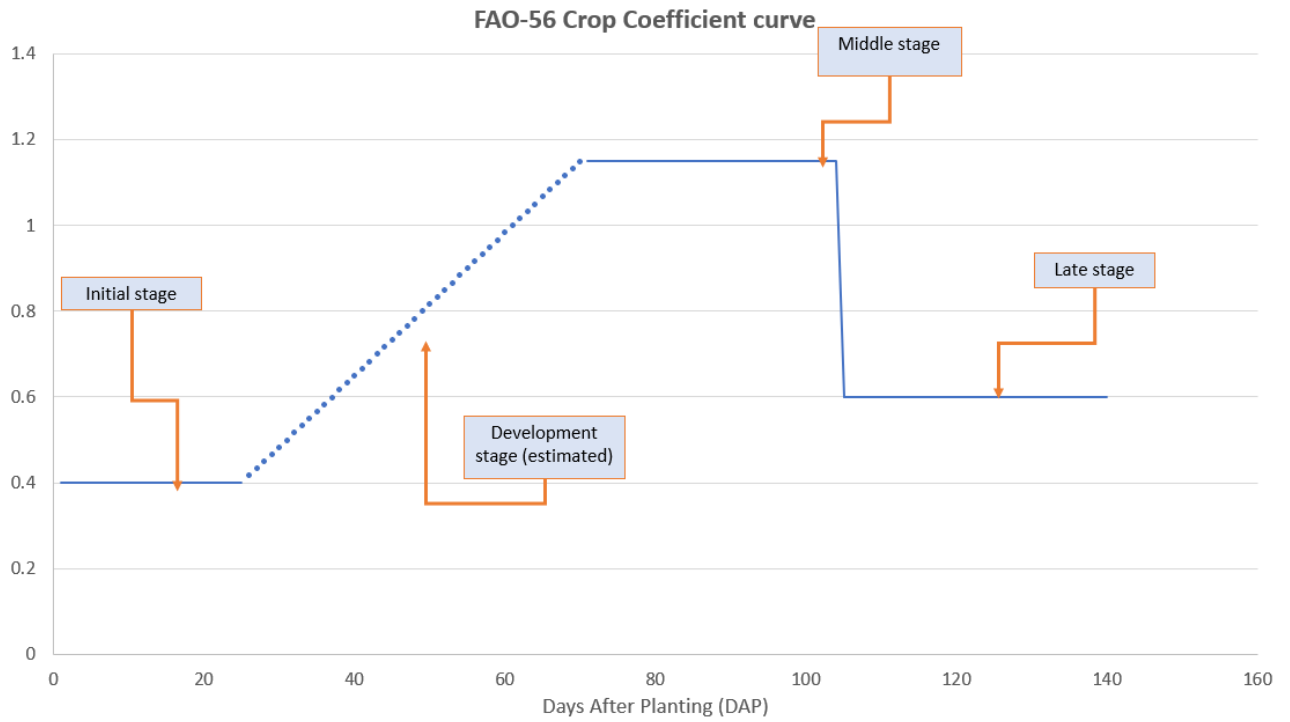


Figure 3.1. Crop coefficient (K_c) curve for peanut according to FAO-56 guidance (Allen et al. 1998).

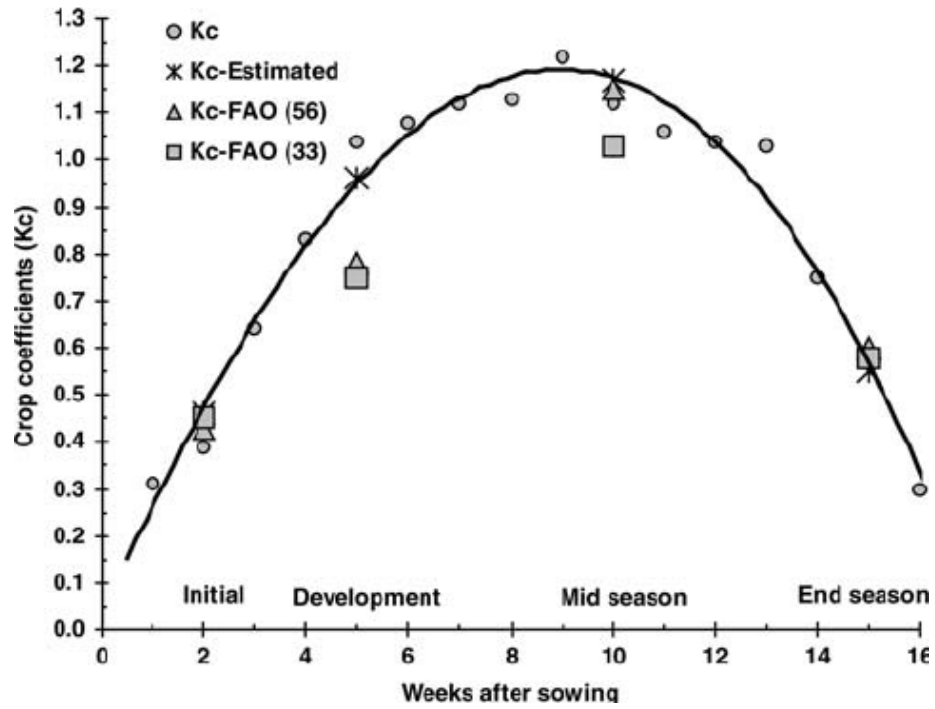


Figure 3.2. Kc curve for peanuts created by Bandyopadhyay, Mallick, and Rana (2005) and compared to FAO 56 and FAO 33 estimated Kc values for specific phenological stages .



Figure 3.3. Peanut production on a county level in Georgia, USA. Research sites' locations are symbolized using a star.

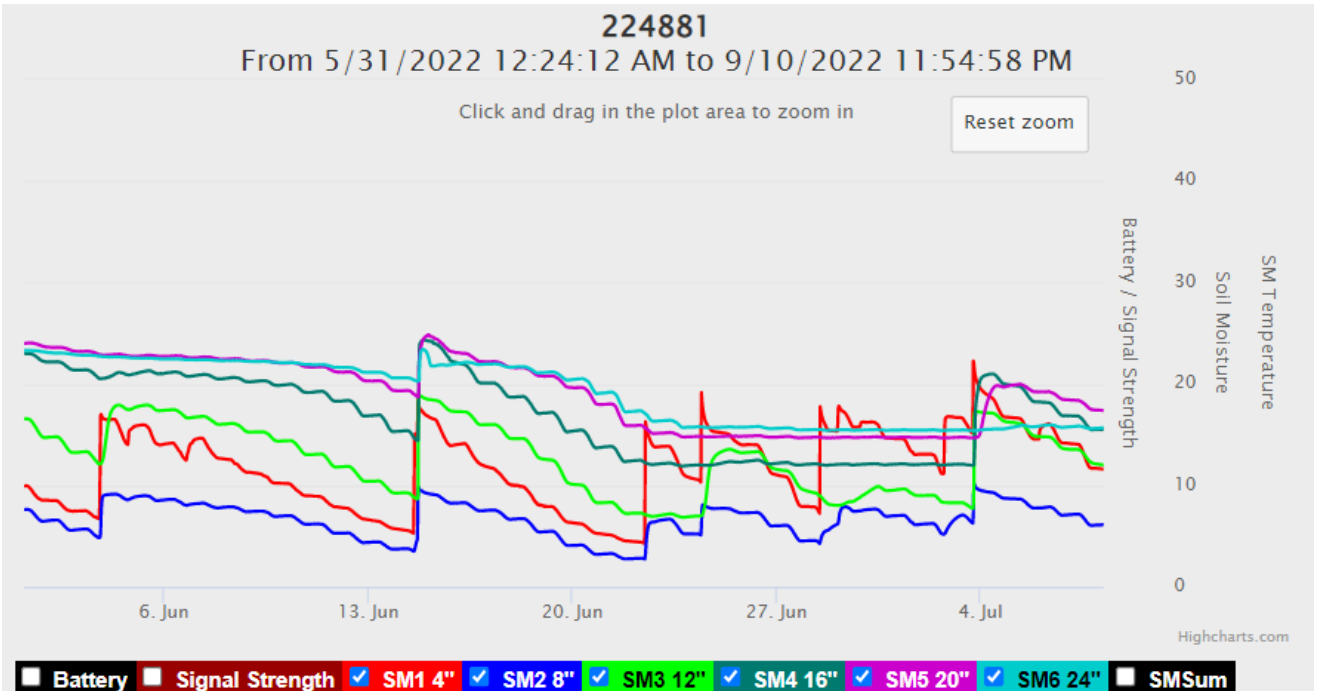


Figure 3.4. Time-series graph depicting soil moisture levels (VWC) from all six depths 0.1m, 0.2m, 0.3m, 0.4m, 0.5m, and 0.6m during June 2022.

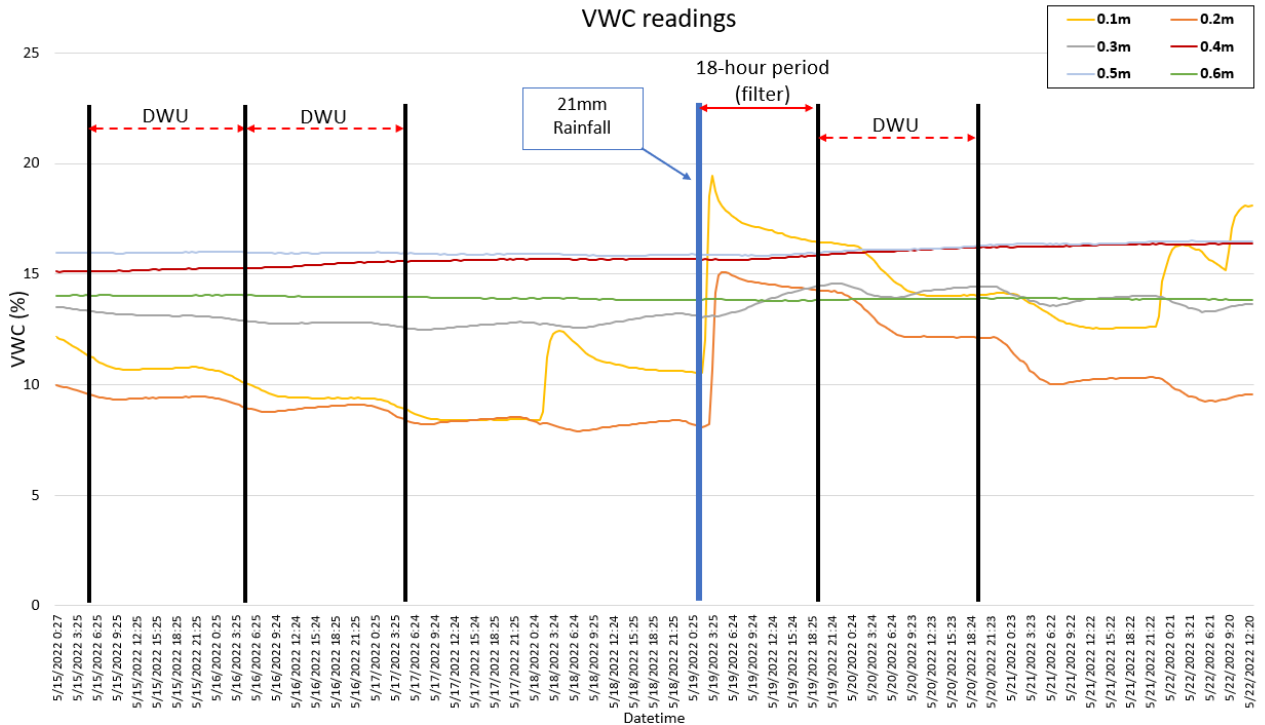


Figure 3.5. Weekly soil moisture levels (VWC) during mid-May depicting the intervals that were utilized to calculate the DWU and how the 18-hour waiting period was applied.

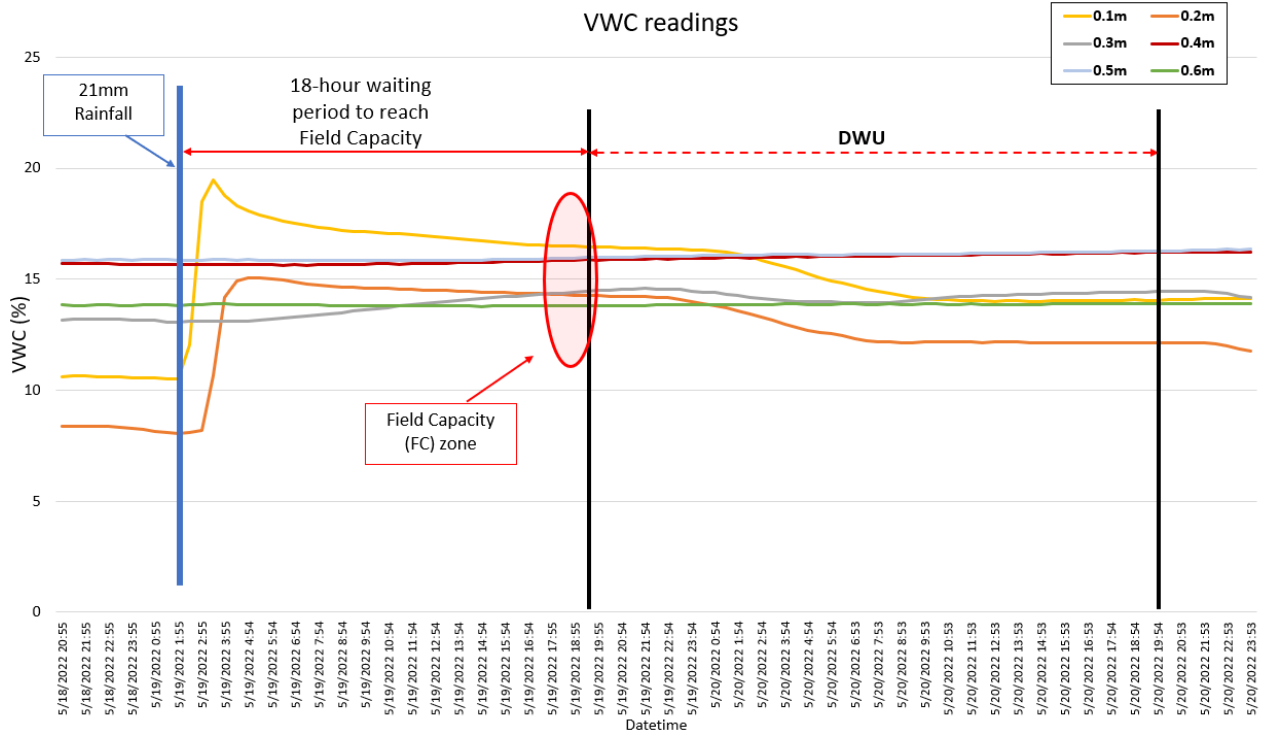


Figure 3.6. 48-hour soil moisture graph demonstrating with detail how the soil profile got in equilibrium after 21mm rainfall event.

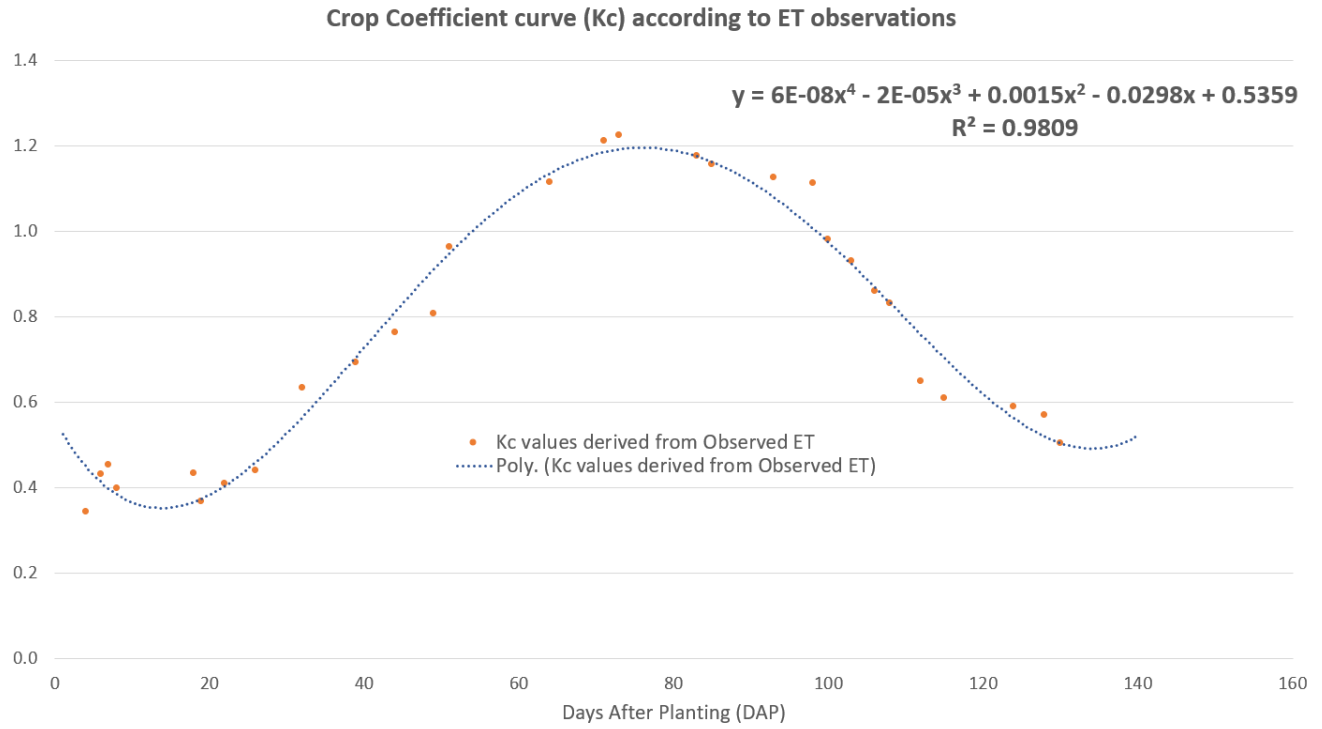


Figure 3.7. First version of Kc curve for peanuts grown in Georgia. Orange dots depict Kc values derived from observed ETc values through the first season.

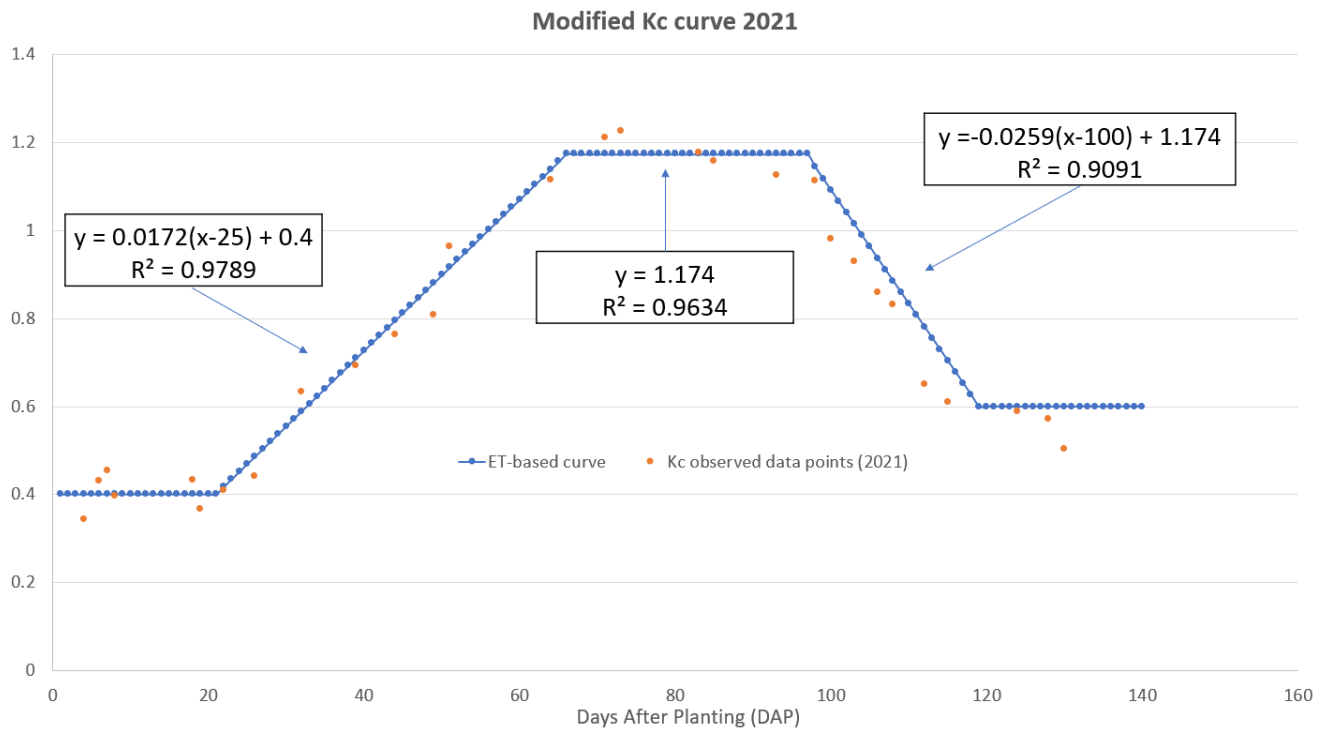


Figure 3.8. Trapezoidal-shaped crop coefficient curve for peanut with equations and R2 values for each section of the curve.

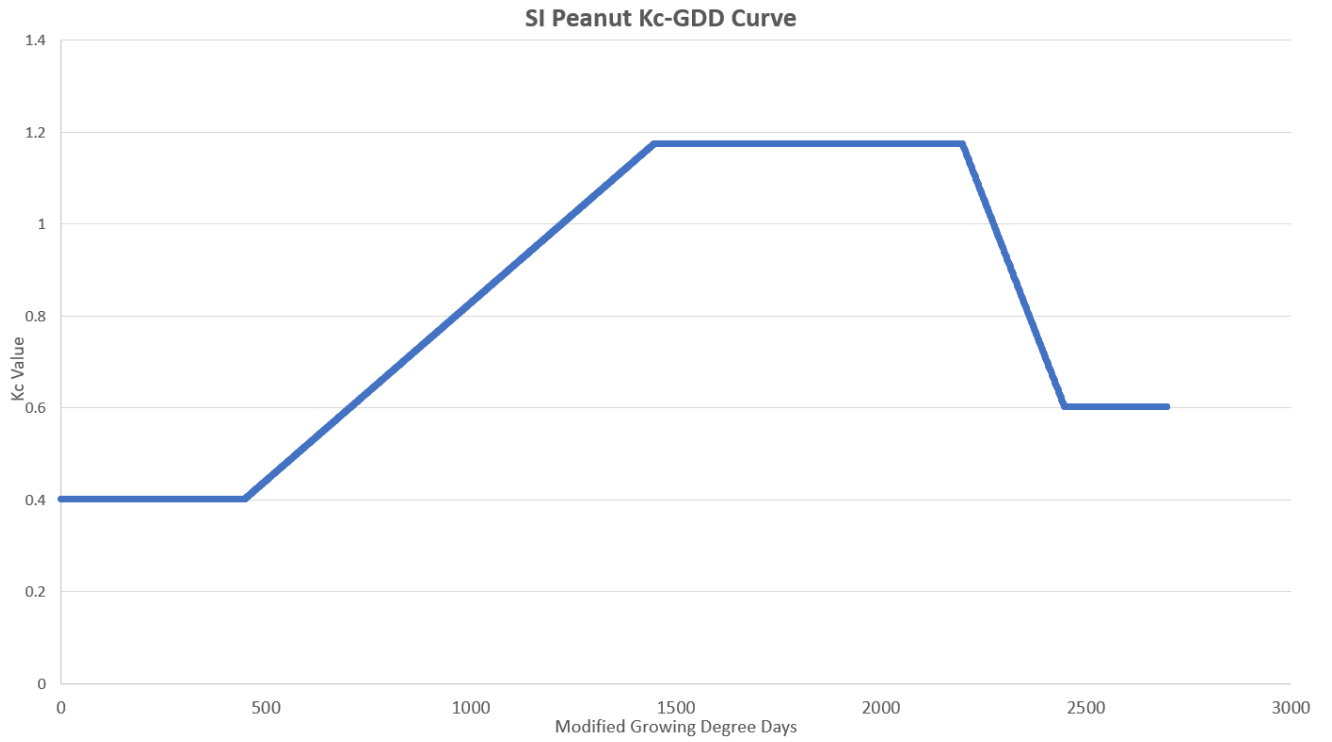


Figure 3.9. Trapezoidal-shaped crop coefficient curve based on GDDs for peanut crop.

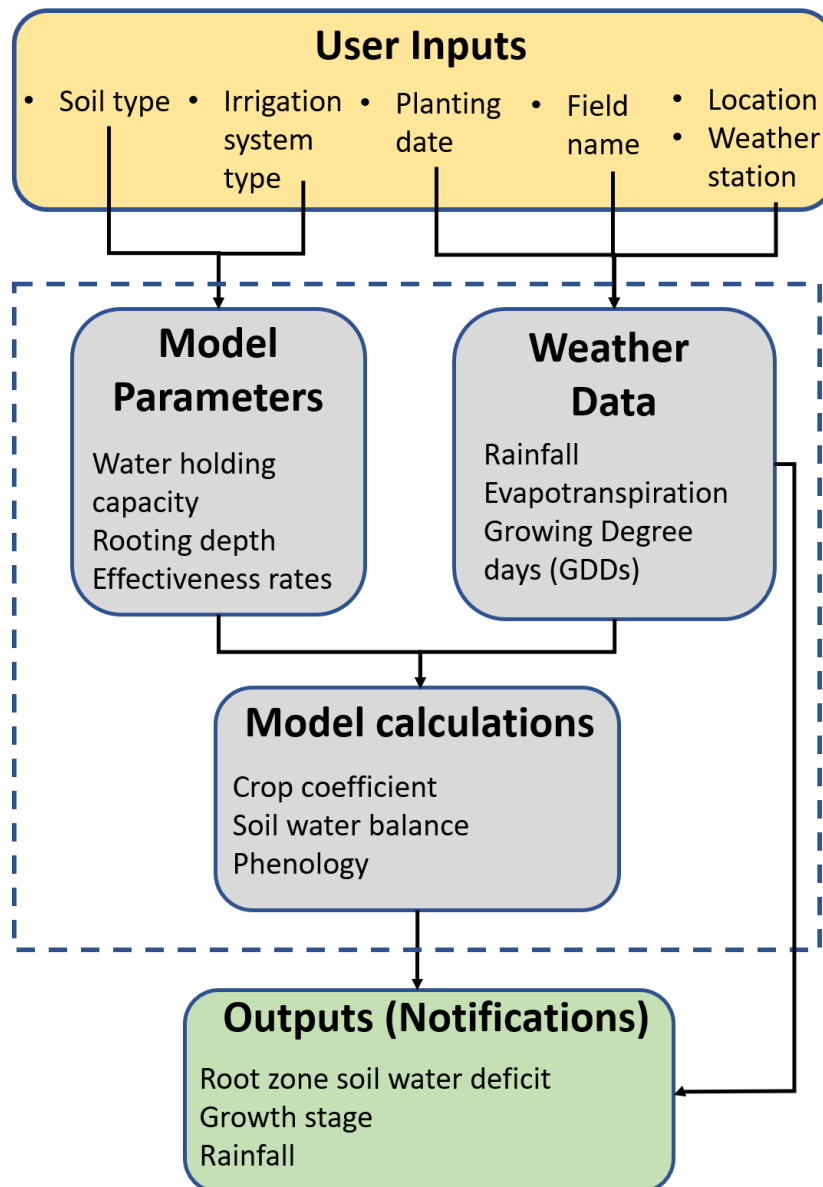


Figure 3.10. Flowchart the of SI peanut model through the CropFit mobile application.

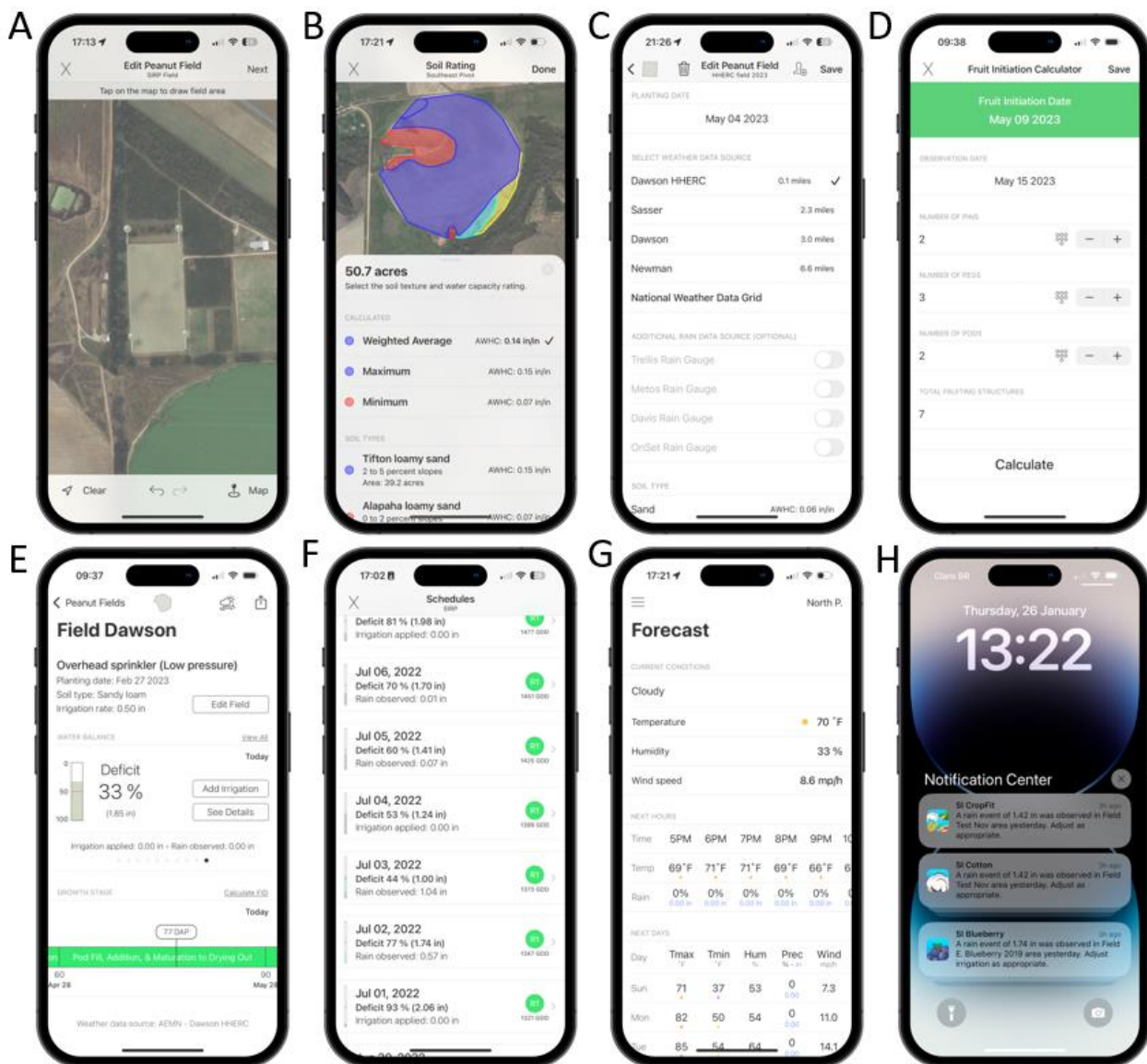


Figure 3.11. Screen capture from CropFit peanut App. A) adjusting location of the field, B) choosing appropriate soil properties, C) selecting meteorological data sources, D) FID estimator interface, E) field overview page, F) RZSWD, accumulated GDDs, and phenological stage, G) weather forecast for next few hours, and H) user notifications.



Figure 3.12. The satellite image of the Newton Lateral field at SIRP depicts the 3 blocks (North, Middle, and South).

Newton Lateral Plot Plan					North					Middle					South				
xxx-x = Plot Number - Treatment																			
VRI Zones	9	////	////	////	////	////	////	////	////	////	////	////	////	////	////				
		111-5		112-9		113-7		211-2		212-1		213-9		311-1		312-8		313-9	
		////		////		////		////		////		////		////		////		////	
	8	114-3		115-8		116-1		214-7		215-5		216-6		314-2		315-5		316-4	
		////		////		////		////		////		////		////		////		////	
	7	117-6		118-2		119-4		217-3		218-8		219-4		317-6		318-7		319-3	
		////		////		////		////		////		////		////		////		////	
	6	121-8	Alley	122-4	Alley	123-9		221-9	Alley	222-6	Alley	223-8		321-6	Alley	322-5	Alley	323-1	
		////		////		////		////		////		////		////		////		////	
	5	124-2		125-9		126-6		224-1		225-3		226-4		324-3		325-2		326-8	
		////		////		////		////		////		////		////		////		////	
	4	127-7		128-3		129-5		227-5		228-2		229-7		327-7		328-9		329-4	
		////		////		////		////		////		////		////		////		////	
	3	131-2		132-8		133-7		231-3		232-9		233-4		331-3		332-1		333-7	
		////		////		////		////		////		////		////		////		////	
2	134-1		135-4		136-6		234-7		235-5		236-8		334-4		335-2		336-9		
	////		////		////		////		////		////		////		////		////		
1	137-5		138-1		139-3		237-6		238-2		239-1		337-5		338-8		339-6		
	////		////		////		////		////		////		////		////		////		
	48 ft	60 ft	48 ft	60 ft	48 ft		48 ft	60 ft	48 ft	60 ft	48 ft		48 ft	60 ft	48 ft	60 ft	48 ft		
									////	Buffer									

Figure 3.13. Plot layout of the Newton Lateral field at SIRP. In 2021 (Year 1) peanuts were planted in the Middle block and in 2022 (Year 2) they were planted in the South block.

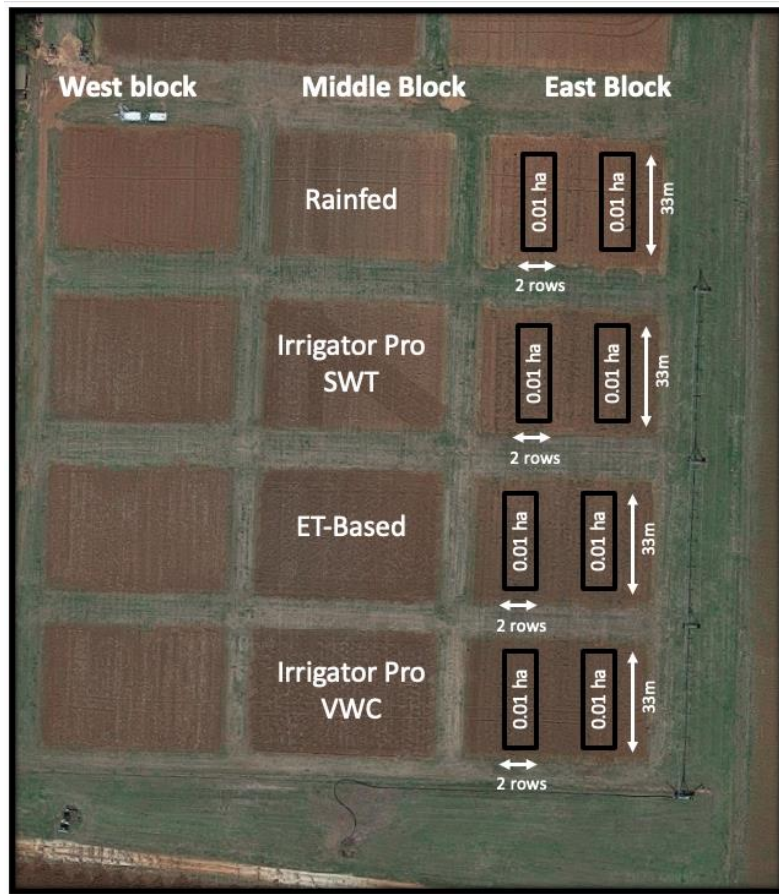


Figure 3.14. The satellite image of the HHERC field depicts the 3 blocks going from west to east.

Each block consists of 4 plots.

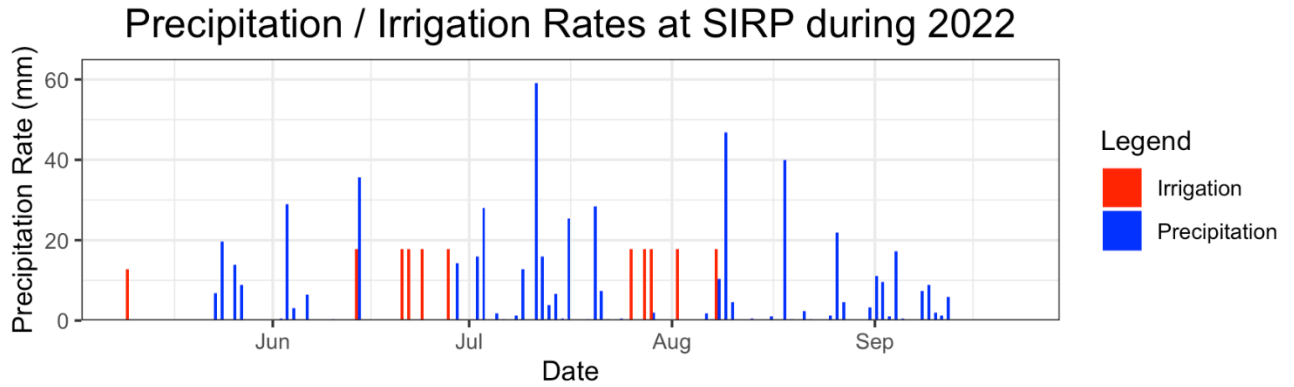


Figure 3.15. Precipitation and irrigation at SIRP during the 2021 (top) and 2022 (bottom) growing seasons. Red bars depict the days when at least one treatment was irrigated. The initial irrigation event (13mm) was used to activate herbicides and promote germination. All other irrigation events were 19mm.

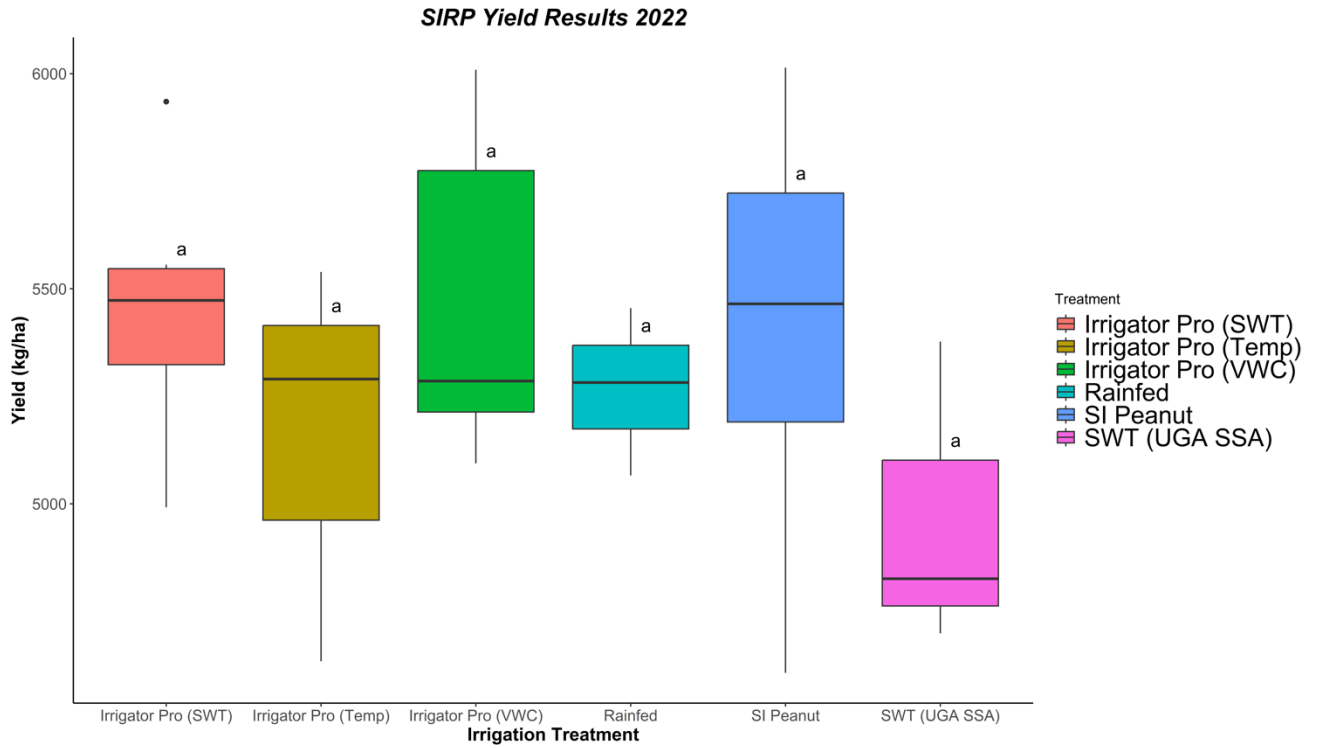


Figure 3.16. Yield results for the five irrigation scheduling treatments evaluated at SIRP during the 2022 growing season. Statistical analyses were conducted using Tukey’s HSD test.

Precipitation / Irrigation Rates at HHERC during 2022

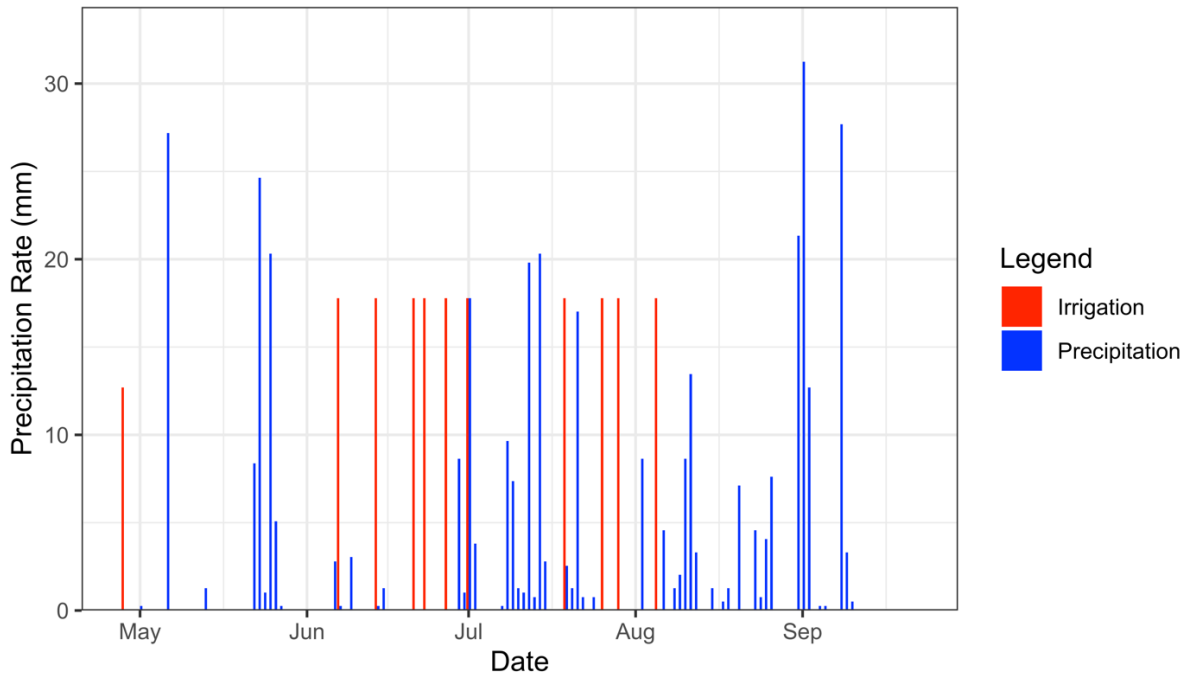


Figure 3.17. Precipitation and irrigation at HERC during the 2022 growing season. Red bars depict the days when at least one treatment was irrigated. The initial irrigation event (13mm) was used to activate herbicides and promote germination. All other irrigation events were 19mm.

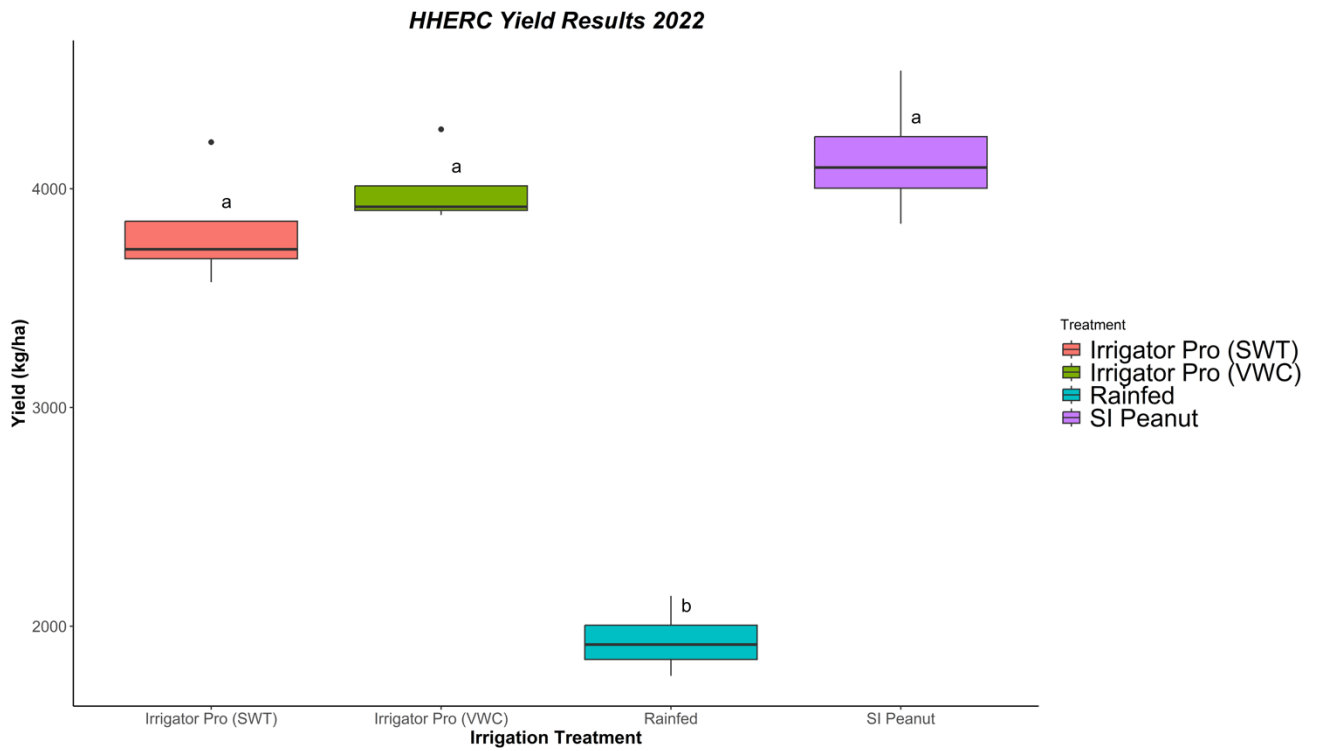


Figure 3.18. Yield results for the four irrigation scheduling treatments evaluated at HERC during the 2022 growing season. Statistical analyses were conducted using Tukey’s HSD test.

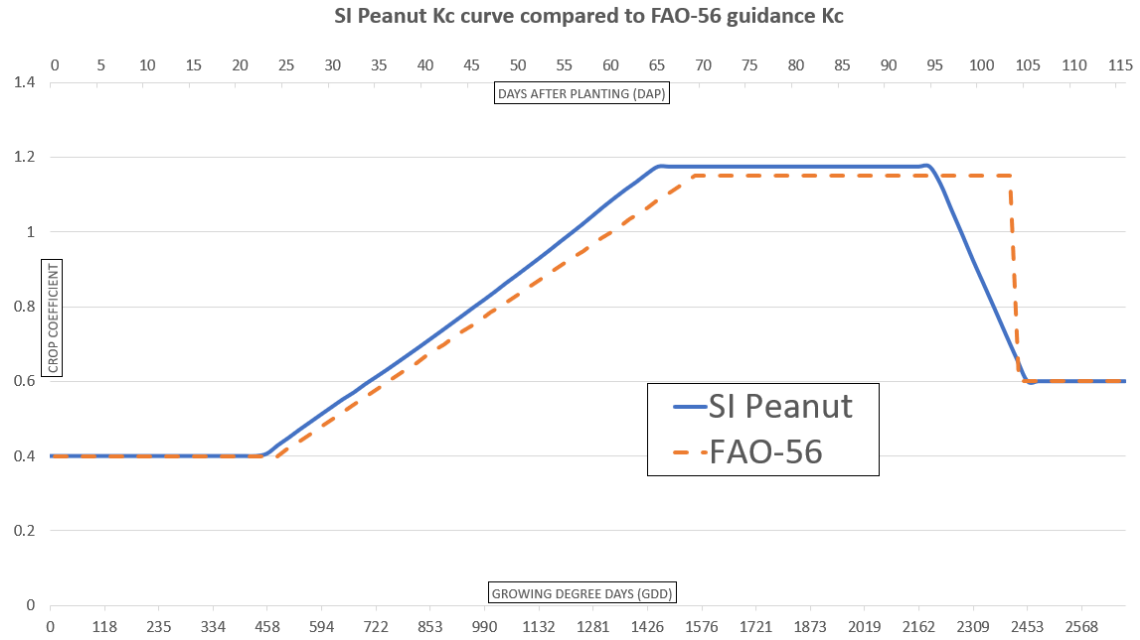


Figure 3.19. Developed Kc-GDD curve compared to standard ET scheduling from FAO-56 guidance (Allen et al. 1998). The FAO-56 curve uses the DAP (top) x-axis while the SI Peanut curve uses the GDD (bottom) x-axis.

CHAPTER 4

CONCLUSIONS

In Georgia, irrigation is used to supplement growing season precipitation in peanut production; however, the yield results from the HHERC field in 2022 highlight the significance of irrigation and its profound impact on crop yield. During late June, as the peanuts entered the development stage, their water requirements gradually increased. Subsequently, in mid-July, a second drought occurred, causing the peak water demand for peanuts. Prolonged drought periods can have severe consequences on productivity. Even the two short drought periods were sufficient to stress the plants, resulting in a 50% reduction in yield compared to the irrigated plots.

To mitigate the detrimental effects of water stress, irrigation was applied more than four times for each treatment during these droughts, preventing yield losses. It is worth noting that accurate weather forecasting can enhance the efficiency of irrigation practices. Growers should consider the possibility of adequate precipitation events in the upcoming days before deciding on irrigation, particularly when the DST recommends irrigation. Improved weather prediction and a better understanding of the impact of water stress on different crop growth stages can lead to the optimization of irrigation water usage.

Project results indicate that the VWC version of Irrigator Pro performs at least as well as the temperature and SWT versions of the model in terms of irrigation applied (SIRP and HERC) and yields (HHERC). Because of this, the VWC version of Irrigator Pro was incorporated into the Irrigator Platform in early 2023 and released for public use in April 2023. Links to the smartphone

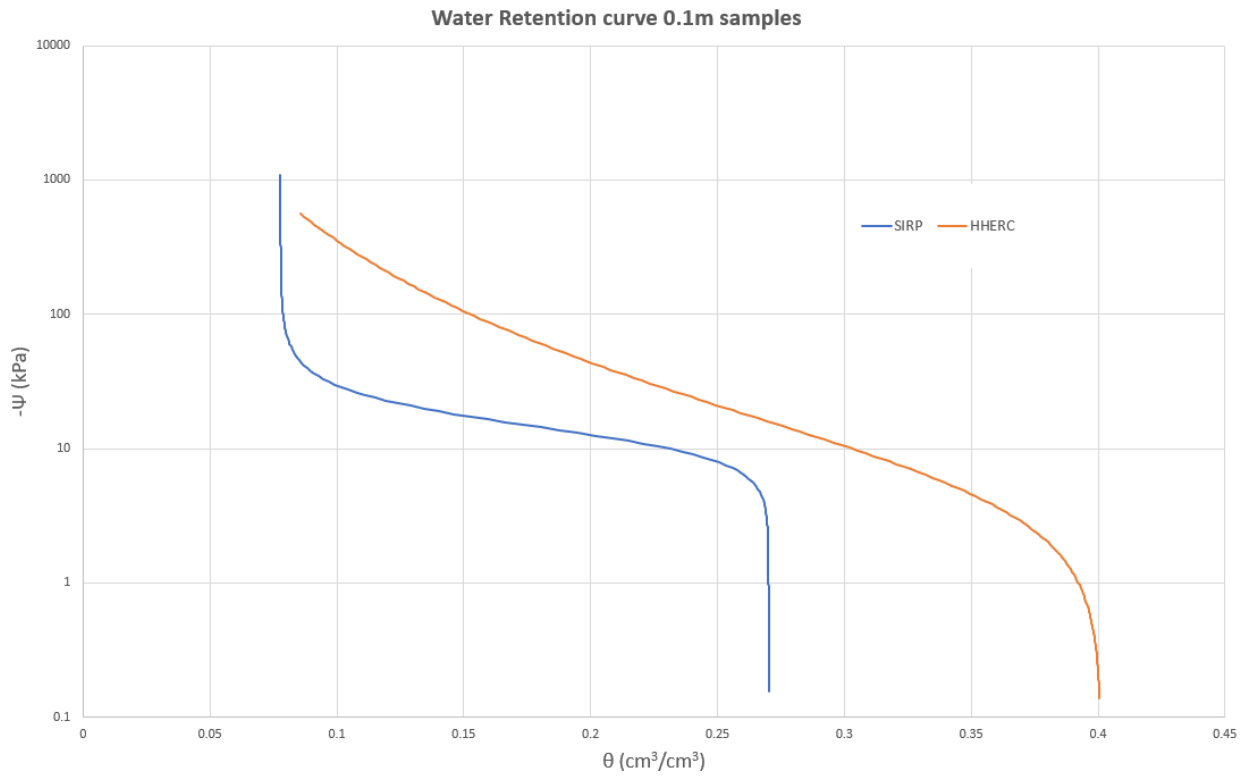
applications for iOS and Android are available on the web-based platform (<https://irrigatorpro.org/>). Tutorials are also available. The model will continue to be evaluated in upcoming growing seasons with plot studies at SIRP and HERC and with on-farm trials. Improvements will be incorporated as necessary.

The results from the project also indicate that the SI Peanut ET-based model performs at least as well as sensor-based irrigation scheduling methods. However, this assessment is based on one year of data and additional testing at the plot and field scale is needed to confirm these findings. Based on the 2022 results, there was enough confidence in the performance of the SI Peanut model that it was incorporated into a beta-testing version of the SI CropFit App and made available to select growers and researchers for evaluation during the 2023 growing season. The SI CropFit App has significant advantages compared to sensor-based irrigation scheduling because no sensors are required to be installed after sowing and prior to harvest reducing capital and labor investments. It also allows growers to run multiple versions of the App for the same field to account for soil differences. However, the App requires accurate precipitation data for the soil water balance model to accurately calculate RZSWDs. Precipitation data from weather stations that are not adjacent to fields or estimates from national meteorological data sets are not reliable in an environment like southern Georgia in which growing season precipitation is driven by localized convective thunderstorms. For the CropFit App to accurately calculate RZSWDs, on-farm precipitation data are needed. Because of this, the App includes options for using precipitation data from grower-owned automated rain gages.

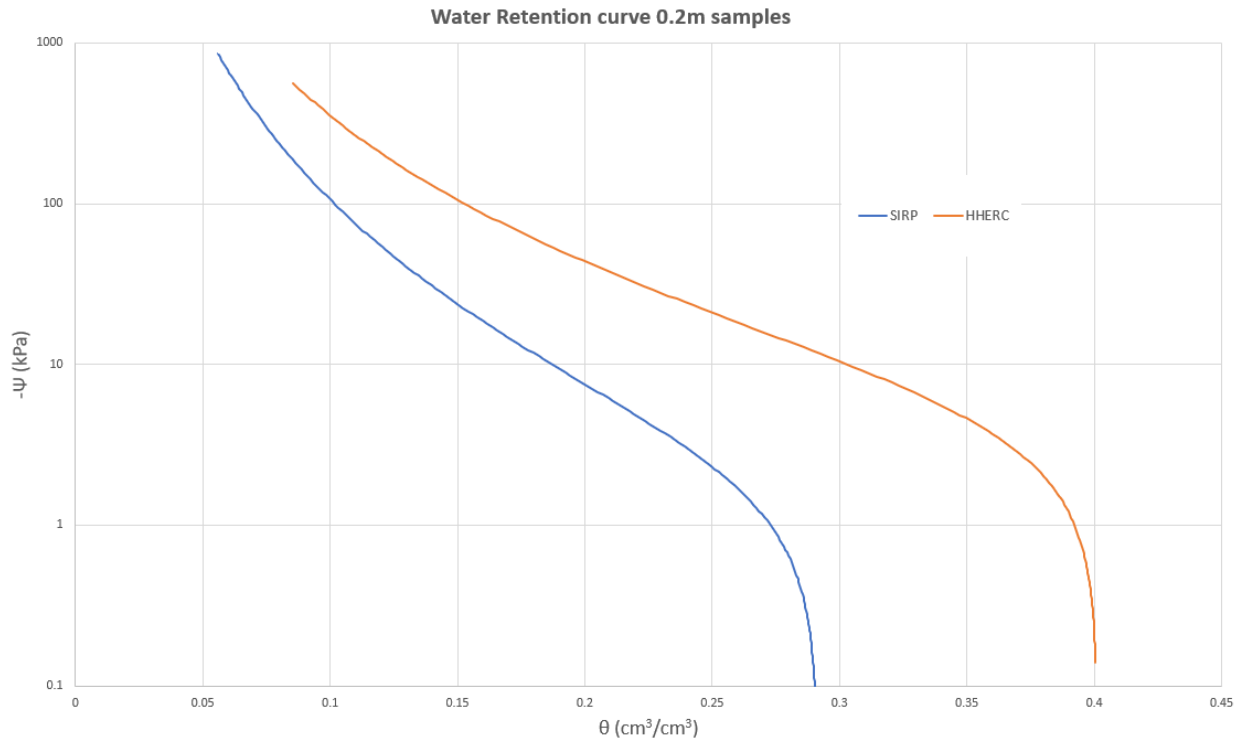
The goal of this component of the project is to make the SI Peanut model with the SI CropFit App publicly available prior to the 2024 growing season. However, the SI Peanut model will continue to be evaluated and improved during upcoming growing seasons in Georgia and

surrounding states. Additional internal features like the Fruit Initiation Date estimator will continue to be improved as well.

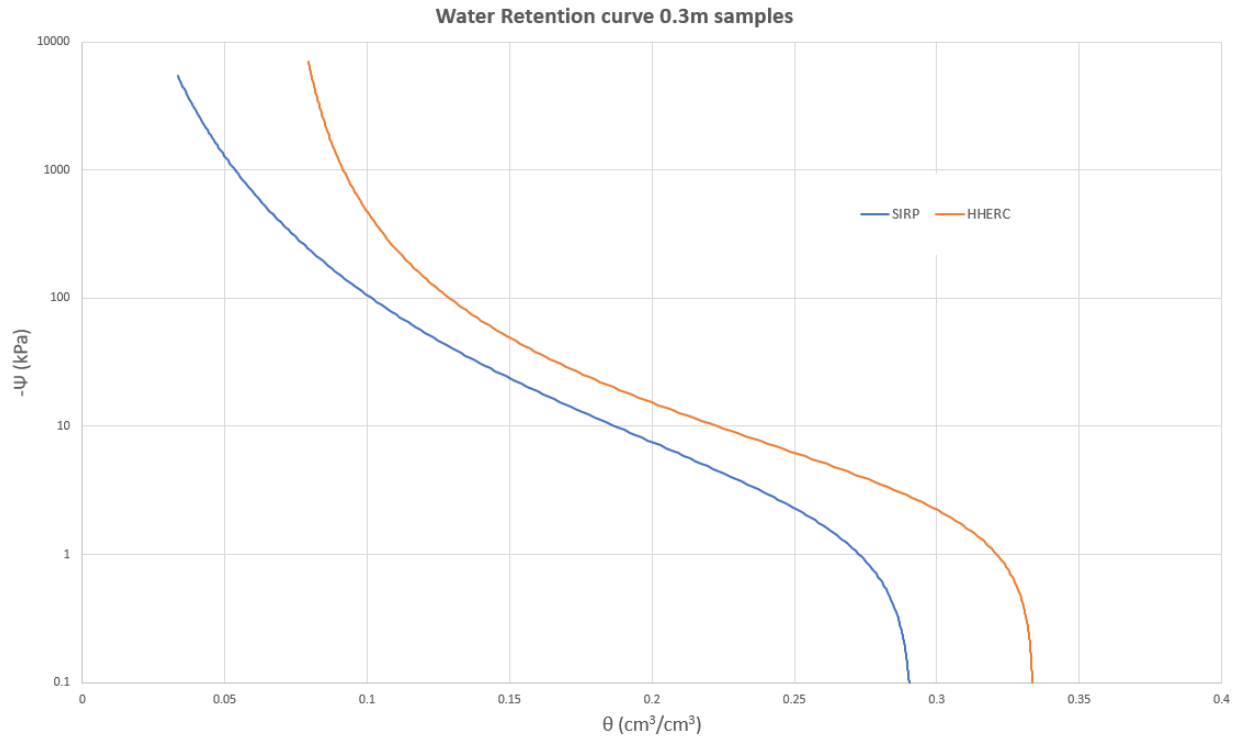
APPENDIX



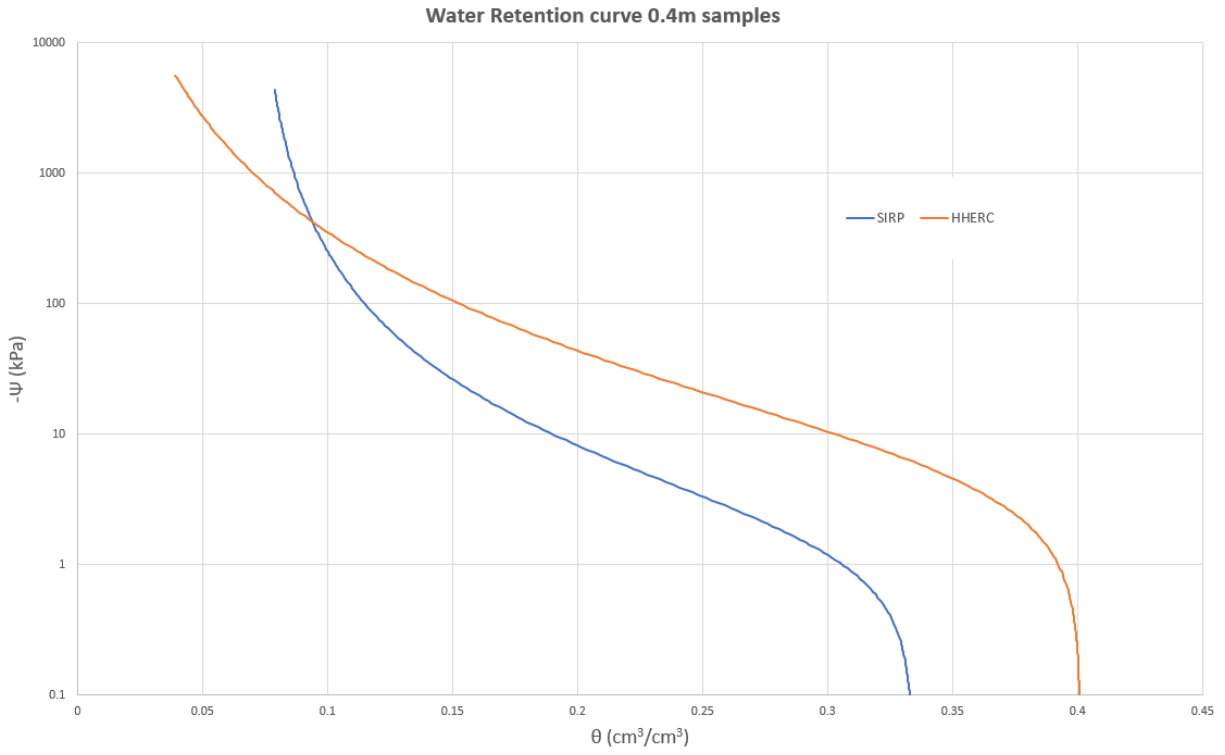
Appendix Figure 1. Water retention curve that was generated from Hyprop 2 equipment for 0.1m depth and both research sites.



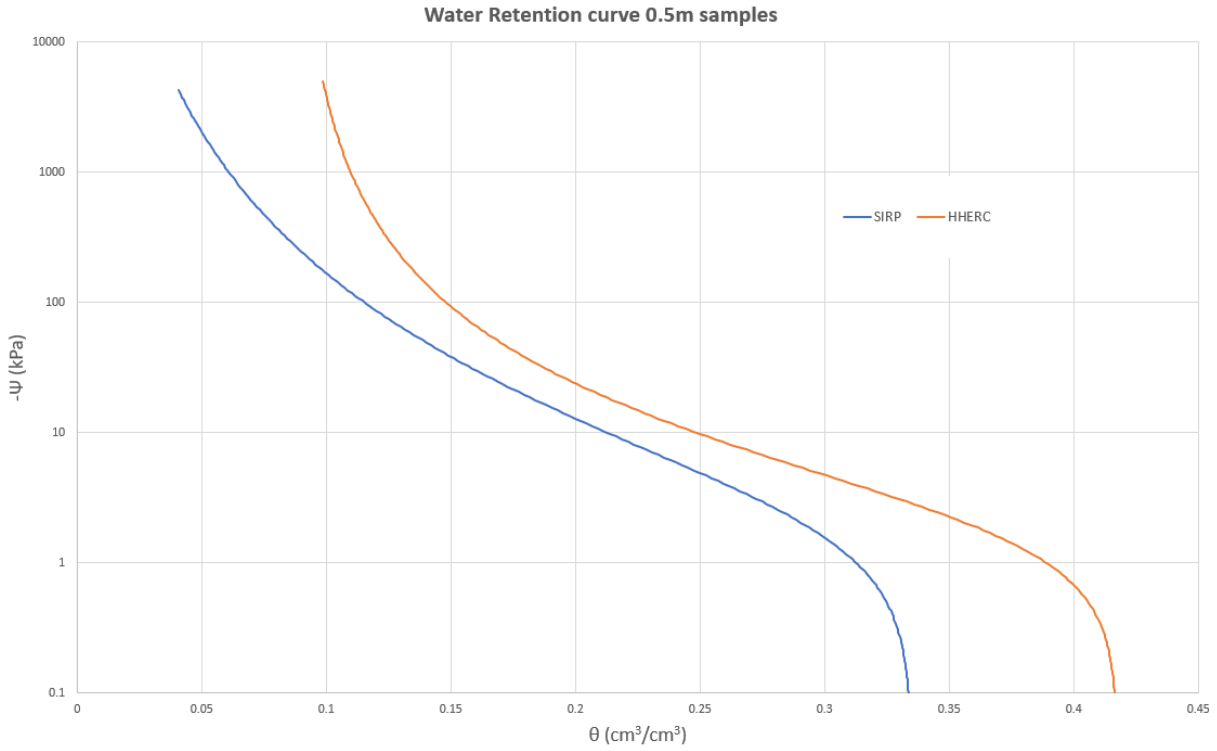
Appendix Figure 2. Water retention curve that was generated from Hyprop 2 equipment for 0.2m depth and both research sites.



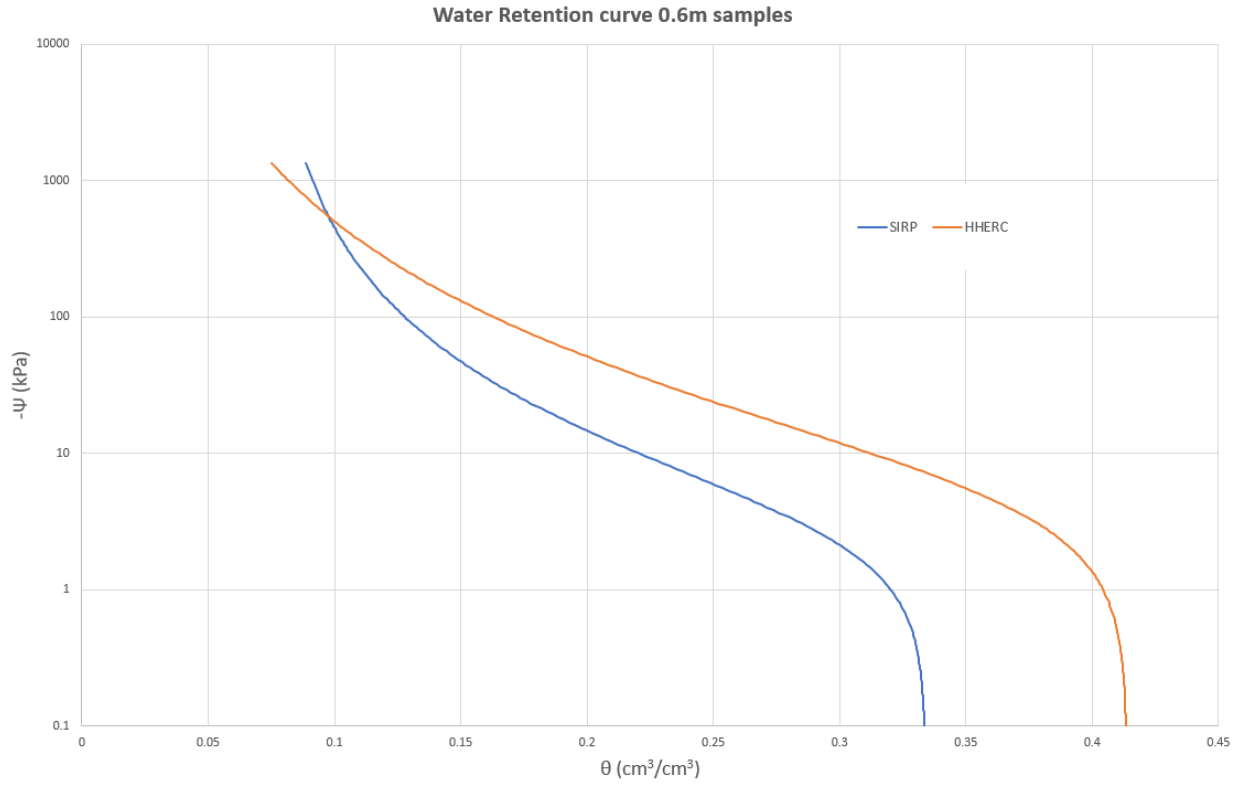
Appendix Figure 3. Water retention curve that was generated from Hyprop 2 equipment for 0.3m depth and both research sites.



Appendix Figure 4. Water retention curve that was generated from Hyprop 2 equipment for 0.4m depth and both research sites.



Appendix Figure 5. Water retention curve that was generated from Hyprop 2 equipment for 0.5m depth and both research sites.



Appendix Figure 6. Water retention curve that was generated from Hyprop 2 equipment for 0.6m depth and both research sites.