INTERANNUAL AND INTRASEASONAL VARIABILITY OF CROP COEFFICIENT IN A PECAN ORCHARD IN GEORGIA

by

KRITI POUDEL

(Under the Direction of Monique Leclerc)

ABSTRACT

The Southeast is a leading pecan-producing region, yet the corpus of research on water requirement of pecan [*Carya illinoinensis* (Wangenh.) K. Koch] trees are scarce. Much of the knowledge stems largely from flood-irrigated arid Southwest studies. This study addresses crop coefficient dynamics across various physiological stages in a Southeastern, micro-sprinkler irrigated orchard. Actual evapotranspiration was measured using an eddy-covariance system and micro-lysimeter. The cumulative water demand for a six- to ten-year-old pecan orchard in the Southeast (680 mm) contrasts sharply from that of the Southwest (1000 mm to 1400 mm). From bud break through harvest, daily pecan evapotranspiration ranged from 0.4 to 6.2 mm and crop coefficient varied from 0.4 early in the season to 1.0 in July. No significant differences in evapotranspiration, crop coefficient and yield were observed between seven- and ten-year-old pecan trees. These results constitute a significant step forward in irrigation scheduling in hot and humid climates.

Keywords: Water management; climate-smart irrigation; Southeastern pecan orchards; water relations; orchard evapotranspiration.

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DEDICATION

I would like to dedicate my work to my ever-loving parents, my brother, my partner and my friends who have constantly been supporting and encouraging me get through this journey of my life.

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CHAPTER 1

INTRODUCTION

Georgia is one of the leading states in pecan [(*Carya illinoinensis* (Wangenh.) K. Koch)] production with a ten-year average of 44,000 tons produced annually followed by New Mexico at 37,000 tons (NASS, USDA, 2024). Notably, in 2020, Georgia produced 64,400 tons of pecans, accounting for almost half of all U.S. production. However, pecan trees are highly sensitive to the drought conditions (Sammis et al., 2004; Liu & Sheng, 2013; Wells, 2015). In mature orchards, irrigation is one of the most important inputs for better yield particularly during the kernel filling period (Deb et al., 2012; Liu & Sheng, 2013; Samani et al., 2011a; Wells, 2015). Wang (2007) mentioned that 30% more water is used by pecans than any other row crops in the Southwest.

While the average rainfall during the growing season in Georgia is 1270 mm, suggested water demand of pecan is 1270 mm to 1470 mm (Sammis 2004; Wells 2015)-annually, based on a combination of stem water potential and soil moisture data. In their study, Worley (1982) and Marco et al. (2021) observed that the rate of evaporation exceeds the rainfall throughout the growing season in hot and humid climates such as that of Georgia and that of Uruguay respectively. This moisture deficit during the reproductive period leads to reduced nut and kernel sizes, a lower pecan nut percentage and can lead to nut drop (Wells 2015; Madero et al., 2017). Marco et al. (2021) reported by irrigating 140 L/plant in every two days, an increase in yield greater than 100% was observed in Uruguay. Similarly, in Georgia, Wells (2017) observed a 89% to 388% increase in growth of young trees with irrigation, and Daniell (1979) reported a 70% increase in yield in similar growing conditions.

Optimal irrigation scheduling is critical to maximize the yield and water-use efficiency in pecan orchards (Sparks 1968; Worley 1982; Sammis et al., 2004; Wells 2015; Marco et al., 2021). The growers' knowledge gap surrounding optimum pecan water requirements in Southeast is significant (Wells 2015). Some of the significant research by (Worley 1982; 1985; Wells 2017) marks the seminal work on irrigation scheduling. Evapotranspiration (ET) is an essential component of the irrigation scheduling(Allen et al., 1998). ET has been measured in fruit trees using several techniques, such as a micrometeorological method i.e. surface energy balance (Sammis et al., 2004), the dual crop coefficient method using both transpiration and soil evaporation inputs (Mashabatu et al., 2023), remote sensing approach (Samani et al., 2009) and lysimeter techniques (García-Tejero et al., 2018; Girona et al., 2011). The crop coefficient (K_c) approach is one of the key tools used to determine the irrigation schedule (Allen & Pereira, 2009). K_c is the ratio of actual evapotranspiration (ET_a) to potential evapotranspiration (ET_0), i.e., evapotranspiration from pristine cropping and well-watered conditions (Allen et al., 1998).

Most of the research on pecan water management in the United States has been done in flood irrigated orchards established in arid and semi-arid climates (Sammis et al., 2004; Samani et al., 2009; Sheng & Liu, 2015) . Research in arid and semi-arid climates has shown variable water use depending on canopy cover and crop management practices. In New Mexico, pecan water use ranges from 1170 to 1400 mm annually, depending on the method and the tree age (Sammis et al., 2004; Samani et al., 2009, 2011). In Texas, using a method similar to the one used by Sammis (2004), Sheng & Liu (2015) found the annual evapotranspiration of mature pecan to be around 1202 mm.

In Uruguay, a hot and humid climate, Marco et al., (2021) reported an increase in yield of seven-year-old pecan trees following the irrigation of 140 L/plant in every two days. This study noted that amongst other variables, large and well-formed kernels are influenced by crop management practices. For instance, actual water requirements must be assessed in each orchard in order to adjust the tree needs. In Georgia, Daniel (1985) suggested 22,440 $Lha^{-1}d^{-1}$ for mature trees during the kernel filling period under drip irrigation on a heavy clay soil. While later addressing the limitation of soil type, Wells (2015) recommended 59,600 $Lha^{-1}d^{-1}$ for a loamy sand soil in similar climatic condition. A drip irrigation rate of 182 L per week and a micro sprinkler irrigation rate of 304-378 L per week showed no significant difference on young pecan trees growth (Wells 2017). Nevertheless, excessive dry periods in coarse-textured soils may require a periodic application of up to 650 L per week with micro sprinklers.

Results from United States (Wang et al., 2007), Spain (Girona et al., 2011) and South Afirca (Mashabatu et al., 2023),all show the variation in water requirements depending on the plant type, tree age, crop height, climate, soil type, canopy cover and growth stage within a season and local weather conditions (Wang et al., 2007; Girona et al., 2011; Mashabatu et al., 2023). Thus, it is essential to have information about actual evapotranspiration (ET_a) for optimal irrigation scheduling and water resources planning and management (Drechsler et al., 2022).

The literature on irrigation scheduling for pecans is numerous in the Southwest U.S (Miyamoto 1985; Sammis et al., 2004; Samani et al., 2009; Zanotelli et al., 2018) in contrast with the Southeast U.S (Sparks 1989; Worley 1982; Wells 2015). The summer peak ET of mature, crowded orchards using flood irrigation in the Southwest is similar to pan evaporation rate for that season (Miyamoto 1982, 1983, 1985).

The study by Daniell (1979) was based on data of 70% evaporation from a class A evaporation pan. This experiment was conducted in heavy clay soil, typically leading to an underestimation of water requirements in lighter textured soils such as loamy sand soil (the soil type of the present study). To account for this limitation, Wells (2007) developed an irrigation schedule based on a study by Daniell (1979) and data from arid climates (Miyamoto, 1983; Sammis et al., 2004) using stem water potential and volumetric water content information for Southeastern for pecan trees. The new reduced irrigation schedule from Wells (2015) resulted in a 38% reduction in irrigation without any impact on nut quality and yield.

Unlike in an arid climate, precipitation accounts for most of the water use of pecans in humid climate like Georgia (Wells 2015; Painter, et al., 2021). The Southeast U.S. has a humid subtropical climate with moist convection and tropical storms as major sources of precipitation during the summer and frontal action in the fall (Kunkel et al., 2013; Praskievicz, 2019; Gavahi et al., 2020). According to the 2023 Intergovernmental Panel on Climate Change (IPCC) report (Calvin et al., 2023), there has been an increase in frequency and intensity of warmer temperature extremes in the Southeastern U.S. when compared to the 1950s. High temperatures recorded inland accompanied with increased land evapotranspiration have resulted in agricultural droughts. The variability in the climate demands the real-time irrigation schedule for the specific region and crop (Garcia-Vasquez et al., 2022). This is in agreement with the study by Wells (2017) which reports the variation in water requirements for pecan growth with rainfall during and within the growing season. The erratic rainfall distribution potentially creates moisture deficiency during the critical period of kernel filling leading to the poor yield and nut quality (Taylor et al., 2009; Wells & Harrison, 2010; Liu & Sheng, 2013; Wells, 2015).

In addition to their climatic differences, the Southeast and Southwest U.S. pecan production use different irrigation practices. Southeastern growers practice micro sprinkler irrigation rather than flood irrigation, which is typical of the Southwestern production. Different methods of irrigation impact the root distribution of pecans by the wetting of the soil (Wells 2017).

Wells (2017) observed drip irrigation to be more efficient on water conservation than micro sprinkler. Moreover, micro sprinkler represents a better alternative to drip irrigation in coarse textured soil in Georgia.

The present research presents the actual evapotranspiration and water need of young pecan trees. This will help farmers refine the standard irrigation schedule using real-time data throughout different physiological stages of pecan using the crop coefficient approach.

GOAL AND OBJECTIVES:

The goal of our study was to record the water demand of a typical pecan orchard in the Southeastern US. The objectives were to estimate evapotranspiration in six to ten-year-old hedged pecan trees using the eddy-covariance system and other supporting instrumentation. Another objective lies in the determination of the crop coefficient pecan orchard in the Southeast.

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CHAPTER 2

INTERANNUAL VARIABILITY OF CROP COEFFICIENT IN A PECAN ORCHARD IN GEORGIA

K. Poudel, M. Leclerc, L. Wells, G. Zhang. To be submitted to Journal of HortScience

ABSTRACT

In a four-year study conducted in a commercial pecan orchard in Georgia, this paper reports on the behavior of the daily crop coefficient throughout the growing season from budbreak to harvest. Specifically, this study characterizes its year-to-year interannual variability. The present study uses an eddy-covariance system measurements and micro-lysimeter measurements to determine the actual evapotranspiration of pecans in hot and humid growing conditions. It examines the de facto irrigation practices used by growers as well as the current irrigation schedule. An average of 16% of evapotranspiration is contributed by grasses between the tree rows throughout the growing season using microlysimetry. Results suggest that throughout the experiment, the intra-annual variability significantly trumps the interannual variability. From bud break through harvest, pecan water use ranged from 0.4 to 6.2 mm day^{-1}, with crop coefficient (Kc) values varying between 0.3 and 1.0 during that period. From the four year study period, the water needs of the pecan trees in hot and humid climate was recorded as 680 mm. The total evapotranspiration of pecans during growing season (Mar – Oct) is 33% higher than the total amount of irrigation recommendation in Georgia while total water input in the field is ~42% higher than the actual water demand of pecan trees. A severe pecan scab infestation which is one of the significant cause of yield loss in the year 2022(~90%) compared to the average yield of 2020 and 2023 (930 $kgha^{-1}$). There is no significant difference in the pecan water use, crop coefficient and thus nut yield between seven- and ten-year-old trees except for the six-year-old trees with lower tree canopy(~23%).

Keywords: water management; climate-smart irrigation; irrigation in Southeastern pecan orchards; water relations in nut trees; orchard evapotranspiration

INTRODUCTION

Pecan [*Carya illinoinensis* (Wangenh.) K. Koch] is a native North American crop with significant economic importance (Sparks, 2005). Pecan land acreage increased by 24% from 2012 to 2022 making Georgia one of the top pecan producers in the United States (USDA, 2024). For example, in 2023, the state produced 40 thousand metric ton of pecans, making it the second-largest pecan producer in the country.

Amidst the effort of reducing input costs and increasing net returns from the orchard, robust and rigorously validated irrigation management practices are among the most important (Wells 2015).

Pecan trees are highly sensitive to drought conditions (Sammis et al., 2004; Wells, 2015). Water restriction during the reproductive period can impact nut drop and pecan nuts percentage (Madero et al., 2017). This is even more acute during high periods of transpiration, late in the season as the distribution of moisture is directed to leaves over nuts (Avila et al., 2000; Marco et al., 2021). However, the impact of water stress on quantity and quality of pecans depends on the cultivar and orchard management practices (Wells 2017). In Georgia, irrigated plants in comparison to non-irrigated ones provided a 70% increase in yield of mature trees (Daniel, 1982) and a 89% to 388% increase in growth of young trees (Wells, 2017). Likewise, in a pecan trees cultivation without irrigation, it incurred more than 100% loss in nut yield in Uruguay (Marco et al., 2021). Specifically, quantifying crop water requirements throughout the different phenological stages can lead to optimum irrigation scheduling (Deb et al., 2012; Liu & Sheng, 2013; Samani et al., 2011a; Wells, 2015).

Crop water use can be determined using the crop coefficient (K_c), which is defined as the ratio of actual evapotranspiration (AE) to potential evapotranspiration (PET) (Doorenbos and

Pruitt, 1977; Allen et al., 1998; Pereira et al., 2015; Zanotelli et al., 2019). K_c varies with species, cultivar, crop height, tree age, spacing, soil management, canopy cover and growth stage within a season and local climatic conditions (Wang et al., 2007; Girona et al., 2011; Mashabatu et al., 2023).

There is several research on pecan water use for cultivation in arid regions such as the Southwestern United States compared to the Southeast (Wells, 2015; Worley, 1982). In dry and arid state of New Mexico, where flood irrigation prevails, pecan water requirements ranged from 1100 to 1400 mm depending on the tree age and the physiological stage (Miyamoto, 1983; Sammis et al., 2004; Samani et al., 2009; Samani et al., 2011). Previous studies observed that typical K_c values ranged from 0.4 early in the season to 1.1 during peak evapotranspiration (ET) period (Abriquesta et al. 2013; García-Tejero et al. (2018); Drechsler et al., 2022). Likewise, in micro-sprinkler irrigated almond and pistachio orchards in California, K_c- 0.4-0.5 in the early season (March) to 1.1-1.3 during the peak season i.e. July and August (Bellvert et al., 2018).

While Georgia receives 1270 mm of average annual rainfall, the seasonal water requirements ranged between 1270 mm to 1470 mm (Sammis 2004; Wells 2015). In the hot and humid climate of Georgia, Wells (2015) and Wells & Casey (2013) reported that a single tree needs approximately 1300 L of water per day during kernel filling period i.e., August and September. Despite all these pioneering studies, the diurnal, seasonal and annual variability in water requirements in pecans needs to be refined (Wells, 2017). The real-time crop consumptive use and its daily variability are critical factors in increasing irrigation efficiency. (Garcia-Vasquez et al., 2022).

The goal of the present study is thus to identify water requirements of mature pecan trees for the Southeast United States. This paper is quantifying the water needs throughout the different physiological stages of the tree during the growing season and between the spanning four years of measurements. This information is then compared to the current irrigation schedule that will help farmers refine the operational irrigation management practices.

MATERIALS AND METHODS

2.1 Site Description

The research was conducted for four years (2019, 2020, 2022 and 2023) in a commercial 372 ha pecan orchard located in Hawkinsville, GA (32°20’35” N, 83°37’43” W) (Fig.1).

The tree spacing was 9m * 15m orchard (cultivar “Desirable” and Pawnee as pollinator) planted in 2013. The height of the tree was measured while climbing the tower in March every season and it varied from 9 m in 2019 to 11 m, 12 m and 13 m in 2020, 2022 and 2023. The predominant soil type in the field is Norfolk loamy sand (Fine,kaolinitic, and thermic Typic Kandiudults) (NRCS/USDA, 2023). The diameter of the tree at breast height (1.2 m) was 22.4 cm in 2022 and 23.2 cm in 2023. Early in the season, the section between the orchard floor is covered by a mixture of grass, wildflowers, clovers and vetch. Later in the season, this vegetation is dominated by Bermuda grass (*Cynadon dactylon L.*). Mowing is done once in June and twice later until harvest operations begin i.e. August and September. Ten to eleven sprays of fungicide, six sprays of herbicide and four sprays of fertilizer are done from the beginning of the season i.e. April until the last spray in August. Foliar application of phosphite, Zinc Nitrate (or Zinc 10%) and Boron 10% at the rate of 3.8 Lha^{-1} is done along the first spray of fungicide in April. Ammonium nitrate (32N-0P-0K) was applied at the rate of 101 $kg.ha^{-1}$ in mid-April and 17 $kg.ha^{-1}$ additionally in May, June and July. Trees are mechanically hedged as described in Wells (2018). Trees were pruned using hedging machine on one side at ~1.85 m from the trunk and at the tops of the trees on east and west side in alternate years. The tops of were pruned at a 45° angle to a height of 12 m on the same side of the tree on which the hedge pruning was done.

Micro-sprinkler irrigation with 1.12 mm nozzle in 5.94 m notched diameter and 15 gallon per hour flow rate was used throughout the four years of the study (2019, 2020, 2022 and 2023).

Micro sprinklers (QN-14, Rain Bird Corporation, Azusa, CA) were placed approximately 1m from the tree trunk in line with the tree row. The meteorological variables over the duration of the experiment are documented in Appendix Table 1 and illustrated on Figure 2. Their interannual variability is presented in Table 1.

2.2 Instrumentation and processing

2.2.1 Eddy-covariance system

The system consists of an omnidirectional fast-response sonic anemometer/thermometer (CSAT3, Campbell Scientific Inc., Logan, UT) measuring the high frequency three-dimensional velocity and temperature. The fast-response open-path infrared CO_2/ H_2O analyzer (LI-7500, Li-Cor Biosciences, Lincoln, NE) measures CO_2 and H_2O density at the height of 10.20 m (2019), 12.80 (2020) and 14.2 m (2022 and 2023). The LI-7500 was calibrated using CO_2 and H_2O free gas, 500 ppm CO_2 gas (±1% uncertainty) and a Li-610 dew-point generator (LI-7500, LI-COR Inc., Lincoln, NE). The gas analyzer was replaced for calibration at approximately each six months as a part of normal maintenance. Measured fluxes represent a spatially weighted average net exchange rate from an area upwind of the flux tower called the 'footprint' as detailed by Leclerc and Thurtell (1990); Leclerc and Foken (2014); Kljun et al., (2015); Arriga et al., (2020). A data logger (CR1000, Campbell Scientific, Logan, UT, USA) was used to collect 10 Hz data from the eddy-covariance (EC) system. The system was powered by two 12 V DC deep-cycle batteries which were charged using a 120 W solar panel.

A weather station (WXT530, Vaisala Corp., Vantaa, Finland) was installed at the top of EC tower to measure atmospheric pressure, temperature, humidity, rainfall, wind speed, and wind direction. Rainfall is measured using a rain gauge (TB4, Hydrological service America, Lake Worth, FL). Temperature probes (HMP60, Vaisala Corp, Vantaa, Finland) were used to measure temperature. The raw data were collected on datalogger CR1000 (Campbell Scientific Inc., Logan, UT) with 30 min average flux table. Any gaps in temperature, solar radiation and VPD are filled using Unadilla Weather Station in the Georgia Automated Environmental Monitoring Network by the University of Georgia located at 32°15’32.2” N, 83°39’41.5” W, approximately 9.3 km south of the research site. The correlation coefficients in 2022 and 2023 were 0.98 and 0.97, 0.97 and 0.96, and 0.91 and 0.94 for air temperature, VPD, and solar radiation, respectively.

The years 2019 and 2022 had significantly higher VPD values in contrast with other years as shown in Figure 2. Other meteorological drivers like temperature, and solar radiation increase reached a maximum during the nut sizing and kernel filling stage in August and September. All the meteorological parameters slowly decreased after August.

2.2.2 Flux calculations and signal processing:

The Eddy Pro Version 7.0.9 (Li-Cor) was used to calculate the 10-Hz data into 30-min average. The same software was used for the footprint analysis to ensure that the evapotranspiration flux data represented the sum of the individual signatures within the field of interest. Kormann and Meixner (2001) footprint equation was used where the sources upwind contributing to the measured fluxes are expressed as:

$$F(x) = \frac{1}{\Gamma(\mu)} * \frac{\xi(\mu)}{x^{1+\mu}} * e^{-\xi/x} \tag{1}$$

Here, the F(x) is the footprint function, i.e., the contribution of the individual sources/sinks to a point flux measurement. ξ is the flux length scale. The distance from the flux system in the wind direction is measured by x. $\Gamma(\mu)$is the gamma function and μ is the dimensionless model constant. This model gives the area’s cumulative source contribution, and the footprint is expressed in percentage of the total flux. The mean footprint length with 90% of the flux data was within 100 m for the research period. Since the fetch was homogenous and pecan orchard spread over 350 ha, the fluxes represented well the evapotranspiration of the pecan ecosystem.

The anemometer tilt correction was done using the planar-fit method (Wilczak et al., 2001) over each month. Spikes removal is done according to (Vickers & Mahrt, 1997). Time lag compensation is done using a covariance maximization. Density fluctuations corrections due to heat and water vapor transfer are made following the Webb-Pearman Leuning method (Webb et al., 1980). Linear detrending was done for an individual 30 min run. The interference in the optical path of the sensor due to rain, fog, and dust is registered by the automatic gain control (AGC) values. Post Eddy Pro processing, the AGC values higher than 90 were withheld from further processing. Only periods with a maximum of 10% of missing values were selected. The transition time of two hours was selected for each month every year (Lapworth, 2006; Moffat et al., 2007; Angevine, 2008). The data following the two hours after sunrise and preceding the two hours before sunset was selected to ensure a well-mixed turbulence regime.

Gaps in the eddy-covariance data caused either by instrument malfunction, or by calm, stable conditions were present following rigorous data filtering. In particular, due to stable atmospheric stratification, a significant percentage of data is removed during nocturnal periods (Rebmann et al. 2005). An R package- (REddyProc, Reichstein and Moffet, 2015) was used for u_* filtering using the built-in function. This function estimates the friction velocity u_* threshold using the moving point test (MPT) which incorporates a slight modification in the binning scheme from Papale et al., (2006).

2.3 Evapotranspiration and crop coefficient estimation

The crop coefficient is calculated as the ratio of actual evapotranspiration (ET_a) to the potential evapotranspiration (PET).

$$K_c = AE/PET \quad (2)$$

where, K_c is the crop coefficient, AE, the actual evapotranspiration and PET, the potential evapotranspiration. AE is calculated using the EC system. Potential evapotranspiration is calculated using the Priestley-Taylor equation represented as follow (Priestley & Taylor, 1972)

$$PET = \propto . \Delta . \frac{R_n - G}{\lambda . (\gamma + \Delta)} \quad (1)$$

where, Δ is the slope of vapor pressure curve (Pa/°C), γ is the psychometric constant (Pa/°C), λ is the latent heat of vaporization(J/kg), α is the dimensionless Priestley-Taylor parameter (1.26).

The psychrometric constant (Pa/°C) was calculated as:

$$\Upsilon = \frac{1.61452P}{\lambda} \quad (4)$$

where P is the pressure (Pa)

whereas Δ was calculated as:

$$\Delta = \frac{4098\ e_a}{(T + 273.3)^2} \quad (3)$$

where e_a is the actual vapor pressure and T is the temperature of air in °C

2.4 Differentiation of evapotranspiration from grasses

The EC system does not discern between ET from the vegetation present on the orchard floor and the ET from the trees and soil beneath them (referred to as the row strip). This differentiation is obtained from laboratory-built micro lysimeters (Boast & Robertson, 1982). These were 25 cm in height, formed by a 11-cm soil column and a 14-cm drainage column as shown in Fig 3. Eighteen micro lysimeters were positioned between rows and beneath trees to quantify the contribution of evapotranspiration from vegetation in the orchard floor from that of the evapotranspiration of the total pecan ecosystem (obtained through the ECflux data). Micro lysimeter measurements were successful after kernel filling period of 2023, i.e., October. This measurement was continued for the year 2024 starting in May through the end of September and data were collected at least twice every week until the end of the growing season.

2.5 Midday stem water potential and volumetric water content

Midday stem water potential (ψ) was determined using a pump-up pressure chamber (PMS Instruments, Albany, OR). Quasi weekly measurements of ψ were made between 1100 EST to 1300 EST from the leaves near the trunk or a main scaffold branch. Prior to each measurement, each leaf to be measured was covered with an aluminum foil bag for 20 minutes to allow equilibration with trunk xylem ψ (Othman et al., 2014). One leaf per tree was measured on each sampling date to keep measurements within close temporal proximity (Wells, 2015).

Volumetric water content (VWC) of the soil was measured throughout the year in 2019, 2020, 2022 and 202. Data were collected 5 m away from the tree trunk using time domain reflectometer (TDR) (CS655, Campbell Scientific, Logan, UT) installed at different depths (20 cm, 40 cm and 60 cm).

2.6 Leaf Area Index measurements (LAI)

Leaf Area Index (LAI) was measured from 20 trees using a plant canopy analyzer (Li-2000, Li-Cor Inc., Lincoln, NE). From each tree, measurements were taken from all four cardinal directions. Measurements were taken in July 16, 2019, collectively in October 20 and October 30, 2020, collectively in September 30 and October 5, 2022 and twice in June 9 and September 22, 2023 to look at the variability in LAI, however, no significant difference was found.

2.7 Data analysis

ET and K_c were compared based on different growth stages. The growing season was divided into four phenological phases: (I) Day of the year (DOY) 60 and 99 as initial phase of budbreak and early foliage/ flower development; (II) DOY 100 and 165 as the period of nut set and early sizing; (III) DOY 166 and 258 as middle-season phase (i.e. the most critical one where nut sizing and kernel filling occur); while (IV) late phase was between DOY 259 and 304, corresponding to post kernel/ nut maturity. The post processing of flux data was done using RStudio (RStudio Team, 2024).

RESULTS AND DISCUSSION

3.1 Temporal Variation in AE, PET and K_c

K_c, the ratio of AE to PET (Fig. 5a), is plotted for the four years of the study period (Fig. 5b). The orchard floor vegetation contribution is tabulated in Table 2. This data is obtained using the micro lysimeter and the EC system. In October 2023, orchard floor vegetation contributed 11% of the total ET. In 2024, the contribution from grass was 11.41% in May, rising to 17.60% in June, 17.55% in July, 22.41% in August, and 18.02% in September. The contribution by the interrow increases shortly after budbreak, peaks in the middle of the season, and decreases during leaf senescence in October. Wang et al., (2014) observed the interrow contribution of 9-20% in global agricultural systems. The present analysis separates the contribution of evapotranspiration from grasses in between the rows for all given years. Thus, the actual evapotranspiration and crop coefficient discussed below are that of pecan trees and soil beneath it.

Pecan dormancy begins in December and continues through March, resulting in very low AE (Abou Ali et al., 2023). During this period, soil evaporation leads to a loss of approximately 0.1 to 2 mm day^{-1} of water (Sammis et al., 2004). Wang et al., (2014) and Sun et al., (2019) found similar results with transpiration to evapotranspiration ratio being lower at the early stage and higher at the later stage from the meta study in the agriculture system in the United States. In pecans, this is due to the reduced evaporation under the canopy as canopy grows to the fullest during the nut sizing and kernel filling stage. However, the corpus of studies on soil evaporation from pecan orchards in the Southeast is virtually inexistent (other than the work by Wells and Casey, 2013 and Wells, 2015).

Figure 5(a) depicts the day-to-day variability in actual evapotranspiration (AE) from the orchard (AE_{all}), AE from pecans and soil (AE_{t+s}) beneath it and potential evapotranspiration (PET) increases from the beginning of the season, phase-I, i.e bud break until the end of season. It increases until the nut sizing and kernel filling i.e., Phase III and the downfall is seen in nut maturation i.e. Phase IV. Since the interrow is not irrigated, for irrigation scheduling, AE from the trees (AE_{t+s}) and Kc of the trees (Kc_{t+s}) are considered. AE_{t+s} in pecan during the current study was maximum in between DOY 166 to 259 i.e., July and August (6.7 mm day^{-1}) analogous to pecan (Miyamoto 1983; Sammis 2004), peach (Abrisqueta et al., 2013), and almond (Bellvert et al., 2018; Garcia- Tejero et al., 2015; Sanchez 2021). It is 32% less than the study in pecans in arid climate in New Mexico (Sammis et al., 2004; Wang et al., 2007). The highest recorded AE where the fruit sizing and kernel filling occur also coincides with the rise in temperatures (Figure 2), maximum LAI (Figure 4), PET (Figure 5a) and highest water input (Figure 6) during these periods. The lower AE observed later in phase IV may be due to reduced physiological demand for water and its input in the field as seen in almond and pistachio orchard in California (Bellvert et al., 2018). However, Figure 7 illustrates similar soil moisture and even less after DOY 259 at the depth of 20 cm in 2020 compared to 2019. So, the major cause of lower water demand and thus K_c in 2019 is because of the lower plant canopy (22% in plant height and 24% in LAI)) as reduced plant canopy affects the water demand of the tree (Wells 2018). The ET and K_c of pecans from seven to ten-year old tree is significantly similar. The daily crop water requirement during the growing period from March through October ranged between 0.3 and 6.7 mm. This variability throughout the growing season in the pecan field also depends on the variation of water input and the energy to evaporate the water in different growing seasons (Figure 11). The PET ranges from 1.02 mm to 7.2 mm day^{-1} throughout the four-year period.

Daily fluctuations in the crop coefficient (Figure 5b) are observed due to variations in both potential evapotranspiration and actual evapotranspiration. The daily Kc_{t+s} during the different growth stages ranged from 0.3 to 1.0 starting from bud break to nut maturation. This range of K_c is similar to what reported by García-Tejero et al., (2018) and Abriquesta et al., (2013) in drip-irrigated almond and peach orchard respectively. Anderson et al., (2017) observed similar findings in a peach orchard where Kc increased around leaf emergence (DOY 100) and a significant canopy cover and K_c ranged between 0.9 to 1.1 at DOY 205 with adequate irrigation. This results from the fact that the plants are losing water at the potential rate. Synder et al., (2001) discussed the factors affecting the differences between AE and PET as 1) light absorption by the canopy (2) crop physiology, (3) leaf age, which influences the stomatal conductance and thus the available energy for transpiration and photosynthesis, and (4) surface wetness influencing evaporation. The variability in Kc values might be due to the diverse meteorological conditions, irrigation, tree physical and biological characteristics, and soil evaporation rates as stated by Sanden et al., (2012), Abrisqueta et al., (2013), Drechsler et al., (2022) and Abou Ali et al., (2023). Unlike 2019, K_c increased in phase IV in 2020, it could have been caused by the biggest rainfall event resulting in an increase in soil moisture as shown in Figure 7.

3.2 Interannual variability in AE, PET and K_c

The contrast of monthly average AE, PET and K_c from March through October is noteworthy (Figure 8). During the study period, AE_{all} and PET closed the gap between July through October (Figure 8) compared to that earlier in the season (March through June) where not only AE_{t+s} but also evapotranspiration contribution from the interrow was lower (Table 2) and so were temperature and solar radiation (Figure 2).

During the peak growing season from July through September, average daily AE_{t+s} was significantly higher in 2023 (3.52 mm), 2020 (3.45 mm) and 2022 (3.00 mm) compared to 2019

(2.77 mm). The lower plant canopy could result in lower crop load and thus lower transpiration which corroborate the lower AE recorded in 2019.

Likewise, during March through May (i.e., bud break to the beginning of nut sizing period), the crop coefficient variability was negligible across years as illustrated in Figure 8. However, from July through September 2019, Kc_{t+s} (0.55) was significantly lower than in 2023 (0.71) followed by the year 2020(0.70) and 2022 (0.66). The variability in AE and Kc in 2019 is reflected in yield data (Figure 12) because of the lower crop load and thus lower water demand of the tree (Wells 2015). Mostly in August, AE in 2023 was the largest (Figure 8), it could be because of larger canopy and higher transpiration rate. Drechsler et al., (2022) also observed the variability of AE and Kc in young almond trees until they reach maturity. In the young almond orchard (three to five years old), 8% of the variability in the Kc in the peak growing period was because of canopy size or water stress. So, the variability between six- and seven-year-old pecan could be because of the transition of young tree to a mature tree. However, significant loss in the yield in 2021 and 2022 signifies the severity of pecan scab infestation because of the failure of farm machinery resulting in zero fungicides application while it requires eight to twelve applications (once in a week or ten days) in the summer.

3.3 AE, PET and Kc during different growth stages

In this study, the four-year average of daily AE_{t+s} was highest in phase III (3.62 mm), followed by phase-II (2.94 mm), phase IV (2.33 mm) and phase I (1.91 mm) (Fig. 9). Since the atmospheric evaporative demand was lowered at phase-IV (Drechsler et al., 2022), there was a reduction in AE as depicted in Figure 5a. Kc_{t+s} was highest in phase IV- 0.68 which is not different from phase III (0.65). The higher Kc in phase IV could be because of the year 2020 when the trees were losing water at potential rate because of higher soil moisture in the field as shown in Figure

7. However, in coastal plain conditions in Georgia, to avoid stress (ψ < -0.78 MPa), mature pecan trees are suggested to irrigated if the volumetric water content reaches below 10% (Wells 2015). Likewise, phase II and I had similar Kc (0.59 and 0.56 respectively).

In sub-humid climate, for non-stressed, well-managed fruit trees, especially apricots, peaches and other stone fruits with active ground cover and in the absence of frosts, the crop coefficient was 0.80, 1.15 and 0.85 for initial, middle and late stage respectively (Allen et al., 1998; Allen & Pierera, 2009; Doorenbos and Kassam, 1979; Doorenbos and Pruitt, 1977; Pruitt (1986); Synder et al., 1989; Wright, 1981, Wright, 1982). There was no significant difference between the year 2020 and 2023 in relation to the different growth stages.

3.4 Stem Water Potential

The stem water potential (ψ) during the study period (2019-2023) ranged between -0.24 to -0.64 MPa. That range falls on the range of -0.45 to -0.70 MPa for well-watered pecan trees from Othman (2014)'s results of ψ following five days after irrigation was withhold where photosynthesis was not reduced.

In the year 2022 and 2023, in this study, the stem ψ fell below -0.5 late in the season i.e. after DOY 250 (Figure 8) when no irrigation is applied resulting in a lower soil moisture (Figure 10). This pattern echoes similar result seen in Drechsler et al., (2022) in a canopy with restricted irrigation during the harvest leading to a lower ψ (increasing stress) with values ranging between -0.3 and -0.5 MPa. The relatively higher stress (lower ψ) is seen in 2019 coincides with peaks in VPD from Table 1. The peaks and dip in the stem water potential resonates with soil water content as shown in Figure 10. Nonetheless, according to Wells (2015) pecan trees in hot and humid conditions exhibit drought stress when stem ψ hovers around -0.78 MPa and according to Othman et al (2014), there is decline in photosynthesis attributed to stomatal limitation below -0.9 MPa.

So, according to that reference, none of the observations in these three years dropped below that value depicting the plants were not in stress.

3.5 Water use of pecans, soil moisture and irrigation

The irrigation guidelines for pecans throughout the growing season in Georgia is recommended by an extension report of University of Georgia totaling 455 mm (Wells, 2017). It begins after the bud break, i.e. in April and ends in October when the nut is in full maturity. In all the years, the water input in the field via irrigation and rainfall meets the pecans' water requirement as measured in this period. An average of 22%, 24% and 26% of soil moisture was maintained in the 20 cm, 40 cm and 60 cm layer depth. There was frequent soil wetting from either irrigation or rainfall as shown by the monthly water input always higher than baseline AE of pecans measured monthly (Figure 11) and field irrigation and rainfall in the field from Figure 6. In the year 2019 and 2023, the field irrigation followed the current irrigation schedule except it did not account for the soil moisture from the rainfall resulting in overirrigation. Other years i.e. 2020 and 2022, 106% more irrigation was applied in a month alternately in August and September respectively. In these years, the supplemental water input in the field as rainfall was not considered by farmers.

There was no irrigation application in 2020 and 2022 in October while ~60 mm of water was applied in 2019 and 2023 (Figure 6). In 2022, the irrigation data was available only after July. 2019 is recorded as the drier year among the other study years with 600 mm of rainfall. In contrast, 2022 had the highest rainfall (1120 mm) recorded. With 84 mm of rainfall in a single day in September, 2020 had 850 mm of rainfall similar to the year 2023.

The average water demand is ~680 mm for seven- and ten-year-old trees in a growing season which is 33% higher than the irrigation schedule. And total water input in the field is ~42% higher than the actual water demand of pecan trees. Despite this, water application remains elevated as shown in Figure 10, which is also evident from stem water potential measurements where the plants are not in stress i.e., $\psi < -0.78$ MPa (Othman et al., 2014; Wells 2015). The current reduced irrigation schedule in the earlier season for pecan in Georgia was suggested because 1) season long water status was similar in full irrigation and reduced irrigation because pecan trees can recover quickly from enhanced irrigation later in the season, 2) there was a 38% reduction in water application with no loss in pecan yield and quality (Wells, 2015). The current water requirement for pecans in Table 6 is for loamy sand soil in Georgia which accounts for the evapotranspiration from trees and evaporation from bare soil beneath it.

From the study, an average 6% of evaporation is recorded from the soil. Some studies from mature almond orchard in California reported 16% and 24% soil evaporation contribution to AE using micro sprinkler (Bellvert 2018) and drip irrigation (Lopez 2015).

3.6 Yield and yield attributes

Pecan yield was observed for five years in the overall field along with the other quality attributes like kernel percentage and nut count (Figure 12). In 2021 and 2022, pecan scab was prominent in the field affecting the yield.

From 2019 to 2023, there was a wide range of pecan production. Notably, 2020 and 2023 had similar yields and kernel percent which was also the case for AE and thus K_c. 2022 had the best kernel percentage which coincides with the higher LAI values in 2022 (Figure 4) and results from hedge-pruned pecans (Wells, 2018) due to increase in source: sink ratio as the trees are mechanically fruit thinned. The average LAI for the years 2019, 2020, 2022 and 2023 observed is 0.66, 0.88, 2.2 (stdev = 0.36) and 1.1 (stdev = 0.27) respectively. The LAI was calculated on both irrigated and non-irrigated pecan trees and there were no significant differences between them. LAI is lower in 2023 because of the stressed trees going into 2023 from 2022 growing conditions where there is massive disease infestation in the orchard or could be because of alternative years hedging that impacted LAI. The lower VPD, solar radiation values and the range of maximum temperature, all have had favorable conditions leading to a high yield in 2020 and 2023 (Appendix Table 2). Plant water relations are also affected by the plant canopy (Drechsler et al., 2022; Wells 2018). Thus, the lower K_c values in 2019 corresponds to lower plant height (22% and 55% higher in 2020 and 2023 respectively), lower plant canopy (24% and 64% increase in LAI in 2020 and 2023 respectively), lower AE and lower yield in contrast to the year 2020 and 2023. On Sep 4 2019, when hurricane Dorian hit Georgia, for entire afternoon the range of maximum wind speed measured 10 km away form the field was 38 to 44 km hr^{-1}. This could have resulted in lower yield in 2019 blowing down trees, broken branches and immature nuts. Although hedged trees have 60% lower wind damage than non-hedged trees due to lowering the center of gravity of the trees (Gilman et al., 2008) and reducing the surface area for wind exposure (Wells, 2018), pecan scab infestation and lower canopy synergistically impacted the yield in that year.

CONCLUSION:

The EC system together with the micro-lysimeter suggested that pecans irrigated with micro-sprinklers in Georgia throughout the growing season (March to October) required 680 mm of water which is 33% more than the recommended amount (455 mm). In seven- and ten-year-old pecan orchards, water use did not significantly differ between years, but it varied significantly between different months and growth stages during the growing period, likely due to the meteorological drivers like temperature, VPD and solar radiation. The maximum and minimum range of meteorological variables in phase III (DOY 166 to 259), which coincides with the nut sizing and kernel filling period, affects the physiology of the plants like photosynthesis and stomatal conductance. These variations impacted the crop coefficient and thus the water demand of the trees affecting the kernel quality and yield.

Pecan water use ranged from 0.4 to 6.7 $mmday^{-1}$ at various growth stages, with crop coefficient (Kc_{t+s}) values ranging between 0.3 and 1.0 in a growing season. There were no significant differences in K_c between seven- and ten-years-old hedge-pruned trees. The atmospheric evaporative demand peaks during July and gradually decreases during nut maturation. The variability in AE and thus Kc depends on morphological and physiological characters of the trees, management practices, irrigation controls and weather. Also, the discrepancy between AE_{all} and PET is more pronounced in young trees and earlier months of growing season as the transpiration contribution increases later in the season with higher foliage. Thus, transpiration-to-evapotranspiration (T/ET) dynamics both between and within growing seasons impact the Kc.

Water demand is high, yet actual plant water uptake is lower. Field reports showed that the water applied in the field exceeds both the recommended irrigation schedule and the water requirements observed in this study. The irregular and localized rainfall in Georgia necessitates precise measurement for effective irrigation scheduling. Despite the recommended schedule, excessive water is applied in the field, as indicated by the non-stress conditions shown in stem water potential measurements. This may be due to the additional consideration of rainfall as part of the irrigation schedule.

In Georgia's hot and humid climate, pecan water requirements are lower than those of the more arid climates. Hotter and drier weather and biotic stress like pecan scab infestation in 2022 led to a significantly lower yield and crop coefficient compared to the other years. Lower plant canopy and water use in 2019 corresponded to the lower Kc. Thus, crop coefficient of the trees varied with the plant canopy, crop load, and age of the tree.

The study's findings on early season water deficit needs and developed crop coefficients can help improve pecan irrigation management in the Southeast. The presented cumulative monthly actual water requirement of pecans from Table 3 and crop coefficient data could be used for the further development of irrigation scheduling. Future work should focus on the transpiration/evapotranspiration dynamics of pecan orchards in different age-groups of pecan orchards.

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TABLES AND FIGURES

TABLES

Table 1: Comparison of vapor pressure deficit (VPD), air temperature (Tair), and solar radiation (R_s) in different years during the growing season (March to October) in 2019, 2020, 2022 and 2023

Year	2019	2020	2022	2023
VPD (kPa)	1.03^{a}	0.78^{c}	0.89^{b}	0.77^{c}
Stddev	0.727	0.522	0.526	0.494
CV	40.034	41.145	36.889	39.077
Tair (°C)	23.18^{a}	22.35^{ab}	22.02^{b}	$21.80b^{c}$
Stddev	3.32	4.56	3.93	4.94
CV	11.48	18.08	14.83	19.89
Rs (Wm^{-2})	567.46^{a}	526.32^{ab}	540.20^{ac}	516.89^{bc}
Stddev	118.95	158.71	119.93	140.71
CV	20.46	29.58	22.39	26.15

[ab]Means followed by the same letter in each column are not different at P<0.05by Welch two sample t-test.

Table 2: Evapotranspiration contribution from grasses (March through October) in the pecan orchard

Year/Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
2023	-	-	-	-	-	-	-	11%
2024	(11%*)	(11%*)	11.41%	17.60%	17.55%	22.41%	18.02%	-

*: (assumed percentage of ET contributions of grasses between rows because of limited data and followed the same contribution for other study years)

Table 3: Comparison of actual evapotranspiration (AE) and crop coefficient (K_c) in different years in 2019, 2020, 2022 and 2023

Month/Year	2019		2020		2022		2023	
AE / Kc	Mar-Oct	Jul-Sep	Mar-Oct	Jul-Sep	Mar-Oct	Jul-Sep	Mar-Oct	Jul-Sep
AE ($mmday^{-1}$)	2.61^{b}	2.77^{b}	3.32^{a}	3.45^{a}	2.90^{b}	3.00^{ab}	3.47^{a}	3.52^{a}
Stddev	0.74	0.74	0.93	1.00	0.87	0.86	0.94	0.89
CV	28.28	28.28	27.87	29.01	29.99	28.76	27.23	25.19
K_c	0.52^{c}	0.55^{b}	0.67^{a}	0.70^{a}	0.63^{b}	0.66^{a}	0.70^{a}	0.71^{a}
Stddev	0.10	0.10	0.09	0.09	0.09	0.10	0.12	0.11

CV	20.02	20.02	13.32	14.92	14.08	13.99	16.71	14.92

[ab]Means followed by the same letter in each column are not different at P<0.001 by Welch two sample t-test.

Table 4: Cumulative current recommended irrigation schedule for pecans in Georgia, field irrigation and rainfall onsite in 2019, 2020, 2022 and 2023.

Year	Current standard irrigation (mm)	Field irrigation (mm)	Rainfall (mm)
2019	455	498	602.50
2020	455	490	850.90
2022	455	484	1120.14
2023	455	368	846.33

Table 5: Cumulative monthly actual water requirement (mm) of pecans in the year 2019, 2020, 2022 and 2023 obtained using eddy covariance system and micro-lysimeter.

Year/Month	March	April	May	June	July	August	September	October
2019	-[NA]	-	-	95	100	97	81	54
2020	50	79	97	91	123	101	79	65
2022	-	-	-	-	107	90	78	65
2023	49	67	85	97	122	115	72	66

[NA]-Data were not collected between March and May in 2019 and between March and June in 2022.

FIGURES

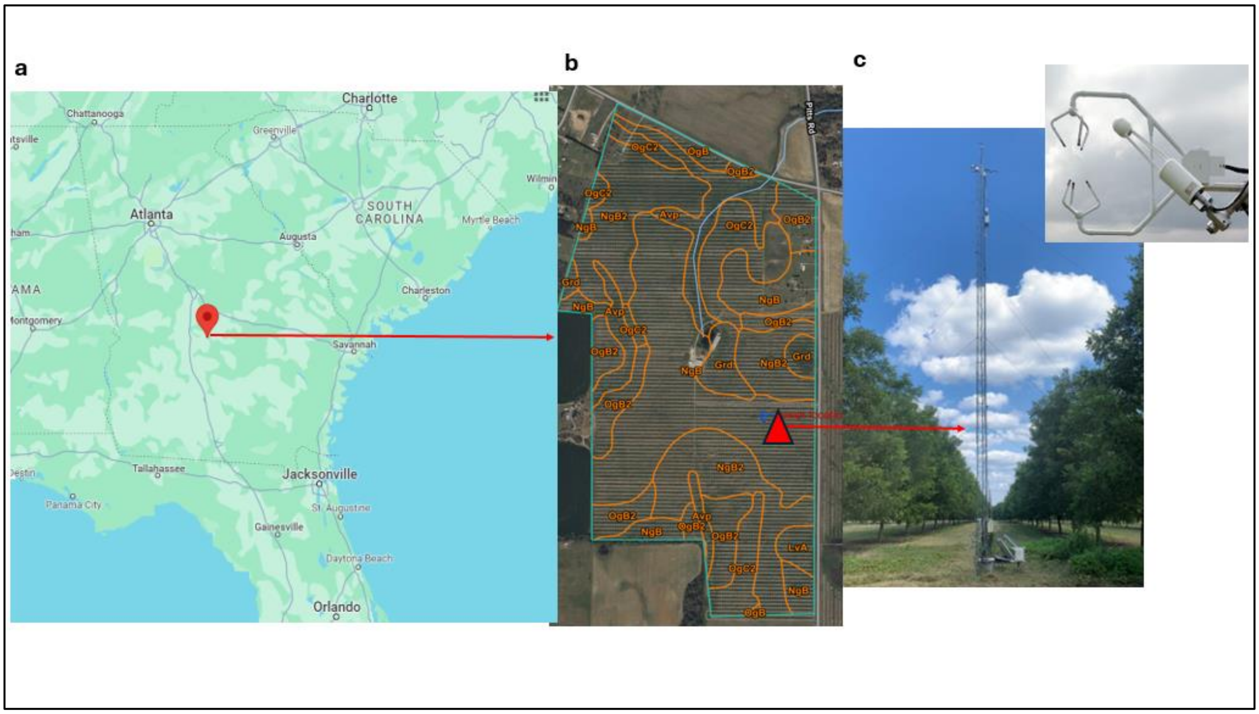


Figure 1:a) The red dot represents the research site (Hawkinsville, Georgia - 32°20'35" N, 83°37'43" W) b)The orange lines delineate the different soil types of the orchard (https://websoilsurvey.nrcs.usda.gov) and the red dot represents the location of tower, c) Tower in between the tree rows with eddy-covariance flux tower which has a CSI omnidirectional open-path sonic anemometer and the Li-Cor fast response open path H_2O/CO_2 analyzer

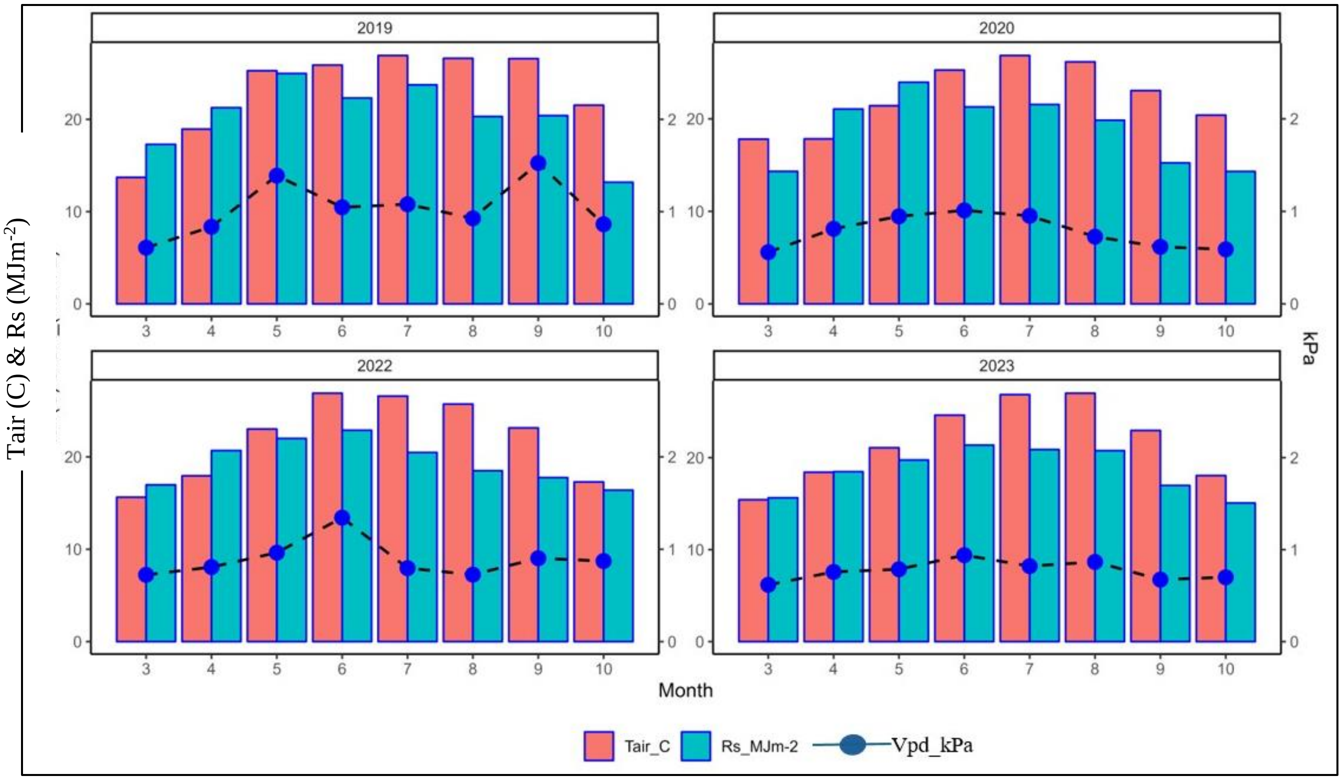


Figure 2:Monthly air temperature (T_{air}), vapor pressure deficit (VPD) and solar radiation(R_s) in 2019, 2020,2022 and 2023 from the Unadilla Weather Station in the Georgia Automated Environmental Monitoring Network by the University of Georgia located at 32°15'32.2" N, 83°39'41.5" W, approximately 9.3 km south of the research site.

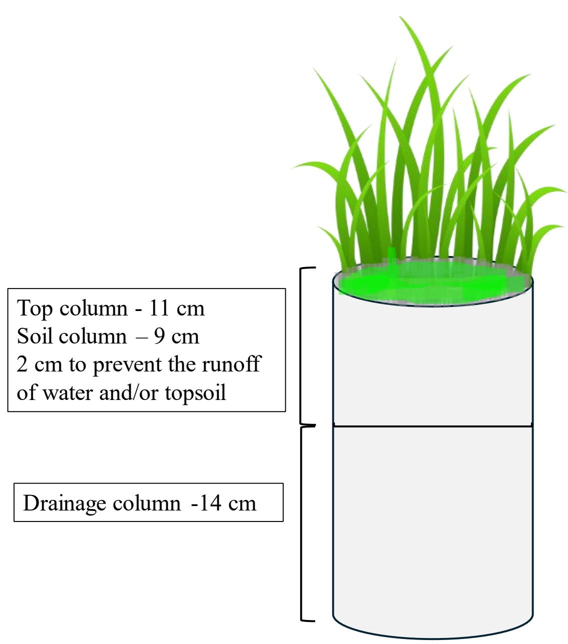


Figure 3: Illustration of micro-lysimeter deployed in the field (below the trees and between the tree rows) with soil and drainage column

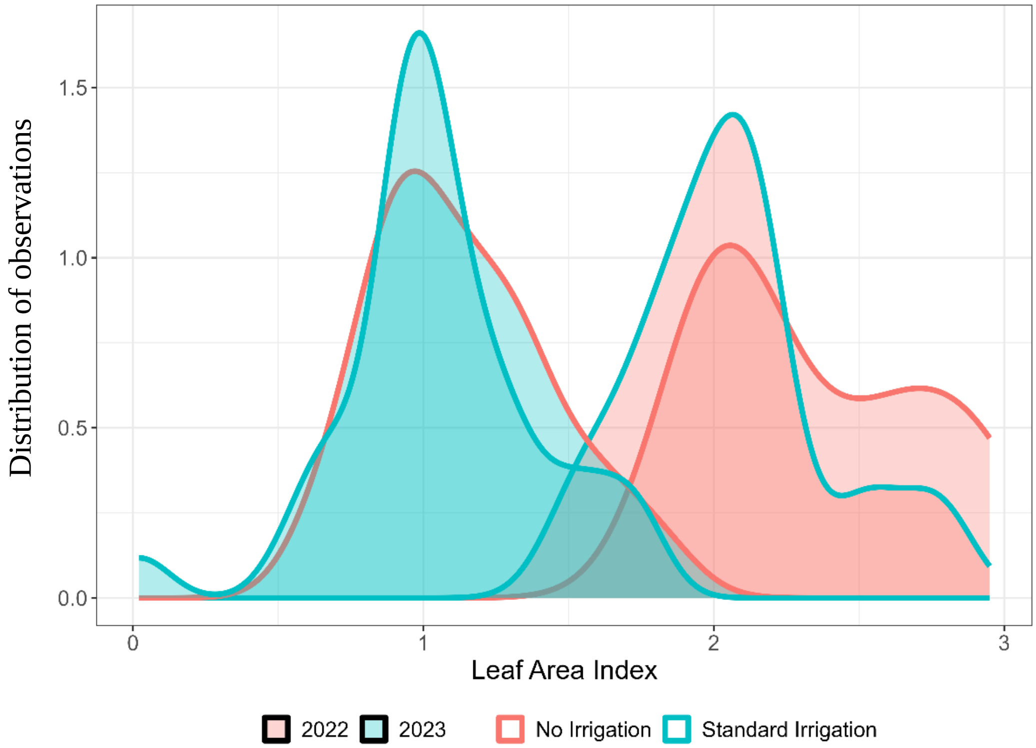
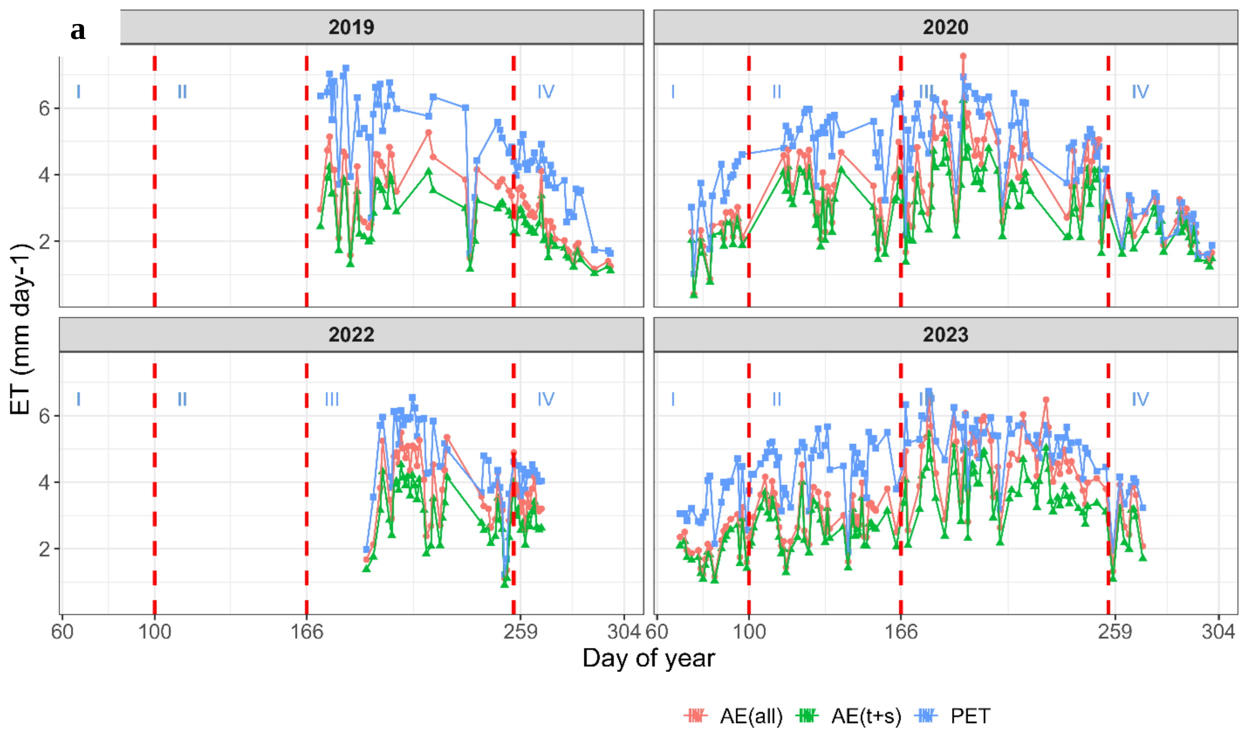


Figure 4: Leaf area index distribution plot with no irrigation and standard irrigation treatment during 2022 and 2023 in pecan



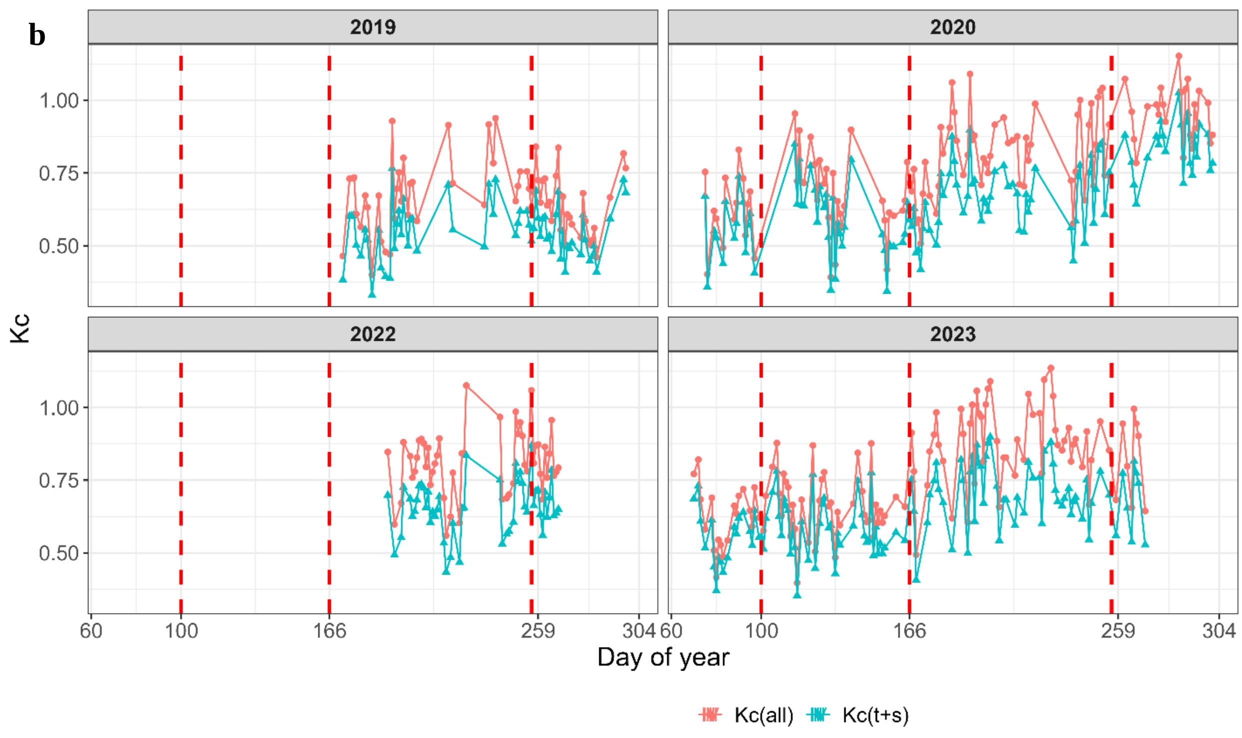


Figure 5: Time series of the temporal variability of (a)actual evapotranspiration of entire orchard (AE_{all}), actual evapotranspiration of trees and soil (AE_{t+s}) and potential evapotranspiration (PET), (b)crop coefficient of the orchard (Kc_{all}) and crop coefficient of trees and soil(Kc_{t+s}) in 2019, 2020, 2022 and 2023. The vertical red dotted line represents the growth

stages of pecan: : (I) Day of the year (DOY) 60 and 99 as initial phase of budbreak and early foliage/ flower development; (II) DOY 100 and 165 as the period of nut set and early sizing; (III) DOY 166 and 258 as middle-season phase (i.e. the most critical one where nut sizing and kernel filling occur); while (IV) late phase was between DOY 259 and 304, corresponding to post kernel/ nut maturity.

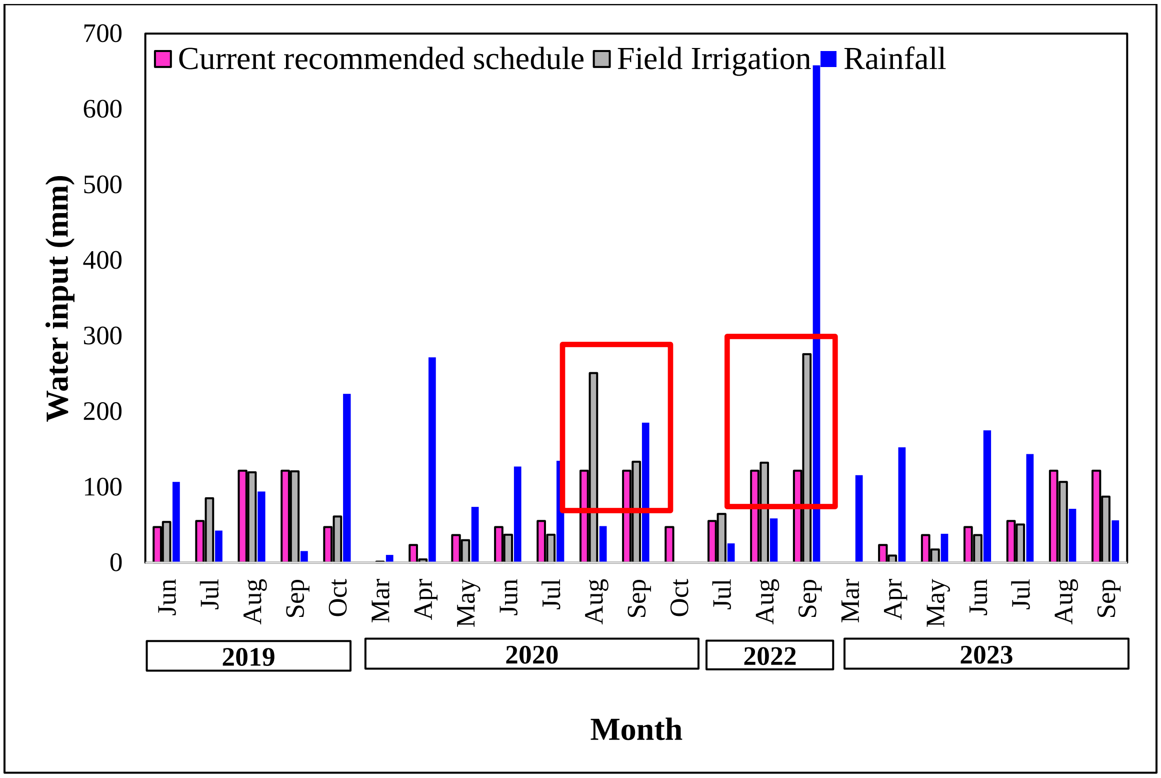


Figure 6: Comparison of current recommended schedule, field irrigation and rainfall in the years 2019, 2020, 2022 and 2023. The red box represents the more water input in the month of Aug and Sep than the current recommended schedule in 2020 and 2022 respectively.

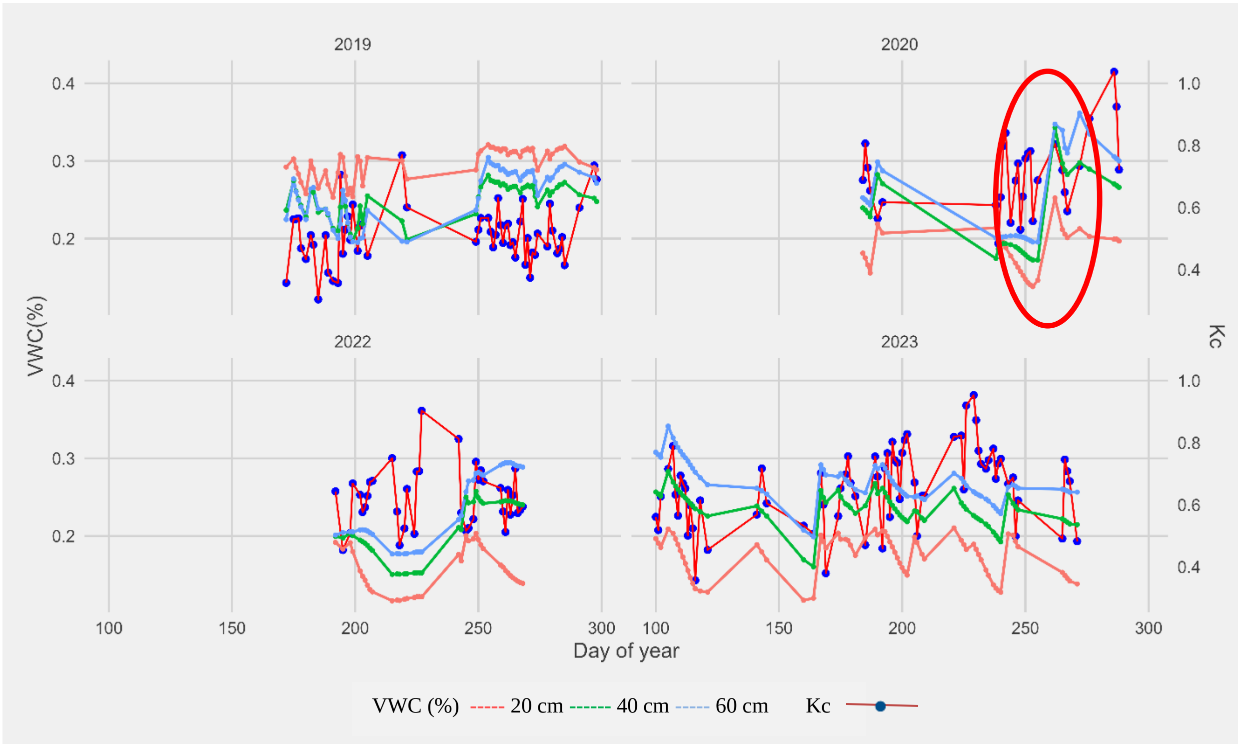


Figure 7: Time series volumetric water content (%)(1-20 cm, 2- 40 cm, 3-60 cm deep) and crop coefficient measured in the year 2019, 2020, 2022 and 2023

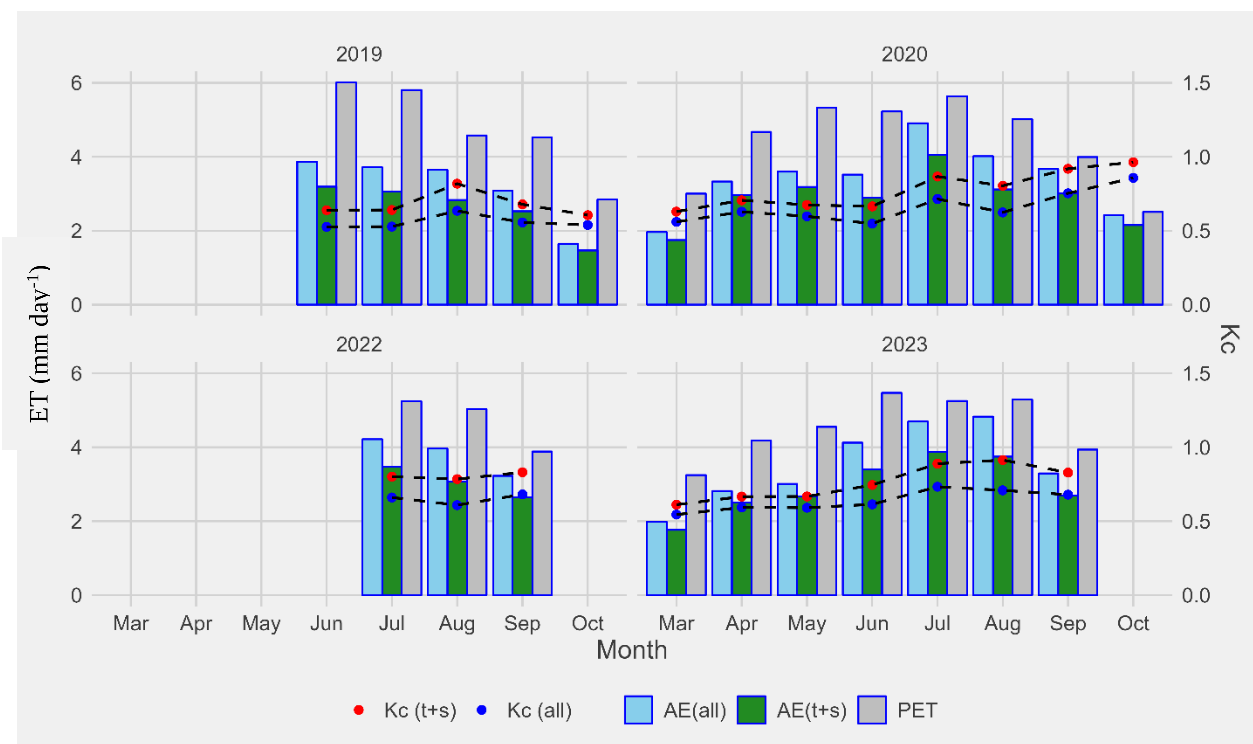


Figure 8: Monthly average of actual evapotranspiration of entire orchard (AE_{all}), actual evapotranspiration of trees and soil (AE_{t+s}), potential evapotranspiration (PET), crop coefficient of the orchard (Kc_{all}) and crop coefficient of trees and soil(Kc_{t+s}) in 2019, 2020, 2022, and 2023.

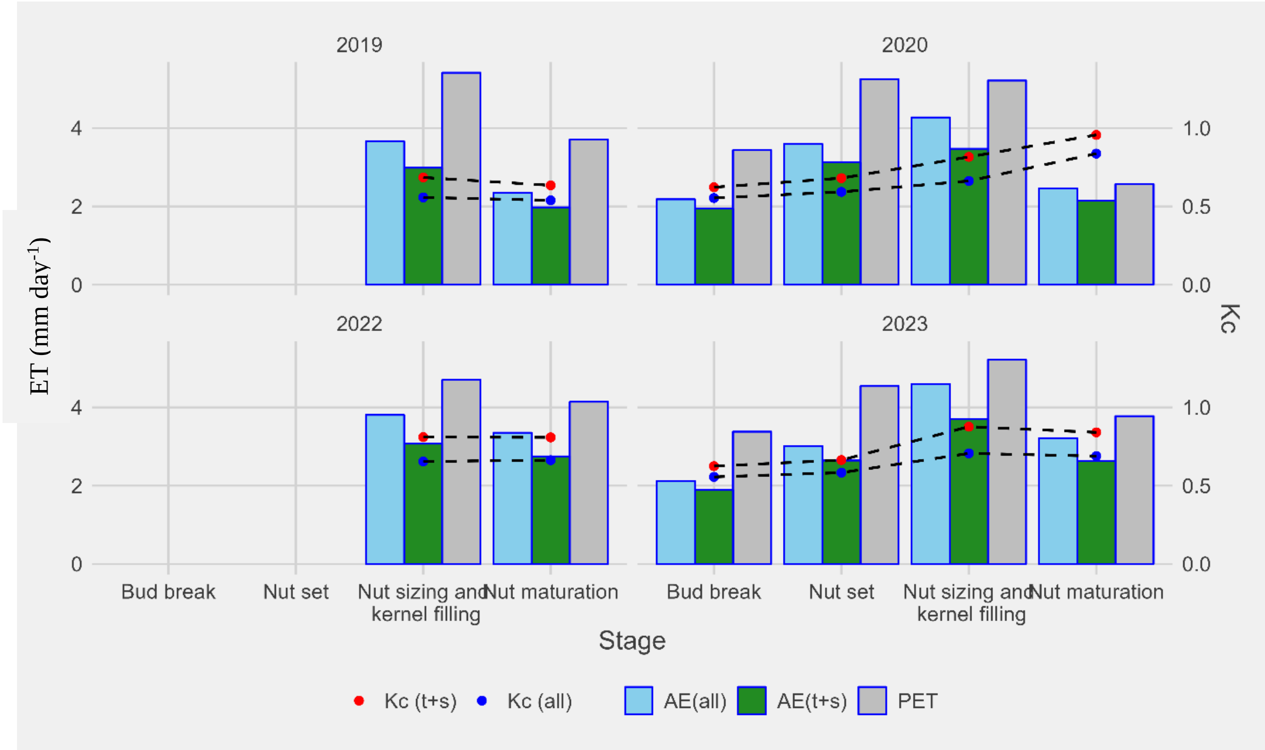


Figure 9: Avergae of actual evapotranspiration of entire orchard (AE_{all}), actual evapotranspiration of trees and soil (AE_{t+s}), potential evapotranspiration (PET), crop coefficient of the orchard (Kc_{all}) and crop coefficient of trees and soil(Kc_{t+s}) in different growth stage i.e., bud break, nut set, nut sizing and kernel filling and nut maturation from the research site during the four-yr experimental period

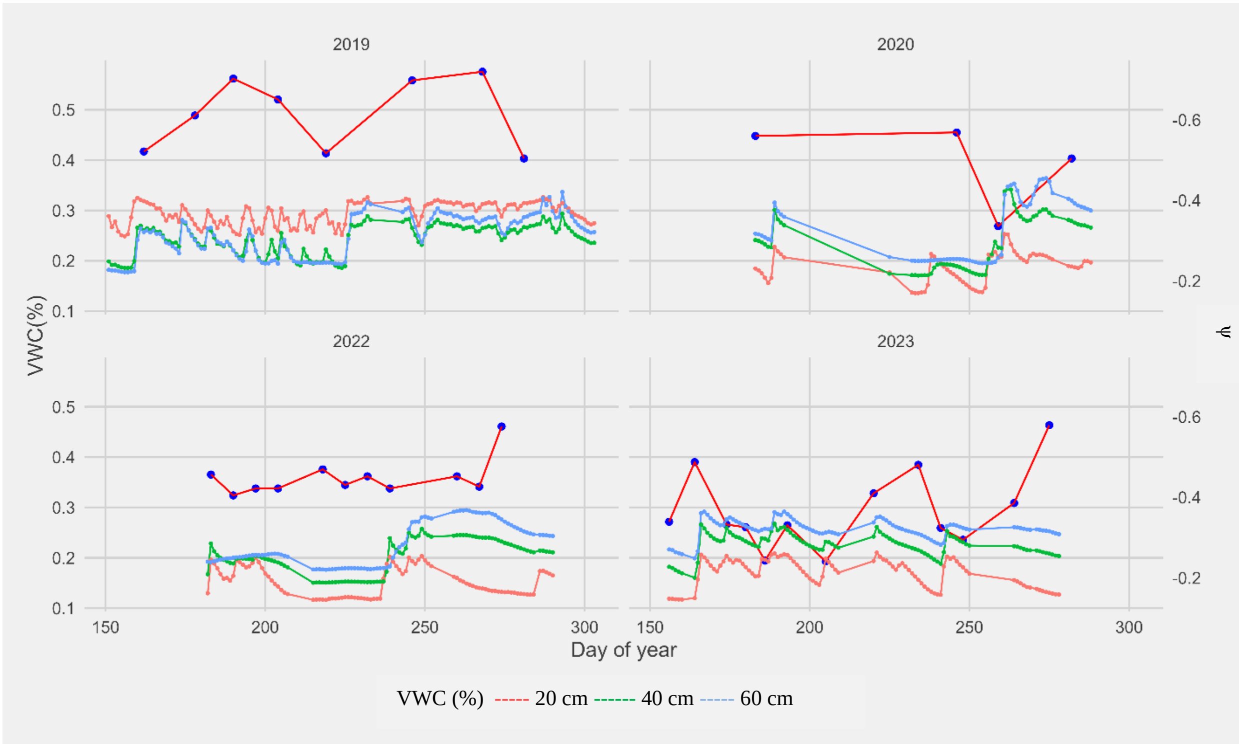


Figure 10: Time series volumetric water content (VWC) at the depth of 20cm, 40 cm, 60 cm and midday stem water potential (ψ) measured in the year 2019, 2020, 2022 and 2023

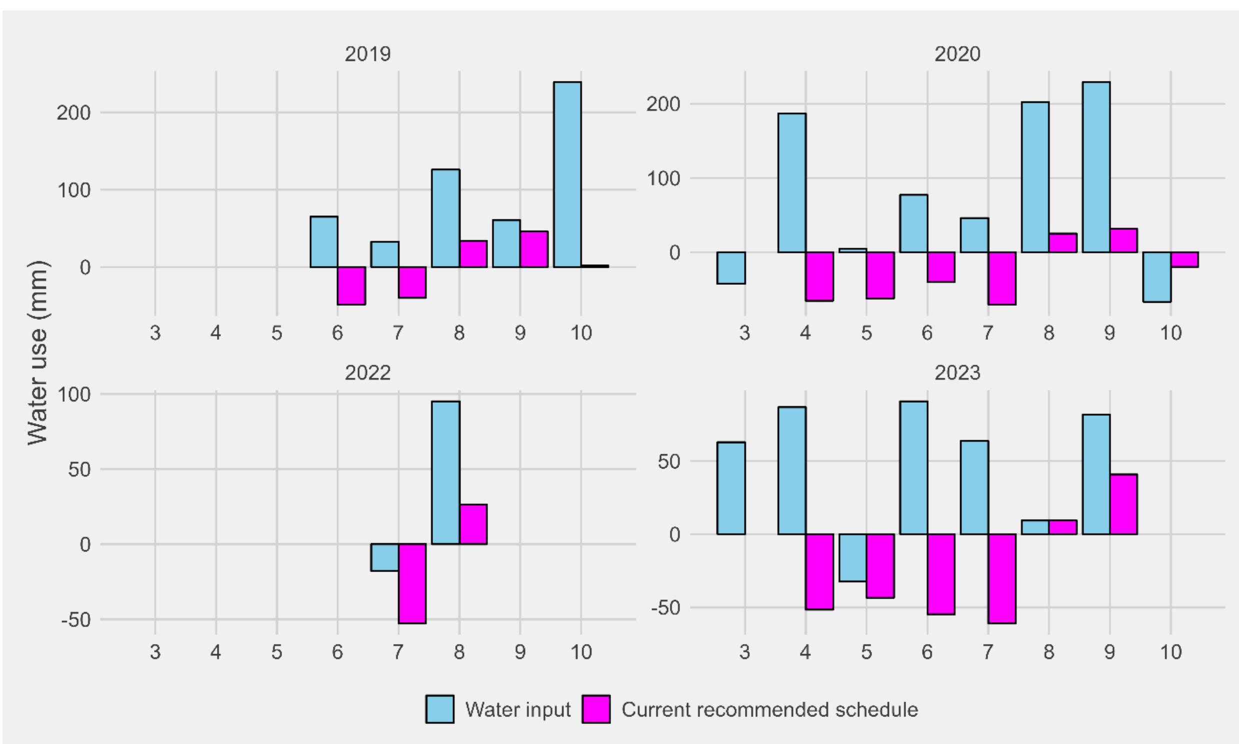


Figure 11: Comparison of current recommended irrigation schedule with the pecan water requirement from this study (as a baseline), and water input in the field

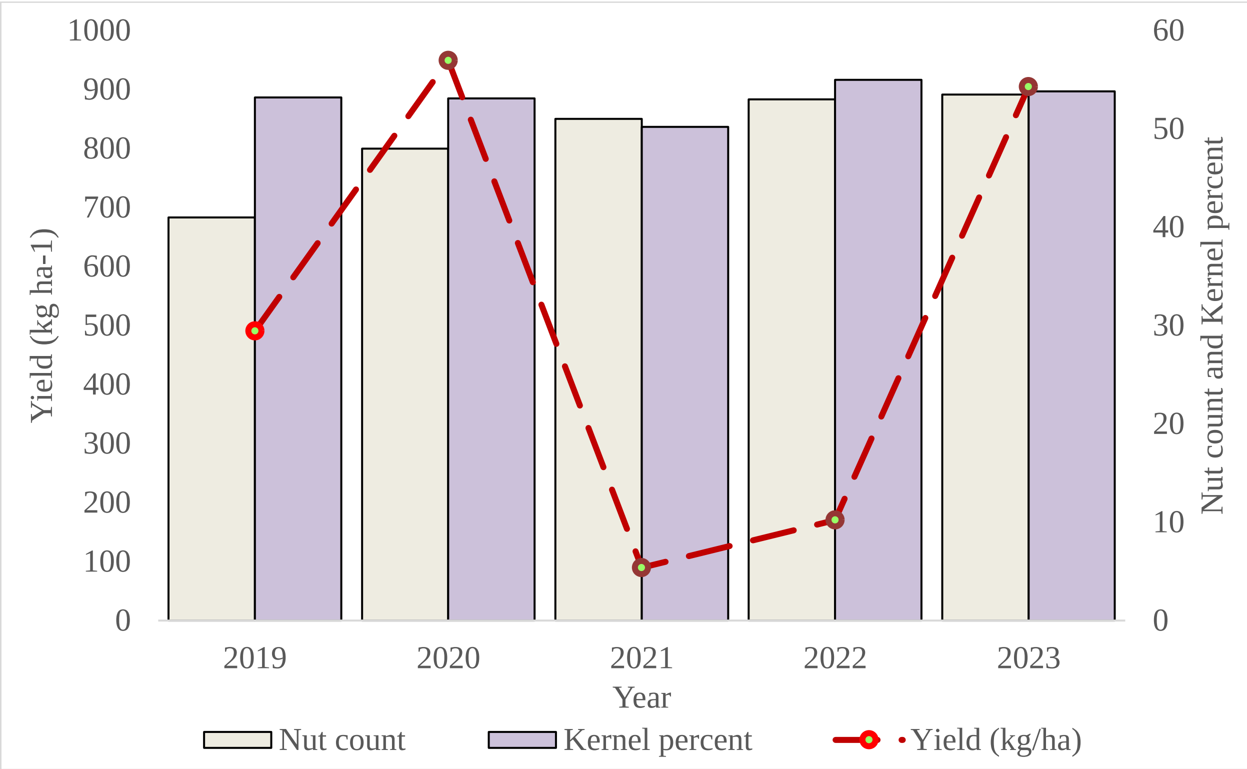


Figure 12: Yield and yield attributes of the commercial orchard for the year 2019, 2020, 2021, 2022 and 2023

CHAPTER 3

CONCLUSION

Pecan is highly sensitive to drought stress. Thus, the growers are conflicted with the yield production in Southeast United States over that of Southwest United States. The water demand of pecan trees in hot and humid climate in Southeast is lower than the hot and arid climate of Southwest. The real-time water use of pecans in the Southeast is important for efficient irrigation scheduling because the water demand varies with soil type, climate and physiological stages. Thus, crop coefficient is derived to estimate the daily variability of water demand for pecans in Georgia. The research uses the eddy covariance system and the micro-lysimeter along with *in situ* meteorological measurements. The result suggested that pecan trees in humid climate like GA require 680 mm throughout the growing season (March to October). The water use ranges from 0.4 to 6.7 mm at various growth stages, with crop coefficient (Kc) values between 0.4 and 1.0 in a growing season. There were no significant differences in water use and K_c between seven and ten-year-old pecan orchards, except for the anomaly like disease infestation in the field when the crop load decreases. Water demand varies significantly between different months and growth stages during the growing period because of the meteorological drivers like temperature, VPD and solar radiation. The atmospheric evaporative demand peaks during July and gradually decreases during nut maturation. The variability in AE and thus Kc depends on morphological and physiological characters of the trees, management practices, irrigation controls and weather. Although the water demand is high, the actual plant water uptake is lower. So, overirrigation could be fatal for plants with more opportunity for disease infestation. The irregular and localized rainfall in Georgia necessitates precise measurement for effective irrigation scheduling. Despite the recommended schedule, excessive water is applied in the field, as indicated by the non-stress conditions shown in stem water potential measurements. This study could be used for the further development of irrigation scheduling. Future work should focus on the transpiration/evapotranspiration dynamics of pecan orchards in different age-groups of pecan orchards.

APPENDIX

Table 1: Weather variables in *2019, 2020, 2022, and 2023*

Year	Month	Average temperature(C)	Average vapor pressure deficit(kPa)	Solar radiation (MJm^{-2})	Rainfall(mm)
2019	June	25.9	1.05	22.32	106.68
	July	26.9	1.08	23.75	42.42
	Aug	26.6	0.93	20.31	93.98
	Sept	26.6	1.53	20.41	15.24
	Oct	21.6	0.86	13.20	223.52
2020	Mar	17.8	0.56	14.32	10.16
	Apr	17.8	0.81	21.06	271.78
	May	21.4	0.95	23.96	73.66
	June	25.3	1.01	21.29	127
	July	26.9	0.95	21.56	134.62
	Aug	26.2	0.73	19.85	48.26
	Sept	23.1	0.62	15.24	185.42
	Oct	20.4	0.59	14.32	NA
2022	July	26.6	0.80	20.48	25.4
	Aug	25.7	0.72	18.50	58.42
	September	23.1	0.90	17.76	15
	October	17.3	0.87	16.40	5.08
2023	Mar	15.4	0.62	15.63	106.68
	Apr	18.4	0.76	18.48	116.10
	May	21.1	0.79	19.74	86.36
	June	24.6	0.94	21.36	149.86
	July	26.9	0.82	20.88	120.65
	Aug	27.0	0.87	20.76	119.38
	Sept	23.0	0.67	16.98	45.72

Table 2:
Weather variables with maximum and minimum recorded values in 2019, 2020, 2022 and 2023

Variables (max to min range)	Avg T_{air} (°C)	Max T_{air} (°C)	Min T_{air} (°C)	VPD (kPa)	Max rain/day (mm)	PET (mm)	Solar radiation (Wm^{-2})
Year							

2019	3.8 - 30	10.8 - 37.6	-2.5 - 24.3	0.1 - 2.4	66	0.31 - 7.30	558 - 8580
2020	8 - 29	12.9 - 36.5	-0.2 - 24.3	0.1 - 1.7	84	0.15 - 6.94	233 - 8064
2022	4.1 - 30.5	13.6 - 38.5	-3.9 - 24.1	0.01 - 2.6	55	0.31 - 7.17	491 - 7844
2023	4.7 - 29.6	11.2 - 37.6	-3.6 - 24.7	0.02 - 1.6	60	0.45 - 6.73	847 - 7719

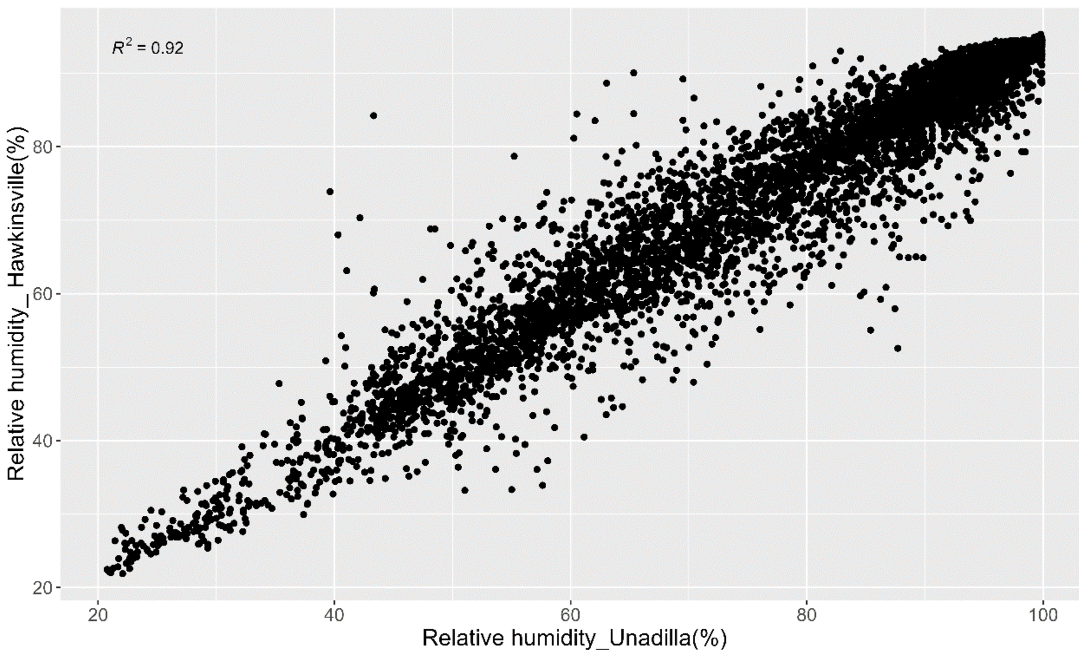


Figure 13. Correlation between relative humidity in Hawkinsville research site to the Unadilla UGA weather station at Unadilla, GA

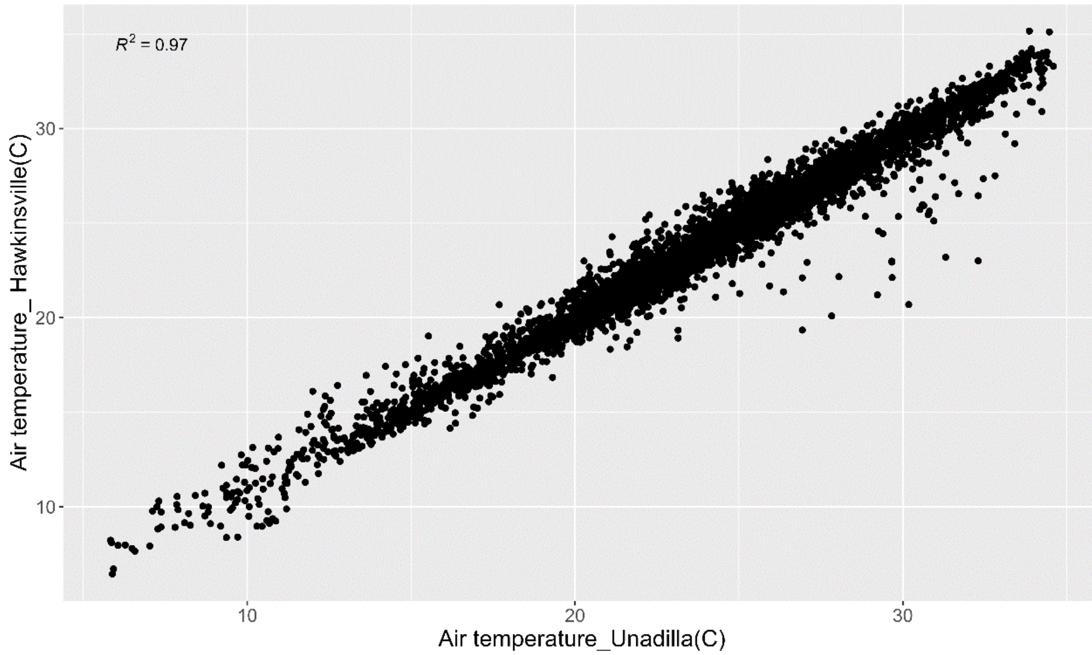


Figure 14. Correlation between air temperature in Hawkinsville and Unadilla UGA weather station at Unadilla, GA

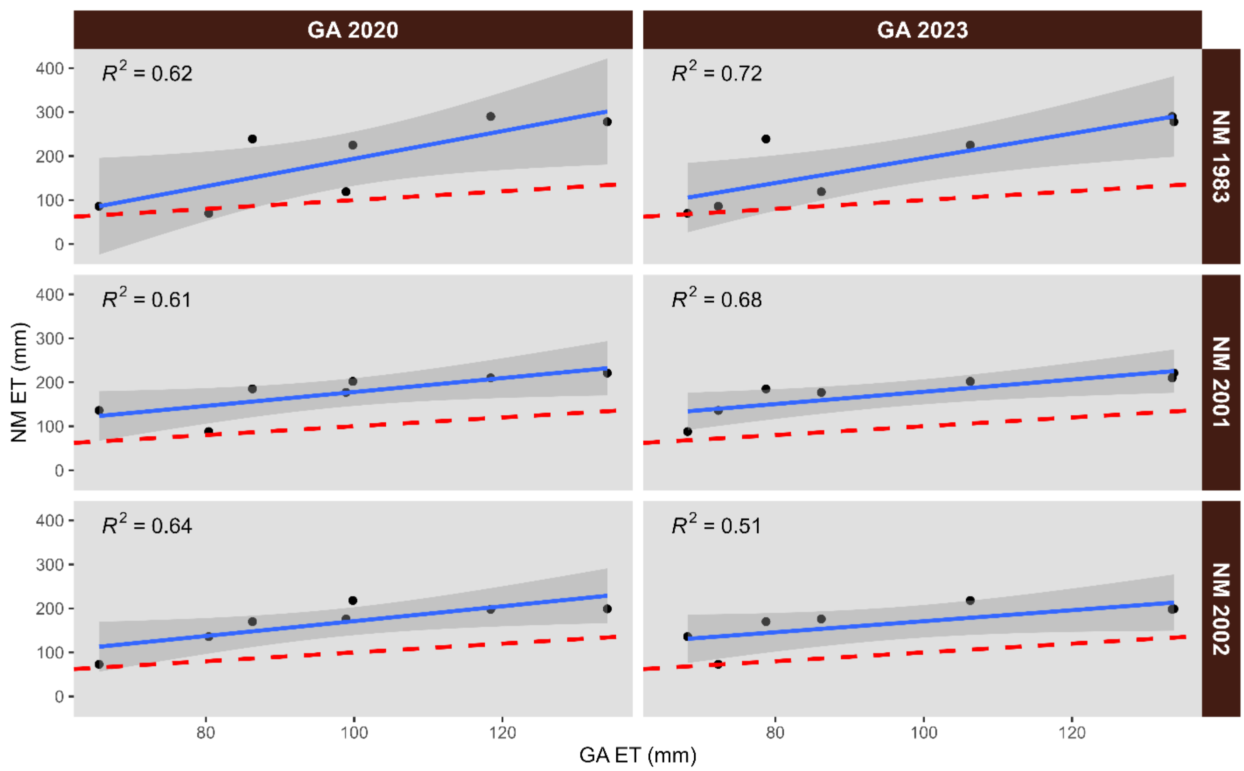


Figure 15: Actual evapotranspiration of Georgia (GA ET) and New Mexico (NM ET) (Sammis et al., 2004). Blue line is the regression line whereas red is 1:1 line.

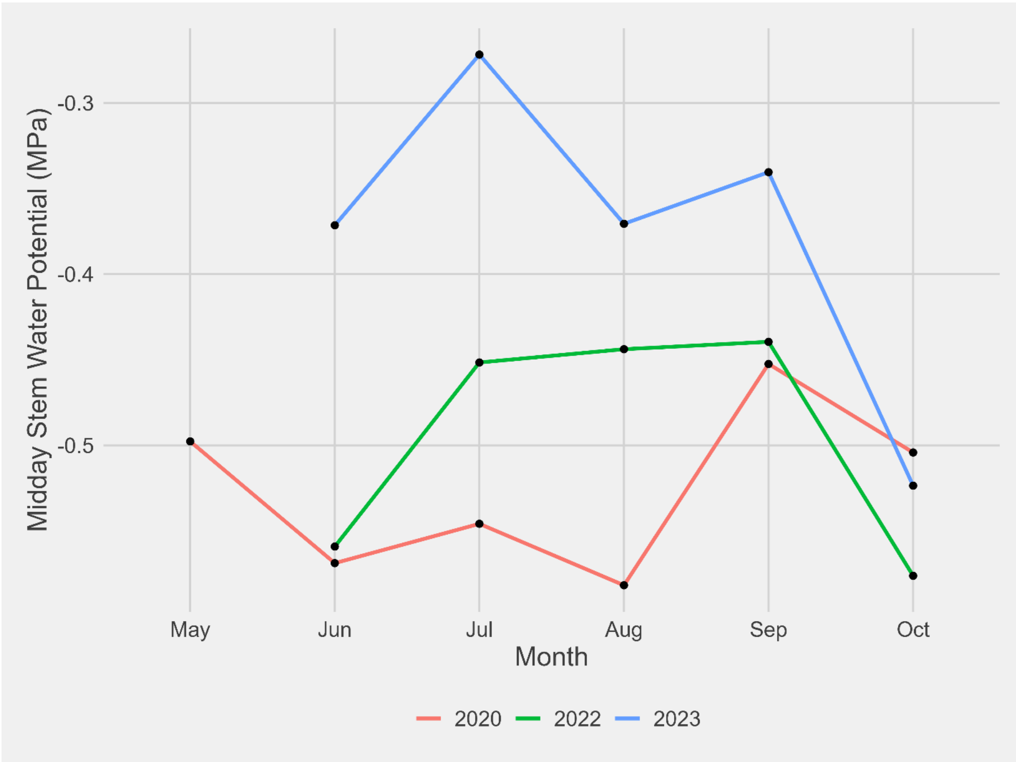


Figure 16: Average midday stem water potential (MPa) in different months during the growing season during 2020, 2022, and 2023

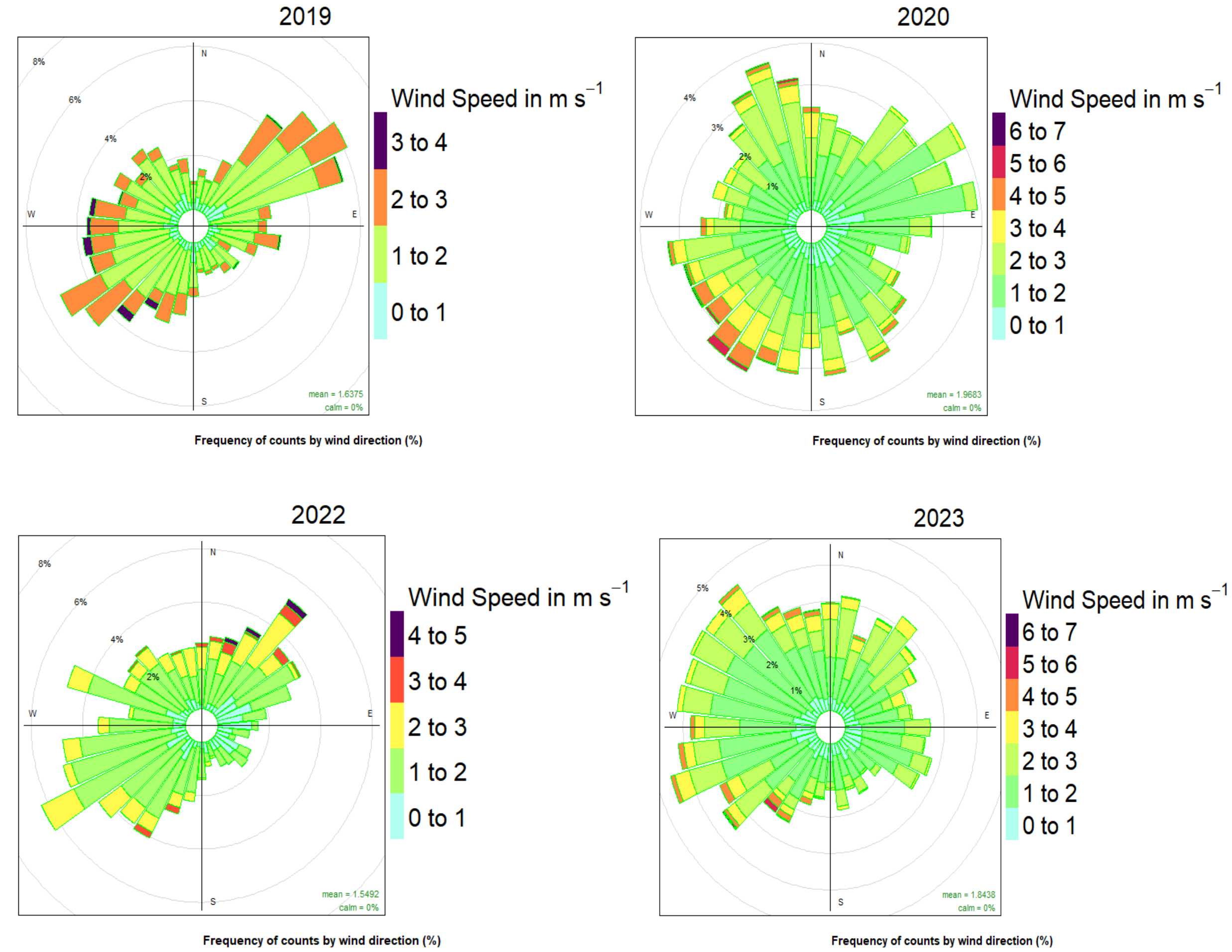


Figure 17: Windrose plot showing the direction of prevailing wind in the pecan orchard during 2019, 2020, 2022, and 2023

Table 5: Comparison of actual evapotranspiration in different years for all given months in 2019, 2020, 2022 and 2023

Month/Years	2019	2020	2022	2023
March		1.75^{a}		1.74^{a}
April		2.96^{a}		2.50^{a}
May		3.20^{a}		2.68^{b}
June	3.44^{a}	3.13^{a}		3.67^{a}
July	3.31^{b}	4.37^{a}	3.75^{ab}	4.18^{a}
August	3.25^{b}	3.57^{b}	3.39^{b}	4.30^{a}
September	2.74^{b}	3.26^{a}	2.86^{ab}	2.92^{ab}
October	1.46^{b}	2.15^{a}		

^{ab}Means followed by the same letter in each column are not different at $P<0.05$.

Table 6: Comparison of crop coefficient in different years for all given months in 2019, 2020, 2022 and 2023

Month/Year	2019	2020	2022	2023
March		0.58[a]		0.54[a]
April		0.63[a]		0.59[a]
May		0.60[a]		0.60[a]
June	0.54[b]	0.59[ab]		0.66[b]
July	0.57[c]	0.77[ab]	0.71[b]	0.79[a]
August	0.73[ab]	0.71[b]	0.68[b]	0.82[a]
September	0.60[c]	0.82[a]	0.74[b]	0.74[b]
October	0.54[b]	0.86[a]		

[ab]Means followed by the same letter in each column are not different at P<0.05.