EVALUATING THE IRRIGATION SCHEDULES OF YOUNG PECAN TREES IN PIEDMONT AND COASTAL PLAINS SOILS OF GEORGIA

by

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(Under the Direction of Gary L. Hawkins and E.W. “Bill” Tollner)

ABSTRACT

Irrigation recommendations for young pecan trees in Georgia’s Coastal Plains conditions with a loamy sand texture are available. Still, there is a dearth of irrigation research related to trees in Georgia’s Piedmont region, where the soils have a greater percentage of clay. The goal of this study during the 2021-2022 growing season was to ensure that young trees have an ample supply of water to promote new root growth while also preventing overirrigation. Soil-based measurements, laboratory soil water retention, in situ infiltration measurements, and ground penetrating radar data were collected. Recommendations were made to increase irrigation at the Piedmont region orchard by 37 liters/week and to decrease irrigation at the Coastal Plains region orchard by 341 liters/week. Thus, irrigation schedules need to be evaluated every growing season as the root systems of the trees mature, with additional soil moisture sensors installed to account for the spatial variance of soil moisture.

INDEX WORDS: Irrigation Scheduling, Coastal Plains, Piedmont, Georgia, Pecan, Soil Moisture Sensors, Matric Potential, Field Capacity, Permanent Wilting Point, Soil Water Tension, Watermark Sensor, Volumetric Water Content

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ABBREVIATIONS AND UNITS

Abbreviation	Description
FC	Field Capacity
K_{fs}	Field Saturated Hydraulic Conductivity
K_{sat}	Saturated Hydraulic Conductivity
LWP	Leaf Water Potential
MAD	Maximum Allowed Moisture Depletion
PAW	Plant Available Water
PLWP	Predawn Leaf Water Potential
PWP	Permanent Wilting Point
SWCC	Soil Water Characteristic Curve
SWP	Stem Water Potential
SWT	Soil Water Tension
VWC	Volumetric Water Content
GPR	Ground Penetrating Radar

Unit	Term	Conversion
Cm	Centimeter	cm = 0.39 in
Ha	Hectare	Ha = 2.47 acres
kPa	Kilopascal	kPa = cb
L	Liter	L = 0.26 gal

CHAPTER 1. INTRODUCTION AND OBJECTIVES

Introduction

The pecan [Carya illinoinensis (Wangenh.) K. Koch] is a deciduous tree native to North America that needs large amounts of water for optimal yield.[1] Georgia is the nation's top pecan producer, accounting for approximately one-third of pecan production in the United States (UGA Extension). Irrigation recommendations for young and mature pecan trees under Georgia's Coastal Plain conditions with a loamy sand texture have been previously developed (Wells, 2015; Wells, 2017b). More research is needed regarding young pecan tree irrigation schedules in the Piedmont region of North Georgia, which is abundant in "Georgia Red Clay" resulting from primarily unhydrated iron oxides, but also partially hydrated iron oxides and manganese iron oxides (USDA, 1975).

Irrigation scheduling should be based on scientific data and can assist in monitoring the quantity and timing of irrigated water applications. Proper irrigation scheduling depends on factors such as evaporative demand, antecedent moisture conditions, soil texture, and plant and soil water status. Irrigation scheduling is crucial as drought stress is one of the primary causes of mortality in young pecan trees (Wells, 2017a). For mature trees, water deficit during nut sizing diminishes the ability of pecan roots to extract soil water, reducing growth and nut size and increasing nut split (Wells et al., 2017). Reduced embryo growth and improper kernel filling are caused by low soil moisture during the kernel-filling stage (Herrera, 1990; Wells et al., 2017).

[1] The use of any company name in this body of work does not endorse the use of the equipment, product or process named, nor any criticism of any similar products that are not mentioned.

Other symptoms include leaf yellowing and leaf drop (Rohla, 2018). The leaf's response to water deficit (drought) closes the stomata, thus ceasing photosynthesis. Conversely, excessive soil moisture can lead to wasted water and root disease.

Irrigation scheduling generally involves soil or plant-based measurements. Estimation of soil moisture by feel is commonly used by farmers but is not recommended due to its limitations in monitoring deeper soil water status. Volumetric water content (VWC) and soil matric potential (soil water tension) measurements are regularly taken for soil-based scheduling. VWC sensors can be an effective tool for accurately managing irrigation application in the agricultural industry and can be used to monitor VWC changes across the entire soil profile or root zone (Sui, 2017). For soil matric potential measurements, tensiometers and Watermark sensors are widely used in the field to initiate irrigation. Irrometer Co. (Riverside, CA) manufactures the Watermark sensor with a soil water tension (SWT) range of 0-239 kPa.

While beyond the scope of this study, plant-based measurements (stem water potential (SWP) and leaf water potential (LWP)) measurements have been utilized in irrigation scheduling for years on crops such as prunes, grapes, peaches, and pecans (Blanco-Cipollone et al., 2017; Gálvez et al., 2014; Mirás- Avalos et al., 2016; Wells, 2015). LWP and SWP measurements are taken using a pressure chamber, in which pressure is applied to a severed leaf and stem that is confined in an airtight chamber. An external pressure gauge measures the pressure necessary to drive water out of the stem of a cut leaf, which equals the water potential (Fulton et al., 2014). As soil moisture depletes, the plant becomes under more stress. Therefore, more pressure is necessary to drive water out of the cut surface of the leaf stem. For taking SWP measurements, a pump-up pressure chamber (PMS Instruments, Albany, OR) is commonly used as it requires no compressed gas source.

Objectives

- Monitor the soil water status at three pecan orchards in Oconee, Toombs, and Hancock County, Georgia, through soil moisture sensors, laboratory soil water retention, and in situ infiltration measurements
- Evaluate the current irrigation schedules at three orchards and make recommendations for future irrigation scheduling
- Examine the differences in soil texture between Georgia Piedmont and Coastal Plains soils
- Improve water use efficiency while ensuring soil moisture conditions for adequate root development
- Determine the effectiveness of locating young pecan tree roots in Georgia Piedmont soils using ground penetrating radar

CHAPTER 2. LITERATURE REVIEW

Field Capacity (FC) and Permanent Wilting Point (PWP)

Proper irrigation scheduling cannot be performed without fully understanding the boundaries of plant available water (PAW). The FC is the amount of water in the soil after the excess has drained away due to gravity, usually taking one to three days. In some finer-textured soils, it may be necessary to wait 4-10 days for the water content to stop changing significantly to reach FC (Campbell). FC represents the maximum amount of water available to the plant for uptake, and generally, water is held to the soil at an FC of 10-33 kPa (10 kPa for sandy soil and 33 kPa for clay soil) (Datta et al., 2017). Ideally, one would irrigate until the soil water is within 90% of FC to leave room for potential rainfall (Irmak et al., 2016). Wells (2015; 2016) recommends using a VWC of 10% or higher, or a VWC of 70-75% of FC, to initiate irrigation for mature pecan trees in loamy sand soil in Georgia.

To maximize crop yields, the soil water content should be between the FC and the maximum allowed moisture depletion (MAD), where plants experience drought stress. The MAD is usually 50% of PAW, or the difference between FC and PWP, in the root zone (Black et al., 2008; Sharma, 2019). For pecan trees, 45-50% of PAW is an adequate threshold (Heerema et al., 2008). PAW is impacted by the water holding capacity of the soil, organic matter content, and the effective rooting depth of the plant. Water is held more tightly in clay soils than sandy soils due to the large specific surface area, high void ratio, small pore sizes, and pores not being as interconnected in clay soils, resulting in higher water holding capacity.

The PWP is the minimum amount of water the soil needs so that plant wilting does not occur. The matric potential that corresponds to the PWP, in which plants cannot take up water beyond this point, is generally 1500 kPa (Rai et al., 2017; Miller and Donahue, 1995). PWP is an intrinsic property of a particular soil and is primarily determined by soil texture and is independent of the type of plant grown in the soil (Regional Salinity Laboratory (U.S.), 1954). This does not necessarily mean that plants start wilting only if the moisture decreases beyond this limit. Some plants can wilt in soils with water content higher than the estimated wilting point, such as when the quantity of soluble salts is relatively high (Karkanis, 1983). Selecting an upper limit (FC) for PAW is challenging because of the reliance on soil texture and soil profile variations in pore size distribution and water conductivity. As an estimate, for most medium to fine-textured soils, the FC is approximately twice the moisture percentage of the PWP. This recommendation is not applicable for coarse-textured soils, but the moisture content corresponding to 10 kPa is a feasible estimate for FC. Measuring FC in situ is challenging as it requires the following (Murray and Shanmugham, 1964):

- Saturating a certain depth of soil by adding excess water
- Minimizing surface evaporation losses
- Eliminating transpiration losses by working on non-cropped fields
- Selecting plots with uniform and free draining soil
- Using soil moisture sensors to observe the time rate of decrease in moisture content until it levels out

Also, the results may not be repeatable and in situ measurements are time and labor intensive. The standard method for determining the FC and PWP of a soil sample in the laboratory consists of using a pressure plate apparatus and saturating the sample while applying 33 kPa pressure for

FC and 1500 kPa for the PWP (Abrol et al., 1968; Oosterveld and Chang, 1980; Richards, 1941). After 48 to 72 hours, the gravimetric water content is taken. Given this, the 33 kPa threshold is somewhat arbitrary and does not represent soils of different textures and with distinct soil horizons (Liang et al., 2016). An SWT value of 33 kPa underestimates the in situ soil water content at FC in coarse-textured soils. It is recommended that FC and PWP be defined for each specific soil and not by a universal soil water tension value (Liang et al., 2016). This can be done through, for instance, determining the FC and PWP from the saturated water content (Karkanis, 1983; Grewal et al., 1990). Additionally, a modern method of using the WP4C Potentiometer (Meter Group Inc., Pullman, WA) can be implemented to determine the PWP at 1500 kPa using the chill mirror dew point method.

Principles of Irrigation Scheduling

Techniques of irrigation scheduling include the water budget approach, soil moisture measuring, and calculating the Normalized Difference Vegetation Index (NDVI) through Landsat data. Soil water content or tension can be estimated by feel and appearance, gravimetric soil moisture testing of field soil samples, tensiometers, electrical resistance blocks, and a modified atmometer (Broner, 2005). These will be explored further in the next section of this report.

When applying the water budget approach, oftentimes, an equation similar to equation (1) below is used (Lamm and Rogers, 2015):

$$Sc = Sp + P + I - R - F - ET \quad (1)$$

"Where Sc and Sp are the plant available soil water amounts in the soil profile on the current and preceding days, ET is daily crop evapotranspiration, R is irrigation runoff, P is effective precipitation, I is the irrigation water applied, and F is flux across the lower boundary of the control volume (taken as a depth well below the rooting depth), all in any consistent unit of length" (Lamm and Rogers, 2015). The flux can also be considered simply deep drainage out of the root zone. To estimate the ET (mm) of a crop, the crop coefficient (Kc) can be multiplied by the reference ET (mm) (ETr). Kc mainly depends on the crop and its growth stage, and ETr is commonly calculated using the FAO Penman-Monteith equation with grass or alfalfa as a reference crop and an unlimited water supply (Allan et al., 1998). ET rates depend on weather conditions (air temperature, wind speed, relative humidity, solar radiation) and cultural practices (pest stress, irrigation amount and frequency, and nutritional management) (FAO). Because of this, the accuracy of the water budget approach is not extremely high, and this approach needs to be calibrated to include soil and plant-based measurements to improve its efficacy (Jones, 2004). Another caveat with using ET data to schedule irrigation is the lack of accurate data for some locations.

Soil-Based Irrigation Scheduling

Two of the more popular techniques for irrigation scheduling are measuring soil water content and soil water tension (SWT). The process of evaluating soil moisture content by feel and appearance involves collecting soil samples from the field at various locations and depths, and subsequently breaking the sample into small pieces and then squeezing them to attempt to form a ball. Next, one forms a ribbon of the soil sample between the thumb and forefinger. Sharma (2018) notes that, "The cohesiveness of the ball is an indication of soil wetness, with ribbon length positively correlated with the soil water content." While this may be an inexpensive method, it takes experience, and the results are highly subjective.

Installing soil water content sensors can overcome the pitfalls of soil moisture by the feel method. It is vital to have sensors at several depths across the effective root zone to obtain a complete picture of the soil water dynamics. Because plant roots can collect water from other soil layers, a water shortage at one depth does not necessarily suggest the crop suffers from water stress (Datta et al., 2017). Time-domain reflectometry (TDR) sensors indirectly measure VWC through the soil's dielectric constant (Ka). For dry soil Ka is less than 1, for air Ka is equal to 1, and for water Ka is around 80 (Fares and Polyakov, 2006). A TDR sensor contains two or more sensor rods in which the travel time of a pulse is measured, and then this value is converted to VWC readings (Ali, 2009). For a frequency domain reflectometry (FDR) sensor, the capacitance or dielectric permittivity (ε) is measured using two electrodes that are separated by a dielectric material (Ali, 2009).

Moreover, Shock and Wang (2011) discussed the use of matric potential measurements in irrigation scheduling. Soil water potential (ψ) is the sum of the following constituents (Lei et al., 1988; Yong, 1999):

ψ_m	Matric potential
ψ_π	Osmotic potential which is equal to the solute potential
ψ_g	Gravitational potential
ψ_a	Air pressure
ψ_p	Pressure potential

ψ_p and ψ_a can be overlooked in unsaturated soils (Shock and Wang, 2011); ψ_g can be ignored if the depth of the soil is approximately the same; in non-saline soils, ψ_s is significantly less than ψ_m (Baker and Frydman, 2009). Therefore, soil water tension (SWT) is essentially equal to ψ_m (Lei et al., 1988). Tensiometers are used for irrigation scheduling and directly measure ψ_m. A tensiometer consists of a water-filled tube with a porous tip and a vacuum gauge. The number of tensiometers required to establish the average SWT at a site and to make comparisons between sites depends on the variability of tension from point to point in the soil (Webster, 1966). Also, if tensiometric data is unavailable, SWT can be estimated through physical parameters such as soil texture and organic matter content (Saxton and Rawls, 2006).

Watermark sensors are granular matrix sensors that measure the resistance between two highly corrosion resistant electrodes. The Watermark Monitor (Irrometer Co., Riverside, CA) correlates the resistance to kPa of SWT using temperature. The most common calibration equation used for relating resistance to SWT was developed by Shock et al. (1998):

$$kPa = (-3.213*R - 4.093) / (1 - 0.009733*R - 0.01205*T) \quad (2)$$

where R is the resistance in kilohms, and T is the temperature in °C. This equation is valid for 10-100 kPa, and linear interpolation is typically used when the tension is outside these bounds. Temperature sensors can be installed at the exact location as the Watermark sensors to be inserted in the calibration equation, or a default temperature of 24 °C can be used. The Watermark sensor requires no on-site calibration, and when installed in the soil, it exchanges water with the surrounding soil, thus staying in equilibrium with it. Specifically, water flows from the soil into the sensor when the soil outside is wet and has a lower tension than the sand inside the sensor. In contrast, water flows from the sensor into the soil when the soil outside is dry and has a higher tension than the sand inside (Rix et al., 2021).

Table 1 provides a description of SWT ranges for the Watermark sensor as defined in the manufacturer manual. Additionally, Table 2 displays descriptions of SWT ranges in medium textured soils by Shock et al. (2013).

Table 1. Watermark Manual Soil Water Tension Guidelines					
Range (kPa)	**Description**	**Range (kPa)**	**Description**	**Range (kPa)**	**Description**
0-10	Saturated soil	30-60	Usual range for irrigation (most soils)	100-200	Soil is becoming dangerously dry for Maximum production. Proceed with caution!
10-30	Soil is adequately wet (except coarse sands, which are beginning to lose water)	60-100	Usual range for irrigation in heavy clay		

Table 2. Soil Water Tension Guidelines for Medium-Textured Soils			
Range (kPa)	**Description**	**Range (kPa)**	**Description**
0-10	Soil is saturated	20-60	Average field SWT prior to irrigation, varying with the crop, soil texture, weather pattern, and irrigation system
10-20	Soil is near field Capacity	80<	Soil dryness
Table by Shock et al. (2013**)**			

Watermark sensors have been widely used in the field. As part of the Dolores Project in southwestern Colorado, Watermark sensors were installed to assist irrigation scheduling in 13 crop fields in 1997 and 12 alfalfa fields in 1998 (Berrada et al., 2001). In several fields surveyed, the Watermark data were more informative of water availability, crop condition, and yield estimates than the water budget approach. The sensors were responsive to wetting and drying cycles appropriately. The authors noted that the sensors are limited in reading soil water tension values wetter than 10 kPa in coarse-textured soils, further described by Shock et al. (2003).

SWT irrigation points highly depend on the soil texture. For example, for silt loam soil, Irmak et al. (2006) recommend initiating irrigation once SWT from the Watermark sensor is in the range of 100-120 kPa. When SWT is 25-45 kPa, PAW is 50% depleted in coarse-textured soils, which signifies that irrigation should be triggered (Sharma, 2019). Herrera and Sammis (2001), specialists from New Mexico State University, suggest applying irrigation water before 50-60% of PAW is depleted. For row crops in Mississippi soils, Krutz et al. (2014) recommend initiating irrigation once the Watermark sensor is in the range of 80-100 kPa. Other factors that determine when to begin irrigation include irrigation capacity or type and crop growth stage. Roach and Gholson (2015) provide additional guidance on interpreting Watermark data from sensors installed in the root zone. The authors noted that, after Watermark sensor installation, the readings at 15, 31, and 61 cm deep might read values such as 5, 3, and 0 kPa, respectively. After a week of no water application through irrigation or rainfall, the SWT values for these depths may read 50, 40, and 0 kPa, respectively. This would indicate that the sensor at 61 cm is out of the crop's root zone since plant uptake is not occurring and the SWT is not increasing. The zone is not constant over time, thus additional Watermark sensors would need to be installed in the future. As discussed by Irmak et al. (2016), Watermark sensors installed at 301, 61, and 91 cm will give a good sign of soil water status in the root zone of most agronomic crops.

Irmak et al. (2016) recommend initiating irrigation when there is a 35% depletion of the total soil water holding capacity per foot of soil layer. These irrigation points were dependent on soil texture, as displayed in Supp. Table 1. As previously mentioned, irrigation initiation points also depend on the crop and type of irrigation system. Some crops are more drought resistant than others, and some irrigation systems apply water quicker than others. SWT irrigation criteria are available for onion bulbs (Coelho et al., 1996; Hegde, 1986), potatoes (Shock et al., 1993; Lynch and Tai, 1989), and many other crops such as corn (Rhoads and Stanley, 1973) and romaine lettuce (Aggelides et al., 1999).

Furthermore, the soil water characteristic curve (SWCC) relates moisture content and matric potential (or SWT) (Fig. 1). Numerous equations have been developed to create soil water characteristic curves (Mohammadi and Meskini-Vishkaee, 2012; Van Genuchten, 1980; Brooks and Corey, 1964; Campbell, 1974; Vereecken et al., 2010). Datta et al. (2017) explained that, "The relationship between VWC and SWT is not linear, with most VWC changes occurring at SWT values of zero to 300 kPa. Beyond 300 kPa, the soil is too dry for the roots of most plants to extract water, and VWC changes per unit change in SWT are significantly smaller." Understanding soil water thresholds is crucial for evaluating soil water content in irrigation scheduling, as these VWC thresholds indicate the availability of soil water for crop uptake.

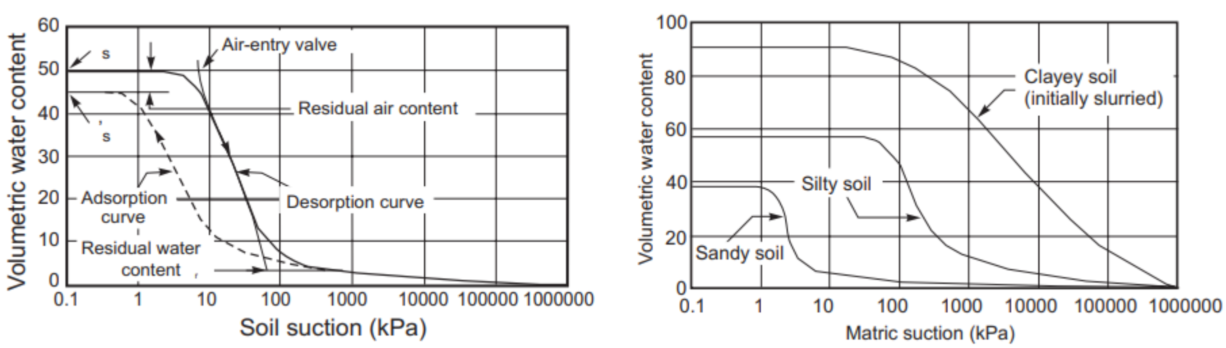

Figure 1. Soil Water Characteristic Curves (Fredlund and Xing, 1994)

Hendrickx et al. (1990) examined the relationship between soil water content and SWT. They noted that variability between the two are quantitatively related by the slope of the soil water retention curve. Soil water characteristic curves are unique to a specific soil type. The more clay in a soil at a given suction, the greater the water content. The pores of sandy soil drain over a small range of suction pressures, which is why the curve is steeper. In sandy soil, the pores are relatively large and once these large pores are emptied at a given suction, only a minimal amount of water remains. In clay soil, a significant change in the water potential is required to remove the same amount of water as in sandy soil. One of the reasons for this is the high surface area of clay soils, leading to more water being adsorbed via electrostatic forces (Bilskie and Campbell Scientific, Inc., 2001).

SWCCs have a hysteresis like character and this relationship is different for drying and wetting processes (Novák and Hlaváčiková, 2019). Some reasons for this are nonuniformity of individual pores (ink bottle effect), connectivity of pores during the wetting and drying phase, and air entrapment (Izady et al., 2008). The endpoint of the adsorption curve may differ from the starting point of the desorption curve because of hysteresis (Fredlund and Xing, 1994). Air entrapment happens during the rewetting process and small pockets of air become trapped in the pore spaces. Because of this, the soil cannot be fully saturated during the rewetting process and will reach a water content lower than the saturated water content (Ochsner, 2019). During the desorption process, one takes a saturated soil sample and applies specific suctions and takes the water content at the various suctions. During the adsorption phase, one gradually wets an initially dry soil. The moisture content at each water potential is higher during desorption than adsorption, as shown in Figure 1. To summarize, soil can have different water contents at the same matric suction depending on whether the water content is achieved through the drying or wetting curve (Or and Tuller, 2004). Thus, the quantity of water that the soil can retain at a particular suction is a function of the drying and wetting history of the soil (Or and Tuller, 2004). For simplicity, hysteresis is often ignored because creating various SWCCs can be laborious and expensive (Royer and Vachaud, 1975).

Obreza et al. (1997) determined soil-water characteristics curves for four soils in the flatwoods citrus groves in southwest Florida (Hendry and Collier counties) and two ridge groves in central Florida, specifically in Polk County. Recommendations were made to use FC values of 5 and 8 kPa for ridge and flatwood soils, respectively. These values are in stark contrast with laboratory measurements of FC, which as aforementioned, are 10 kPa for sandy soil and 33 kPa for medium or fine-textured soils. This relates to the point by Liang et al. (2016), that these thresholds may not be applicable to all soils. Soil texture is relevant in this case because a very slight increase in matric potential (drier soil) generates a more severe drop in VWC in fine sandy soil than in other soil types, as also indicated by Hendrickx et al. (1990).

Plant-Based Irrigation Scheduling

Plant water status measurements can benefit irrigation scheduling (Clark et al., 1970). If plants are under significant water stress, photosynthetic activity completely ceases, and thus plant death occurs (Ghorashy et al., 1971). It is recommended to use soil VWC sensors combined with stem water potential (SWP) measurements to get an overall idea of the soil profile and plant. SWP is often measured in the field using a pressure chamber which measures the magnitude of the pulling force required in a plant to extract water from the soil and transfer it to the leaves (UC Davis). The most valuable time to take SWP measurements for irrigation scheduling is at midday (1300-1500 HR) when the level of tension is typically at its maximum for the day (UC Davis). A drawback of SWP is that it does not allow for temporal comparisons. The measured value becomes impacted by soil water availability and climatic conditions on the measurement day (Suter et al., 2019). Because of this, some models allow for the comparison of SWP values across temporal scales under predefined reference climatic conditions (air temperature) and seasonality (day of the year) (Suter et al., 2019).

The original pressure chamber built by Scholander et al. (1964) and coined the Sholander Pressure Chamber can be used to measure predawn and midday leaf SWP. Predawn leaf water potential (PLWP) measurements are taken before sunrise. They are assumed to be in equilibrium with the soil water potential due to no transpiration, but this is not always the case. Due to contradicting literature, PLWP is generally not used as the only source for irrigation scheduling. For example, Améglio et al. (1998) noted that PLWP measurements are not recommended as an irrigation tool for crops in areas with heterogeneous soil humidity and low volume irrigation (i.e., drip). Also, a significant reason for the lack of usage of PLWP measurements in irrigation scheduling is the time that pressure chamber measurements must be taken. Results from a study from Donovan et al. (2001), in which various plant species were sampled and LWP, soil water potential, and xylem pressure potential were measured, concluded that for 15 of the species, the predawn LWP was significantly more negative than the predawn soil water potential, therefore they were not in equilibrium. Likewise, midday LWP measurements are not recommended as an irrigation scheduling practice due to microclimate fluctuations surrounding the leaves (Deloire et al., 2020).

Midday SWP measurements were previously used for irrigation scheduling for various crops such as apples, almonds, pears, and olives (Shackel, 2011; Naor, 2000). Moriana et al. (2012) irrigated olive trees based on midday SWP threshold values of - 1.2, -1.4, and -2 megapascal (MPa). In cherries, SWP has correlated with leaf stomatal conductance and shoot growth rates, with shoot growth stopping once midday SWP dropped between -1.5 and -1.7 MPa (Shackel et al., 1997). For midday SWP measurements, the leaves near the trunk are covered with an aluminum foil or mylar bag for a specific amount of time before being placed in the pressure chamber. Consequently, this stops transpiration and allows the SWP to equilibrate with the LWP. At midday, plant transpiration and photosynthesis rates are at a maximum. Begg and Turner (1970) used a pressure chamber to measure LWP and SWP in field-grown tobacco. For the midday SWP measurements, a polyethylene bag covered with aluminum foil was placed on the leaf and left on overnight to prevent transpiration. McCutchan and Shackel (1992) followed similar steps on prune trees. Bagging the leaves overnight can be inconvenient because it requires two trips to the study site. On pecan orchards, midday SWP values have also been utilized for irrigation scheduling (Othman et al., 2014; Deb et al., 2012; Wells, 2017b; Wells, 2015). Fulton et al. (2001) recommend to, considering similar environmental conditions across an orchard, sample one leaf per tree for ten trees to get an idea of the average water stress from midday SWP. For orchards with variable conditions, additional measurements should be taken. Also, the authors concluded that a bagging period of 10 minutes or longer was deemed appropriate for accurate SWP measurements.

Pecan Irrigation and Water Requirements

Irrigation leads to a 300% increase in growth for young pecan trees (Wells, 2017b). Microirrigation (drip and microsprinkler) is recommended to apply water to the root zone of pecan trees efficiently. Microsprinklers wet a more extensive root zone area and require more water application than drip irrigation due to higher evaporation losses. Drip irrigation systems can reach efficiencies of 90 to 95% (Bresler, 1990). While this may be true, drip systems can have issues with being clogged. The uniformity with which water is dispersed throughout a microsprinkler irrigation system determines its efficiency (Mane and Ayare, 2013). Microsprinklers are typically 85-90% efficient. Special consideration is needed when selecting an irrigation system as overirrigating pecan trees have downsides such as leaching of nutrients out of the root zone, deep percolation (water losses), higher energy costs due to pumping, and waterlogged soils (which may lead to pecan scab) (Heerema, 2021). Waterlogged soils in young trees can lead to roots dying from a lack of oxygen.

Regarding total water needs, they vary due to factors such as region, tree age, soil texture, and type of irrigation. The differences in the literature indicate the need for local research into pecan irrigation requirements. In Georgia, mature trees need as much as 152 cm of total water per year, with an average rainfall of around 127 cm (Wells, 2016). Note that a large portion of this rainfall is lost to evapotranspiration, but rainfall may supplement 30 to 50% of the water requirements for Georgia pecans (Wells, 2014). Also, during the kernel-filling stage, irrigation is needed due to substantial water uptake, and rainfall will not be sufficient. In the western part of the U.S., Miyamato (1983) estimated that mature trees need around 99-130 cm of total water per growing season.

Wells (2015; 2017b) provides current irrigation recommendations for Georgia's mature and young pecan trees. To summarize Wells (2015), in southeastern U.S. conditions, reduced irrigation during the early season (April-July) is sufficient for mature trees. Still, during the kernel-filling stage, increased irrigated water application is needed. For mature trees in Georgia during the kernel-filling stage with drip irrigation, Daniell (1979) recommends applying 22450 L/ha/day, although this study was done in heavy clay soil. 46770 L/ha/day may lead to higher yields in some soils (Wells et al., 2017).

Wells (2016) notes that mature trees may require up to 1325 L/day during the nut filling stage. McEachern (1995) estimates that mature trees require over 1083 L/day. Table 3 from Wells (2016) displays the current recommended pecan irrigation schedule for mature trees in Georgia with microirrigation based on Wells (2015). The water requirement is not constant across the growing season. The capacity of the drip and microsprinkler irrigation system is at

100%, supplying 33674-37416 L/ha/day during the kernel-filling stage. As aforementioned, during these months, water stress is at its highest, and stress is not just a function of soil moisture but a function of the crop load. It is currently recommended that mature pecan trees in clay soils receive the lower end values in Table 3, and trees in more sandy soils should receive water amounts on the higher end of the range.

Table 3. Mature Georgia Pecan Irrigation Schedule

Month	L/ha/day	Percent of Full Capacity (%)
April	6061-6735	18
May	8755-10102	27
June	12123-13470	36
July	15153-16837	45
August	33674-37416	100
September	33674-37416	100
October	13470-14966	40

Table from Wells (2016)
** Notes: Turn off irrigation for three days if it rains 2.5 cm or more from budbreak to the onset of kernel filling. Through the kernel filling stage, turn irrigation off if it rains 5.1 cm or more (Wells, 2014).

In Wells' (2017b) study on young pecan trees in southeastern U.S. conditions, trees receiving microsprinkler applications of 303 L/week (80 gal/week) had significantly more growth than non-irrigated trees. The main recommendation from this study was that microsprinkler applications of 303 to 379 L/week (80-100 gal/week) and drip irrigation applications of 182 L/week (48 gal/week) are sufficient for 1 to 3-year-old young pecan trees. Sandier soils might need up to 651 L/week (172 gal/week) from microsprinkler irrigation during dry periods. Specifically, on young trees in loamy sand and sandy loam soils until year five, 379 L/week is recommended.

Tables 4 (Acebes-Doria et al., 2020) and 5 (modified from Johnson et al., 1994) display recommended irrigation schedules for young trees in Georgia and Galveston, Texas. Table 4 mainly applies to loamy sandy soils, and Table 5 to general well-drained soils. If prolonged drought conditions are present, irrigation may need to continue into the winter. These data are meant to be used as guidelines and show the effect of regional differences. The Johnson et al. (1994) recommendations are similar to those from Millican (2020) and Stein (1995).

Table 4. Young Georgia Pecan Tree Irrigation Schedule (L/Tree/Week)

Late March-May	June-September	October
379	379-492	Turn off irrigation

Table from Acebes-Doria et al. (2020)
**Notes: For 1 to 3 year old trees

Table 5. Young Texas Pecan Tree Irrigation Schedule in Well Drained Soil (L/Tree/Week)

Tree Age	April -May	June	July-August
1st year	26	53	79
2nd year	53	106	212
3rd year	106	212	424
4th year	212	424	848

Table modified from Johnson et al. (1994)

Soil and Root System

For optimal growth, pecan trees need well-drained soil, preferably those with a clay subsoil and a texture with sand such as sandy loam (Wells, 2017a). Specifically, Rosborough et al. (1950) recommend 0.46 to 0.91 m of sandy soil overlying a porous clay subsoil. Soil survey maps should be used to gain detailed information about characteristics such as slope, saturated hydraulic conductivity (K_{sat}), and soil texture. Pecan roots in sandy soil may reach 2.74-3 m depth, but only 0.91-1.83 m depth for other soils (Wells et al., 2017). However, roots rarely grow deeper than 1.52 m in pecan orchards in Georgia (Woodroof JG and Woodroof NC, 1934). Because of the differences in root growth and water holding capacity, trees with distinct soil textures should have different irrigation schedules. Due to the higher water holding capacity of clay soils, there should be longer intervals between irrigations than sandy loam soil (Herrera and Sammis, 2001).

A significant part of irrigation is understanding the effective root zone, which depends on the crop, fertility management, and soil texture. The effective root zone contains the main body of roots and is where most of the water is stored in the soil. Approximately 70% of the water extracted by a crop's root system is acquired in the top half of the root zone; 20% of the water from the next 25%; 10% of the water from the bottom 25% of the root zone (USDA, 2005). According to Herrera and Sammis (2001), "The depth for soil moisture management in irrigation (91 cm for pecan orchards) often is referred to as the "effective root zone" or the "effective rooting depth." Generally, depth containing about 80% of the total root mass is used to estimate effective root depth. Of that depth, about 40% of the total water requirement comes from the top one-fourth of the effective root zone." Wells (2016) states that pecans take up most of the water in the upper 81 cm.

Furthermore, the pecan root system consists of a taproot, lateral root, and feeder/fibrous roots. As explained by Woodroof JG and Woodroof NC (1934): "(1) Taproots grow straight down and determine the depth of penetration of the roots under the particular conditions; (2) lateral roots usually grow in a horizontal direction straight from the tree at a depth of from 30.5-61 cm and determine the lateral spread of roots under the existing conditions; (3) fibrous roots, grow in all directions from the laterals. Fibrous roots are subject to constant dying and replacement because of varying growing conditions; mycorrhizal roots, which are a type of fibrous roots and grow in dense masses throughout the entire area in which roots are growing."

In the first three years, the tree develops a root system and trunk, and in year four, larger scaffold limbs are developed (Sawyer, 2019). During the third year, the height of the tree, depth of taproot, and spread of laterals are approximately equal (Woodroof JG and Woodroof NC, 1934). In a cultivated pecan orchard, the region in which roots are most dense is usually from 30-46 cm below the soil surface (Woodroof JG and Woodroof NC, 1934). According to Wells (2017a), most pecan roots are concentrated in the top 15-46 cm of soil and are most dense near branch tips. Regarding the lateral roots, most of them occur in the upper 91-122 cm of soil for mature trees. Roots of mature pecan trees generally grow to about twice the spread of the branches (Wells et al., 2017; Byford, 2005). Pecan orchards in Georgia have numerous roots within the top 45-60 cm (White and Edwards, 1978).

The young tree root system consists of small and large roots, with most of the small roots being associated with mycorrhizal fungi (Woodroof JG and Woodroof NC, 1934). In the third growing season, the pecan roots reach as far laterally as the tree is tall. Figures 2 and 3 from Woodroof JG and Woodroof NC (1934) exhibit the root spread of 6 and 12 year old pecan trees. The circle on these figures shows the orientation of the largest lateral roots. After five years, tree growth occurs in all directions, but there is minimal additional root deepening. Notice the differences in lateral root growth between the two figures.

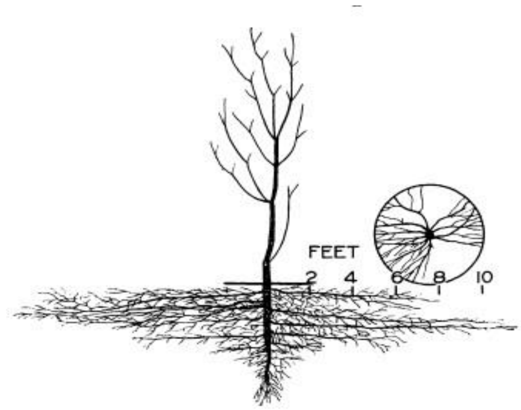

Figure 2. Root Spread of 6 year old Pecan tree (Woodroof JG and Woodroof NC, 1934)

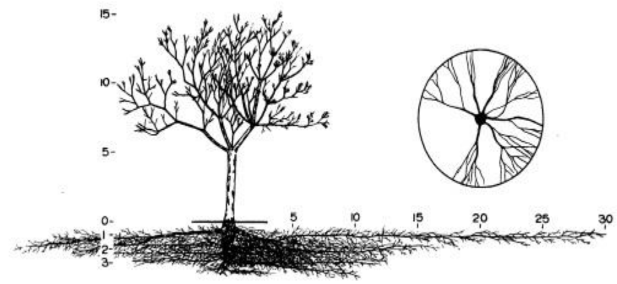

Figure 3. Root Spread of 12 year old Pecan Tree (Woodroof JG and Woodroof NC, 1934)

In addition, root growth is not constant throughout the growing season: early season root growth (April-May) occurs in the upper 46 cm of the soil profile; mid-June growth in the upper 30 cm; July and August growth occurs below 30 cm; root growth in October has all but stop, but minimal root growth may occur at 76-107 cm deep (Wells et al., 2017). In the winter months, root growth is minimal and will generally not occur below soil temperatures of 18 °C (Wells, 2017a).

Ground Penetrating Radar

Ground penetrating radar (GPR) works by using an antenna to send short pulses of very high frequency electromagnetic energy into the soil and then recording the resulting echoes due to the dielectric contrast between two materials. If the two materials are soil and water, for example, there is a high dielectric contrast, and the reflection strength will be large and noticeable. Soils with high electrical conductivity and dielectric permittivity, such as clay, restrict penetrating depth; thus, penetration depth of GPR is inversely related to clay content (Doolittle).

GPR is commonly used for surveying subsurface materials such as metal or PVC pipes and underground utility lines. GPR has been used to detect tree roots and is sufficient for mapping coarse root systems. Plant root research using GPR is currently focused on coarse roots because the minimum detectable root size is 0.25-0.5 cm for high frequency antenna (1500-2000 MHz) (Cui et al., 2011; Wielopolski et al., 2000). Hruska et al. (1999) mapped the coarse (> 3 cm diameter) root system of 50 year old oak trees. Butnor et al. (2001) used GPR to detect tree roots across various soil textures in the Southeastern United States with 400 MHz and 1500 MHz antennas. Roots in soils with high clay content, like in the Piedmont region, were difficult to decipher and penetration depth was limited. GPR in sandy soils led to greater resolution. The 1500 MHz antenna gave the best resolution and was able to detect roots as small as 0.5 cm in diameter. GPR resolution is, "The smallest object that can be individually sensed from other objects" (Liu et al., 2018). The authors listed four factors that affect detecting tree roots with GPR:

- Electromagnetic gradient existing between a root and the soil
- Size, shape, and orientation of a root
- Presence of scattering bodies within the soil
- Antenna frequency

Scattering bodies such as rocks can make it difficult and impossible to identify closely spaced roots and can cause interference. With regards to antenna frequency, the lower the frequency, the large the penetration depth, but the lower the resolution of shallow objects. Higher frequencies allow for greater resolution and detecting shallow objects.

As aforementioned, GPR is thought to be ineffective in locating fine crop roots of less than 2 mm in diameter (Pierret et al., 2005; Pauli et al., 2016). A study by Liu et al. (2018) was the first to indicate the GPR can detect agricultural fine roots and measure fine root characteristics at a bulk soil level. A 1600 MHz antenna was used to scan for roots of winter wheat and energy cane.

CHAPTER 3. SITE DESCRIPTION AND METHODOLOGY

Site Description

Table 6 illustrates the location, dominant soil texture, age of trees, and irrigation of each site. Historical average weather data for the three sites are shown in Supp. Table 2. Site 1 is in the Piedmont region of Georgia, specifically in the city of Bogart. Soils on the site have a medium and moderately fine texture with typical available water holding capacities of 1.45-2.08 mm of water/cm of soil (Keller and Bliesner, 1990). The trees are of Lakota, Cape Fear, and Caddo varieties. The tree spacing is 12.2 m between rows. The average total precipitation for the city is approximately 128 cm (georgiaweather.net). The average maximum temperature ranges from 11 °C in January to 32 °C in July, and the average minimum temperatures range from -0.4 °C to 20 °C during the same months.

Table 6. Study Sites Described

Site	Location	Dominant Soil Texture	Age of Trees (years)	Type of Irrigation	Size (ha)
1	Oconee County	Clay Loam/Sandy Clay Loam	Young (<3)	Microsprinkler	26
2	Toombs County	Loamy Sand	Young (<2)	Microsprinkler and Drip	2
3	Hancock County	Sandy Loam	Young (<4) and Mature trees (>50)	Microsprinkler and Subsurface Drip	30

During the 2021 growing season on Site 1, irrigation was turned on mainly on Mondays and Thursdays for a total of 303 L/tree/week, as recommended by Wells (2017b). Each tree received water from two microsprinklers at 38 L/hr for two hours. The microsprinklers are manufactured by Bowsmith (Exeter, CA) and are Fan-Jet PC series model PC-10 (blue/black) with a violet nozzle corresponding to 10 psi. The spray pattern is full circle alternating high/low trajectories with an approximate diameter of 4.57 m. Using equation (3):

$$Q*T = A*d \tag{3}$$

where Q = flow rate (m^3/hr), T = time (hours), A= area (m^2), and d = depth (m), gives the depth of water application of each microsprinkler for two hours as 0.46 cm, assuming 100% efficiency (0.38 cm assuming 85% efficiency). On Site 1, irrigation was turned on during other days, but this was primarily the regular irrigation schedule. Irrigation is divided up into two phases, where one half of the farm receives irrigation on a different schedule. This is because half of the trees are currently three years old, and half are two years old. The farm owner carefully observed the weather forecast and delayed irrigation when rain was expected. During the 2022 growing season, irrigation started in late April with a schedule of every other day for 1 hour and 15 minutes. After testing the output of various microsprinklers, the output was closer to, on average, 56.8 L/hr. This equates to 0.38 cm applied for each irrigation event, assuming 100% efficiency (0.33 assuming 85% efficiency).

Site 2 is in the Coastal Plains region of Georgia, in Lyons, Ga. Specifically, it is located at the UGA Vidalia Onion and Vegetable Research Center (32°01'09.7" N, 82°13'11.8" W). The soils are Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). The trees are of 10 different low input varieties. The average total precipitation for the city is approximately 130 cm (U.S. Climate Data). The average maximum temperature ranges from 16 °C in January to 34 °C in July, and the average minimum temperatures range from 2 °C to 22 °C across the same months. Unlike Site 1, Site 2 runs on one schedule for all the trees on site. The tree spacing is 25 feet in the row and 50 feet between rows. The soils on this site are of coarse texture, with typically available water holding capacities of 0.62-1.04 mm of water/cm of soil (Keller and Bliesner, 1990). The microsprinklers are set in the row, 1.2 m from the tree. The microsprinkler spray pattern is similar to that at Site 1 and covers a diameter of 5.5 m and supplies 113.6 liters/hr. The brand name is Maxijet (Dundee, Fl). For the trees with microsprinkler irrigation, there is only one per tree. During the growing season in 2021, irrigation was turned on approximately 4 hours per day. This schedule was set by the irrigation system installer. Using equation (3) with 100% efficiency, each microsprinkler applies 1.91 cm (1.6 cm assuming 85% efficiency) of water at each irrigation event. The drip irrigation output at Site 2 was measured with a bucket, and the output was 5.3 L/hr. Irrigation for Sites 1 and 2 was turned off in November. During early in the 2022 growing season (study ended June 1, 2022), irrigation started on May 5th and ran MWF at 16:00 for four hours. This corresponds to a microsprinkler application, without removing for inefficiency, of 1362.8 L/week. The maximum rate possible on Site 2 in 2022 was set to 37416 L/ha/day.

Site 3 is in Sparta, Ga, along Georgia's fall line, separating Piedmont from the Coastal Plains region. Because of this, the soils in the area are unique and do not fall into Piedmont or Coastal Plains soil categories. The soils are mostly moderately coarse textures with available water holding capacities of 1.04-1.45 mm of water/cm of soil (Keller and Bliesner, 1990). The dominant soil type is Pacolet sandy loam (Fine, kaolinitic, thermic Typic Kanhapludults). The young trees are Cape Fear variety, and the mature trees are Stuart. The average annual total precipitation for the city is approximately 118 cm (georgiaweather.net). The average maximum temperature ranges from 12 °C in January to 33 °C in July, and the average minimum temperatures range from 0.3 °C to 21 °C across the same months.

The young trees run on microsprinkler irrigation, while the mature trees have subsurface drip irrigation on one side of the tree. The microsprinklers apply 68.1 L/hr, and the subsurface drip irrigation system supplies 1.7 L/hr, with an emitter every 30.5 cm. The spray pattern for the microsprinkler is a 1/2 circle, and the brand name is TeeJet Technologies (Tifton, GA). The mature trees were harvested in November. Irrigation was cut off when soil moisture sensors were installed on site. Tree spacing is 18.3 m in rows and between rows. In the early 2022 growing season (study ended June 1, 2022), irrigation ran seven days a week for three hours per day, equating to 1431 L/week for the microsprinklers.

Some years ago, on Site 1, topsoil was applied on the surface of the entire orchard, which means the surface texture was possibly altered. Web Soil Survey cannot account for these intricate site-specific details. Refer to Supp. Table 3 for soil texture throughout the soil profile at each tree at each site. Additionally, Table 7 presents FC and PWP data for each site from Web Soil Survey. These data are not exact but still follow a particular trend. Site 1 has a higher VWC at FC and PWP due to its higher clay content than the other two sites. The FC and PWP values in Table 7 are reasonable, as they are in the ranges of values you would typically see in literature for the reported soil textures (Datta et al., 2017). Also, for Site 2, Rawls et al. (1982) report an FC of 13% and PWP of 5% for Tifton loamy sand. With regards to K_{sat}, sandy clay loams and clay loams are typically in the range of 2-5.1 mm/hr, and loamy sand and sandy loams in the field of 20.3-61 mm/hr (Panagos et al., 2014). Rawls et al. (1982) report a K_{sat} of 61 mm/hr for loamy sand.

Table 7. Soil Physical Properties (Web Soil Survey)				
Site	**Tree**	**Depth (cm)**	**FC**	**PWP**
1	A	0-18	24.5	17.5
		18-107	33.5	28.3
	B1, B2	0-8	24.3	17.4
		8-66	33.7	25.1
		66-91	21.0	13.3
	C1, C2	0-13	29.5	16.7
		13-91	35.5	25.2
2	A	0-28	14.0	5.4
		28-56	20.8	13.2
		56-152	23.8	17.8
	B	0-28	14.0	5.3
		28-56	20.7	13.0
		56-152	24.8	18.3
3	A, B, C	0-28	14.0	5.3
		28-56	20.7	13.0
		56-152	24.8	18.3

FC = water content at field capacity (at 33 kPa), and PWP = water content at permanent wilting point (at 1500 kPa)

Site 1 (Oconee County)
Site 2 (Toombs County)
Site 3 (Hancock County)

2021 and 2022 Weather Conditions

Weather conditions for the growing months during the 2021 pecan season are exhibited in Table 8 from georgiaweather.net. For April and May 2022, weather data is presented in Table 9. Although root growth may occur in October, it is normally minimal. However, because irrigation was still being applied in October, data for this month is still insightful. During the

2021 growing season from April to September, trees on Sites 1, 2, and 3 received 63.4, 81.8, and 71.4 cm of rain, respectively. Average total precipitation for Sites 1, 2, and 3, based on historical values from georgiaweather.net, are 61.5, 65.9, and 57.5 cm, respectively. Based on this, Site 2 had 15.8 cm of rain greater than the season average, and Site 3, 13.9 cm. For reference, total precipitation for the 2020 growing season for Sites 1, 2, and 3 were 90.7, 80.5, and 92.7 cm, respectively. From April-September 2021, August was the rainiest month for Sites 1 and 3, and July for Site 2.

Table 8. Weather Conditions During Growing Season (2021)

Parameters	Site	Apr	May	Jun	Jul	Aug	Sep	Oct
Average Temperature (°C)	Site 1: Min	8.88	13.39	18.90	20.65	20.98	16.56	12.82
	Site 1: Max	22.06	25.64	29.18	30.35	30.69	27.38	23.29
	Site 2: Min	11.31	15.40	21.12	21.85	22.84	18.79	14.91
	Site 2: Max	24.90	29.02	31.22	32.16	32.07	30.14	26.76
	Site 3: Min	8.79	13.04	19.17	20.80	21.44	16.82	13.49
	Site 3: Max	23.63	27.37	30.39	31.55	31.67	28.52	24.53
Total Precipitation (cm)	Site 1	7.95	11.53	11.28	13.00	12.78	6.86	21.74
	Site 2	7.39	12.88	17.12	20.42	14.73	9.22	9.17
	Site 3	3.71	7.34	15.06	8.51	19.25	17.53	6.32
Number of Rainy Days	Site 1	3	6	15	13	14	11	11
	Site 2	5	4	16	18	15	7	9
	Site 3	4	8	11	12	20	9	9

Table 9. Weather Conditions During Growing Season (2022)			
Parameters	**Site**	**Apr**	**May**
Average Temperature (°C)	Site 1: Min	8.71	15.87
	Site 1: Max	22.11	28.05
	Site 2: Min	12.00	17.81
	Site 2: Max	25.72	30.27
	Site 3: Min	8.80	16.03
	Site 3: Max	23.88	28.90
Total Precipitation (cm)	Site 1	8.33	9.96
	Site 2	9.60	9.83
	Site 3	12.40	7.26
Number of Rainy Days	Site 1	7	5
	Site 2	6	13
	Site 3	4	9

Average minimum and maximum temperatures during the 2021 growing season did not vary significantly from the historical averages. For Site 1, the most significant difference between the average monthly minimum temperature and the historical average was 1.48 °C during August, when the average monthly minimum temperature was greater than the historical average by this amount. For the average monthly maximum temperature, all months during the growing season were slightly less than the historical averages, with a 1.65 °C difference being the greatest in July. On Site 2, the largest difference between the average monthly minimum temperature and the historical average was 1.34 °C also during August, in which the average monthly minimum temperature was greater than the historical average by this amount.

For the average monthly maximum temperature during 2021, like on Site 1, all months during the growing season were less than the historical averages, with a 1.73 °C difference being the greatest, occurring in July. On Site 3, the largest difference between the average monthly minimum temperature and the historical average was 1.33 °C during August, in which the average monthly minimum temperature was greater than the historical average by this amount. For the average monthly maximum temperature, like on Sites 1 and 2, all months during the growing season were less than the historical averages, with a 1.17 °C difference being the greatest, which occurred in July.

For April and May of the 2022 season, total rain on Sites 1, 2, and 3 were 18.29, 19.43, and 19.66 cm of rain, respectively. For comparison, the total precipitation in these months in 2021 on the three sites was 19.48 cm, 20.27 cm, and 11.05 cm, respectively. Compared to the 2021 season, average minimum and maximum temperatures in May at all sites were greater in 2022.

Methods

Weather

Precipitation data were recorded using the ECRN-50 (Meter Group Inc., Pullman, WA), which uses a single-spoon mechanism and tips at 1 mm of precipitation and irrigation; accuracies are ± 2% (Meter Group). Weather data such as precipitation and temperature (minimum and maximum) were also collected for the three sites from georgiaweather.net in 15 minute increments. The closest station to Site 1 was 2.41 km away, to Site 2, 24.14 km away, and Site 3, 9.33 km away.

Field Capacity and Wilting Point Laboratory Tests

To compare FC values from Web Soil Survey, tempe pressure cells (Soilmoisture Equipment Corp., Goleta, CA) were employed. Tempe cells (Fig. 4) consist of plexiglass top and bottom plates and a middle sampling core made of metal which contains the soil as extracted to represent field conditions. They can be used to determine soil water retention characteristics in the 0-1 bar range. First, a porous ceramic plate was placed in the plexiglass bottom to separate the soil sample from the bottom hole through which the water meets the cell. Once the bottom of the plexiglass was assembled, it was placed in a container filled with water to saturate the ceramic plate. The plate was saturated before the soil core was added. The soil in the core was ensured to have contact with the ceramic plate that was in the base and a firm seal around the O-ring. Once the soil core was added to the bottom of the tempe cell assembly, water was added to the container to saturate the sample. For the final assembly, the core was placed into the middle of the two plexiglass parts to make a complete tempe cell that was sealed with O-rings at all connecting parts. The sample was left in water until full saturation was reached (Supp. Fig. 1). Once saturated, the sample was removed from the water and then connected to an air hose that supplied air pressure of 33 kPa for 24 hours. After this time, the air hose was removed, and the tempe assembly was reweighed to determine the field capacity from the soil water content.

Figure 4. Tempe Cell Components (ICT International)

The WP4C (Supp. Fig. 2) was used to determine the permanent wilting point. Using the WP4C, the method developed by Meter Group determines the relative humidity of the air above a sample in a sealed chamber (ASTM D6836). Once the sample comes into equilibrium with the vapor, the relative humidity is determined using the chilled mirror method, which involves chilling a tiny mirror until dew starts to form. The first step was placing the soil sample into a cup until the bottom was evenly covered, but headspace was left, and then into the drawer of the instrument. Then a knob was turned to seal the chamber to allow for the dew to form inside the mirrors. As stated in the manual, for an accurate measurement, the sample temperature (Ts) should be close to the sample block temperature (Tb). The WP4C displayed the temperature difference in the sample temperature screen. If the sample was colder than the sample block temperature (Ts-Tb is a negative number), the WP4C waited to start reading until its temperature increased to 1 °C below the sample block temperature. Next, measurements started, and when completed, the WP4C displayed the final water potential and temperature of the soil sample.

Field Saturated Hydraulic Conductivity

Field saturated hydraulic conductivity (K_{fs}) measurements were taken using the SATURO Dual Head Infiltrometer (Supp. Fig. 3) (Meter Group Inc., Pullman, WA). Single and double ring infiltrometers require you to know or estimate the macroscopic capillary length factor, but the SATURO measures infiltration at two different pressure heads to find (rather than estimating or guessing) the soil macroscopic capillary length factor. The setup consists of an insertion ring, infiltrometer, water reservoir, and a control unit. Once water is pumped into the ring, the control unit maintains the ponded water level determined beforehand. There is a pressure transducer inside the ring to measure the height. After the desired soaking period, the instrument measures the infiltration rates (i_1 and i_2) with the ponded water at the two depths (D_1

and D_2). The control system then calculates the field saturated hydraulic conductivity with the infiltration rates. The system creates a run time series, which consists of a soaking period and then followed by two cycles for high and low ponding depths (pressure heads). The software solves for the K_{fs} using equation 4, where i_1 and i_2 represent the infiltration rates, and D_1 and D2 represent the ponding depths. The settings used for the SATURO during each run are displayed in Supp. Table 4.

$$K_s = \frac{\Delta(i_1 - i_2)}{D_1 - D_2} \tag{4}$$

Soil Texture and Organic Matter Tests

Soil samples were sent to the UGA Agricultural & Environmental Services Laboratories (AESL) for soil texture and organic matter tests. For soil texture, the hydrometer was utilized to determine the percent of sand, silt, and clay in the samples. This method is explained further in the literature (Bouyoucos, 1927; Gavlack et al., 2005), but to summarize, under Stoke's law, larger particles settle out of suspension faster than small particles. Particle size can then be determined using the observed hydrometer level after specific amounts of time. The laboratory uses the "loss on ignition" method for three hours at 360 °C to determine the organic matter content. Results of soil texture (% sand, silt, and clay) and organic matter are reported in percentage by weight.

Tree Selection

Supp. Table 5 presents the total number of sensors installed at each site. Site 1 had significantly more sensors installed because each VWC sensor installed was used to measure VWC at one depth, whereas, on Sites 2 and 3, the AquaCheck probe (AquaCheck Ltd, Cape Town, South Africa) installed could measure moisture content at 20, 41, and 61 cm (Supp. Fig. 4). Another reason for this is that only on Site 1 were sensors installed in the middle of the row to see the effect of plant uptake of water on VWC and SWT. Sensors were installed near five trees on Site 1, with each tree being around the same age (1-2 years). Site 1 had three areas used for analysis. At the first area, both Watermark and VWC sensors were installed near the same tree (Fig. 5). At the second and third areas, Watermark sensors were placed next to one tree and VWC sensors next to another (Supp. Figs. 5, 6, 7, 8). Tree A is around 248 m above mean sea level, Tree B1 and B2, 244 m, and Tree C1 and C2, 256 m.

Figure 5. Site 1 Tree A Soil Moisture Sensors

On Site 2, two trees had sensors installed next to them, one tree with microsprinkler irrigation and one with a drip irrigation (Supp. Figs. 9, 10). Tree A with microsprinkler irrigation was roughly 61 m above mean seal level, and Tree B with drip irrigation, 58 m. On Site 3, sensors were placed near two mature trees and one young tree (Supp. Figs. 11, 12, 13). Tree A and B are roughly 164 m above mean sea level, and Tree C, 165 m.

Watermark Installation

During the 2021 growing season, data collection started in early July on Site 1, late July on Site 2, and late September on Site 3. In 2022, data was collected until June 1, 2022. At each site, Watermark 200SS matric potential sensors were installed at 20, 41, 61, and 81 cm, representing the zones where pecans take up most of their water (Wells, 2016). These sensors measure SWT, or the force necessary for plants to extract water from the soil. Soil matric potential (SWT) values are negative, but the negative sign was ignored, and the absolute values used instead. The installation process of Watermark sensors is well defined in previous literature as well as in the Watermark manual (Irmak et al., 2016; Mafuta et al., 2013; Thompson et al., 2006). Before installation, the sensors were solvent welded with ABS to PVC cement to 1.27 cm (1/2 in.) class 315 PVC pipe, which allows for easier installation and removal and protects the sensors wires. A 0.32 cm (1/8 in.) hole about 0.64 cm (1/4 in.) from the end of the PVC pipe was made to allow water to drain if it becomes trapped in the pipe. The sensors were then conditioned by soaking and letting them dry out and repeating this process days before installation. As indicated in the sensor manual, "This ensures quick response to changing soil moisture conditions. If a sensor is only soaked and then installed, several irrigation cycles must pass before it will respond accurately" (Irrometer Co.). During the installation process, a slurry made of soil extracted from the augered hole was poured into the hole to prevent any erroneous readings due to poor contact with the soil. After, the PVC pipe with the attached sensor was installed vertically into the hole at the different depths (Fig. 6). At each site, these sensors were either connected to the Watermark Monitor 900M (Irrometer Co., Riverside, CA) or the Aqua Trac Pro logger (AgSense, Huron, SD).

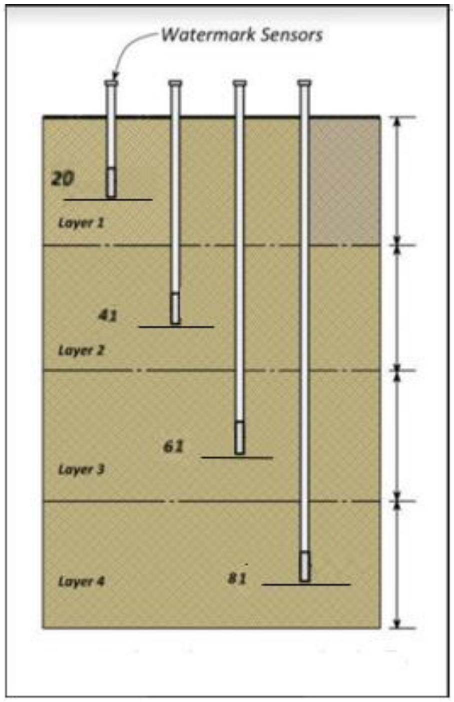

Figure 6. Watermark Sensor Installation at 20, 41, 61, and 81 cm

Data from the 900M monitor were manually downloaded using the WaterGraph software. The logger can hold around 4032 records or 42 days' worth of data recorded every 15 minutes. The initial SWT readings were due to the surrounding slurry, therefore time for soil water conditions to settle was allowed before the data were analyzed. At each site, a temperature sensor was installed next to the trees to be used in the calibration equation to convert resistance to SWT (equation (2)). This was necessary to account for the variations in soil temperature.

Soil Water Content Sensor Installation

At each site, capacitance soil moisture sensors were installed in the root zone of pecan trees at 20, 41, 61, and 81 cm deep. Additionally, at Tree A on Site 1, a 10 cm VWC sensor was installed. The location of installation for all sensors on each site is shown in Supp. Figures 14, 15, and 16.

Further information about the VWC sensors used in this study is displayed in Supp. Table 6. The T12, GS3, 10HS, and 5TE capacitance sensors are manufactured by the Meter Group Inc. (Pullman, WA). The AquaCheck probes are by AquaCheck Ltd (Cape Town, SA). Each sensor manual was referenced for proper installation instructions. When possible, the sensors were inserted horizontally, which interferes the least with the natural flow of water through the soil profile (Fig. 7). At 81 cm on Sites 2 and 3, VWC sensors were attached to a PVC pipe and inserted vertically. The sensors were then connected to the ports on the ZL6 or EM50 data loggers (Meter Group Inc., Pullman, WA) or the Aqua Trac Pro logger. Every logger was set up to record VWC sensor measurements every 15 minutes. Data from the EM50 were downloaded using a Micro-USB communications cable, while data from the ZL6 data logger were accessed via zentracloud.com. The EM50 is powered by five AA batteries, but the ZL6 and Aqua Trac Pro loggers are solar powered. The ZL6 and Aqua Trac Pro loggers were oriented south facing to maximize sunlight. Data from the Aqua Trac Pro were accessed remotely via wagnet.net.

Figure 7. Volumetric Water Content Sensor Installation

Statistical Analysis

SPSS Statistics (IBM Corp, Armonk, NY) was used to analyze descriptive statistics of the soil moisture data points from each site. Specifically, the minimum, maximum, median, mean, and standard deviation of the SWT and VWC data points were determined in SPSS.

Before inputting the data into SPSS, the data were grouped by the type of sensor, tree location, site, and whether the data point was in season or out of season using Microsoft Excel (Microsoft Corporation, Redmond, WA). In season data points were those before October 2021, and out of season those from October to March 2022.

Ground Penetrating Radar

GPR has been used for years for the determination of root diameter, root biomass, and root depth (Liu et al., 2016). This made an attractive option for determining root spread for this study since physical removal of soil was not necessary. With the help of UGA's Department of Anthropology, the SIR-2000 (Geophysical Survey Systems, Inc., Nashua, NH) was used on Site 1 to detect the spatial distribution of pecan tree roots on a three year old and a one year old tree. A 500 MHz antenna was used to transmit electromagnetic waves (pulses) to the receiver, which collected the reflections of objects detected beneath the soil surface. The instrument was gradually moved over the soil surface along specified grid lines. The profile grid was 2 x 4 m. The scanning time was 60 nanoseconds (ns). The process of using GPR at Site 1 is displayed in Figure 8. GPR-SLICE (Ground Penetrating Radar Imaging Software, Woodland Hills, CA) is a unique process that recreates GPR data using estimation algorithms. This was then used to create 2D time slices of the GPR data for both trees.

Figure 8. Ground Penetrating Radar on Site 1

CHAPTER 4. RESULTS

Field Capacity and Wilting Point Laboratory Tests

Table 10 displays the results from the tempe cell FC and the WP4C PWP lab tests. Proper cores and replications are important to get an accurate reading since all the values are interrelated. Site 1 had FC values ranging from 25.31% to 33.69%. On average, Site 1 had the highest average FC and Site 2 had the lowest. Within Site 1, the soils from Tree C1 had an average FC of 28.66%, and from Tree A, 28.84%. Only one sample was collected from Tree B1 due to its close proximity to Tree A, but the FC was 34.88%. Note that the soil texture test from one sample collected near Tree B1 revealed that the texture was clay loam, so 34.88% is a reasonable value. Because of this, the sample had the highest equivalent water depth.

Regarding bulk density, Site 2 had the highest values, with an average of 1.5 g/cm^3. Bulk density increases with profile depth due to changes in organic matter content, porosity, and compaction, but these values represent surface bulk density. Sandy soils have relatively high bulk density since total pore space is less than clay and silt soils. Some samples at Site 1 had higher bulk densities than at Site 3. High bulk densities, usually in sand, can lead to lower porosity and saturated water content.

Table 10. Laboratory Soil Water Retention Data							
Location	Tree	Bulk Density (g/cm^3)	Volumetric Field Capacity (%)	Equivalent Water Depth (cm)	Saturated Water Content (%)	Wilting Point (%)	Plant Water Available (%)
Site 1	Tree A	1.23	27.53	1.65	49.87	6.91	20.62
		1.31	25.31	1.52	45.91	5.94	19.37
		1.24	33.68	2.02	55.84	4.09	29.59
	Tree B1	1.02	34.88	2.09	58.20	11.81	23.08
	Tree C1	1.48	30.19	1.81	41.91	7.61	22.58
		1.41	28.92	1.74	44.71	8.16	20.76
		1.3	26.87	1.61	47.20	7.71	19.16
Site 2	Tree A	1.48	13.66	0.82	43.58	2.51	11.16
		1.45	11.01	0.66	44.19	2.00	9.05
		1.59	16.76	1.01	39.81	3.73	13.03
Site 3	Tree A	1.06	25.76	1.55	58.28	6.18	19.58
		1.28	21.10	1.27	47.84	4.17	16.93
		1.26	22.40	1.34	50.23	5.71	16.69
Site 1 (Oconee County) Site 2 (Toombs County) Site 3 (Hancock County)							

Field Saturated Hydraulic Conductivity

Table 11 displays the K_{fs} results using the SATURO on Sites 1, 2, and 3. On average, Site 2 had the highest average K_{fs}, with a value of 5.5 cm/hr. The averages of Sites 1 and 3 were 4.2 and 4 cm/hr, respectively. The SATURO infiltrometer was ran over 30 times, but a large portion of the runs were invalid due to water leaking through the seal or reoccurring water level errors, even when there was ample water. If there are any leaks through the seal, the readings will be higher than expected because the system will assume that the water infiltrated, when in fact, it leaked out the sides of the infiltrometer head.

Table 11. Field Saturated Hydraulic Conductivity Data		
Site	**Tree**	**Units (cm/hr)**
Site 1	Tree A	5.1
	Tree B1	3.5
	Tree C1	4.1
Site 2	Tree A	5.1, 5.4, 5.9
Site 3	Tree A	3.8, 4.2

Soil Texture and Organic Matter Tests

Table 12 exhibits the results of the surface soil texture and organic matter tests from the UGA Agricultural & Environmental Services Laboratories (AESL). The values in this table represent the soil surface measurements, and the results are in percentage by weight. The percent sand, silt, and clay for each soil sample were plotted on the soil texture triangle (Fig. 9). The red dots in Figure 9 show the soil texture of three samples near each tree used for the study from Site 1. The blue dots represent the soil texture of the samples from Site 2, and the orange dots represent the soil texture from Site 3.

Table 12. Surface Soil Texture and Organic Matter Results
Results are reported in percentage by weight

Site	Tree	OM	Sand	Silt	Clay	Soil Type
1	A	4.25	66.90	20.80	12.28	Sandy Loam
	B1	8.93	40.90	24.80	34.28	Clay Loam
	C1	5.58	54.90	18.80	26.28	Sandy Clay Loam
2	A	1.87	80.8	10.88	8.28	Loamy Sand
	B	5.82	82.8	6.80	10.36	Loamy Sand
3	A	3.93	63.2	30.8	6	Sandy Loam
	B	2.55	83.2	14.8	2	Loamy Sand
	C	3.67	75.2	18.8	6	Sandy Loam

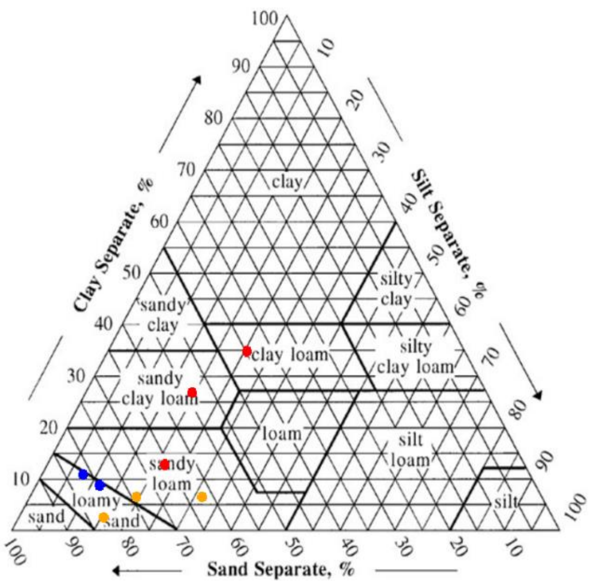

Figure 9. Soil Texture Triangle for Surface Samples
Red dots are for Site 1, Blue dots for Site 2, and Orange dots for Site 3

Most of the soils on Site 1 are clay loam and sandy clay loam, but the soil texture tests showed the spatial differences on Site 1, as well as the differences in the results from Web Soil Survey. The USDA (1987) defines sandy clay loam as having 20-35% clay, less than 28% silt, and 45% or more sand. The soil sample collected next to Tree A on Site 1 was identified as sandy loam. To be labeled sandy loam using USDA classification, there are two paths. First, a soil sample contains 20% or less clay, and the percentage of silt plus twice the percentage of clay exceeds 30 and has 52% or more sand. The second pathway is that a sample contains 7% or less clay, 50% or less silt, and 43-52% sand. The soil sample near Tree B1 was clay loam, meaning it contained 27-40% clay and 20-45% sand, and near Tree C1, sandy clay loam. The soil sample near Tree B1 had the least amount of sand at 40.9%, and as previously mentioned, it needed at least 45% sand to be labeled sandy clay loam. Site A’s sample had too little clay to be labeled sandy clay loam at only 12.28%.

On Site 2, as expected, both samples were loamy sand. Most of the soil on Site 2 is Tifton Loamy sand. To be loamy sand, there are upper and lower limits. For the upper limit, the soil must contain 85-95% sand, and the percentage of silt plus 1.5 times the percentage of clay is no less than 15. For the lower limit, the soil must contain 70-85% sand, and the percentage of silt plus two times the percentage of clay is not greater than 30.

For Site 3, two out of three samples were sandy loam, and one was loamy sand. Sandy loam is the dominant soil texture on the site, but like on Site 1, spatial variations exist on Site 3. Site 3's soils have less clay than Site 2 but have more silt. Soils near Tree B on Site 3 were the anomaly, having a loamy sand texture due to the high percentage of sand.

Moreover, the organic matter content lab test results revealed that the soil sample near Tree B1 on Site 1 had the highest organic matter content at 8.93%. Averaging on a site, Site 1 had an average organic matter content of 6.25%, Site 2, 3.85%, and Site 3, 3.38%.

Soil texture results from Site 1 down to 81 cm are exhibited in Table 13. Results are available for samples collected near Tree A and Tree C1. These samples were sent to the lab before results in Table 12 were received. As expected, the texture is clay from 61-81 cm. The sandy loam texture that appeared in Table 12 is also present, except this time from 0-20 cm. The percent sand, silt, and clay for each soil sample were plotted on the soil texture triangle (Fig. 10).

Table 13. Site 1 Soil Texture Results
Results are reported in percentage by weight

Tree	Depth (cm)	Sand	Silt	Clay	Soil Type
A	Surface	56.8	8.88	34.3	Sandy Clay Loam
	0-20	72.9	10.80	16.3	Sandy Loam
	20-41	42.8	8.72	48.5	Clay
	41-61	36.9	6.88	56.2	Clay
	61-81	32.8	9.04	58.2	Clay
C1	Surface	42.9	12.96	44.2	Clay
	0-20	52.9	12.96	34.2	Sandy Clay Loam
	20-41	54.9	12.96	32.2	Sandy Clay Loam
	41-61	34.9	6.96	58.2	Clay
	61-81	36.9	14.88	48.2	Clay

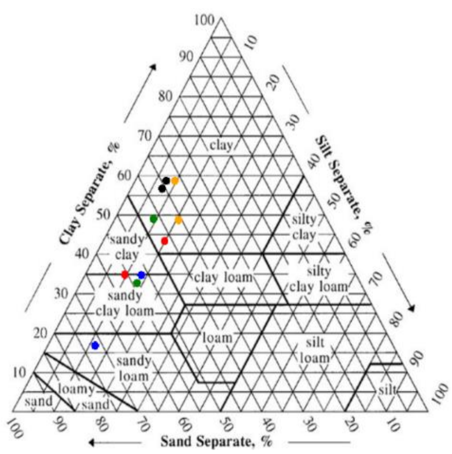

Figure 10. Soil Texture Triangle for Site 1.
Red dots are for surface, Blue dots for 0-20 cm, Green dots are for 20-41 cm, Black dots are for 41-61 cm, and Orange dots for 61-81 cm

Watermark Sensor Data for the 2021 Growing Season

Site 1 (Oconee County)

Table 14. Site 1 Watermark Statistics

Depths (cm)	In season (kPa)						Out of season (kPa)*					
	n	min	max	median	mean	std	n	min	max	median	mean	std
Tree A[1]												
20	8096	9	239	99	119	86	13539	4	239	19	54	60
41	8096	2	95	21	25	21	13539	3	71	8	17	16
61	8096	0	158	55	62	48	13539	5	120	21	40	35
81	8096	0	126	38	50	40	13539	1	68	10	22	20
Tree B1[2]												
20	1778	8	224	22	36	41	15776	3	181	17	33	37
41	1778	1	132	19	28	28	15776	1	129	15	30	31
61	1778	1	77	37	37	23	15776	7	31	20	20	6
81	1778	4	70	38	37	18	15776	3	114	27	36	26
Tree C1[3]												
20	8783	2	239	138	137	96	17470	1	183	15	54	60
41	8783	0	192	60	67	50	17470	0	75	9	22	22
61	8783	1	86	33	36	21	17470	0	62	10	20	17
81	8783	2	57	31	31	12	17470	1	68	15	25	17

[1]: July 8-September 30, 2021
[2]: September 12-September 30, 2021
[3]: July 1-September 30, 2021
*Out of season values are from October 1, 2021, to March 31, 2022 (gaps in data are due to data logger malfunctioning)

Hourly soil water tension data during part of the 2021 growing season for each tree are displayed in Supp. Figures 17, 18, and 19. Rainfall throughout the study period is shown on the secondary y-axis. There are five bands on the graphs, each representing the ranges in Table 1: 0-10 kPa, 10-30 kPa, 30-60 kPa, 60-100 kPa, and > 100 kPa. While the goal would be to keep moisture between FC and the 50% MAD, without a specific SWCC for the soils at Site 1, this is unattainable. Using ranges from Table 1 and Table 2 is a feasible option without exact threshold values due to the soil texture differences on Site 1, but for the soils on Site 2, exact thresholds are available from Liang et al. (2016).

Statistical data for each sensor are displayed in Table 14. The fluctuations of SWT throughout the growing season were due to factors such as rainfall and/or irrigation as well as evapotranspiration. SWT decreased with water application and increased because of plant uptake. At this point during the growing season, the sensors had already been in the soil for about two weeks, thus they were acclimated to wetting and drying cycles.

Tree A at Site 1

The 20 cm sensor had the most variability, with a standard deviation (SD) of 86. Due to the skewness in the data, the median is a better measure to describe the distribution of the data than the mean for the 20 cm sensor because there are a significant number of outliers near 239 kPa. This is because, on numerous occasions, the tension went in the danger zone above 100 kPa, meaning the soil was dangerously dry. The mean of the 20 cm sensor is 119 kPa and the median 99 kPa, meaning the data set distribution is skewed right. Thus, the time periods during the growing season where the tension was 239 kPa led to a higher mean. With a median of 99 kPa, the 20 cm sensor was considerably dry, near the 100 kPa danger zone. For the 41, 61, and 81 cm sensors, the medians were 21, 55, and 38 kPa, respectively. The 41 cm sensor stayed relatively wet, with an average kPa of 25, which is near field capacity. The averages of the 61 cm and 81 cm sensors were higher than the 41 cm. Also, the 61 cm and 81 cm sensors reached maximums of 158 kPa and 126 kPa, respectively, on September 14th and within 30 minutes of each other. This was the hottest day of the month, with a maximum temperature of 31 °C. The 41 cm sensor only had a maximum of 95 kPa, which occurred on September 13^{th}, the second hottest day of the month.

A noticeable trend from Supp. Figure 17 is the drying out of the 20 cm sensor to near or at the maximum of 239 kPa on multiple occasions. The first time this happened was from July 14th to July 20th, when the 20 cm sensor dried out from 14 to 234 kPa. Over this period, there was rain on July 15th (0.025 cm), July 17th (0.305 cm), July 18th (0.051 cm), and July 19th (0.508 cm). Calculating the rate of change of the 20 cm sensor from July 14th-20th, the sensor dried out at a rate of 35 kPa per day. For reference, the rate of change over this same period for the 41, 61, and 81 cm sensors were 6, 5, and 3 kPa per day, respectively. Again, this behavior of the 20 cm sensor occurs between July 29th and August 1st. During these days, there was no rain or irrigation. Once the 20 cm reached its maximum on August 1st, it stayed there until August 13th. During this period, there was irrigation on August 5th and 9th, and rainfall totaling 1.52 cm. Given this, the tension in the 20 cm sensor never dropped below 239 kPa. Also, during this period, the 41 cm responded to irrigation on August 5th, dropping from 65 to 3 kPa, while the deeper sensors had no response. Similarly, after irrigation on August 9th, the 41 cm sensor dropped from 64 to 5 kPa, while the deeper sensors had no response. After a 0.64 cm rainfall on August 11th, where the 41 cm sensor drops from 53 to 2 kPa and the deeper sensors have no response, the 20 cm sensor stays at 239 kPa. Irrigation on August 12th triggers a response of the 41 and 61 cm sensors, but not the 20 cm. Finally, on August 13th, the 20 cm sensor dropped from 239 to 137 kPa. No rainfall or irrigation occurred on this day, and no other sensor on Site 1 had a similar response.

From examining the data, one can see that the 20 cm sensor dried out to 239 kPa on occasions when irrigations were skipped or dried out over the weekend. The 10 cm depth VWC sensor at Tree A was used as guidance to see when irrigation occurred on Site 1. Records of exact dates of irrigation during the 2021 growing season were not collected. As aforementioned, the irrigation schedule at Site 1 was mostly Mondays and Thursdays. Drying out over the weekend was apparent between September 9th and September 13th.

There were irrigation events where only the 61 cm sensor responded or where the 61 and 81 cm sensors did not respond. For example, after irrigation on July 26th, the upper three sensors reacted, while the tension in the 81 cm increased throughout the day. On August 5th, 9th, and 11th, only the 41 cm sensor responded to irrigation. The responsiveness of the 41 cm sensor to irrigation explains why it had the lowest mean and median SWT. No response of the deeper sensors also happened on August 26th, September 2nd, and September 13th. On August 23rd, irrigation was cut on, and the 20 cm sensor dropped from 117 kPa to a low of 34 kPa. The 61 cm dropped from 26 kPa to 10 Pa, but the 81 cm tension did not change, meaning the irrigation water did not reach the sensor. Also, the 41 cm sensor fell from 19 kPa to 2 kPa, meaning the soil was fully saturated. At this point, gravitational water was being lost due to drainage. Even after rainfall of 1.17 cm on August 31st, the deeper sensors showed no response. After this event, the 20 cm sensor reading went from 234 to 48 kPa, and the 40 cm sensor from 210 to 6 kPa.

Root growth typically all but stops in October, but since irrigation was still being applied on Site 1, although the exact dates are unknown, Watermark data were regularly downloaded from the 900M Monitor. After rain on October 8th, the 20 cm dried out to 239 kPa on October 18th and stayed at 239 kPa until it rained on October 22nd. There was no rain or irrigation between these days.

Tree B1 on Site 1

Due to issues with various Watermark 900M Monitors used at Tree B1, consistent data throughout the study period are not available. Data are available later in the growing season, in mid-September, as shown in Supp. Figure 18. For the data available, the sensors had good soil contact and responded to irrigation appropriately. The median SWT values for the 20 and 41 cm sensors were 22 and 19 kPa, meaning the soil was at or near field capacity for most of the time. The 61 and 81 cm sensors had medians of 37 and 38 kPa.

After an irrigation event on September 13th, the 20 cm sensor dropped from 224 to 11 kPa, and the 41 cm from 132 to 3 kPa. The deeper sensors did not respond. As previously mentioned, for the same event, at Tree A, only the 20 and 41 cm sensors responded as well. It took 2.7 cm of rain on September 20th to bring all the sensors to saturation. After this, until irrigation on September 27th, the 20 cm sensor dried out at 14.9 kPa per day to 89 kPa, and the 41 cm sensor at 11.21 kPa per day to 63 kPa. Unlike Tree A, the deeper sensors did not respond to irrigation on this day. Same as at Tree A, every sensor responded after irrigation on September 30th, which brought the SWT to in or near the range of 0-10 kPa.

Tree C1 on Site 1

Supp. Figure 19 displays a graph of the Watermark sensor data at Tree C1 on Site 1. Data collection started on July 1, 2021, but like the sensors at Tree A, the sensors at this tree were installed weeks previously. Like at Tree A, the 20 cm had the highest standard deviation, being 96. The 61 cm and 81 cm sensors stayed relatively wet, with maximum values of 86 and 57 kPa, respectively. With mean values of 36 and 31 kPa, respectively, the 61 cm and 81 cm sensors stayed near the FC range of 10 to 33 kPa. Unlike at Tree A, the sensors at Tree C1 had close means and medians, meaning the data were closer to a symmetrical distribution. Like the sensor at Tree A, the 20 cm sensor at this tree dried out to 239 kPa during the study period. The mean of the 20 cm sensor from July 1st to October 1st was 137 kPa, which is higher than the mean of the 20 cm sensor on Tree A. One of the reasons for this is the lack of response to irrigation by the sensors at Tree C1.

The 20 cm sensor has the same behavior as the sensor at Tree A, where it dried out to 239 kPa. This happens between July 22nd and August 1st. The 20 cm at Tree A also dried out to 239 kPa on August 1st and stayed at 239 kPa until the rain event on August 17th, which, like at Tree A, brought the 20 cm, 61 cm, and 81 cm sensors to saturation and the 41 cm to field capacity range. Between July 22nd and August 17th, there was a total of 3.81 cm of rain, but the tension in the 20 cm sensor stayed at 239 kPa until an 8 cm rain event on August 17th. Irrigation was also turned on July 26th, but none of the sensors at Tree C1 responded. The 20 cm sensor then dried out to 239 kPa on August 26th and stayed at the maximum until rain on September 15th and 16th, totaling 2.11 cm, when it was brought back to saturation. From August 26th to September 15th, irrigation was running on September 2nd, September 9th, and September 13th, but none of the sensors at Tree C1 showed a response. There was also 4.62 cm of rain during this period. As seen by the data, the soil water tension dynamic at Tree C1 was quite different from the expected behavior observed at Tree A. As aforementioned, the sensors at Tree C1 were not as responsive to irrigation as the sensors at Tree A. If we examine three irrigation events on August 23rd, August 26th, and September 13th and compare Tree A and Tree C1, this becomes apparent. On August 23rd at Tree A, the 81 cm sensor did not respond to irrigation, but all the other sensors did. As aforementioned, at Tree C1, none of the sensors responded to the irrigation, with the SWT increasing throughout the day. On August 26th, the 20 and 41 cm sensors at Tree A responded to irrigation, but the deeper sensors did not. At Tree C1, none of the sensors responded. The same occurred on September 13th. The data show that the SWT at Tree C1 only dropped drastically after large rain events on, for example, on July 7th, July 20th, August 17th, September 16th, September 20th, and October 5th. Even with the lack of response to irrigation, the deeper sensors were, on average, wetter than their counterparts at Tree A. With the trees at Tree

C1 being one year young, this is unsurprising. Unlike the deeper sensors at Tree A, the ones at Tree C1 never once entered the danger zone above 100 kPa.

Hourly Average Watermark readings for Site 1 are shown in Figure 11. Only Tree A and Tree B1's readings were averaged together because these sensors responded to irrigation and rainfall appropriately during the study period. Adding Tree C1's data would greatly affect the drying and wetting trends because, during the times of irrigation, the Watermark readings were still showing as dry.

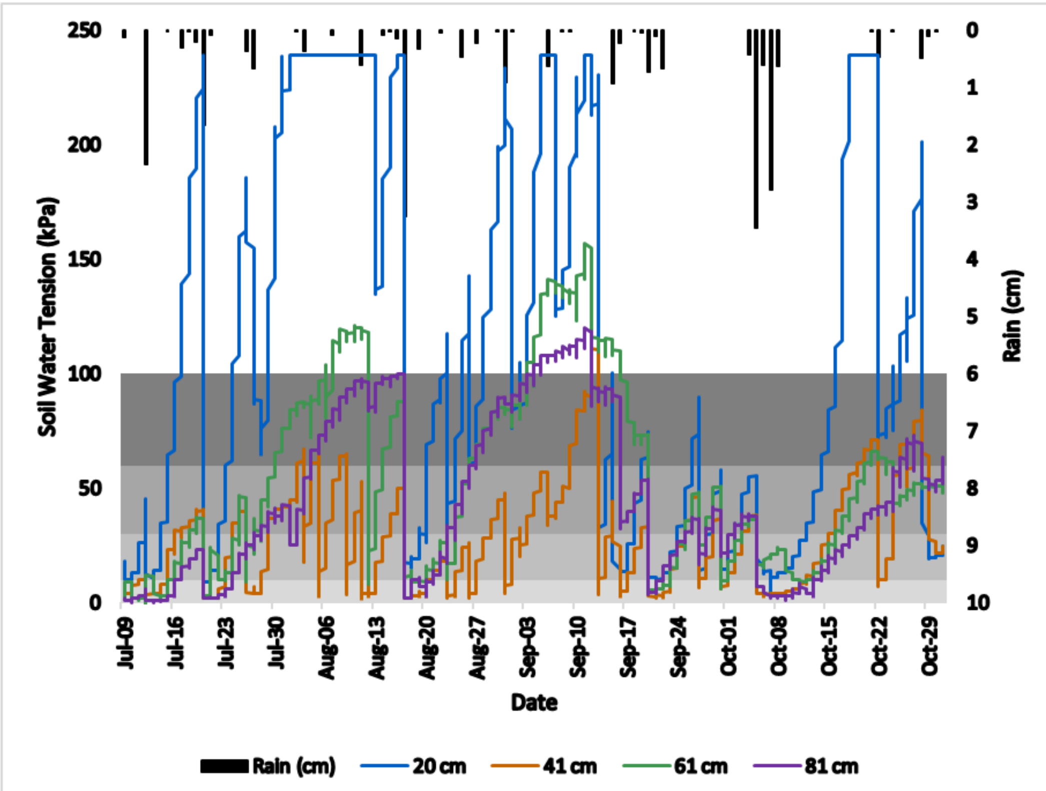

Figure 11. Site 1 Average Watermark Data (2021)
(The gray bands represent 0-10 kPa, 10-30 kPa, 30-60 kPa, and 60-100 kPa)

Site 2 (Toombs County)

Table 15: Site 2 Watermark Statistics

Depths (cm)	In season (kPa) n	min	max	median	mean	std	Out of season (kPa)* n	min	max	median	mean	std
Tree A[1]												
20	5777	0	90	3	12	20	18258	1	21	11	11	4
41	5777	0	79	5	12	17	18258	3	16	10	10	3
61	5777	0	16	1	3	5	18258	0	15	6	6	4
81	5777	0	15	0	2	4	18258	0	24	2	3	4
Tree B[2]												
20	5056	0	54	12	15	16	17369	0	50	12	15	11
41	5056	0	79	3	18	24	17369	1	41	12	13	7
81	5056	0	24	0	5	8	17369	0	21	5	7	7

[1]: July 28-September 30, 2021
[2]: August 5-September 30, 2021
*Out of season values are from October 1, 2021, to March 31, 2022 (gaps in data are due to data logger malfunctioning)

Tree A on Site 2

Figure 12 displays the soil water tension data in hourly increments from the Watermark sensors on Tree A on Site 2 starting on July 28, 2021. There are three bands representing saturation (0-10 kPa), FC to 50% MAD (10-30 kPa), and dry soil (30-239 kPa). 10 kPa is a published value for FC for Tifton loamy sand for 0-38 cm (Liang et al., 2016). 25-30 kPa is a typical threshold for 50% PAW (Datta et al., 2017; Melvin and Martin, 2018) for these soils.

Table 15 shows the statistical data for both trees on Site 2, with Tree A having microsprinkler irrigation and Tree B having drip irrigation. The median SWT values for the 20, 41, 61, and 81 cm sensors at Tree A are all in the saturation range. Because the mean SWT is greater than the median for all the sensors, similar to the sensors on Site 1, the data are skewed to the right. The 61 and 81 cm sensors having averages of 3 and 2 kPa, respectively, indicate that the soil was saturated deeper down. The 81 cm sensor stayed at 0 kPa for almost the entire study period, which is evident by the median being 0 kPa. The standard deviation for the sensors decreased with depth, with the 20 cm sensor having the most variation. The 20 cm sensor peaked at 90 kPa, 41 cm at 79 kPa, 61 cm at 16 kPa, and 81 cm at 15 kPa. The 20, 41, and 61 cm sensors had a maximum SWT on September 7th, while the 81 cm SWT peaked on September 9th.

After the sensors were in the soil on July 28th, the 81 cm sensor stayed at 0 kPa until August 18th, where the sensor started to read values between 1 and 7 kPa. This behavior signals the lack of roots at this depth, or that the roots were not utilizing water at this depth. The average of the 61 cm sensor was 3 kPa, and the median 1 kPa.

From September 1st to the 7th, the 20 cm sensor dried out at 11.27 kPa per day, 41 cm sensor, 8.2 kPa, and the 61 cm sensor, 0.45 kPa per day. From September 1st to the 9th, the 81 cm sensor dried out 1.9 kPa per day. Based on the Watermark data, irrigation could have been turned off for some period in early September, which would explain why the sensors dried out.

On September 7th, there was no rain reported on either georgiaweather.net or the ECRN-50 gauge on site. Irrigation must have been cut on because the 20 cm sensor dropped from 85 to 0 kPa, 41 cm sensor from 79 to 0 kPa, and 61 cm from 16 to 1 kPa. The 81 cm did not respond to irrigation. After this event, the sensors stayed in or near the saturation range of 0-10 kPa for the rest of the growing season.

Also, because irrigation was still being applied in October, all the sensors had average SWT values of less than 5 kPa. For out of season values, from October 2021 to March 2022, the mean and median SWT values were fairly close for all sensors, and the soil was almost saturated for the entire off season.

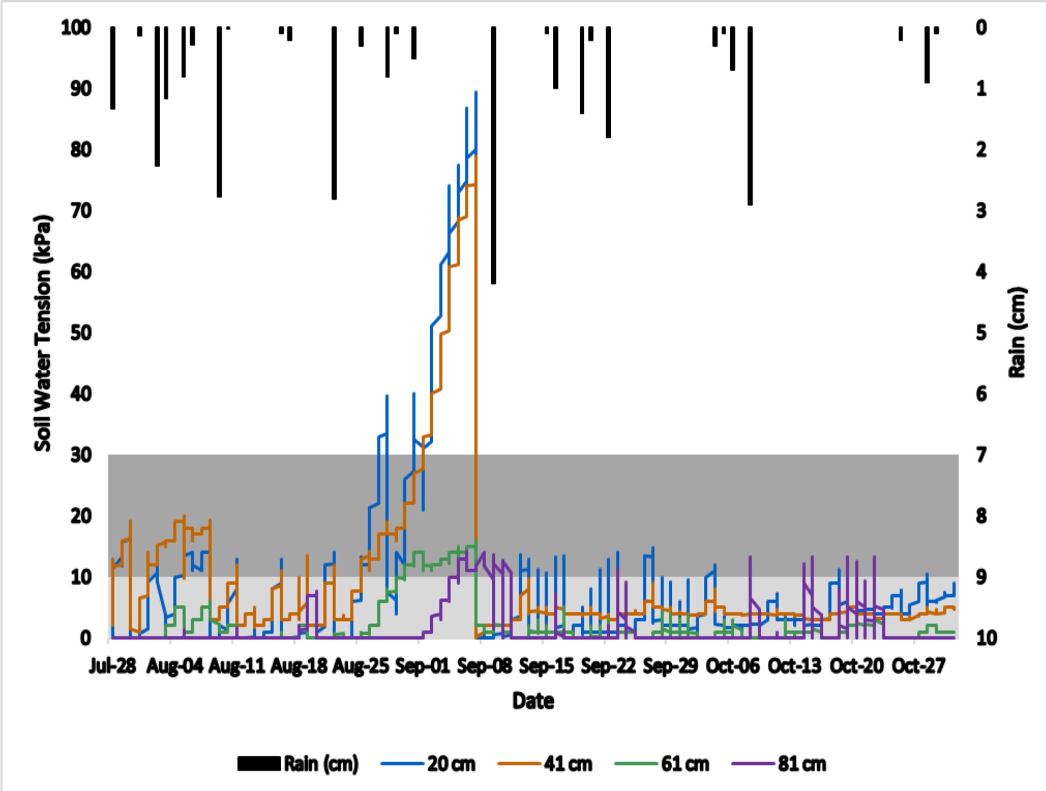

Figure 12. Site 2 Tree A (Microsprinkler Irrigation) Watermark Data (2021)
(The gray bands represent 0-10 kPa and 10-30 kPa)

Tree B on Site 2

Watermark data for Tree B during the 2021 growing season with drip irrigation are shown in Figure 13, with the same gray bands as in Figure 12. The data displayed start on August 5, 2021. The 41 cm sensor malfunctioned multiple times during the study, so only the 20, 61, and 81 cm sensor data are shown. The sensors at Tree B were, on average, drier than those at tree A during the study period. The 20 and 41 cm sensors at Tree B had higher medians, 12 and 3 kPa, respectively. The 81 cm had a median of 0 kPa, the same as at Tree A. As previously mentioned, feeder roots were most likely not developed at this depth.

The maximum SWT for the 41 cm sensor was at 79 kPa, compared to a maximum of 54 kPa for the 20 cm sensor. Along with the highest maximum, the 41 cm sensor had the highest variance as well, with a standard deviation of 23.56. The 20 cm sensor peaked on September 8th, and the 41 and 81 cm sensors on September 7th. Figures 12 and 13 look similar, with the most noticeable drying out period being between September 1st and September 7th -9th. From September 1st to its peak on September 8th, the 20 cm sensor dried out 3.57 kPa per day. For the 41 cm sensor, it dried out 3.72 kPa per day from September 1st until its peak. For the 81 cm sensor, it dried out 1.17 kPa per day from September 1st until its peak.

Another trend from the sensors at Tree B is that after irrigation events, sometimes not every sensor responded. This occurred, for example, on August 11th, when the 41 and 81 cm sensors were brought to saturation, but the 20 cm sensor had no response. The 20 cm sensor also had no response to irrigation on August 13th, August 16th August 18th, and September 7th.

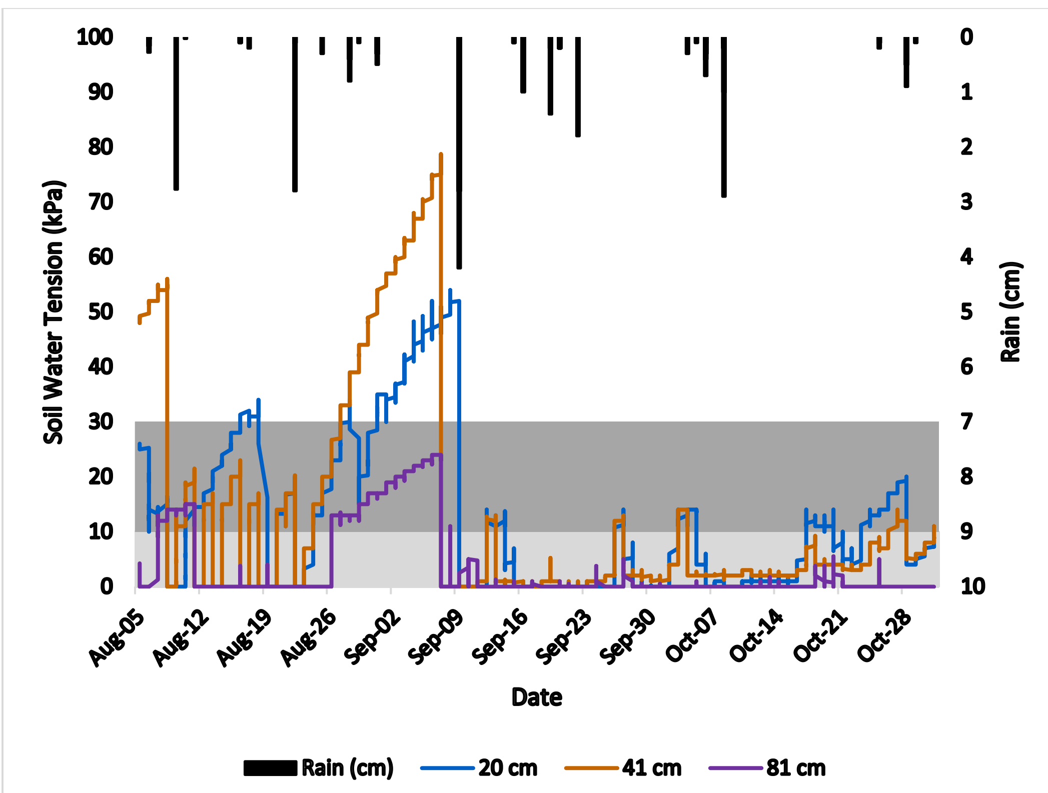

Figure 13. Site 2 Tree B (Drip Irrigation) Watermark Data (2021)
(The gray bands represent 0-10 kPa and 10-30 kPa)

Volumetric Water Content Sensor Data for the 2021 Growing Season

Site 1 (Oconee County)

For Site 1, some of the VWC data from the sensors are in Supp. Figure 20. The sensors did not respond to irrigation as expected, likely due to the installation method. The 20, 41, 61, and 81 cm sensors only had noticeable responses to heavy rain. The likely culprit was that too large of a hole was dug, which affected the bulk density and structure of the soil. When the hole was backfilled, the soil was packed too tight, thus preventing light rain and irrigation events from percolating down. In the future, a smaller hole should be augured, and sensors should be installed using an installation tool. Therefore, only the Watermark data from Site 1 will be explained further.

Site 2 (Toombs County)

Table 16. Site 2 Volumetric Water Content Statistics

	In season (%)						Out of season (%)*					
Depths (cm)	**n**	**min**	**max**	**median**	**mean**	**std**	**n**	**min**	**max**	**median**	**mean**	**std**
Tree A[1]												
20	5777	12.3	17.0	14.9	14.8	0.9	18258	14.4	37.3	15.8	15.9	0.7
41	5777	9.1	16.3	11.7	12.0	1.4	18258	12.2	40.0	13.8	13.8	1.4
61	5777	19.0	34.5	20.5	21.9	3.7	18258	21.2	34.6	21.7	22.2	1.8
81	4859	27.3	40.6	30.1	30.9	2.8	17472	28.8	41.6	30.1	31.0	2.7
Tree B[2]												
20	5056	12.5	25.2	19.1	18.8	3.2	17369	16.3	38.0	20.4	20.5	2.7
41	5056	13.2	26.1	21.3	19.8	4	17369	16.5	41.2	19.2	19.9	3.1
61	5056	17.2	34.8	28.7	27.4	4.5	17369	24.4	36.7	27.3	27.9	2.6
81	5420	12.6	46.7	17.8	23.8	10.7	17472	21	44.5	27.0	27.5	4.9

[1]: July 28-September 30, 2021
[2]: August 5-September 30, 2021
*Out of season values are from October 1, 2021, to March 31, 2022 (gaps in data are due to data logger malfunctioning)

VWC data are shown for Site 2 Tree A with microsprinkler irrigation at 20, 41, 61, and 81 cm depth in Figure 14, and statistics in Table 16. The data start on July 28, 2021. The average

FC from the tempe cell tests was 13.8%, and this is represented as the dotted line on Figure 14. As texture changes to fine sandy loam and sandy clay loam on Site 2, so does the FC. As a result, the dotted line is not the FC for deeper layers, which is evident by seeing the seemingly high VWC values from the 61 and 81 cm sensors. A reported value for FC on Tifton loamy sand at 81 cm is 29.7% (Stansell, 1976). Even after assuming the FC at this depth is this value or using an FC of 23.8% (from Web Soil Survey), the 81 cm sensor is still above this after irrigation. The PWP of 5.4% from Web Soil Survey is shown by the solid black line. For reference, Rawls et al. (1982) reported an average PWP of 5.5 %, which was based on 1500 kPa.

All sensors had averages and means that were near or above FC. The main trend is that the 61 and 81 cm sensors approached saturation numerous times, with saturation being, on average, 42%, determined from the lab tests on surface samples. As a result, gravitational water was lost due to deep drainage. The high spikes and then decrease in soil water content for the deep sensors are a result of saturation and then drying out to field capacity. Unlike the deeper sensors at Site 1, the deeper sensors at Site 2 respond to almost every irrigation event.

Surprisingly, the 41 cm sensor, on average, was the driest during the study period, clearly dipping below FC. The drying out period for all VWC sensors corresponded with the drying out period of the Watermark sensors installed at the same tree from August 24th to September 7th. An apparent trend is the behavior of the sensor in the probe at 20 cm after irrigation and rainfall. The 20 cm sensor did not vary substantially, with the lowest standard deviation of 0.89. The VWC stayed between 12.3% and 17% the entire period from July 28 to September 30, 2021. Consistent moisture content is ideal for pecan trees, so these are favorable conditions.

The sensors at Tree B stayed above the FC line for almost the entirety of the growing period, but as aforementioned, the FC line is based on soil surface measurements. The 81 cm sensor had the greatest standard deviation, which is evident by the behavior of the sensor. The most noticeable trend in Figure 15 is the drying and wetting of the 81 cm sensor after irrigation. The sensor is saturated after applied water and dries back to field capacity quickly. The same drying out period occurs from August 24th to September 7th.

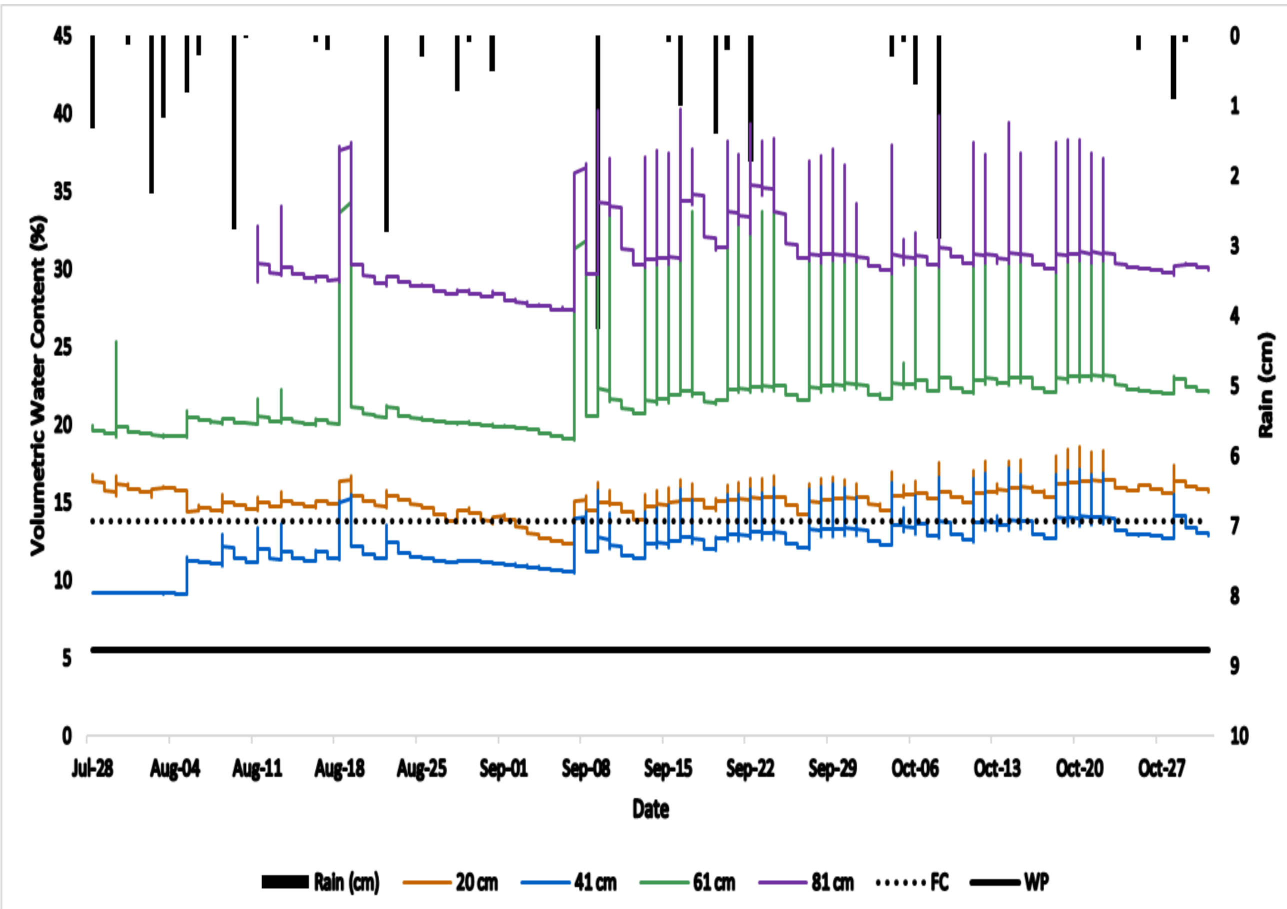

Figure 14. Site 2 Tree A (Microsprinkler Irrigation) Volumetric Water Content Data (2021)
FC (Field Capacity) is indicated as dotted black line; WP (Wilting Point) is indicated as solid black line

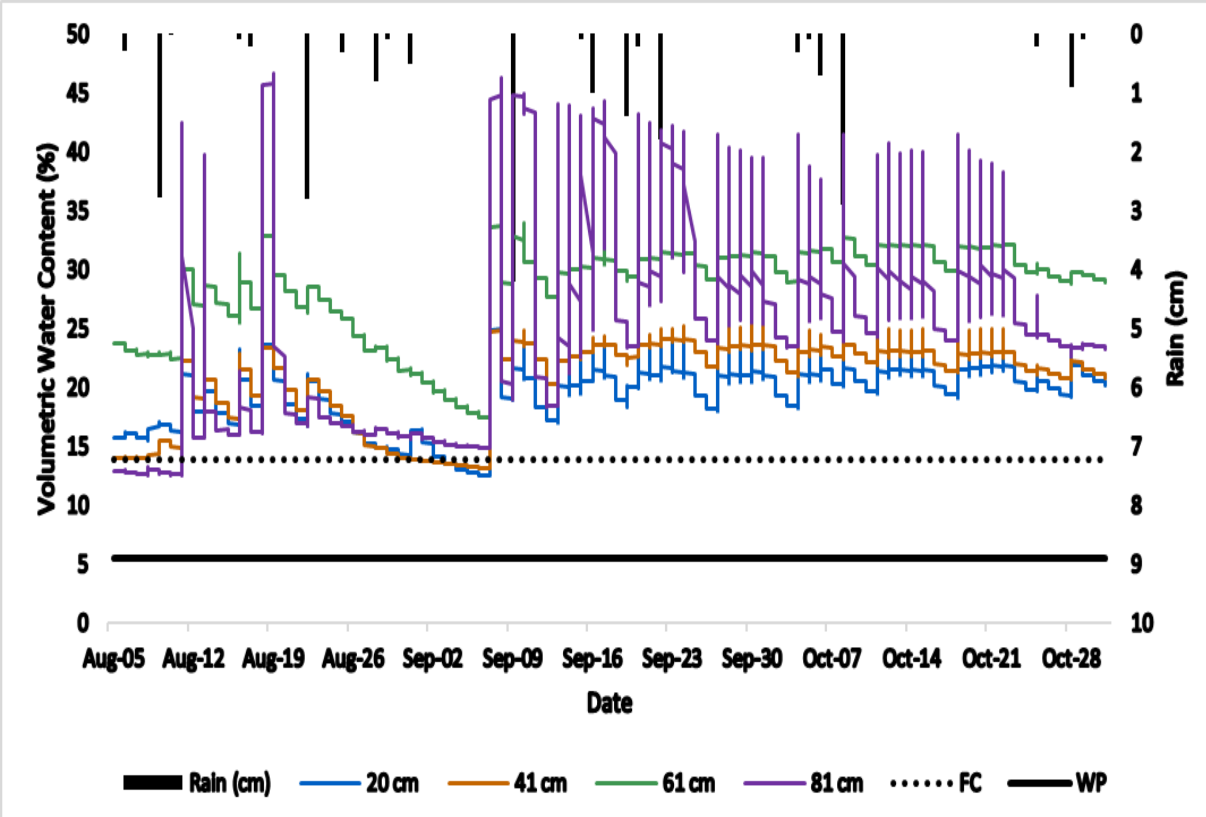

Figure 15. Site 2 Tree B (Drip Irrigation) Volumetric Water Content Data (2021) FC (Field Capacity) is indicated as dotted black line; WP (Wilting Point) is indicated as solid black line

Watermark Readings for the 2022 Growing Season

Site 1 (Oconee County)

Tree A on Site 1

On Site 1 in May 2022, irrigation was running every other day, three to four times a week, for an hour and 15 minutes. If using 38 L/hr as the flow rate based on the Bowsmith manual for the irrigation system at Site 1, this equals 285 liters for one week and 380 liters for the next. The flow rate was measured on five microsprinklers, and the results were 57, 45, 50, 50, and 50 L/hr. With 50 L/hr being the average measured, actual irrigation rates were closer to 375 L for one week and 500 L the next week. As previously mentioned, irrigation was increased based on the 2021 season data in order to keep more consistent soil moisture during the 2022 season by irrigating every other day instead of twice per week.

Watermark data for the three trees are shown in Supp. Figures 21, 22, and 23 from March 15th to June 1st. Irrigation started in late April. The ECRN-50 data indicated when irrigation was applied. The sensors stayed relatively wet until late April when plant uptake started increasing. This is also when bud break started. Similar to the 2021 season, there were times when only the upper sensors responded to irrigation, noticeably on May 2nd. This also occurred on May 9th and May 11th, where only the 20 and 41 cm sensors had decreases in soil water tension. During this period, the 61 and 81 cm sensor readings were under 33 kPa, so they were still sufficiently wet. The 81 cm sensor started drying out after this. Irrigation water was only wetting the 20 cm sensor for most of the irrigation events from April 22nd to June 1st. After an irrigation event on May 16th, in which only the 20 cm responded, the sensor stopped responding to water application until a 2.4 cm rainfall on May 23rd made all the sensors significantly respond. Irrigation occurred on May 18th, 20th, and 22nd. Because the sensor did not respond to irrigation on these days, the tension went above the 100 kPa danger zone. Only after large rainfall events is every sensor saturated, or does every sensor respond to irrigation. Rainfall on May 25th and 26th, totaling 6 cm, brought all sensors near or in the saturation range, and a rain event of 1.27 cm on May 30th made only the upper three sensors react. The deeper sensors did not respond to irrigation according to the Watermark data.

Tree B1 on Site 1

What is interesting about the Watermark readings at Tree B1 is the response to irrigation of the sensors. From the readings it is clear from the data that the 61 and 81 cm sensor data is inaccurate, likely due to bad contact with the soil. After an irrigation event on May 2nd, the 20 and 41 cm sensors respond by dropping from 12 to 6 kPa, and 28 to 18 kPa, respectively. After the irrigation event on May 7th, the 20, 41, and 81 cm sensors responded. The 20 cm sensor went from 28 to 18 kPa, and the 41 cm sensor from 41 to 34 kPa. The 20 and 41 cm sensors reacted after irrigation on May 9th, going from 35 to 14 kPa, and 31 to 25 kPa, respectively. Also, only the 20 cm had a noticeable response to irrigation on May 11th, going from 18 to 11 kPa. Like at tree A, the 20 cm sensor responded to irrigation on May 16th, dropping from 34 to 22 kPa, and the 41 cm sensor from 60 to 49 kPa. Only the 20 cm sensor responded to the irrigation event on May 18th, going from 39 to 35 kPa. The sensors do not respond to irrigation on May 20th or 22nd, which is why the SWT increases above 100 kPa before rain on May 23rd brings the 20 cm near saturation and the 41 cm sensor from 152 to 125 kPa. Same as at Tree A, only after large rainfall events is every sensor saturated. The 20 cm sensor data at Trees A and B1 are presented in Figure 16. According to the data, before the sensors stopped responding to irrigation around May 18th, the SWT was significantly less than what was seen in the 2021 growing season. There was no drying out over 100 kPa like there was in the previous season.

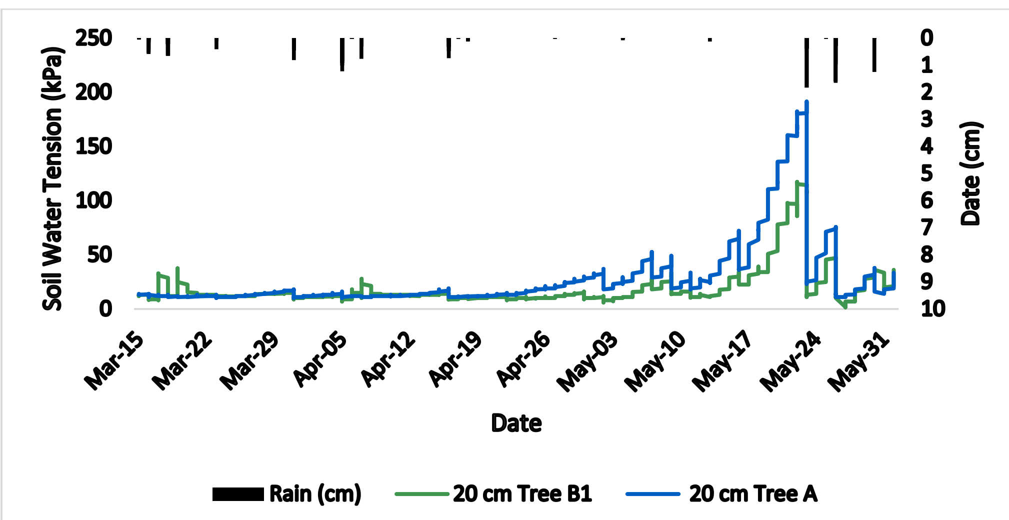

Figure 16. Site 1 Tree A and Tree B1 20 cm Watermark Data (2022)

Tree C1 on Site 1

During the 2021 growing season Tree C1 Watermark sensors did not respond to irrigation. The 20 cm sensor during the study period in the 2022 season did respond to every irrigation event, but very minimally. The kPa difference before and after irrigation for most irrigation events was small (<7 kPa). There seems to be a response to irrigation on May 7th, where the 20 cm sensor drops from 18 to 13 kPa. The other sensors showed no response. There also was a small response to irrigation for the 20 cm sensor on May 9th, going from 17 to 13 kPa, while the deeper sensors showed no response. Same for irrigation on May 11th, with the 20 cm going from 17 to 14 kPa. For the irrigation event on May 16th, the 20 cm sensor went from 24 to 18 kPa, with the other sensors showing no noticeable response. On May 18th, the 20 cm sensor goes from 21 to 16 kPa after the irrigation event, with the deeper sensors showing no response. After irrigation on May 22nd, the 20 cm sensor dropped from 20 to 12 kPa. The sensors at Trees A and B1 did not respond to irrigation during this event. Only the 20 and 41 cm sensors responded to rain on May 23rd, and all sensors responded to rain on May 26th. Even given the low response to irrigation, the sensors indicate that the soil was adequately wet.

Site 2 (Toombs County)

Figures 17 and 18 display Watermark data at Site 2 from March 15 to June 1, 2022. Statistical distribution is showed in Supp. Table 7. Irrigation at Site 2 started on May 5, 2022, with a schedule of MWF for 4 hours a day, starting at 16:00. The trees were two years old in 2022. As indicated by the Watermark data, rainfall kept the soil wet at Tree A until rainfall stopped on April 18th. Then, all soil layers dry out until rain on May 3rd and irrigation on May 5th. Plant uptake by the deeper layers is apparent during this time period because the sensors dry out beyond FC. The rate of change for the 20 and 41 cm sensors from April 19th to May 3rd was

6.8 kPa and 6.11 kPa per day. The 61 and 81 cm sensors had rates of change of 1.39 and 1.19 kPa, respectively.

The behavior of the sensors was similar to the 2021 season. The sensors primarily stayed in the saturation range, occasionally drying out in the FC to 50% MAD range (10-30 kPa). Every time the sensors started drying out to the readily available water zone (FC to 50% MAD), coincidentally, irrigation was cut on, which saturated the soil after every event. The 81 cm sensor stayed in the readily available water zone for a significant portion of the season, which is ideal.

At Tree B when irrigation was cut on May 5th, only the 61 and 81 cm sensors responded. The 61 cm sensor was reinstalled on April 14th because it malfunctioned during the 2021 season. Like the 20 cm sensor during the 2021 growing season, the 20 cm sensor in the 2022 growing season did not respond after numerous irrigations. The lack of response to irrigation is the reason for the behavior of the 20 and 41 cm sensors throughout the growing season. The deeper sensors were saturated after every irrigation event. These sensors stayed in the saturation zone for the entire period, from May 5th to June 1st.

Regarding the distribution for Tree A from April 1st to June 1st, median kPa values for the 20, 41, 61, and 81 cm sensors were 10, 8, 4, and 10 kPa, respectively. The median is a better measure to explain the data because irrigation wasn't turned on until May 5th, and the SWT was in the danger zone for the 20 and 41 cm sensors at Tree A and for all the sensors at Tree B. As a result, this greatly affected the mean SWT. The median SWT for sensors at Tree B was 23, 13, 11, and 7 kPa, respectively.

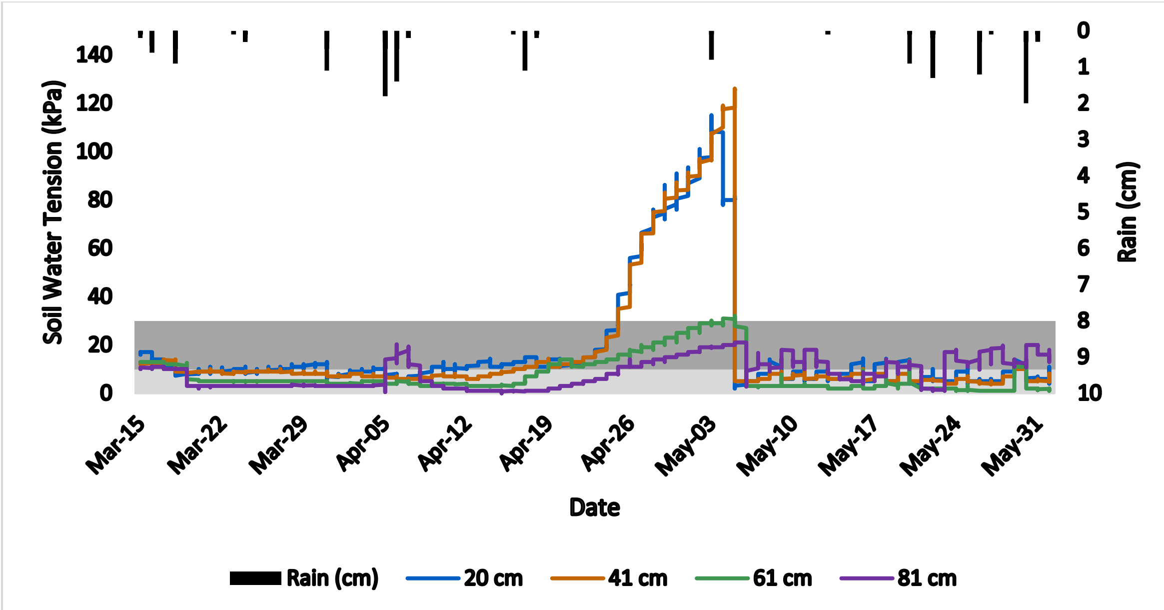

Figure 17. Site 2 Tree A (Microsprinkler Irrigation) Watermark Data (2022)
(The gray bands represent 0-10 kPa and 10-30 kPa)

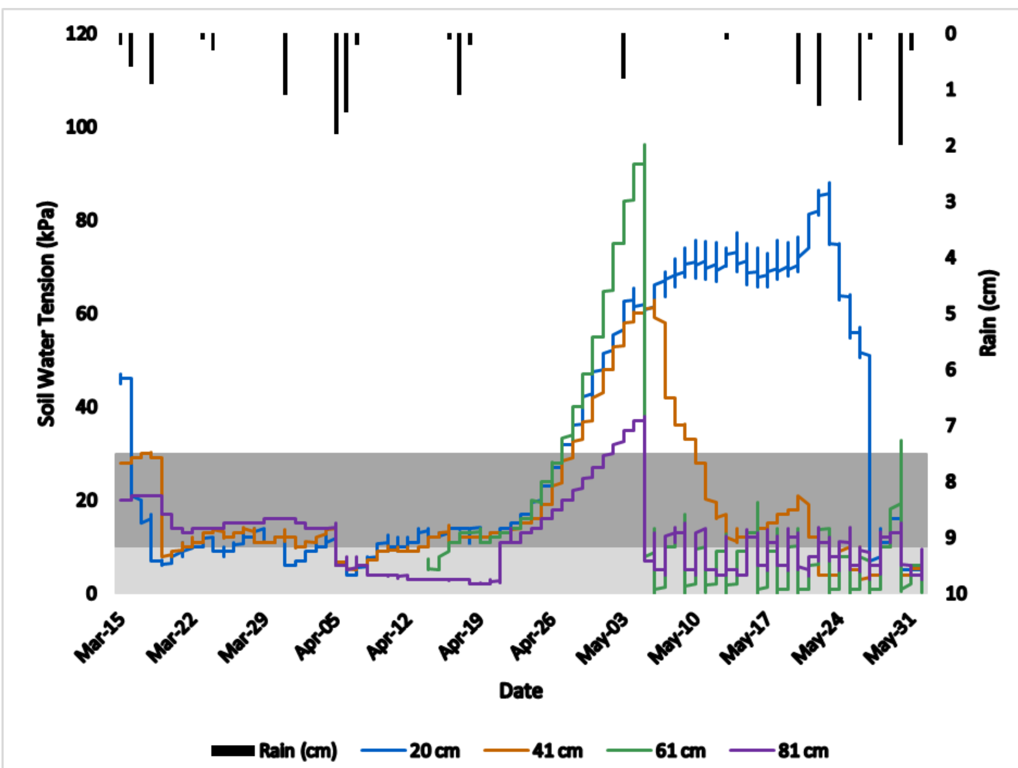

Figure 18. Site 2 Tree B (Drip Irrigation) Watermark Data (2022)
(The gray bands represent 0-10 kPa and 10-30 kPa)

Site 3 (Hancock County)

For the 2022 growing season, irrigation started in mid-April, and the schedule was every other day for three hours. When rain was expected, irrigation was not cut on. The Watermark data were more informative than VWC data due to gaps between the Aquacheck probe leading to high spikes and then quick drainage. As displayed in Figure 19 (young tree), the soil stayed wet (saturated zone) during March and the beginning of April due to the amount of rain. The three bands on this figure represent 0 kPa to FC (15 kPa), FC to 50% MAD (40 kPa), and > 40 kPa.

From examining the Watermark data, irrigation ran daily from April 14th -25th. Because of this, the soil stayed saturated, never having time to dry out. Drying out started to occur on April 27th until rain (4.3 cm) on May 23rd brought all the sensors to saturation. Rain on May 26th (5.9 cm) keeps the soil wet for the rest of the month. This drying out occurred because irrigation was not turned on during this period. The top three sensors dried out above the 50% depletion line because of this. Calculating rates of change for some of the sensors from May 3rd until rain on May 23rd, the 20 cm sensor dried out around 7.6 kPa per day. The rate of change for the 41 cm over this period was around 5.7 kPa per day. One noticeable trend in Figure 19 is the stair step behavior of the lines, which indicates that during the night, the tension levels off, while during the day, plants are transpiring. This stair step behavior will not occur unless roots are taking up water at this depth.

The behavior of the Watermark sensors at the mature tree (Tree B) on Site 3 was like that of the young tree, as shown in Supp. Figure 24. Once irrigation was cut off the 20 cm sensor dried out. The upper three sensors dried out above the 50% depletion line. The 20 cm sensor value started to level off at 150 kPa around May 14th, indicating the roots were not taking up water at this depth anymore as the SWT stopped increasing. As displayed on the graph, root uptake was apparent down to 81 cm, whereas for the young tree, there is minimal drying out, with the sensor drying to 29 kPa before rain on the 23rd.

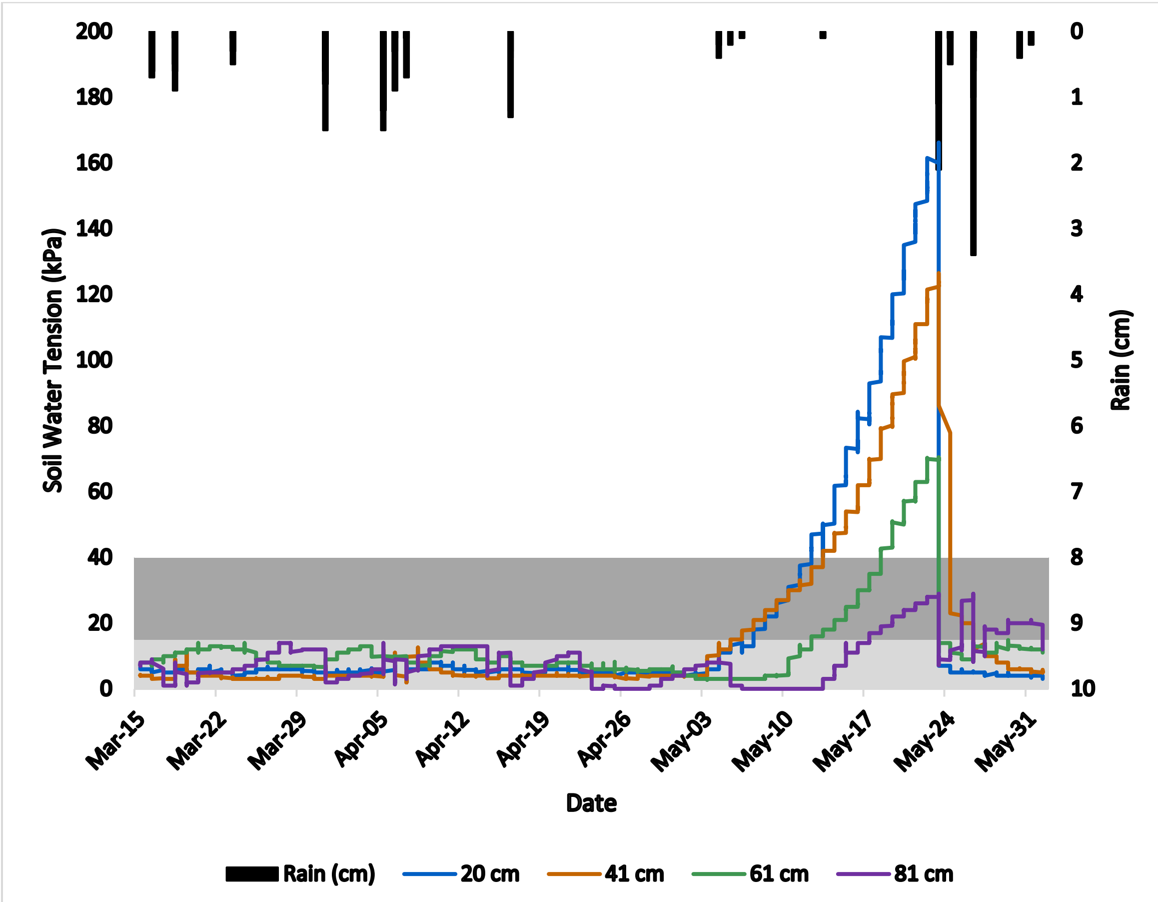

Figure 19. Site 3 Tree C (Young Tree) Watermark Data (2022)
(The gray bands represent 0-15 kPa and 15-40 kPa)

Volumetric Water Content Readings 2022

Site 2 (Toombs County)

Because irrigation was only running MWF during the May 2022, instead of every day, the pattern of some of the sensors at Tree A are different than the 2021 season. Refer to Supp. Table 8 for the statistical distribution of the VWC data for April-May 2022. The large increases in soil moisture from the 61 and 81 cm sensors last season were not apparent in the 2022 season.

For some irrigation events, the 81 cm sensor didn't respond (May 13th and May 21st), which is different than the response in the 2021 season. This indicates water did not reach this depth. The 81 cm sensor should not be saturated after irrigation, so this is an improvement over the 2021 season.

Like the Watermark sensors, the VWC sensors dried out at the beginning of the season before irrigation on May 5th. Even if there might be a soil texture change at Site 2 from loamy sand to possible sandy clay loam, which has a higher FC, the 81 cm was clearly too wet. Using the FC line from the tempe cells tests does not account for interpretation due to soil texture changes with depth. Even after assuming the FC of 29.7% as did earlier, as FC at this depth, the 81 cm sensor was still above this value after irrigation (Supp. Fig 25).

At Tree B, 81 cm data are not available due to the EM50 logger malfunction, but a graph of the other VWC data from the probe is shown in Supp. Figure 26. Like in the 2021 season, the sensors stayed above the FC line. The soil moisture behavior at Tree B was the same as at Tree A. Plant uptake is evident, starting in April. This is near the time of bud break, so this is to be expected. Because of the irrigation frequency, soil moisture was consistent after May 5th.

Ground Penetrating Radar on Site 1 (Oconee County)

Figure 20 displays the time slice from the three year old tree representing a depth of 0.2-0.3 m. The color palette is false colored. The difference in permittivity between the layers determines how much energy is reflected. Blue in this plot represents undisturbed soil, and the green-orange-red discoloration indicates a change in the soil's dielectric properties, which by interference represents root presence. The colors represent the reflection coefficient, shown in equation (5):

$$\frac{\sqrt{\varepsilon 1} - \sqrt{\varepsilon 2}}{\sqrt{\varepsilon 1} + \sqrt{\varepsilon 2}} \qquad (5)$$

where ε1 and ε2 are dielectric constants of two different mediums. The top half of the fraction in equation (5) denotes the reflected amplitude, and the bottom half denotes the incident amplitude. For the one year old tree, the GPR data show no consistent pattern, but for the three year old tree, there is obvious soil disturbance. This is evident by the heavy green-orange-red discoloration in Figure 20, meaning there is disturbance at least 4 m wide. There is evidently a strong difference in the dielectric properties of the soil and an object. This could mean that the roots are likely at least 4 m wide. The taproot is shown near the middle of the plot with the light blue dot.

Supp. Figures 27 and 28 display all the time slices from the three year old and the one year old tree, respectively. The upper left plot is the soil surface. As you move from left to right, the depth of the radar image moves downward into the ground until it reaches 60 ns. The maximum depth, as shown on the last time slice, is 1.4 m. The depth was determined from using an equation similar to equation (6)

$$d_a = Vt/2 \qquad (6)$$

where "d_a" is apparent depth, "V" is propagation velocity, and "t" is two way travel time. The propagation velocity depends on the dielectric constant of the soil, and the two way travel time is 60 ns. An algorithm in GPR-SLICE determined the propagation velocity. The soil was represented as a block with a single dielectric constant. Unknown objects such as saprolite may appear further down in the soil. Due to the high conductivity of clay, penetration depth using GPR is limited. As you go deeper into the soil, the taproot starts to disappear, and the soil swallows the taproot.

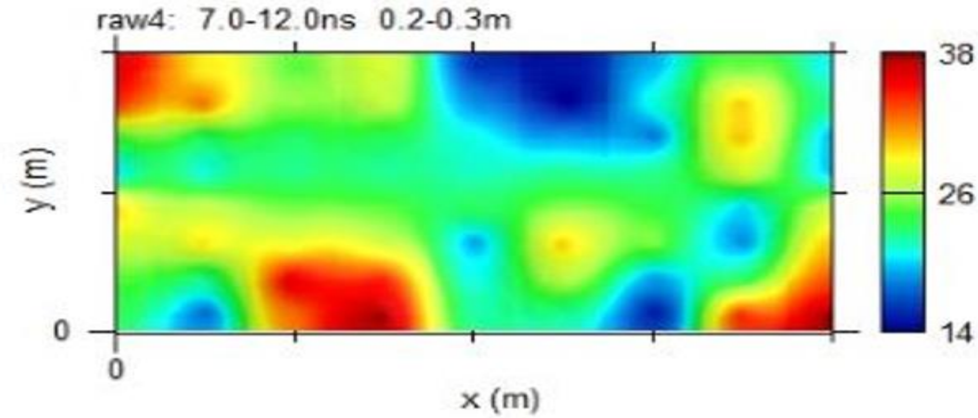

Figure 20. Ground Penetrating Radar Time Slice from 3 Year Old Tree (x axis is 4 m, y axis is 2 m)

CHAPTER 5. DISCUSSION

Soil Texture and Organic Matter Tests

The soil texture results revealed the spatial differences in soil texture on the farm scale. Site 1 has a mix of sandy loam, sandy clay loam, clay loam, and clay soils at different depths. The impact of changing soil texture as depth increases on soil moisture will be discussed later. The addition of topsoil on Site 1 some time ago possibly could have altered the existing soil texture on the surface. The soils at Site 2 had uniform texture, but this was to be expected, as this is what is indicated on soil maps. Besides the one loamy sand sample, the samples at Site 3 were in accordance with soil maps.

With regards to the organic matter content, under similar climate conditions, the organic matter content in fine-textured soils is two to four times that of coarse-textured soils (Prasad and Power, 1997). Likewise, if you have sandy soil, 2% organic matter may be the upper end of what you can maintain, whereas, in clay soils, 2% is considered very low (Sawyer, 2021). This is partly because coarse-textured soils are more aerated and will have less organic matter due to the presence of oxygen, resulting in quick decomposition. Fine-textured soils tend to have smaller pores and less oxygen than coarser soils. All things being equal, this could explain why Site 1 had, on average, the highest organic matter content, at 6.30%. One of the samples from Site 2 had the lowest organic matter content (1.87%) out of all the samples collected across all sites, which is logical due to the loamy sand texture.

Laboratory Soil Water Retention Data

Site 1's FC values ranged from 25.31% to 33.69%, similar to what is found in the literature for sandy clay loam/clay loam soils and like the values from Web Soil Survey. For reference, in a study by Rawls et al. (1982), FC for sandy clay loam and clay loam soils ranged from 18.6-32.4%, and 25-38.6%, respectively. Average FCs for these soil textures were 25.5% and 31.8%, respectively. To determine these values, 33 kPa was applied.

With Site 2 being loamy sand, it was expected that the FC of the samples collected from this site would be the lowest. Given that 33 kPa was applied for FC determination, and the FC of sandy soils is closer to 10 kPa (Liang et al., 2016), the FC from Site 2 is not the exact FC. For reference, the average FC for loamy sand soils reported by Rawls et al. (1982) was 12.5%. In a study by Stansell et al. (1976), the FC for Tifton loamy sand at the soil surface was 12.9%. This corresponded to between eight and nine kPa. This speaks to differences in soil even within the same soil series and the method used for FC determination. Given that the FC from temple cell tests using 33 kPa was between 11.1 and 16.8%, with an average of 13.8%, it can be surmised that the actual FC is much higher. For Tifton Loamy sand, the FC was 18%, determined using the Van Genuchten method described by Liang et al. (2016), which corresponded to 10 kPa. FC by Ma et al. (2000) for Tifton loamy sand at the surface was 14%, which is the same value as Web Soil Survey. For the sandy loam soils on Site 3, the FC ranges were higher than those reported from Web Soil Survey but still acceptable values and in the range reported by Rawls et al. (1982). Previous literature regarding FC values for Pacolet sandy loam was not found. Thus, based on the soil texture, the FC values from the tempe cell tests were adequate.

The PWP values from every sample from the WP4C were lower than expected and drastically different from the values in the literature. The low values from PWP determination using the WP4C call for a re-examination of the method conducted, and multiple replications, which would help find what factors were responsible for the unexpected results. The trends of the PWPs, albeit with inaccurate numbers, still hold true. Site 2, on average, had the lowest PWP and PAW by a significant margin and Site 1 the highest, which makes sense considering the soil texture. Reported values for PWP at 1500 kPa for Tifton loamy sand are 2.9 % (Stansell et al., 1976) and 5% (Liang et al., 2016; Ma et al., 2000). Note that the FC and PWP values change as you go deeper into the soil profile, in which FC and PWP increase. The PAW values are all inflated due to the low PWP. Without accurate values of PWP, PAW cannot be determined.

Field Saturated Hydraulic Conductivity (K_{fs})

Because the K_{fs} varies from site to site and even within a site, comparing it to K_{sat} can be challenging since K_{sat} is usually determined in the lab. It is well known that K_{sat} is dependent on soil texture (Hillel, 1980). Rawls et al. (1982) reported average K_{sat} values for sandy clay loam, clay loam, loamy sand, sandy loam, and clay of 0.68, 0.23, 6.11, 2.59, and 0.06 cm/hr, respectively. Site 2's values were slightly less than that reported for loamy sand soil, which is plausible given air entrapment which leads to the K_{fs} being lower than K_{sat}, as discussed earlier.

It was expected that the K_{fs} at Site 1 would be lower because the soils are sandy clay loam, clay loam, and clay. K_{fs} is typically lower than K_{sat}, but the values at Site 1 are all significantly higher than what is seen in the literature. Even using the Soil Water Characteristics program included with the SPAW (Soil Plant Air Water) version 6.02.74 installation package, the estimated K_{sat} was 1.5 cm/hr for Site 1. This was determined by inputting information such as the % sand, % clay, and % organic matter. Because Site 3 is dominated by sandy loams, in theory, K_{fs} values should have been much lower than at Site 1, but this was not the case. Antecedent moisture conditions could have played a role, but K_{fs} is also impacted by soil structure, as macropores can lead to higher than normal values. Also, as mentioned earlier, the fact that years ago, an abundance of topsoil was added to the soil on Site 1 could be a reason why the K_{fs} values were significantly higher than expected. Spatial and seasonal variation also affects K_{fs} (Moustafa, 2000). While FC and PWP typically increase with depth, K_{fs} normally decreases, especially on Site 1, where there is a transition from sandy loam/sandy clay loam to clay in the B horizon.

VWC and Watermark Data

Site 1 (Oconee County)

The two main trends from the Watermark data from the 2021 growing season were the drying out of the 20 cm sensor and the deeper sensors rarely responding to irrigation. The lack of response is not necessarily a negative behavior. If the deep sensors showed a large response to the irrigation event, like at Site 2, less water is required. Generally speaking, if the deep sensors show no response to the irrigation event, the amount of water applied is adequate or could be increased. The deeper sensors responded to irrigation when the upper layers were wet, which is a result of gravitational drainage. Percolation from layers occurs when the soil moisture exceeds field capacity. The amount of percolation is a function of the hydraulic conductivity and the average soil water content above field capacity (Mercado, 1993). Quite possibly, the soil moisture deficit in the upper layers was large enough to store the water in the upper layers. Soil moisture deficit is defined as the difference between FC and current soil moisture times the thickness of the soil. If the upper layers had a significant deficit, then this could explain why percolation to deeper layers was minimal. If the deficit was larger than this amount of irrigation applied, quite possibly, the water was stored in the upper layers. Also, the trees could have absorbed the water before percolating down. Another explanation could be that once the irrigation water hit the clay layers below 20-41 cm, it moved laterally due to capillary action because of the micropores in clay.

The 20 cm depth Watermark sensor's pattern during 2021 can be explained by higher evaporative effects since it's closer to the soil surface. Another reason could be the presence of lateral roots taking up water since the roots on young trees are shallow. The sandy topsoil could also be a cause, as sandy soils dry out faster than clay soils.

Based on the data from the 2022 season, some Watermark sensors required reinstallation to accurately respond to irrigation. Although the deeper sensors did not respond to irrigation, it is unknown if this was due to poor data or water not reaching this depth. Likely, cracking of heavy clay soil as a result of the installation method of the sensors using the slurry led to poor soil to sensor contact over time. This is discussed in detail by Irmak et al. (2016), and Peries and Enciso (2009). Additionally, contact loss between the Watermark sensor and soil is particularly noticeable in tree crops during large gaps in irrigation. After discussing with the staff at Irrometer Co., they mentioned that poor contact was the most likely reason for the lack of response of some of the sensors. The installation method of the Watermark sensor is also most likely why the sensors at Tree C1 in the 2021 season did not respond to irrigation. Oddly, the 20 cm sensor at Tree C1 responded to every irrigation event in 2022, however, the response was minimal. A better way to install the Watermark sensors would have been to follow the method by Irmak et al. (2016), where no slurry is used, and the sensors are installed using a 2.22 cm (7/8 in.) soil probe. This ensures good contact between the sensor and the soil and maintains soil physical properties such as bulk density and pore size distribution.

Before the 20 cm sensor at Tree A stopped responding to irrigation after May 16th and Tree B1 after May 18th, patterns were consistent, and the soil was adequately wet. This is ideal because young pecan trees need consistent moisture, not transitioning from wet to dry soil and vice versa. Consistent moisture keeps soil temperatures cooler near the surface which prevents feeder roots from dying. After the 20 cm sensors stopped responding, multiple gallons of water were applied to the soil surface over the sensors, and there was no response. This was done as a suggestion by the staff at Irrometer Co.

Site 2 (Toombs County)

As discussed earlier, the primary trend from the Watermark and VWC sensors at Site 2 during the 2021 and 2022 study periods was that the sensors stayed saturated or near saturated, even down to 81 cm. In May 2022, cutting back to three days a week led to less deep percolation, as evident by the Watermark and VWC sensors. The 81 cm sensor readings in May 2022 did not have the massive spikes that occurred in 2021. The upper sensors were saturated after some irrigation events; thus, irrigation could have been delayed or cut back. The 20 cm Watermark data at Tree A on Site 2 signal that after irrigation, the soil may reach FC after 24 hours or so, and then irrigation was cut on. As previously mentioned, the goal is not to keep the soil between saturation and FC but rather between FC (or 90% of FC) and the 50% MAD line, which for this soil type is generally in the 25-30 kPa range.

A significant reason for the saturation at the deeper layers was the K_{fs} of the soil determined from using the SATURO at Site 2, which was, on average, higher than the other sites. A high K_{fs} with a loamy sand texture with minimal lateral movement means that irrigation water percolates quickly deep down the profile, which explains the behavior of the 81 cm Watermark and VWC sensors. This relates to behavior found at Tree B. The unresponsiveness of the 20 and 41 cm depth Watermark sensors at Tree B on Site 2 in parts of 2021 and 2022's growing period is likely due to the nature of drip irrigation. Drip irrigation typically wets a small area, whereas microsprinklers wet a larger surface area, which is advantageous for developing the lateral root systems of young pecan trees. Given that the soils are loamy sand on Site 2, as aforementioned, there is minimal lateral movement of water, water infiltrates downward faster. Vice versa, on clay soil, drip irrigation may cause ponded water. There has been research on the wetting patterns of drip irrigation on various soil textures. In a study by Diamantopoulos and Elmalogou (2012), in which the soil water distribution patterns for various soil textures were determined after subsurface drip irrigation, water infiltrated deeper into the profile in loamy sand soil than in the silty clay loam soil. This was due to the high hydraulic conductivity, which led to a significantly more vertical spread of water than horizontal. In the silty clay loam soil, the vertical spread was only slightly larger than the horizontal. The findings are consistent with those from Siyal and Skaggs (2009). As an additional reference, findings from Tawutchaisamongdee et al. (2018) were that after drip irrigation in sandy clay loam, water moves laterally and vertically evenly, whereas in loamy sand, water moves faster and more vertically. The differences in wetting patterns of drip and microsprinkler irrigation are shown in Figure 21 by Herrera and Sammis (2002), which relates to the differences in Watermark sensor behavior between Tree A and B on Site 2.

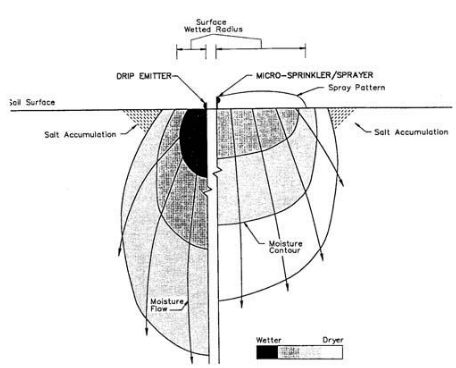

Figure 21. Wetting Pattern of Drip and Microsprinkler (Herrera and Sammis, 2002)

The irrigation applied in both growing seasons was significantly higher than the recommended 379 L/week (Wells, 2017a) for young pecan trees on loamy sand soil through the third leaf using microsprinklers. If Site 2 were using the 379 L/week schedule and irrigating every other day, it would equate to 95 L/day for a four day week, and 126 L/day for a three day week. This is not feasible for the irrigation system at Site 2 because the application rate for the microsprinkler on this site is 113 L/hour, and irrigation is typically run for 3-4 hours on loamy sand soils because water is lost due to deep percolation. If Site 2 were to try to irrigate the recommended amount per week without changing the irrigation system, irrigation would be turned on for less than one hour on some days. As a reference, in the study by Wells (2017b), 25.36 and 54.13 L/hour microsprinklers were used on Tifton loamy sand.

With the 5.5 m diameter of the microsprinkler at Site 2, a large portion of this water is going far from the lateral root system of a two year old tree, so the trees aren't receiving the full 1362 L/week, not accounting for efficiency losses. This was noticed after observing irrigation at Site 2 on several occasions.

According to the data, in 2021, there was minimal plant uptake at 61 and 81 cm depth, which was to be expected for first year trees. During year one, the lateral root system is weak for pecan trees (Toumey, 1929). During year two, lateral root growth increases, and the laterals near the surface are necessary for bracing the tree. During year three, the width of the root system is approximately equal to the height of the tree. According to McEachern (2015), while 90% of the total water and nutrient uptake is in the upper 91 cm, most of the water and nutrient uptake by pecan trees is in the upper 30 cm. This point was evident by the data on Site 2 as well as Site 1. The water beyond 81-91 cm is survival water, so on Site 2, there is no valid reason to have the soil at 81 cm saturated throughout the first growing season.

One aspect that could have possibly affected the results at Site 2 is the effect of sandy soil on the response to irrigation of the Watermark sensor. In Irmak and Haman's study (2001) on the performance of the Watermark 200SS sensor in sandy soils (loamy fine sand and fine sand), the sensor did not respond to changes in soil matric potential when the values were lower than 10 kPa (loamy fine sand) and 11 kPa (fine sand). The authors noted that this is a particular concern when 10 kPa is used as a trigger point for irrigation schedules in these soils. This relates to the Watermark data at Site 2 because 10 kPa was used as FC. As a result, if using 10 kPa as a threshold for irrigation using the Watermark sensor in sandy soils, the sensor may prove unreliable.

Site 3 (Hancock County)

Because irrigation was eventually cut off at Site 3 in late April, the lack of data precludes any thorough analysis of the irrigation scheme. Essentially, there are only data for around 11 days of irrigation, from April 14th –25th. Because of the daily irrigation, the SWT stayed in the saturated zone. Irrigation was started after the soil had been saturated because of rainfall. The tension in all the sensors only enters the FC to 50% MAD zone when irrigation is cut off. After talking with the farm manager, the plan is to increase irrigation to four hours per day for both mature and young trees. This would equate to increasing weekly irrigation by 477 liters. As root growth progresses for young pecan trees through the season, this increase may or may not be warranted.

CHAPTER 6. NEXT STEPS AND CONCLUSION

Next Steps

In the future, the location of sensors based on the drip and microsprinkler emitter needs to be evaluated. Due to the spray pattern observed at Sites 1 and 2 (Supp. Fig 29), many spots around the tree received more irrigation water than others due to preferential flow paths as a result of water hitting the canopy and falling to the surface. This would have affected the analysis of the irrigation scheme had sensors been placed at this location. This is the nature of microirrigation, as it is deemed sufficient to wet 40-60% of the soil surface after irrigation for adequate tree performance (Schwankl).

Moreover, the exact values from the Watermark sensor and the soil moisture sensors/probes cannot be entirely correlated due to the calibration method of both sensors, as the VWC sensors use a calibration equation to convert dielectric permittivity to VWC, while the Watermark sensor operates by converting resistance to SWT using temperature. To estimate SWC from the Watermark sensor, one would have to develop an SWCC. A field calibrated SWCC could be determined, as described by Rudnick et al. (2015). There are other methods of creating an SWCC, such as through pedotransfer functions (Saxton and Rawls, 2006) using variables such as % sand, % silt, % clay, % organic matter content, and % gravel content. These are not recommended for irrigation scheduling for pecan trees because many of these methods use 33 kPa as FC for all soil types. Although 33 kPa was used for the tempe cell tests, the data were still useful in that they gave certain trends and allowed for comparison of the values to the data in the literature such as Rawls et al. (1982). Even by looking at the Watermark data on Site

2 and finding the sensor-based FC after large rain events or irrigation, the SWT was in the range of 10-15 kPa. For future work on soil moisture monitoring in orchards, sensor based FC is a viable option (Vories and Sudduth, 2021).

Root distribution coefficients need to be investigated for young pecan trees, which will enable the averaging of SWC and SWT across the soil profile. If root distribution coefficients are estimated, irrigation can be initiated based on the weighted average of the sensors. The Clemson Watermark Calculator (Plumblee et al., 2019) can be used to average SWT values and then indicate whether irrigation needs to be initiated based on soil texture and allowable depletion. This calculator uses the SWCCs from Irrometer Co. as a guide. The caveat with using this calculator is that if depths of 20, 41, 61, and 81 cm sensors are input, it assumes even root distribution, therefore weighting coefficients of 0.25. Because pecan roots are not evenly distributed, this method is likely not the best way to schedule irrigations. The pecan root system is more likely an inverted pyramid (Wells, 2020) than a bundle of evenly distributed roots.

Conclusion and Recommendations

The VWC and Watermark data from the 2021 growing season on Site 1 (Oconee County) in Georgia's Piedmont region indicated the drying of the upper layers (20 cm) of soil to a soil water tension (SWT) of 239 kPa, and that water was primarily stored in the upper layers after irrigation events. The behavior was expected because of mostly sand (by weight) in the upper layers and clay in the B horizon. Also, soil in the upper layers is subject to higher evaporation rates and that the roots of young pecan trees are shallow explained the soil moisture behavior. This brings cause for concern because pecan roots grow best with consistent moisture throughout the growing season, not in conditions with high soil moisture variability. Because of this, recommendations for the 2022 season were made to switch from irrigating with microsprinklers for two days a week to every other day, thus increasing irrigation by, on average, 37 L/week. In April and May 2022, the SWT at 20 cm sensors on Site 1 stayed consistent, mostly under 50 kPa. This was the goal of changing the irrigation schedule, which was to prevent the peaks of the Watermark sensor at 239 kPa. Given this, the sensors stopped adequately responding to irrigation in late May. The Watermark sensors at 61 and 81 cm depth did not respond to irrigation in the 2022 season. It is recommended that the sensors be reinstalled to determine if the cause is irrigation water not reaching these depths or loss of contact between the soil and sensor.

For the young trees on Site 2 (Toombs County) in Georgia's Coastal Plains soils (Tifton loamy sand), the data showed that water was lost due to deep percolation after irrigation. Soil moisture readings (volumetric water content and soil water tension) at all depths stayed in the saturation range during most of the 2021 season study period. Based on the soil moisture data, root growth at 81 cm was not evident, thus soil saturation at irrigation at this depth was not warranted. To prevent deep percolation the water content must be managed between field capacity and the maximum allowable depletion zone (50% of available water), called the readily available water zone. The irrigation schedule in May 2022 was set for MWF for four hours each event, totaling 1363 L/week for microsprinkler application. The May 2022 season soil moisture data suggested that saturation at 81 cm was less frequent, but the upper layers were not in the readily available water zone. Recommendations were made to decrease irrigation frequency to three hours per day for three days a week. Cutting back one hour per irrigation event for trees with microsprinkler irrigation equates to a savings of 341 L/ week. The hope is that reducing the time by one hour will not wet the soil profile as heavily and create fewer saturation occurrences. Delaying irrigation to allow the water content to be in the readily available water zone is also recommended.

For Site 3 (Hancock County), located at the fall line between the Coastal Plains and Piedmont region and abundant in Pacolet sandy loam, more soil moisture data is needed for an accurate assessment of the irrigation schedules, as irrigation was turned on for approximately ten days during the 2022 study period. For those ten days, however, daily irrigation kept the soil in the saturation range, outside the readily available water zone of 15-40 kPa.

Regarding the other data collected throughout this study, the field saturated hydraulic conductivity (K_{fs}) values were higher than the application rate of the irrigation systems on each site, thus negating runoff. Site 2 had the highest average K_{fs}, which could explain the lack of response to irrigation for some of the sensors at the tree with drip irrigation on Site 2 because of the poor lateral movement of water through loamy sand soils and greater and faster vertical movement. The ground penetrating radar (GPR) results from a three year old tree on Site 1 possibly indicate a lateral root growth of young trees in the Piedmont region of 4 m. GPR tests on pecan orchards in the Piedmont region of Georgia are rarely performed, thus further testing using GPR to identify the root system of pecan trees on heavy clay soils (> 50% clay) is warranted.

Irrigation recommendations cannot be made for all young pecan trees in Georgia Piedmont soils based on the data from this study alone. More data is needed, and more sensors need to be installed before extrapolating the given results. Besides not enough soil moisture data from Site 1 (Oconee County Orchard), some of the limitations of the study are the lack of soil moisture data from Site 3 (Hancock County orchard) and lack of replication of laboratory soil water retention and field saturated hydraulic conductivity measurements.

Additionally, based on this study, irrigation schedules need to be evaluated every growing season, with additional soil moisture sensors installed to account for the spatial variance of soil moisture. To summarize, for future use regarding irrigation scheduling, the following are recommended:

- Greater number of soil moisture sensors on site to account for lateral growth of roots
- Development of soil water characteristic curves for each site
- Incorporation of plant-based measurements (i.e., stem water potential) to determine how young trees respond to changed irrigation schedules
- Development of weighted averages for soil moisture sensors based on root distribution

Incorporating these facets will allow for a more accurate analysis of irrigation schedules for young pecan trees in Georgia Piedmont and Coastal Plains soils.

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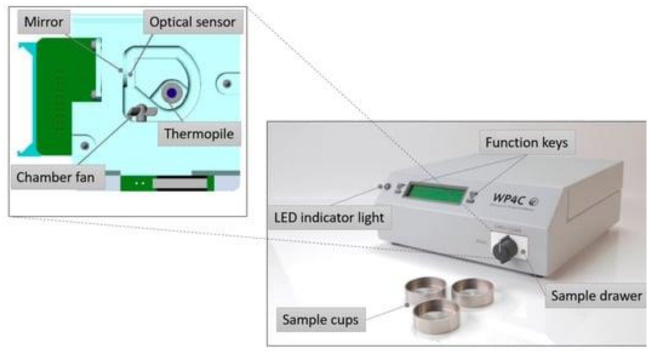
APPENDIX

Supplemental Figures

Supp. Figure 1. Saturating soil cores for field capacity tests



Supp. Figure 2. WP4C components and views of the front and inside of the chamber block (Haghverdi A., et al., 2020)

Supp. Figure 3. SATURO Set Up

Supp. Figure 4. AquaCheck Probe

Supp. Figure 5. Site 1 Tree B1

Supp. Figure 6. Site 1 Tree B2

Supp. Figure 7. Site 1 Tree C1

Supp. Figure 8. Site 1 Tree C2

Supp. Figure 9. Site 2 Tree A

Supp. Figure 10. Site 2 Tree B

Supp. Figure 11. Site 3 Tree A

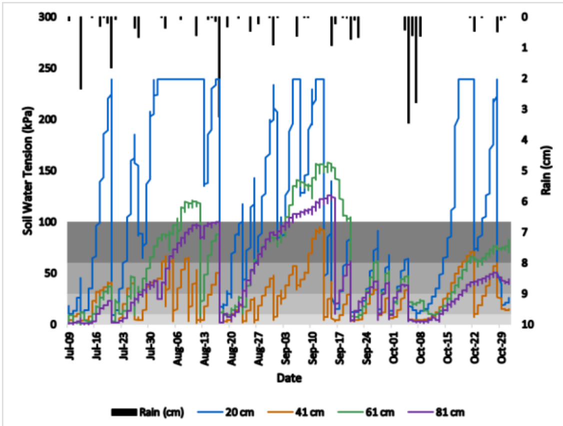
Supp. Figure 12. Site 3 Tree B

Supp. Figure 13. Site 3 Tree C

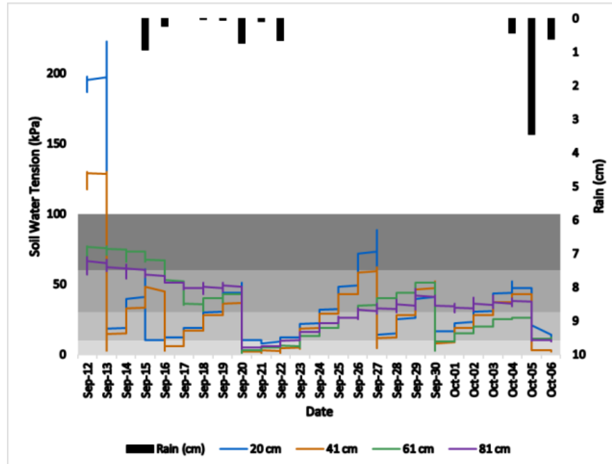
Supp. Figure 14. Site 1 Sensor Placement

Supp. Figure 15. Site 2 Sensor Placement

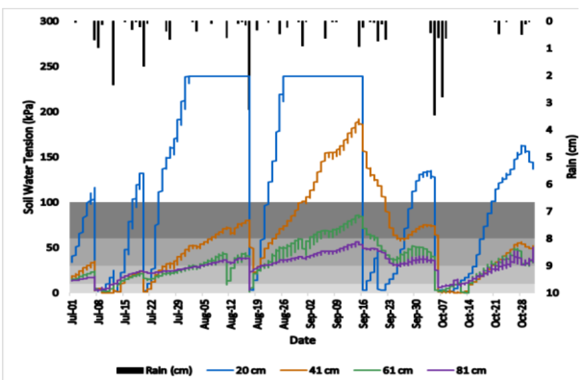
Supp. Figure 16. Site 3 Sensor Placement



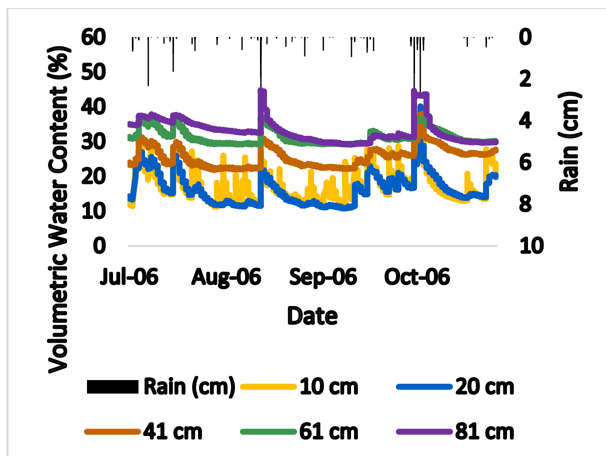
Supp. Figure 17. Site 1 Tree A Watermark Data for the 2021 Growing Season



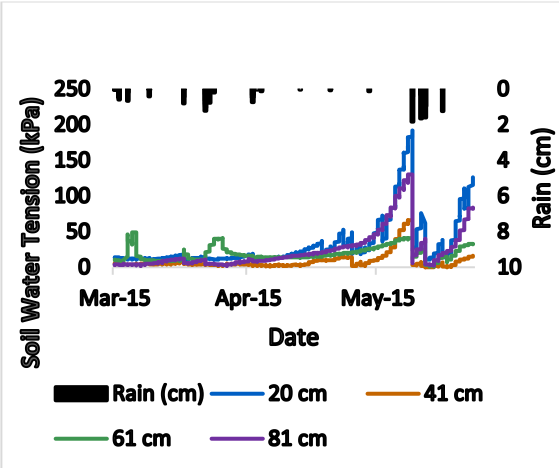
Supp. Figure 18. Site 1 Tree B1 Watermark Data for the 2021 Growing Season



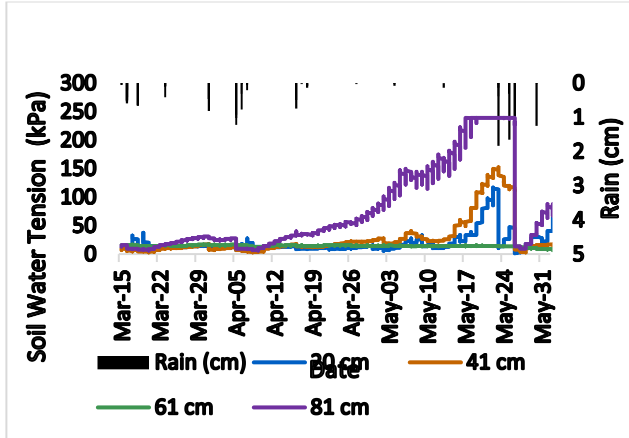
Supp. Figure 19. Site 1 Tree C1 Watermark Data for the 2021 Growing Season



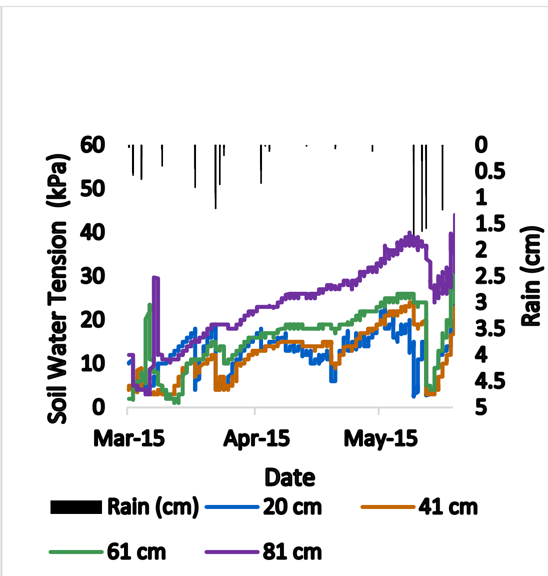
Supp. Figure 20. Site 1 Tree A Volumetric Water Content Data for the 2021 Growing Season



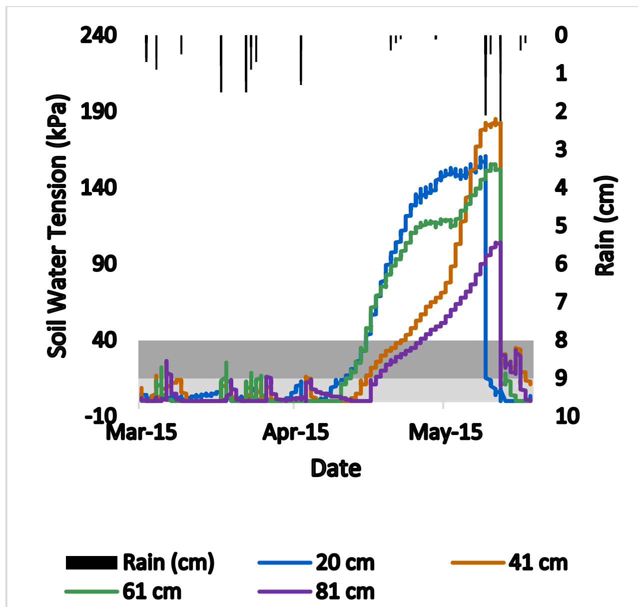
Supp. Figure 21. Site 1 Tree A Watermark Data for the 2022 Growing Season



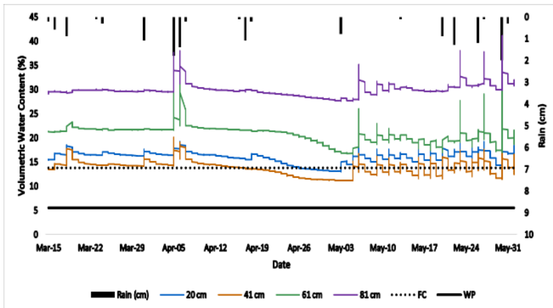
Supp. Figure 22. Site 1 Tree B1 Watermark Data for the 2022 Growing Season

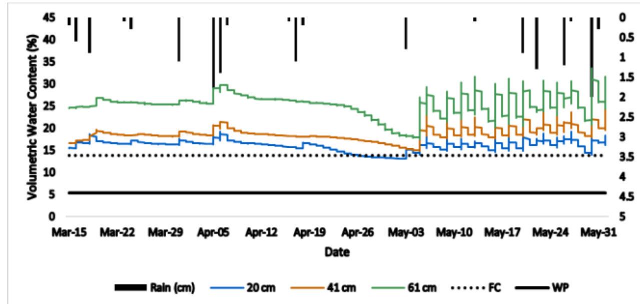


Supp. Figure 23. Site 1 Tree C1 Watermark Data for the 2022 Growing Season



Supp. Figure 24. Site 3 Tree B Watermark Data for the 2022 Growing Season



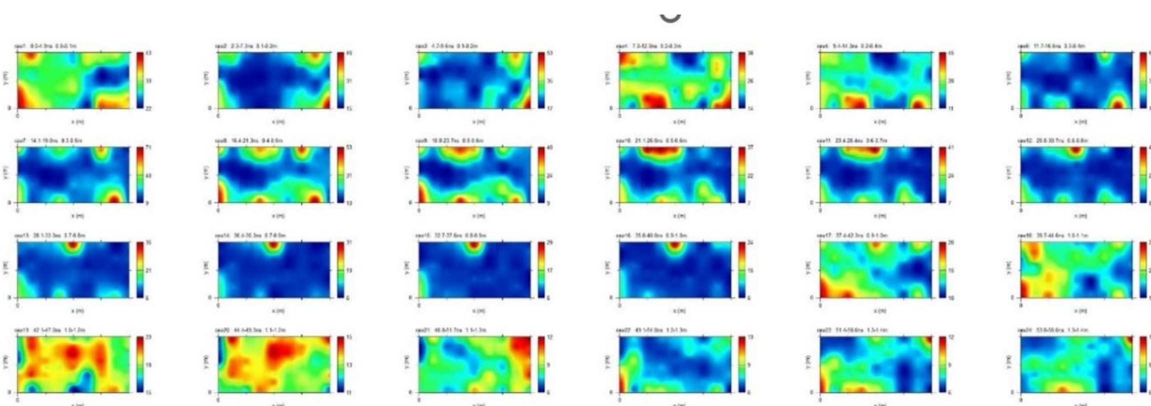


Supp. Figure 25. Site 2 Tree A (Microsprinkler Irrigation) Volumetric Water Content Data for the 2022 Growing Season

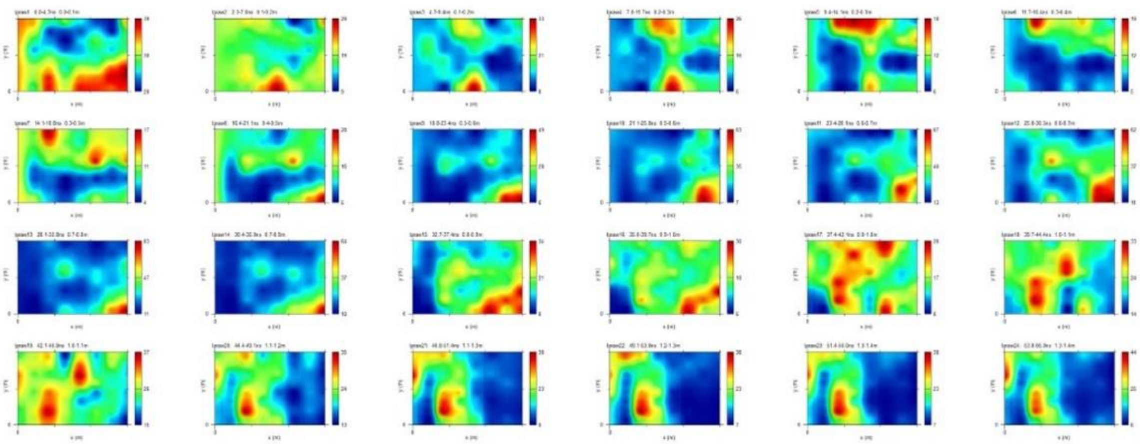
FC (Field Capacity) is indicated as dotted black line; WP (Wilting Point) is indicated as solid black line

Supp. Figure 26. Site 2 Tree B (Drip Irrigation) Volumetric Water Content Data for the 2022 Growing Season

FC (Field Capacity) is indicated as dotted black line; WP (Wilting Point) is indicated as solid black line



Supp. Figure 27. Ground Penetrating Time Slices for 3 Year Old Tree (x axis is 4 m, y axis is 2m)



Supp. Figure 28. Ground Penetrating Time Slices for 1 Year Old Tree (x axis is 3 m, y axis is 2m)

Supp. Figure 29. Microsprinkler Spray Pattern

Supplemental Tables

Supp. Table 1. Irmak et al. (2016) SWT Irrigation Initiation Points

Soil	Range (kPa)	Soil	Range (kPa)	Soil	Range (kPa)
Silty clay loam topsoil with silt clay subsoil (Sharpsburg)	75-80	Fine sandy loam	45-55	Bottom land silt loam (Wabash, Hall)	75-80
Silt loam topsoil (Keith)	80-90	Sandy loam	30-33	Fine sand (Valentine)	25-20
Upland silt loam topsoil with silty clay loam subsoil (Hastings, Crete, Holdrege)	90-110	Loamy sand (O'Neil)	25-30		

Supp. Table 2. Average Weather Conditions for each Site (georgiaweather.net)

Parameters	**Site**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Temperature (°C)	Site 1: Min	8.78	13.5	17.89	19.89	19.50	16.28	9.89
	Site 1: Max	23.22	27.11	30.61	32.00	31.39	28.11	23.11
	Site 2: Min	11.5	16	20.11	21.72	21.50	18.72	12.50
	Site 2: Max	26.39	30	32.72	33.89	33.28	30.72	26.11
	Site 3: Min	9.61	14.11	18.39	20.50	20.11	16.89	10.50
	Site 3: Max	23.72	27.72	31.28	32.72	32.00	29.11	24.11
Total Precipitation (cm)	Site 1	10.26	10.31	9.88	11.38	10.08	9.60	9.12
	Site 2	8.03	9.58	11.84	14.07	12.70	9.73	7.47
	Site 3	9.17	8.94	9.09	11.68	9.88	8.74	6.86
Number of Rainy Days	Site 1	9	9	11	12	11	8	7
	Site 2	8	8	11	14	12	9	7
	Site 3	8	8	10	12	10	8	6

*Site 1 average is from 1957-2016
*Site 2 average is from 1956-2016
*Site 3 average is from 1961-2016

Supp Table 3. Soil Horizons (Web Soil Survey)

Site	Tree	Typical Profile					
		A		B		C	
		Texture	Depth (cm)	Texture	Depth (cm)	Texture	Depth (cm)
1	A	Ap: Sandy Clay Loam	0-18	Bt: Sandy Clay	18-107	Loam	107-152
	B1, B2	Ap: Sandy Clay Loam	0-8	Bt: Clay	8-66	Sandy Loam	91-152
				BCt: Sandy Clay Loam	66-91		
	C1, C2	Ap: Clay Loam	0-13	Bt1: Clay	13-91	Loam	130-178
				Bt2: Clay Loam	91-130		
2	A, B	Apc: Loamy Sand	0-28	Btc1: Fine Sandy Loam	28-56	Sandy Clay Loam	165-203
				Bt (c1/c2/v1/v2): Sandy Clay Loam	56-152		
3	A, B, C	Sandy Loam	0-10	Bt: Clay Loam	10-64	Sandy Loam	109-203
				BC: Sandy Loam	64-109		

Supp. Table 4. SATURO Soak Time and Pressure Head Configuration

Soil Type	Soak Time (min)	Low Pressure Head (cm)	High Pressure Head (cm)	Hold Time at Pressure (min)	Pressure Cycles (count)	Total Run Time (min)
Wet Loamy Sand	15	5	10	15	2	75

Supp. Table 5. Number of Sensors Installed

Site No.	# of VWC Sensors	# of Watermark Sensors	# of Trees
1	26	24	5
2	4	7	2
3	6	12	3

Supp. Table 6. Volumetric Water Content Sensors Information

Sensor	Temperature	Dielectric Permittivity	Conductivity	Max Vol of Influence
AquaCheck Probe	√	√		-
TEROS 12	√	√	√	1010 mL
10HS		√		1320 mL
GS3	√	√	√	160 mL
5TE	√	√	√	715 mL

Supp. Table 7. Site 2 Watermark Sensor Data for April-May 2022

	kPa					
Depths (cm)	n	min	max	median	mean	std
Tree A						
20	6221	2	115	10	21	27
41	6221	3	128	8	21	30
61	6221	1	32	4	8	8
81	6221	0	21	10	9	6
Tree B						
20	5885	4	88	23	37	28
41	5885	3	63	13	19	15
61	4591	0	98	11	19	22
81	5885	2	38	7	11	9

Supp. Table 8. Site 2 Volumetric Water Content Sensor Data for April-May 2022

	%					
Depths (cm)	n	min	max	median	mean	std
Tree A						
20	6221	13.0	21.2	16.1	15.8	1.2
41	6221	11.1	21.9	13.5	13.5	1.5
61	6221	16.6	34.5	20.3	20.3	1.8
81	5951	27.6	41.4	29.8	29.9	1.4
Tree B						
20	5885	15.5	30.9	20.5	20.6	2.5
41	5885	14.9	25.7	18.5	18.6	1.5
61	5885	17.5	33.6	25.0	25.0	2.8