NUMERICAL MODELING OF ROOT ZONE WATER UPTAKE IN A MICRO-IRRIGATED PECAN ORCHARD

by

SUKHVIR KAUR

(Under the Direction of MONIQUE LECLERC and NANDITA GAUR)

ABSTRACT

Georgia is the largest producer of pecan, (C*arya illinoinensis)* in the southeastern USA and accounts for one-third of the nation’s pecan production. The trends in rainfall patterns, temperature, and CO_2 concentration have been changing from year to year. HYDRUS 1D, a numerical model, was used to simulate the water movement through different soil layers to optimize irrigation scheduling. The HYDRUS model was calibrated for the year 2020 using soil moisture measurements which were used to validate the model for 2021. Statistical results suggested that the model was well-calibrated and validated to perform prediction scenarios. Using calibrated hydraulic parameters, three prediction scenarios (P1, P2, and P3) were performed to evaluate the soil storage. The irrigation amount was the same in P1 and P2 and doubled the irrigation amount for P3. It was found that P1 had the maximum soil water storage and less water loss through drainage, Thus, of all three scenarios, P1 is most likely a better strategy to maximize soil water content.

INDEX WORDS: Root water uptake; HYDRUS 1D; irrigation scheduling; pecan water use; tree water use; soil water content

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CHAPTER 1

INTRODUCTION

Pecan, (*Carya illinoinensis*), is a deciduous tree native to North America and is in the same family as the English nut, black walnut, and hickory (*Juglandaceae*). It requires long hot summers and moderately cool winters. The United States is the world's largest producer of pecan and Georgia is the leading state in its production. According to a report by The United States Department of Agriculture (USDA), the production of pecans in Georgia totaled 305 million pounds with orchard bearing acreage of 134,000 in 2020 (U.S.D.A, 2021).

Pecan trees require an ample supply of water during the growing season for both tree growth and nut quality (Deb et al., 2012; Deb et al., 2013; Liu & Sheng, 2013; Samani et al., 2009). A few studies in other states reported that a single tree needs approx.1300 liters of water per day during its peak season (Wells, 2015; Wells & Casey, 2013). Pecan trees require about 152 cm of total water during the growing season. Georgia receives an average of 127 cm of annual rainfall distributed throughout the year (Wells, 2015). This water deficit results in moisture stress for pecans that tends to occur during the most critical stage i.e., the kernel filling stage in August and September. As a consequence, pecan growers can experience economic losses due to the production of poor quality nuts and a reduction in yield (Taylor et al.; Wells, 2015; Wells & Harrison, 2010). Hence, to avoid moisture stress at this critical stage, frequent irrigation has to be applied to supplement rainfall (Wells, 2017).

Irrigation also needs to be applied considering uncertain weather patterns that are occurring as a result of global warming. These changes will gradually impact the growth and yield of crops (the United States Environmental Protection Agency, 2017). Agriculture is exquisitely sensitive to changes in climatic patterns. Extreme events such as droughts and floods can both impact pecan production. Drought conditions at the critical growth stages in pecan production and floods at the ripening or harvesting stage result in the decrease of yield or sometimes lead to the death of the crops (Asseng, 2013; Knox et al., 2014).

The amount of water required by pecans depends on several factors which include tree age, density, variety, canopy cover (open or closed), irrigation availability, and soil type (Deb et al., 2011; Samani et al., 2009). The spatial and temporal variability in weather conditions, especially rainfall highlights the importance of irrigation management in the Southeast (Salazar, 2012). While flood irrigation has traditionally been the most widely used method in southwestern United states (Lombardini & Basso), more efficient micro-irrigation methods like sprinkler and drip irrigation are being increasingly used in Georgia (Wells, 2017). Available literature on water requirements for pecans are based in the southwestern U.S. and a direct translation of those results to the southeastern U.S is hard because of variations in climate and available irrigation methods.

In the past, pecan orchards in Georgia were typically irrigated based on several studies conducted in arid climates or based on the growers' experience and visual observations of crop growth and yield. Wells (2013) developed the current irrigation schedule based on stem water potential and volumetric water content (θ) for growers in the southeast U.S. The new irrigation schedule by Wells, (2015) provided a 38% reduction in irrigation water without impacting nut quality and yield. This effort can be extended to incorporate more soil and weather-specific irrigation schedules that can consider short-term flash droughts during the growing season. Several tools or models can be used for irrigation scheduling by computing crop water requirements and soil water content.

Among available models, the HYDRUS 1D model has been widely used to simulate soil water movement to estimate irrigation requirements under different irrigation scenarios to optimize root water uptake (RWU) (Akhtar et al., 2013; Tan et al., 2014; Ventrella et al., 2019). The HYDRUS model simulates the water flow in variably saturated soils and can model the water flow, solute, and heat transport in the soil profile (Šimůnek et al., 2006). It can be used both as short term (one dimensional either horizontal or vertical laboratory column flows) or as long term (multi-dimensional field studies). It works well in both conditions when all the model parameters are known and when some of the parameters are calibrated and validated from the observed data. In HYDRUS-1D, soil water flow is modeled using Richard’s equation, which represents the water movement in soil profiles under unsaturated conditions (Šimunek et al., 2012). More description regarding HYDRUS can be found at (Ma et al., 2010; Simunek et al., 1998; Simunek et al., 2005; Šimunek et al., 2012; Šimůnek & Weihermüller, 2018).

Yield and irrigation models for pecans are available for the southwestern USA (Andales et al., 2006; Sammis et al., 2013). However, soils and climate differences necessitate the development of these models for the Southeast. Thus far, there are no such models studied for the Southeastern US. Therefore, the main objectives of this study were to:

1. Use well-validated HYDRUS-1D model to represent the soil hydrology for a soil prevalent in southeastern U.S. pecan orchards
2. Evaluate water supplementation efficiency using different irrigation strategies under typical conditions

3. Estimate the potential crop water uptake using the model developed for possible future weather conditions

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CHAPTER 2

NUMERICAL MODELING OF ROOT ZONE WATER UPTAKE IN A MICRO-IRRIGATED PECAN ORCHARD

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ABSTRACT

The pecan (C*arya illinoinensis*) is a fast-growing industry in Georgia as it is the largest producer of pecan in the southeastern USA. It also accounts for a one-third of the nation's pecan production. Pecans require an ample supply of water to grow and to maximize the yield and nut quality. In order to maintain yield and prevent losses to growers, irrigation is needed to supplement rainfall. But this increased demand on water is stressing already strained shared water resources in the state. One solution to enhance the optimum use of water is to optimize irrigation scheduling such that irrigation can be minimized without compromising the quality of nuts or yield. Thus, the main goal of this study was to optimize the currently used irrigation schedule using a soil hydrology model, HYDRUS-1D that can simulate water through different layers of soil profile. The HYDRUS-1D model was calibrated and validated for a soil type commonly found in South Georgia. Firstly, the model was calibrated using observed soil moisture data from 2020 and the calibrated hydraulic parameters were used to validate the model for conditions observed during 2021. The R^2, Root mean square error (RMSE) and relative error (RE) during calibration were 0.72, 0.027 cm^3 cm^{-3},7.16% whereas 0.70, 4.56% and 0.021 cm^3 cm^{-3} in validation. Three hypothetical irrigation scenarios (P1, P2 and P3) were compared with the current irrigation schedules in terms of water application efficiency and the best irrigation strategy was evaluated on the basis of higher soil water content in the soil profile with minimum losses in the form of drainage. Irrigation was applied every day in P1 whereas in P2 irrigation was just applied only one day once a week. In P3 irrigation amount was doubled than the current irrigation schedule. It was found that reducing the time and

increasing the frequency of daily irrigation lead to higher soil water content with minimum water loss by drainage. Also, water loss was maximum and root water uptake was minimum in P3 irrigation scenario.

1. INTRODUCTION

Georgia is one of the major pecan-producing states in the southeastern U.S with a fast expanding pecan industry. In 2020, the total pecan production in the U.S was increased by 18 % (302 million pounds) over the past year (265 million pounds) (USDA, 2021). According to a report by the Census of Agriculture, 2017, Georgia solely contributes about 29% of the total pecan production within the United States (USDA, 2021). It also ranked first in U.S pecan production in 2020 with a total production of 142 million pounds from 129,000 harvested acres (USDA, 2021). However, while the pecan industry is fast growing in this region, the success of this industry depends largely on maintaining high yields while using minimal water resources considering changes in climate and increased stress on shared water resources.

1.1 Water-Use in Pecans

Water requirements of pecan trees varies with tree size, tree density, weather conditions and soil type (Garrot et al., 1993). It also varies with crop load, soil type, plant age and the region (Wells, 2015). As expected, mature pecan trees require a large amount of water during the growing season (Deb et al., 2011; Miyamoto, 1983; Mokari et al., 2022; Othman et al., 2014; Wang, Miller, et al., 2007). More specifically, mature trees typically needs about 152 cm of total water during the growing season which is higher than the average annual rainfall of 127 cm that the humid region of Southeast U.S receives (Wells, 2015). The resulting moisture stress tends to occur at the kernel filling stage which is the water highest demanding stage (Wells, 2015).

However, even the slightest moisture stress throughout the different growth stages will reduce pecan quality and yield. Moisture stress can impact all five different phenological stages in the following ways (a) between bloom and shell hardening the nuts will be small; (b) during shell hardening the shell will be thinner than normal; (c) during kernel development stage following a normal supply in the early stages the nuts will be of normal size but will exhibit poorly developed kernels; (d) during kernel development following a short supply at the time of shell formation, nuts will be small, well filled, or overfilled; (e) during the entire growing season the nuts will be small and poorly filled (Magness, 1955). The effect of water stress on water use efficiency (WUE) and nut quality is more prominent during the nut filling stage. More water supplied at the elongation (June) and expansion (July) stages of the nuts will increase the nut size. There is however a negative relationship between nut size and kernel quality. Sparks (1995) found that the nut size can be regulated by applying the required amount of water. It has been reported that nut size and kernel mass can be increased by 100% if the trees are irrigated well during the kernel filling stage (Marco et al., 2021). Using a crop water index, Garrot et al. (1993) found that when pecan trees are relatively non-stressed and healthy, the highest yield can be achieved. Therefore, maintaining non-moisture stress conditions is very important to enhance yield, quality, and economic return (Sammis et al., 2004) and this water deficit demand is met by irrigation (Wells, 2015).

Pecans are extremely sensitive to the amount of irrigation water applied. A study conducted by Garrot et al. (1993) stated that yield was reduced by 5% to 24% when irrigation water was reduced from 5% to 52%. Also, an irrigation reduction of 52%, lead to a reduction in nut weight by 8%. By the same token, Garrot et al. (1993) also showed that trunk growth was reduced by 27%, over a three period. Hence, the right amount of irrigation is pertinent to the success of pecans in the Southeast. In the backdrop of increased stress on surface and groundwater resources, the development of efficient irrigation strategies is both timely and acutely pressing to maximize pecan production (Deb et al., 2011; Wells, 2015).

1.2 Water uptake in pecans

The water uptake by pecan trees changes as the tree grows since the roots of pecan trees grow at a much faster rate than the branches during the first few years of growth (Woodroof & Woodroof, 1934). The depth of the root zone depends on soil depth, type, and drainage (White Jr & Edwards, 1978). The pecan root system contains a taproot which grows deep vertically into the soil profile, lateral roots grow horizontally from the tree, and fibrous roots which grow laterally from lateral roots (Woodroof & Woodroof, 1934). The roots of a mature tree are almost double the size and density of the canopy of the same tree.

In both the Southeast and Southwest, it has been reported that feeder roots are only present in the upper 60-80 cm (Privette, 1979; Said, 1984; Wells & Harrison, 2010). Thus, pecan trees extract the majority of the water up to 80 cm in a soil profile, and water below this depth is considered survival water to keep the trees alive but is not used for fruit production (Wells & Harrison, 2010). The soil moisture in this layer also affects the quality and size of nuts in pecan production (Samani et al., 2009; Sparks, 1996; Wells, 2015; Wells & Harrison, 2010).

The current pecan irrigation schedule followed by growers in the southeast U.S was developed by studying the relationship of stem water potential and θ on loamy sand soil at Tifton, Georgia (Lenny, 2015). The different soil types, climatic variations, and short-term seasonal droughts necessitate a refinement in the current irrigation schedule. More efficient irrigation strategies can be developed by conducting time-consuming and labor extensive field studies or through modeling of soil water balances and crop productivity (Zhou H et al., 2019). Thus, the HYDRUS-1D model can be used to simulate soil water content, RWU, deep drainage (Er-Raki et al., 2021, Simunek et al., 2008, Simunek et al., 2006) and to perform irrigation scheduling.

1.3 HYDRUS-1D

The HYDRUS model (Simunek et al., 2005; Simunek et al., 2008) is a vadose zone hydrology model used to simulate water use for several agronomic and horticultural crops in studies related to root zone water uptake, irrigation (Autovino et al., 2018; Azhdari, 2008; Deb et al., 2011; He et al., 2017; Iqbal et al., 2020; Khorami et al., 2013; Phogat et al., 2010; L. Wang et al., 2021; Zheng et al., 2018), nutrient uptake (Kadyampakeni et al., 2018; Mokari et al., 2019), leaching (Freiberger et al., 2018) and fertigation (Doltra & Muñoz, 2010; Kadyampakeni et al., 2018; NAVABIAN & JALILNEJAD, 2016; Phogata et al., 2013).

The HYDRUS -1D model has been used in several studies related to soil-water and deep percolation estimation (Tafteh & Sepaskhah, 2012); to enhance water use efficiency by decreasing drainage (Zheng et al., 2017); to simulate soil water dynamics of wettable, water repellent and non-water repellant soils (Wang et al., 2018); and to quantify water fluxes in flood irrigated pecan orchard (Deb et al., 2011). HYDRUS 1D has been used to estimate RWU and to increase irrigation efficiency which leads to water conservation in apples (Zheng et al., 2018). It has also been used in irrigation scheduling by providing an estimation of soil water content in the soil profile, by estimating soil matric potential at field capacity (Lena et al., 2022) and to simulate soil water content for different soil types, climate, and vegetation (Caiqiong & Jun, 2016; Chen et al., 2014; Fan et al., 2012; Silva Ursulino et al., 2019; Xu et al., 2005; Zhang et al., 2011). In the southwestern USA, a similar study was conducted on modeling water fluxes in the root zone in pecan orchards using HYDRUS 1-D (Deb et al., 2011). But to the best of our knowledge, there are limited studies regarding water use efficiency and irrigation scheduling in pecans in the southeast other than the seminal study by Wells, (2015).

Given the need to maintain the quality and yield of pecans while preserving and optimizing the use of shared water resources, it is essential to optimize the current irrigation scheduling in the southeastern U.S. Thus, the main objectives of this study were i) to develop a validated model to represent a dominant soil in the southeast ii) and to evaluate different irrigation scenarios for maximizing available water to trees.

2. MATERIALS AND METHODS

2.1 Experimental site and field measurements

2.1.1 Site description:

This study was conducted in a micro-irrigated commercial pecan orchard, King Spring, near Hawkinsville, Georgia. The orchard was planted in 2013. ‘Desirable’ pecan trees were planted with a row spacing of 15 m and a tree spacing of 9 m within each row. The average height of the trees was 12.5 m. The coordinates of the research site are $32^{\circ}\ 34'.4923"N\ 83^{\circ}62'6915"W$. The mean annual temperature is 17.8°C. This site receives an average annual precipitation of 1.2 m (U.S climate data, 2018). The soil series at the experiment site is characterized as Norfolk (NgB) retrieved from Soil Survey Geographic database (SSURGO). The sand, and clay content for a typical Norfolk soil series are shown in Figure 1.

The orchard is irrigated using micro-sprinklers with a flow rate of 59 liters per hour. Irrigation was applied according to the current pecan irrigation schedule in the Southeast given by Wells (2017).

Two mature pecan trees were selected to simulate water uptake dynamics in the root zone.

2.1.2 Soil measurements

Soil moisture content (SMC) was continuously monitored in the root zone of the two selected trees. Time Domain Reflectometer (TDR) sensors (CS655, Campbell Scientific, Logan, UT) were installed at three different depths of 20cm, 40cm, and 60cm at two different distances of 2m and 3m from the tree trunk to measure soil moisture throughout the year in 2019, 2020 and 2021. SMC data were recorded to a CR1000x datalogger (Campbell Scientific, Logan, Utah, USA) at a 15-min interval which was powered by two deep-cycle marine batteries connected to a solar panel. The hydraulic conductivity (K_s) was measured at the surface (5 cm) and at the subsurface (40 cm) using the Saturo-meter (METER Group) and Borehole Permeameter (Aardvark Permeameter). Two depth measurements were selected based on the field observations and soil horizon depth available from SSURGO (Soil Survey Geographic database) to estimate the surface hydraulic conductivity and that of the limiting layer (Figure 2).

2.1.3 Meteorological data measurements

Climatological data were obtained using the weather station installed by The University of Georgia (Georgia, Automated Environmental Monitoring Network) at approximately 34 km from the research site and included potential evapotranspiration (PET), relative humidity, wind speed and direction, air temperature, and soil temperature (HMP60, Vaisala Crop, Vantaa, Finland) (Figure 5).The experimental site received 103 cm, 144 cm, and 148 cm of rainfall during 2019, 2020, and 2021 respectively which was measured in the field and by weather station by a tipping bucket rain gauge (TB4, Hydrological service America, Lake Worth, FL) (Figure 3).

i. Potential Evapotranspiration

The potential evapotranspiration (PET) data obtained from the nearest weather station data i.e., at Unadilla, Ga. is calculated using the modified Priestley- Taylor equation (Priestley & Taylor, 1972).

$$ET_{pt} = \alpha . \frac{\Delta . (R_n - G)}{\lambda_v . (\Delta + \gamma)} . 1000 \qquad 1)$$

where,

ET_{pt} : Priestley-Taylor evapotranspiration (mm day^{-1})

α =1.26: an empirical constant accounting for the vapor pressure deficit and resistance values [-], α is 1.26 for open bodies, but has a range less than 1 for humid conditions to almost 2 for arid conditions

Δ: Slope of saturation vapor pressure-temperature curve (kPa C^{-1})

G : Soil heat flux density (MJ m^{-2} day$^{-1)}$

λ_v : Volumetric latent heat of vaporization, 2453 MJ m^{-3}

γ : The psychrometric constant (kPa C$^{-1/}$)

ii Crop Coefficient

The crop coefficient (dimensionless) was used to estimate water use specific to the pecan crop (Wu et al., 2021). It tends to change with different environmental conditions, surface roughness changes, plant characteristics and different growth stages (Allen et al., 1998; Doorenbos, 1977; Irmak & Haman, 2003; Rai et al., 2017; Wu et al., 2021). Thus, reference ET for pecans (eq. 4) was estimated by multiplying the Priestly-Taylor PET with the crop coefficient (Brown et al., 2021).

$$ET_p = K_c.\alpha.\frac{\Delta.(R_n - G)}{\lambda_v.(\Delta + \gamma)}.1000 \qquad 2)$$

Monthly crop-coefficient (K_c) values were obtained from earlier pecan studies in the southwest (Samani et al., 2011; Simmons et al., 2007; Wang, Miller, et al., 2007; Wang, Sammis, et al., 2007). To suit the southeast climate conditions, the monthly coefficients were calibrated within the range of coefficients measured in other regions (Table 1).

iii Precipitation and irrigation data

Precipitation and irrigation data were collected directly in the field during the growing period of 2020 and 2021 and the rest of the year from the nearest weather station as mentioned above.

Table 2.

2.2 HYDRUS 1D

In soil water-based scheduling, soil water is monitored daily, and irrigation is scheduled when available water begins to decrease in the soil profile, thus, causing a reduction in both evapotranspiration and yield. In this study, we estimated the changes in soil water in the soil profile using HYDRUS 1-D. The HYDRUS 1-D model was developed by Simunek et al. (1998) to simulate water, heat, and solute movement in saturated-unsaturated media. Simulations for water movement, heat, and solute have been done for several trees and agronomic crops using the HYDRUS 1-D model (Deb et al., 2013; Li et al., 2014; Tafteh & Sepaskhah, 2012; Tu et al., 2021; Wang et al., 2014). Under the present micro-irrigation scenario, the water flow is predominantly vertical (one-dimensional), therefore, Hydrus 1D, version 4.17 model (Šimůnek & Weihermüller, 2018) was used in the present water simulation in the study. HYDRUS assumes the water flow to be isothermal liquid flow and is modeled by using Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial Z} + 1\right)\right] - S \qquad 3)$$

where t is the time, (cm^3 cm^{-3}), h is the soil water pressure head (cm), Z is the spatial coordinate (cm) defined as positive upward, $K(h)$ is the unsaturated hydraulic conductivity function (cm d^{-1}) and S is the sink term representing water uptake by plant roots (cm d^{-1}), which is daily evapotranspiration. The van Genuchten-Mualem model (Van Genuchten, 1980) has been selected for soil-water retention and hydraulic conductivity $K(h)$ functions:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(ah)^n]^m} \quad , \qquad h \leq 0 \qquad 4)$$

$$\text{With } m = 1 - \frac{1}{n} \text{ and } S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad 5)$$

where θ_r and θ_s denote the residual and saturated volumetric water contents (cm^3 cm^{-3}), respectively; a (cm^{-1}) and n (-) are fitting parameters of the soil-water characteristic curve; l (-) is the pore connectivity parameter (=0.5); and S_e (-) is the relative saturation. The model parameters namely, θ_r, θ_s, α, n and K_s were estimated inversely using soil moisture data from 2020, and the same was validated using data from 2021.

2.2.1 HYDRUS 1-D inputs

2.2.2 Model Set-up

i) *Domain*

A 150 cm long soil column of loamy sand was selected to represent the soil domain to test the model parameters since the highest density of pecan roots are in the top 80 cm of soil. Based on the depth of soil horizons for the Norfolk soil series and visual observations of different layers of soil column, the soil domain was divided into two different layers (0-35 cm and 36-150 cm) (Figure 4a). The domain was discretized into 151 nodes. The nodes at the surface were made finer than the sub-surface so that model can accommodate dynamic changes at surface boundary conditions (Figure 4a).

Three observation nodes are located at the same depth where the TDRs were installed for soil moisture measurements which were at 20 cm, 40 cm, and 60 cm from the surface where soil moisture was measured (Figure 4b).

ii) Model spin-up

A 291 day-long period in 2019 was used to spin the model. The model spin-up was done to develop initial conditions for calibration and to reduce the impact of initial conditions on further simulation (Brunetti et al., 2019; Meyer et al., 2014; Vogel, 2019). The initial estimate of the van Genuchten soil hydraulic parameters were estimated using the Carssel and Parrish database available in HYDRUS-1D (Carsel & Parrish, 1988) and the values of hydraulic conductivity were measured in the field. These parameters were then estimated during the calibration process (Kanzari et al., 2018; Wang et al., 2018). The pore connectivity parameter (l) was assumed as 0.5.

iii) Initial and boundary conditions

The initial conditions were provided in terms of soil moisture. The moisture content data from the output of the spin-ups was used as initial conditions for calibration. The soil surface was subjected to atmospheric boundary conditions (BC) with specified values of potential evapotranspiration, precipitation, and irrigation. Therefore, upper boundary conditions were set to “Atmospheric BC with surface layer.” The water table was much deeper than the domain throughout the study period; thus, the bottom boundary was characterized by free drainage conditions.

2.2.3 Model Calibration and validation

The HYDRUS-1D simulation was performed in two stages i.e.- calibration and validation. Calibration is inverse modeling and is a procedure to better parameterize a model for a particular problem by adjusting the input parameters within reasonable range until the simulated output closely represents measured data (Arnold et al., 2012; Park et al., 2006; Šimunek et al., 2012). The calibration was performed using soil moisture data collected during 2020 (DOY 1 to DOY 366). HYDRUS-1D uses the Marquardt-Levenberg technique which is a local optimization scheme for inverse estimation of hydraulic parameters from measured data (Er-Raki et al., 2021; Marquardt, 1963; Šimunek et al., 2012) or estimated data. Soil moisture data, made at a distance of 2m from the tree trunk at a depth of 20cm, 40cm, and 60 cm from 2020 were used to inversely estimate hydraulic parameters. The hydraulic parameters obtained after calibration are given in Table 3. The validation was performed by comparing simulated with observed soil moisture data for the year 2021 (DOY 1 to DOY 300).

2.2.4 Statistical evaluation

The accuracy of simulated versus the observed θ was evaluated by visual observations and by using three metrics- the Root mean squared error (RMSE), relative error (RE), and coefficient of determination (R^2). These metrics were calculated separately for soil moisture measurement at each depth and also for all depths together.

1. RMSE:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}} \qquad 6)$$

2. RE:

$$RE = \sum_{i=1}^{N} \frac{|O_i - P_i|}{O_i} \, X \, 100\% \qquad 7)$$

3. $R^{2:}$

$$R^2 = \frac{[\sum_{i=1}^{N}(O_i - \bar{O})(S_i - \overline{S})]^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2 \sum_{i=1}^{N}(S_i - \bar{S})^2} \tag*{8)}$$

Where O_i is the observed soil moisture data, $\bar{O}$ is mean value of O_i, S_i is the simulated soil moisture data, $\bar{S}$ is the mean value of S_i and N is the number of data points.

2.2.5 Prediction Scenarios

Three prediction scenarios were evaluated to assess the impact of irrigation frequency and duration on RWU of trees. A well-validated model was used to simulate crop water use for the year 2021 under the following irrigation scenarios: -

i) Increase the frequency of the irrigation by irrigating everyday (P1)
ii) Total weekly irrigation application just once at the beginning of the week (P2)
iii) Doubling of the current irrigation amount (P3)

In scenarios P1 and P2, the total amount of water applied as irrigation was equal to that actually applied during the year. The prediction analysis was performed to evaluate whether a different irrigation scenario would have resulted in greater RWU or greater available soil moisture content.

3. RESULTS AND DISCUSSION

3.1 Model Calibration and Validation

The hydraulic parameters in HYDRUS 1D were calibrated for soil moisture using data from the year 2020. The high frequency component of the data corresponds to irrigation or precipitation events while the low frequency changes occur as a result of seasonally changing evaporative demand. The time series plots (Figure 6) for each different layer (20 cm, 40 cm, and 60 cm) show that the model captures the trend (R^2 values = 0.50, 0.75 and 0.80) of the observed soil moisture data. Sharp increases in simulated soil moisture data before DOY 150 and after DOY 200 show that the simulations responded quite accurately to rainfall and irrigation events. During DOY 150-200, the model was able to capture the low frequency changes in the observations that arise as a result of increased evaporative demand in the dry period, however it significantly underestimates the high frequency components that occur due to water application. This is likely an outcome of a mismatch between the actual irrigation or rainfall applied in the field and reported in the records for model input. The corresponding values of R^2, RMSE and RE (%) are 0.72, 0.02 $cm^3\,cm^{-3}$, and 7.16 % for calibration are shown in Table 5. These statistical prediction indicators and visual observations indicated that the calibrated hydraulic parameters were acceptable to validate the model for 2021.

The model was validated using the calibrated parameters and observed soil moisture data during 2021 from DOY 1 to DOY 300 (Figure 7). Based on the R^2 and RMSE values for each layer (0.73, 0.65, 0.68 and 0.008, 0.02, 0.02 $cm^3\,cm^{-3}$.), it was found that simulated data was in good agreement with observed data (Figure 7). The effect of rainfall and irrigation can be seen in the shallowest depth of soil moisture measurements i.e., 20 cm (Figure 6a). However, discrepancies can be seen for a later period during the season where the model is biasedly overestimating the soil moisture data. These low frequency discrepancies can be attributed to inadequate information on crop coefficients. The crop coefficients have not been developed for pecans in the southeast and were calibrated in this study based on the range observed in the Southwest and South Central. Crop coefficients are also sensitive to local weather conditions and using coefficients calibrated in 2020 for simulating 2021 may not be accurate especially since the two years experienced different weather conditions. Sensitivity analysis was conducted to assess the sensitivity of moisture estimates to evapotranspiration and verified that it was sensitive. Another reason for these discrepancies could be the calibration of soil moisture sensors or small errors during data collection and measurements (Silva Ursulino et al., 2019). Most of the discrepancies in simulation were observed during the transition of wet to dry and dry to wet during growing season. The statistical results show ($R^2 = 0.70$ and RMSE = 0.02) that HYDRUS can predict or simulate rapid fluctuations soil moisture data in top layer (20cm) due to rainfall, irrigation, evaporation, and run-off events. Along with the top layer, deeper layers are also modeled at a reasonable accuracy for longer-term processes like transpiration and capillary redistributions (Chen et al., 2014). The difference between simulated and observed soil moisture data was small as the RMSE values are small with a range of 0.0008 $cm^3 cm^{-3}$ to 0.002 $cm^3 cm^{-3}$ and a range of R^2 is between 0.65 to 0.73 for the three depths (Table 4). The correspondence between simulated and observed soil moisture data during the validation period of 2021 is shown in Figure 8b. The relative error (%) measurement for uncertainty between simulated and observed data for three layers is 3.2 %, 7.39 %, and 4.16 %. Based on visual observations of the trend and statistical comparisons, it can be concluded that HYDRUS-1D performed well for simulating soil moisture data for 2021.

3.2 Prediction analysis

In order to determine the efficacy of the current irrigation schedule and compare it with other schedules, the calibrated and validated hydraulic parameters were used to evaluate various irrigation scenarios which might be difficult to perform in the field considering the long seasonal durations and intensive labor work in the field. Since the total amount of water applied is deemed necessary for good pecan yield (Wells, 2015), we did not alter the total amount of irrigation water applied to the crop for scenarios P1 and P2. The validated model was used to assess the soil moisture for three different prediction scenarios for pecans on loamy sand soils in the southeastern U.S (Figure 9).

Root water uptake

The information on root water uptake (RWU) can help to develop sustainable irrigation strategies (Kuhlmann et al., 2012). It can provide information regarding soil water balance and water use by plants (X. Wang et al., 2021). As discussed earlier, feeder roots of pecans are present in the upper 60-80 cm (Deb et al., 2011; Wells & Harrison, 2010). The maximum root length density was found in the upper 60 cm of the soil surface and decrease with soil depth (Deb et al., 2011). Therefore, RWU was also maximum from the upper soil depths and decreases gradually in the deeper layers. It has also been observed that an increase in RWU coincide with the bud breaking stage of trees i.e., April and it was maximum during DOY 150 to DOY 250 when PET, VPD was also higher (Figure 10).

Percolation

The simulation of percolation also shows higher water loss in P2 and P3 (Figure 11). In P2, when irrigation provided over the course of longer hours for just one day a week, the soil may get saturated, and any additional irrigation led to water loss by drainage. Such conditions can also lead to water logging and oxygen depletion in the root zone which can affect the root growth (Wells & Harrison, 2010) and in HYDRUS resulted in a lower water uptake. When PET and RWU were at the highest (DOY 140 -DOY150), the lowest magnitude of percolation was observed. Similar results were found by Dash et al. (2015); Tafteh and Sepaskhah (2012); Xu et al. (2017). Therefore, it is indicated that there is an increased risk of water loss by percolation in P2 and P3. The simulated evapotranspiration was highest in P2 and P3 and the lowest in P1. Hence, water losses by evapotranspiration and deep percolation are maximum in P2 and P3. In future, further studies are necessary for actual percolation and evapotranspiration measurement to validate these HYDRUS 1-D simulations.

Simulated water content for different irrigation scenarios

Simulations were performed to evaluate the θ under different irrigation scenarios (Figure 9). It has been observed that θ was the maximum in P1 scenario in which irrigation amount was distributed daily throughout the week as opposed to every other day as was done per the current irrigation schedule. In P2, all the water was applied as irrigation once a week and in P3, doubling the current irrigation, resulted in lower θ (Figure 12). The simulated minimum, maximum and average θ for all the layers was higher in P1 among the three scenarios (Table 6). Simulation results also indicated higher bottom flux in P2 and P3 scenarios (Figure 11). The total water storage the in the soil profile (0-150cm) was also highest in P1 when irrigation amount was same as that of current schedule (Figure 14). In P 2, large amounts of irrigation were applied once week which resulted in the loss of water from the soil profile by percolation and lead a to reduction the in the soil profile for the rest of the week.

Therefore, of all prediction scenarios, the maximum soil water content with maximum root water uptake and minimum water loss by bottom flux was be achieved by P1 irrigation scenarios. However, further efforts would be necessary to validate this finding at the field level.

4. CONCLUSION

Inverse modeling was performed using observed soil moisture data from 2020 to calibrate the hydraulic parameters of the model. The calibrated parameters from 2020 were used to validate the model. HYDRUS was able to simulate sharp increase in soil moisture data because of irrigation, rainfall and evaporation events. Therefore, good agreement between observed and simulated moisture was observed during validation for all the soil layers which indicated HYDRUS was a good fit to perform various irrigation scenario analysis. The R^2 and RE (%) values were 0.72 and 7.16 during calibration in 2020 and 0.70 and 4.85% during validation in 2021.

Three prediction analysis (P1, P2, and P3) were performed under three different irrigation scenarios. The results indicated that soil water storage and volumetric water content were higher whereas cumulative evapotranspiration and deep percolation was lowest in P1 among three prediction scenarios. Water losses by deep percolation was 20%, 21%, 25% and 26% for current irrigation, P1, P2, and P3. When the final irrigation amount was same, P2 and P3 had a high root zone pressure head (DOY 148- DOY 152) (Figure 15). The cumulative evapotranspiration was also higher in P2 and lower in P1. Soil water storage was maximized in P1 followed by the current irrigation schedule, P2 and P3. Therefore, among all the predictions scenarios, P1 had lowest cumulative evapotranspiration and drainage (following current schedule) and highest water storage in soil profile.

Finally, this study can be considered as the basis for future studies regarding simulation of soil water content, actual evapotranspiration and drainage under different weather conditions and soil types. However, actual crop coefficient measurements from the field will help reduce the discrepancies between simulated and observed data. Further studies can also be conducted to evaluate the effect of reduced irrigation schedules on yield and soil water content in profile during pre-kernel filling stages when water demand is lower.

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6. TABLES AND FIGURES

TABLES

Table 1 Monthly actual K_c measured in southwest U.S and adjusted K_c for southeast U.S.

S.no	Month	Actual K_c	Adjusted K_c
1	January	0.38	0.38
2	February	0.36	0.36
3	March	0.39	0.39
4	April	0.59	0.59
5	May	0.87	1.5
6	June	1.02	1.5
7	July	1.04	1.5
8	August	1.24	1.5
9	September	1.26	1.25
10	October	0.84	0.84

Table 2 Irrigation data collected at the experiment site during 2020 and 2021

	2020	2021
DOY	Irrigation (cm/day)	Irrigation (cm/day)
111	0.00	0.85
112	0.00	0.00
113	0.00	0.85
114	0.00	0.00
115	0.00	0.00
116	0.00	0.00
117	0.00	0.00
118	0.00	0.85
119	0.00	0.00
120	0.00	0.85
121	0.00	0.00
122	0.00	0.00
123	0.00	0.85
124	0.00	0.00
125	0.00	1.48
126	1.70	0.00
127	0.00	1.48
128	1.70	0.00
129	0.00	0.00
130	1.70	1.48
131	0.00	0.00
132	1.70	0.00
133	0.00	0.00
134	1.70	1.48
135	0.00	0.00
136	1.70	0.00
137	0.00	1.48
138	0.00	0.00
139	0.00	1.48
140	0.00	0.00
141	0.00	1.48
142	0.00	0.00
143	1.70	0.00
144	0.00	1.48
145	0.00	0.00
146	0.00	1.48

147	1.70	0.00
148	0.00	1.48
149	1.70	0.00
150	0.00	0.00
151	1.70	1.48
152	0.00	0.00
153	0.00	1.48
154	1.70	0.00
155	0.00	1.48
156	1.70	0.00
157	0.00	0.00
158	1.70	0.00
159	0.00	0.00
160	0.00	1.48
161	1.70	1.48
162	0.00	0.00
163	0.00	0.00
164	0.00	0.00
165	1.70	1.48
166	0.00	1.48
167	0.00	1.48
168	2.12	1.48
169	0.00	1.48
170	2.12	0.00
171	0.00	0.00
172	2.12	1.48
173	0.00	1.48
174	0.00	1.48
175	2.12	1.48
176	0.00	0.00
177	0.00	0.00
178	0.00	1.48
179	0.00	1.48
180	0.00	1.48
181	0.00	1.48
182	2.12	1.48
183	0.00	0.00
184	2.12	0.00
185	0.00	1.48
186	2.12	1.48
188	0.00	1.48

189	0.00	1.48
190	0.00	0.00
191	0.00	0.00
192	0.00	1.48
193	2.12	1.48
194	0.00	1.48
195	0.00	1.48
196	2.12	1.48
197	0.00	0.00
198	0.00	0.00
199	0.00	1.48
200	2.12	1.48
201	0.00	1.48
202	0.00	1.48
203	0.00	1.48
204	0.00	0.00
205	0.00	0.00
206	0.00	1.48
207	2.12	1.48
208	0.00	1.48
209	0.00	1.48
210	2.12	1.48
211	0.00	0.00
212	2.12	0.00
213	0.00	2.55
214	2.12	2.55
215	0.00	2.55
217	2.12	2.55
218	2.12	2.55
219	2.12	2.55
220	2.12	2.55
221	2.12	2.55
222	2.12	2.55
223	2.54	2.55
224	2.54	2.55
225	1.06	2.55
226	2.54	2.55
227	2.54	2.55
228	2.54	2.55
229	2.54	2.55
230	2.54	2.55

231	2.54	2.55
232	2.54	2.55
233	2.54	2.55
234	2.54	2.55
235	2.54	2.55
236	2.54	2.55
237	2.54	2.55
238	0.00	2.55
239	0.00	2.55
240	2.54	2.55
241	2.54	2.55
242	2.54	2.55
243	2.54	2.55
244	2.54	2.55
245	2.54	2.55
246	2.54	2.55
247	2.54	2.55
248	2.54	2.55
249	2.54	2.55
250	2.54	2.55
251	2.54	2.55
252	2.54	2.55
254	2.54	2.55
255	2.54	2.55
256	2.54	2.55
257	2.54	2.55
258	2.54	2.55
259	2.54	2.55
260	2.54	2.55
261	2.54	2.55
262	0.00	2.55
263	0.00	0.00
264	2.54	0.00
265	2.54	0.00
266	2.54	0.00
267	2.54	0.00
268	2.54	0.00
269	2.54	0.00
270	2.54	0.00
271	2.54	0.00
272	2.54	0.00

273	2.54	0.00
274	2.54	0.00
TOTAL	190	207

Table 3 Calibrated hydraulic parameters obtained from HYDRUS 1 D

	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm h^{-1})
0-35 cm	0.100	0.35	0.002351	1.220	46.03
36-150 cm	0.0007	0.45	0.001999	1.3284	51.82

Table 4 The root mean square (RMSE), relative error (RE) and r^2 values for calibration (2020) and Validation (2021) of three different depths (20cm, 40cm, and 60cm) from the soil surface

	Soil depth (cm)	20	40	60
Calibration (2020)	RMSE (cm^3 cm^{-3})	0.02	0.03	0.02
	RE (%)	5.46	8.54	1.82
	R^2	0.50	0.75	0.80
Validation (2021)	RMSE (cm^3 cm^{-3})	0.008	0.02	0.01
	RE (%)	2.10	7.36	4.21
	R^2	0.73	0.65	0.68

Table 5 The overall statistical analysis of calibration and validation during 2020 and 2021

	Calibration (2020)	Validation (2021)
RMSE ($cm^3\ cm^{-3}$)	0.02	0.02
RE (%)	7.16	4.56
R^2	0.72	0.70

Table 6 The simulated minimum, maximum, and average soil water content for irrigation scenarios for three different soil layers

20 cm			
	Minimum ($cm^3\ cm^{-3}$)	Maximum ($cm^3\ cm^{-3}$)	Average ($cm^3\ cm^{-3}$)
Current	0.27	0.34	0.30
P1	0.28	0.35	0.31
P2	0.24	0.30	0.26
P3	0.28	0.35	0.31
40 cm			
	Minimum ($cm^3\ cm^{-3}$)	Maximum ($cm^3\ cm^{-3}$)	Average ($cm^3\ cm^{-3}$)
Current	0.28	0.43	0.35
P1	0.33	0.48	0.38
P2	0.25	0.38	0.31
P3	0.28	0.41	0.34
60 cm			
	Minimum ($cm^3\ cm^{-3}$)	Maximum ($cm^3\ cm^{-3}$)	Average ($cm^3\ cm^{-3}$)
Current	0.28	0.43	0.35
P1	0.33	0.48	0.38
P2	0.25	0.38	0.31
P3	0.28	0.41	0.34

FIGURES

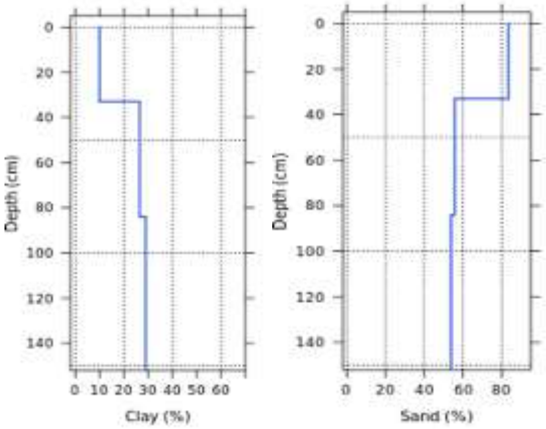


Figure 1 Clay and Sand percentage in the NgB soil series at the site

Figure 2 Soil core collected from the experiment site

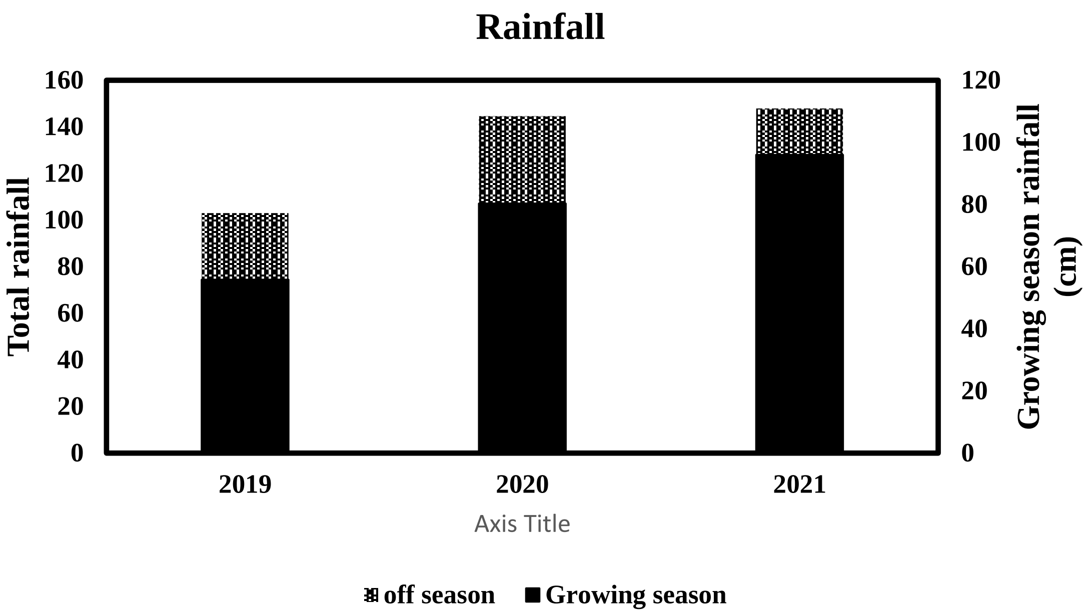


Figure 3 Rainfall data annually and during 2019, 2020 and 2021

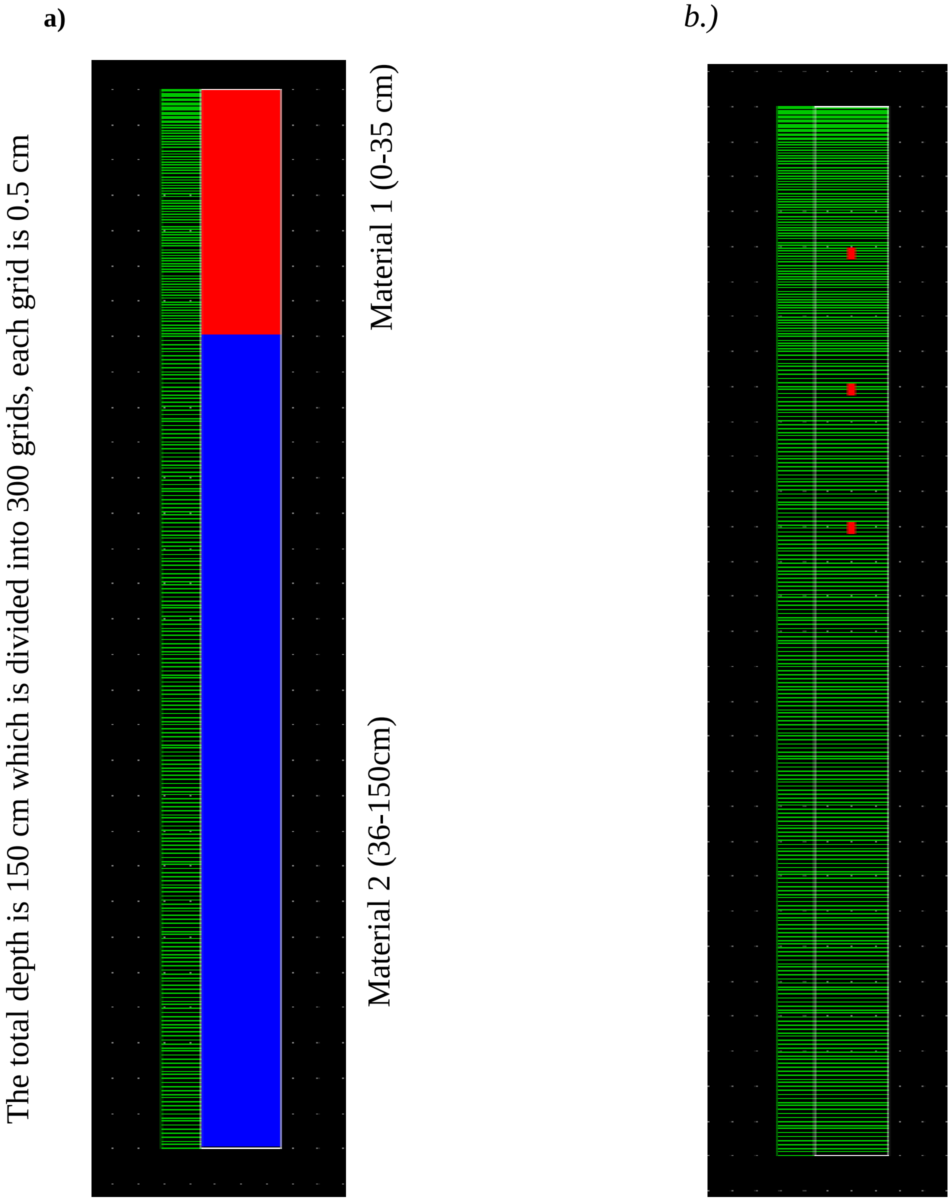
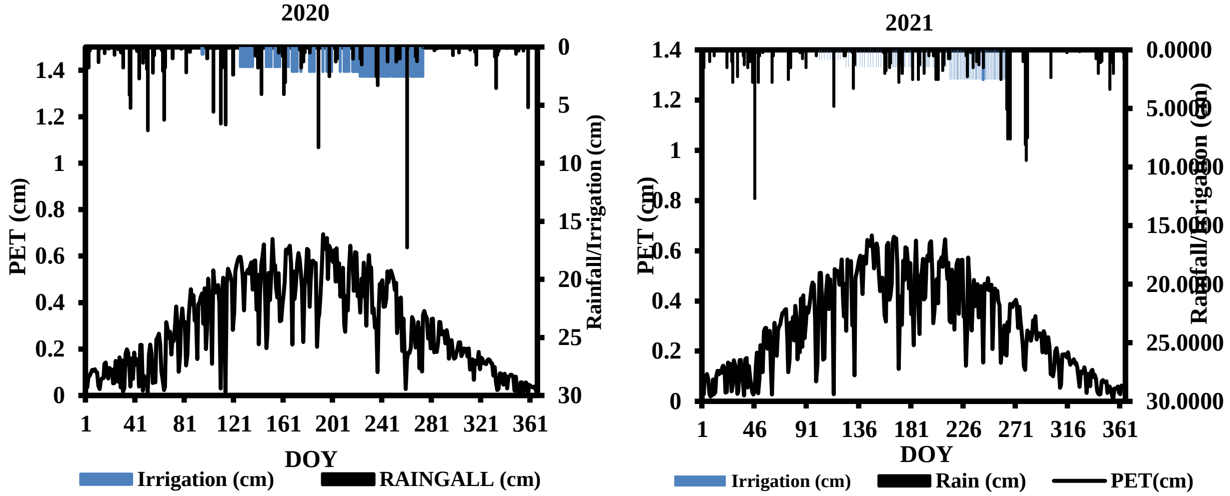


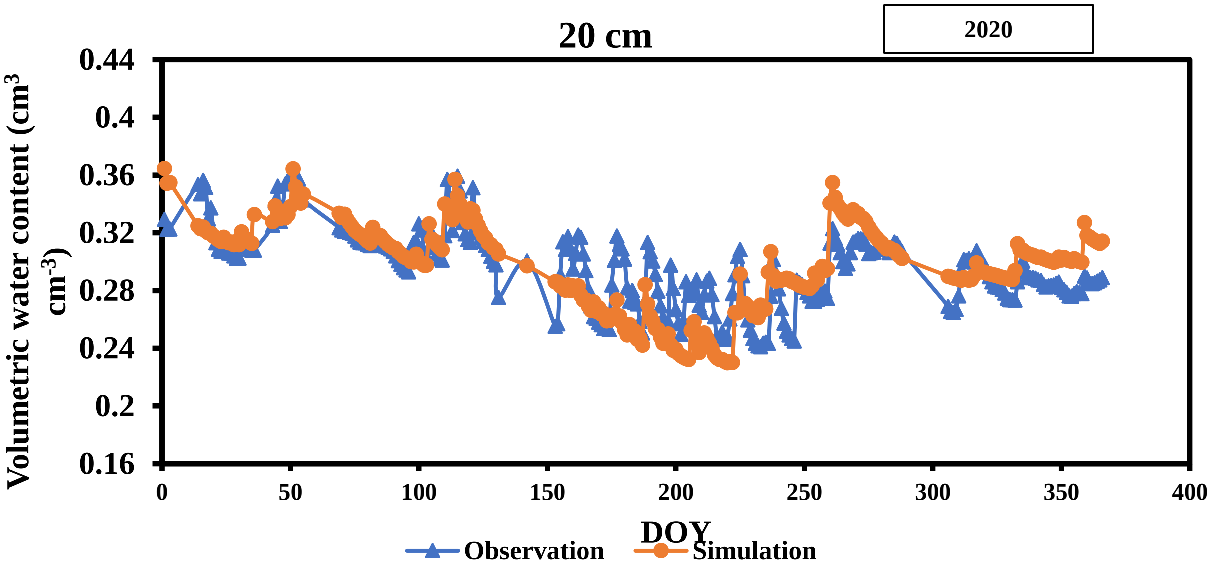
Figure 4 a) Model domain of 150 cm represents as a soil column divided into two different layers, Red (0-35 cm) as material 1 and Blue (36-150 cm) as material 2 and b) observation nodes placed at 20cm, 40cm, and 60 cm.



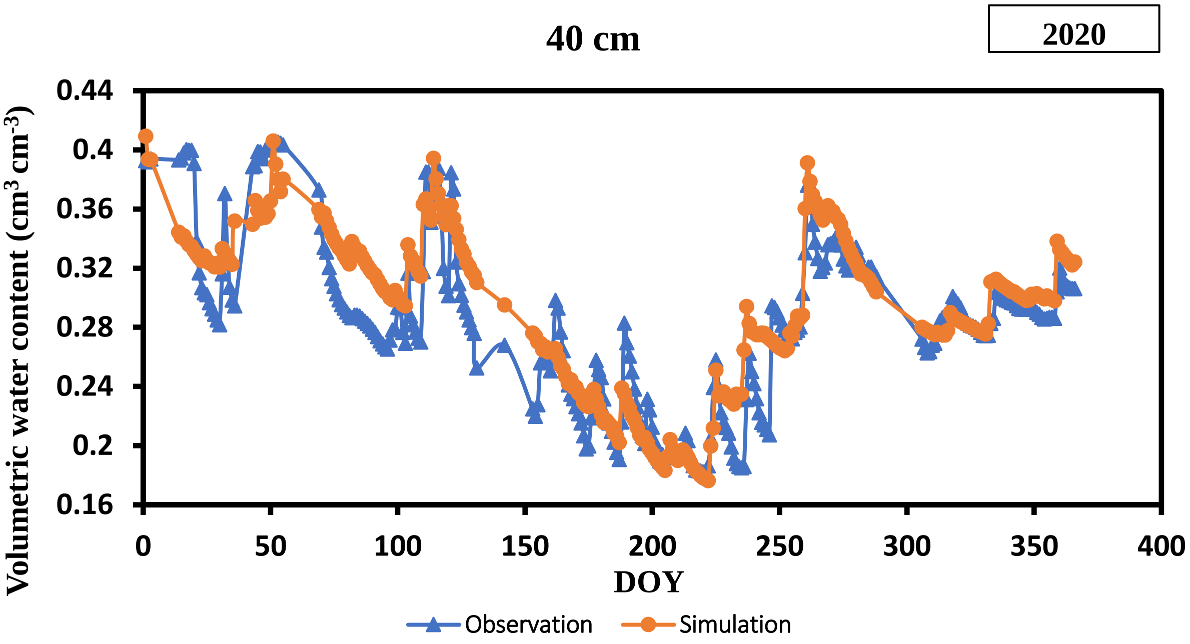
a.) *b.)*

Figure 5 Calculated daily potential evapotranspiration and recorded precipitation and irrigation data in a) 2020 and b) 2021 for calibration and validation

a.)



b.)



c.)

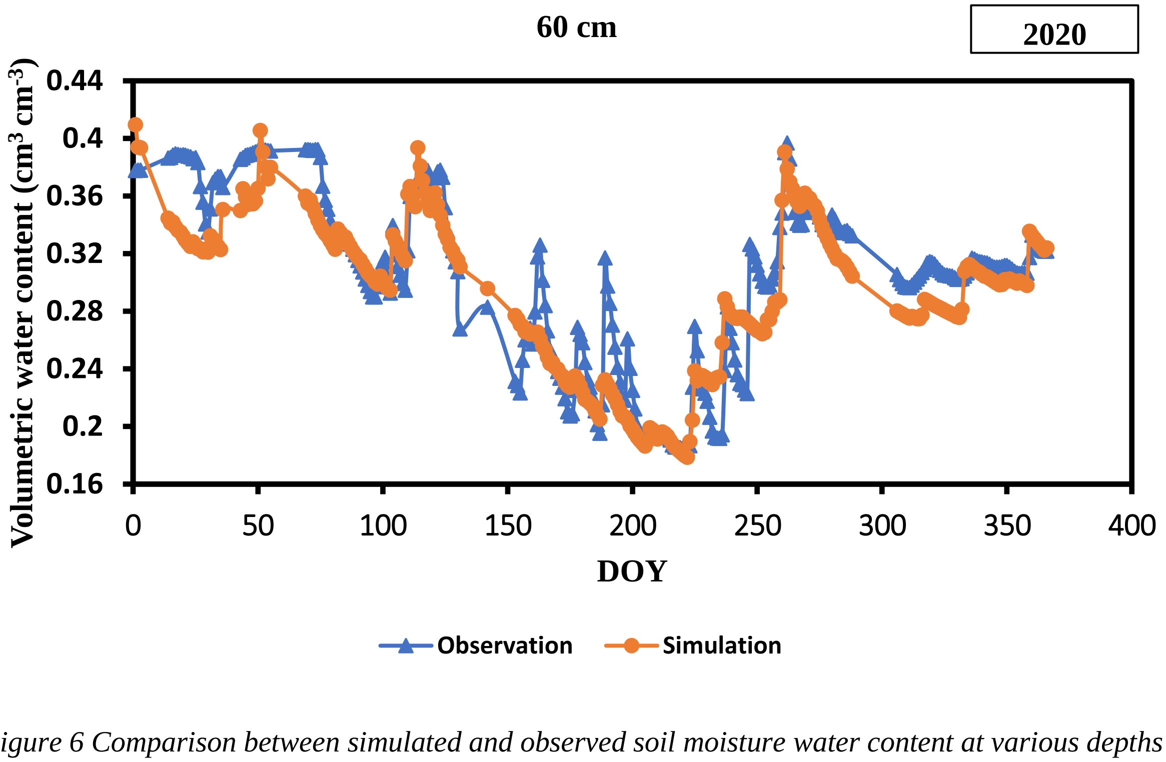
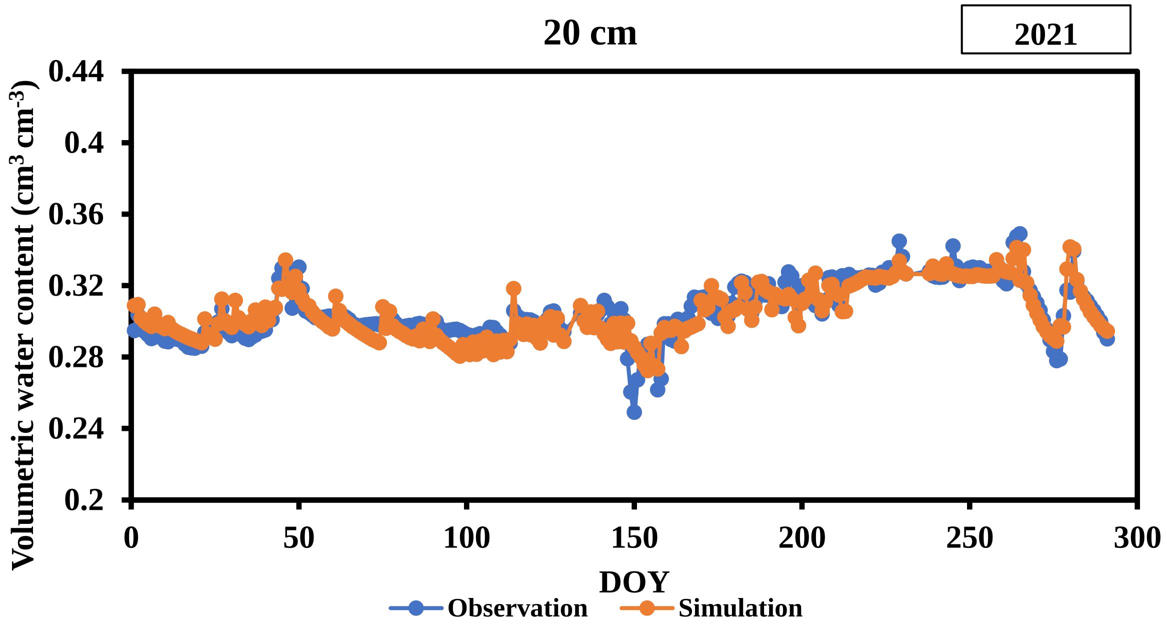
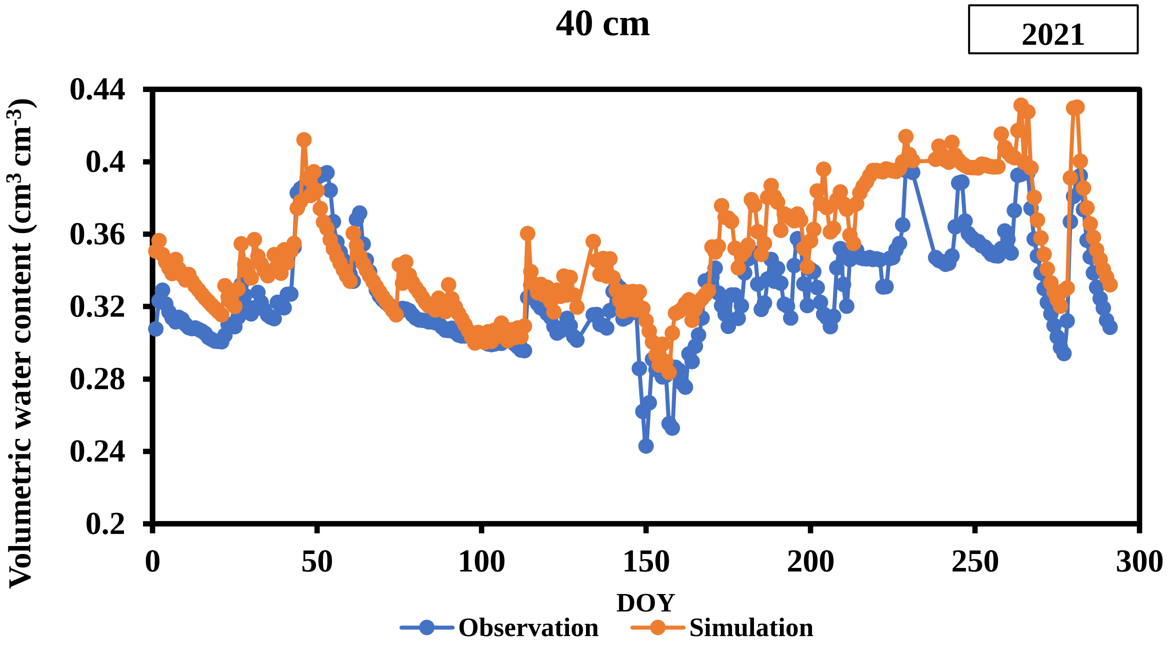


Figure 6 Comparison between simulated and observed soil moisture water content at various depths a.) 20 cm, b) 40 cm, and 60 cm from soil surface during calibration in 2020 (DOY 1 to DOY 365)

a.)


20 cm
2021
Volumetric water content (cm^3 cm^{-3})
0.44
0.4
0.36
0.32
0.28
0.24
0.2
0
50
100
150
200
250
300
DOY
Observation
Simulation

b)


40 cm
2021
Volumetric water content (cm^3 cm^{-3})
0.44
0.4
0.36
0.32
0.28
0.24
0.2
0
50
100
150
200
250
300
DOY
Observation
Simulation

c)

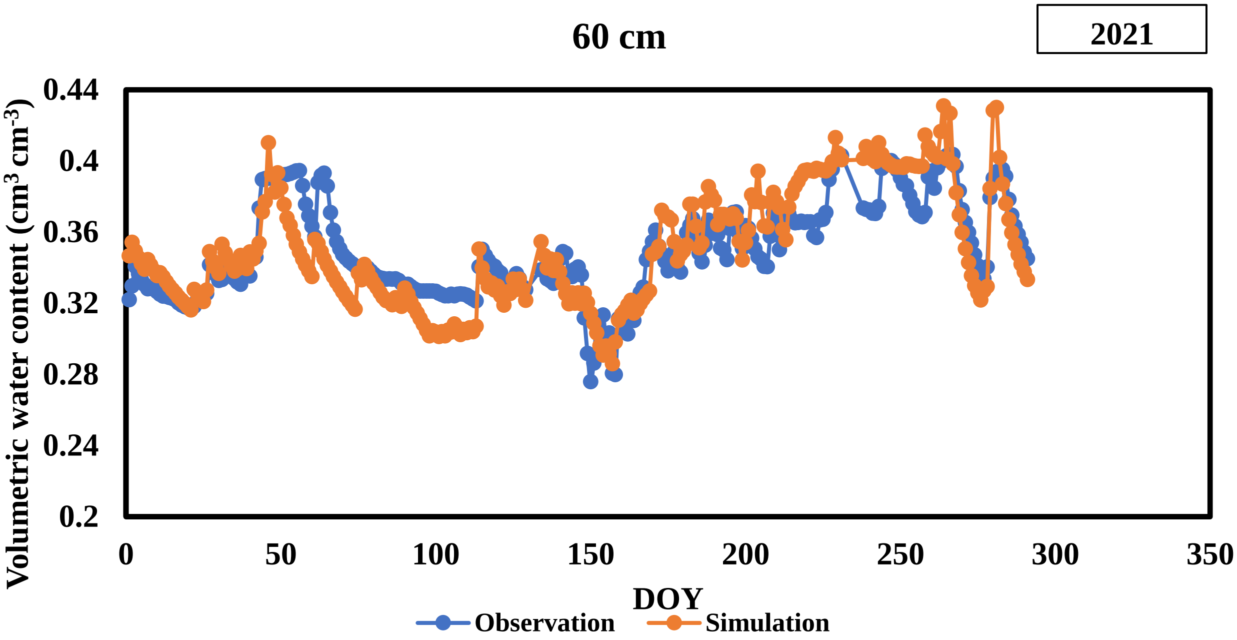
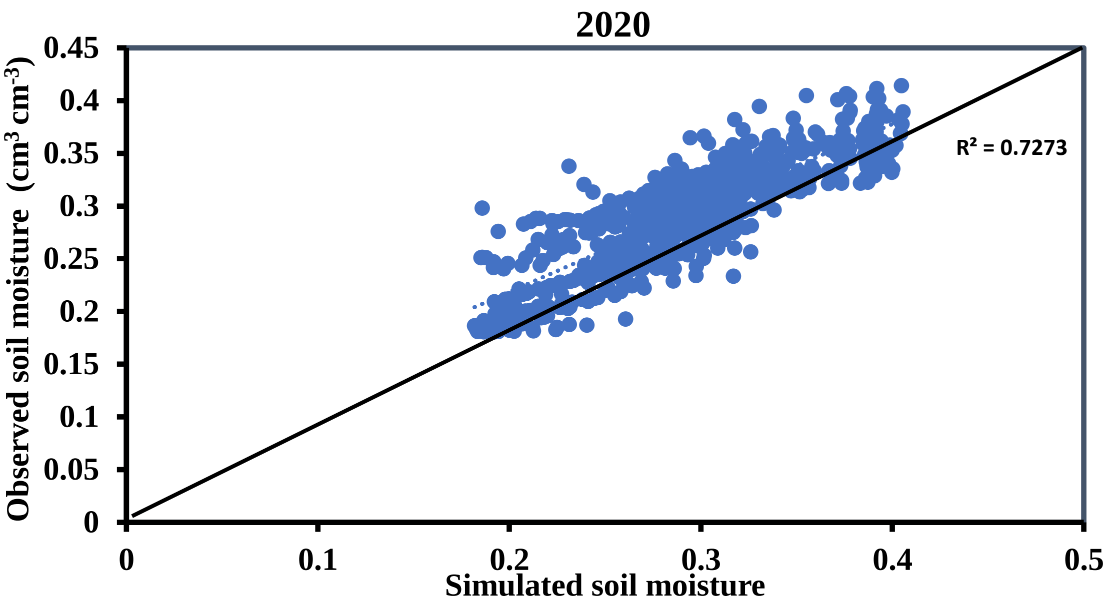


Figure 7 Comparison between simulated and measured water content at three different soil layers a) 20 cm, b) 40 cm, and c) 60 cm during validation period of 2021 (DOY 1 to DOY 300

a)



b.)

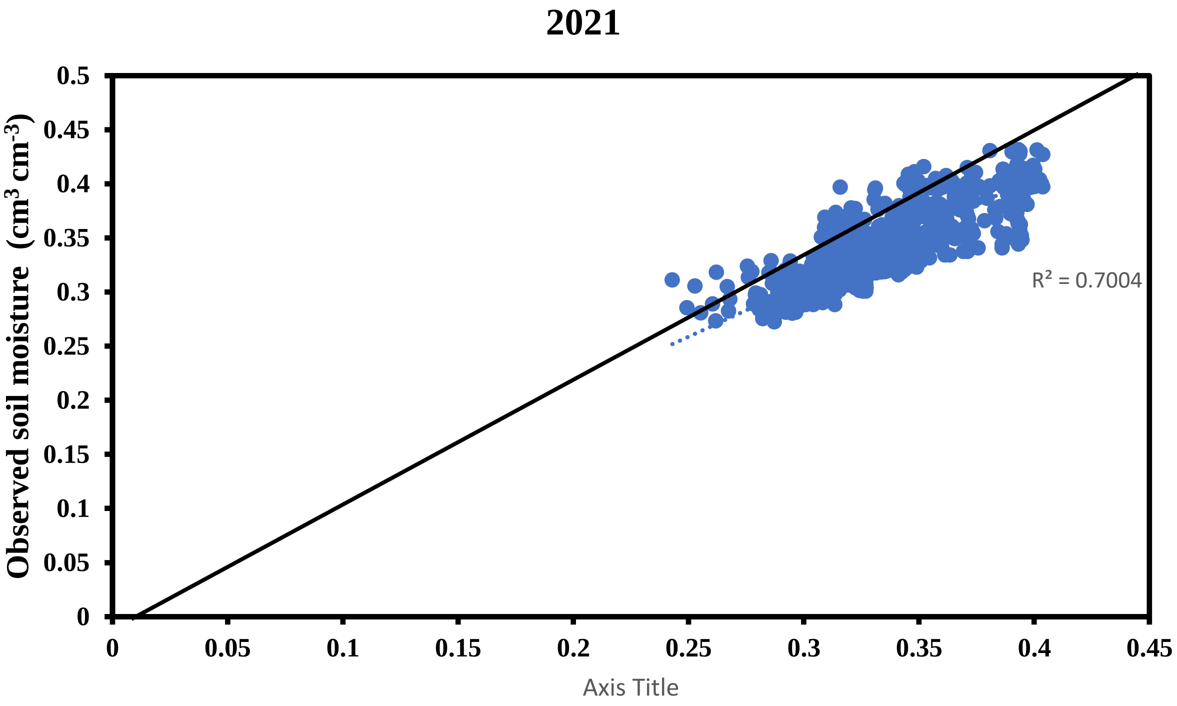
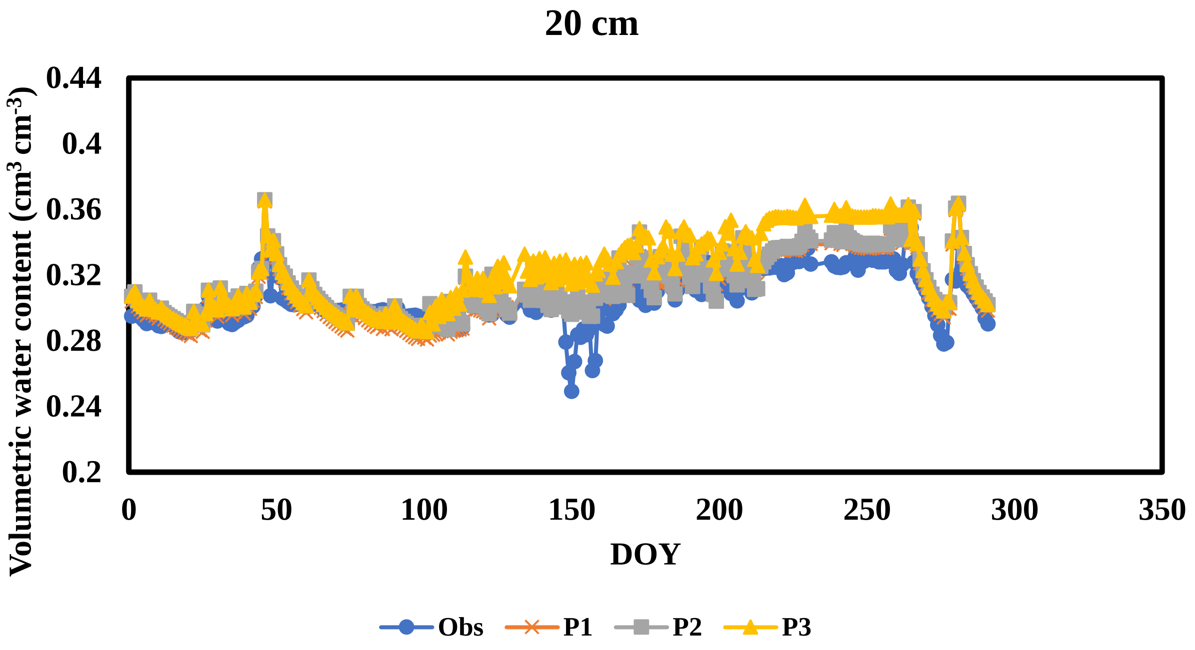
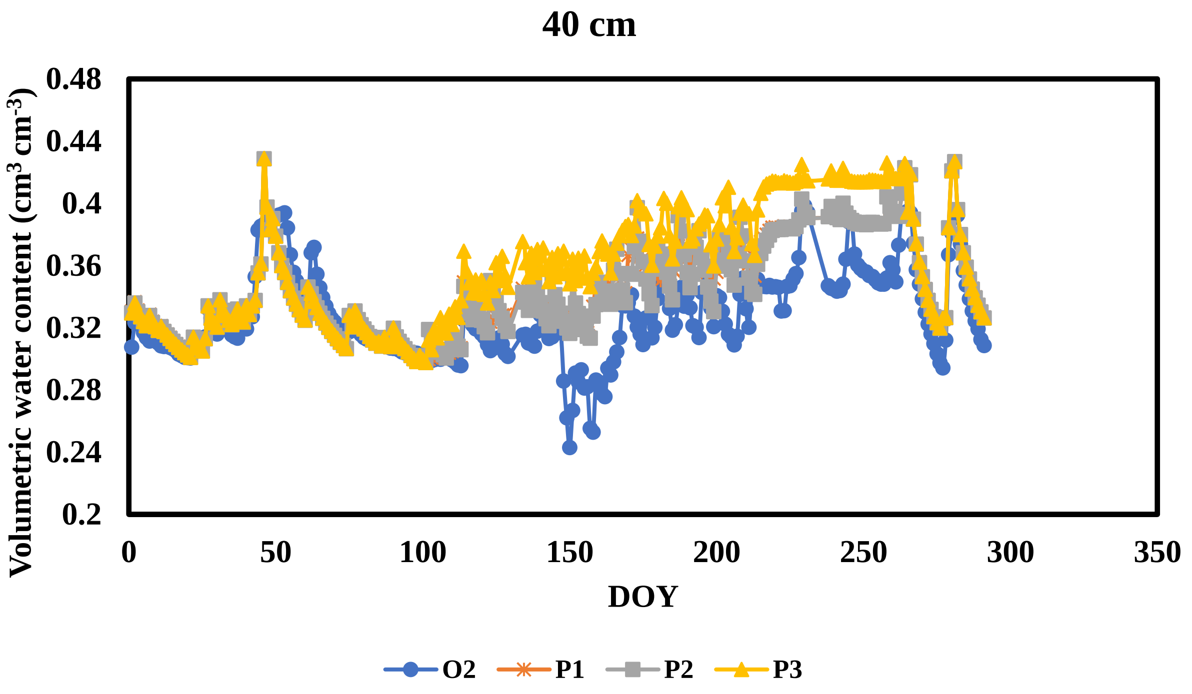


Figure 8 The correspondence between simulated and observed soil moisture data in (a) 2020 (Calibration) and (b)2021 (Validation)

a)


20 cm
Volumetric water content (cm³ cm⁻³)
0.44
0.4
0.36
0.32
0.28
0.24
0.2
0
50
100
150
200
250
300
350
DOY
Obs
P1
P2
P3

b)


40 cm
Volumetric water content (cm³ cm⁻³)
0.48
0.44
0.4
0.36
0.32
0.28
0.24
0.2
0
50
100
150
200
250
300
350
DOY
O2
P1
P2
P3

c)

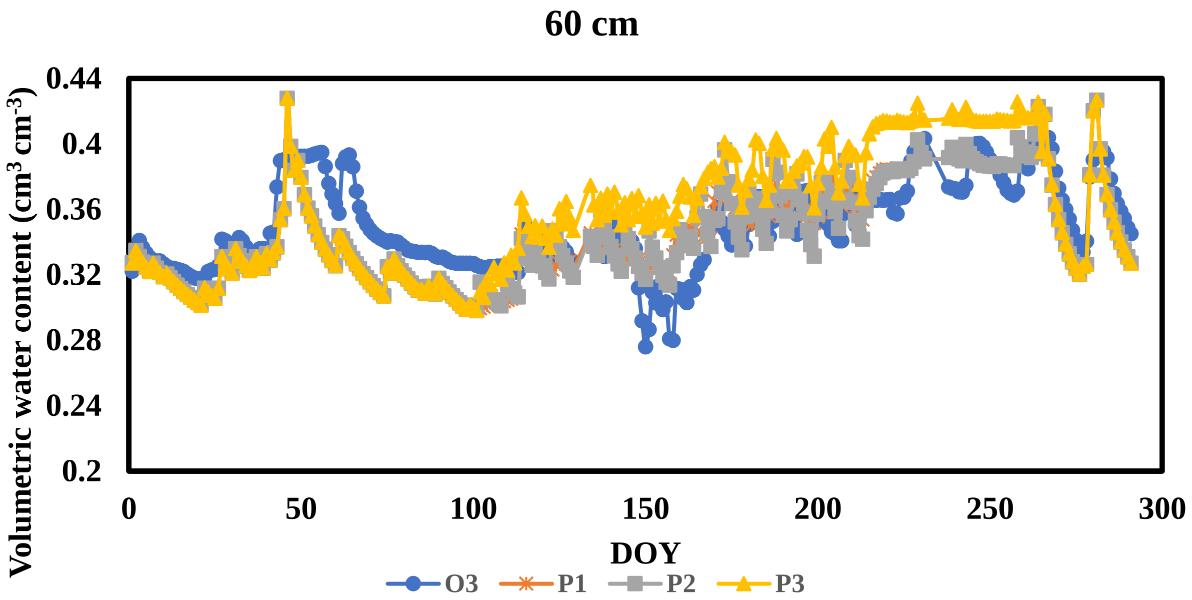


Figure 9 Comparison between three different irrigation scenarios (P1- distribution of irrigation throughout the week, P2- Irrigated just once a week and P3- double the current irrigations schedule) at three different depths at a) 20 cm, b) 40 cm and c) 60 cm from the surface

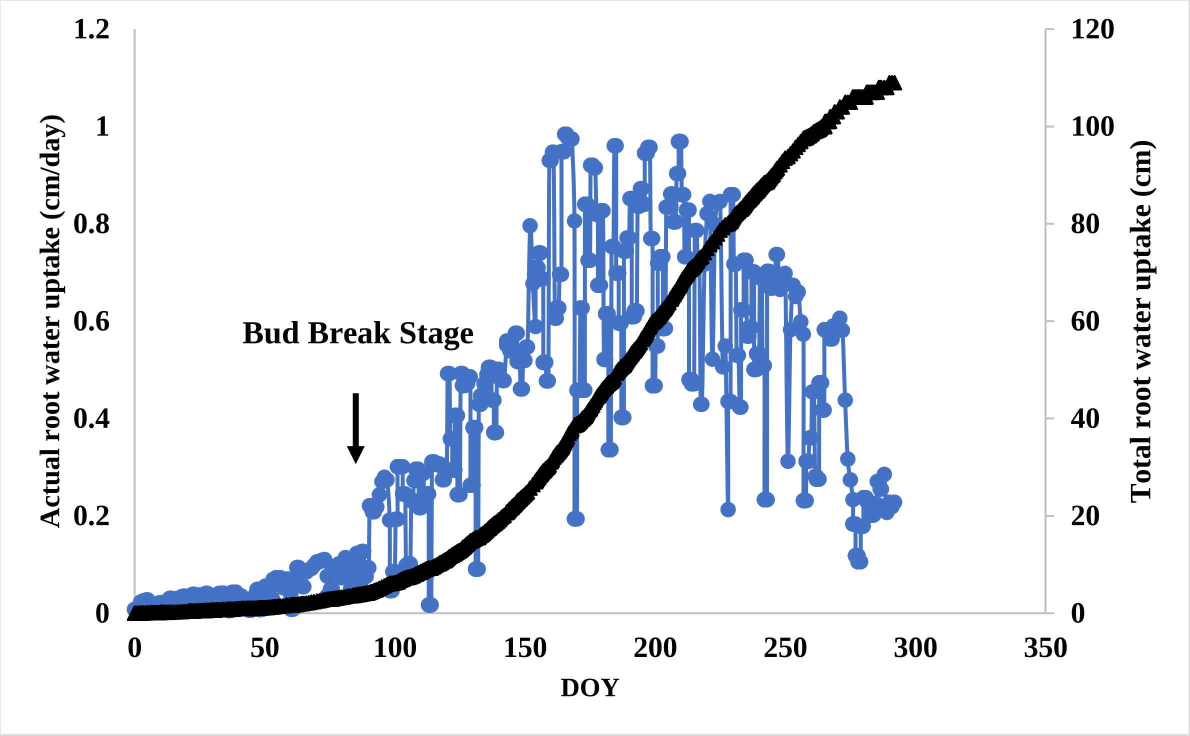


Figure 10 Actual and total root water uptake of pecans in 2021

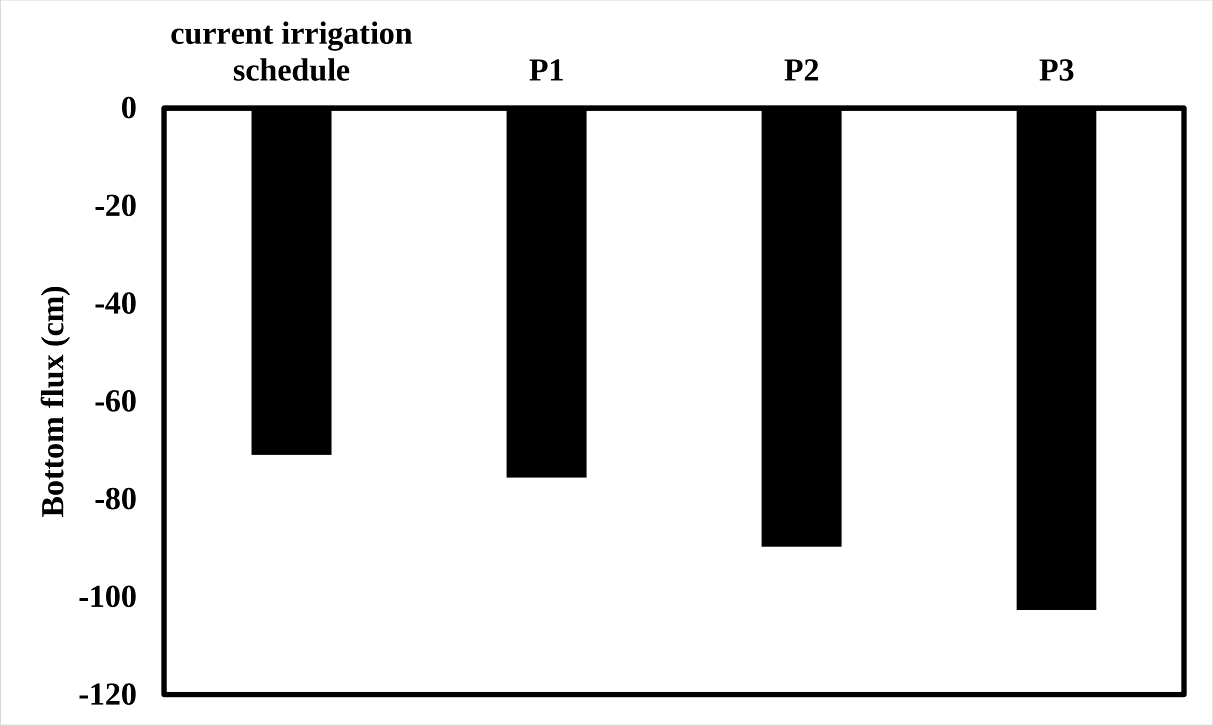
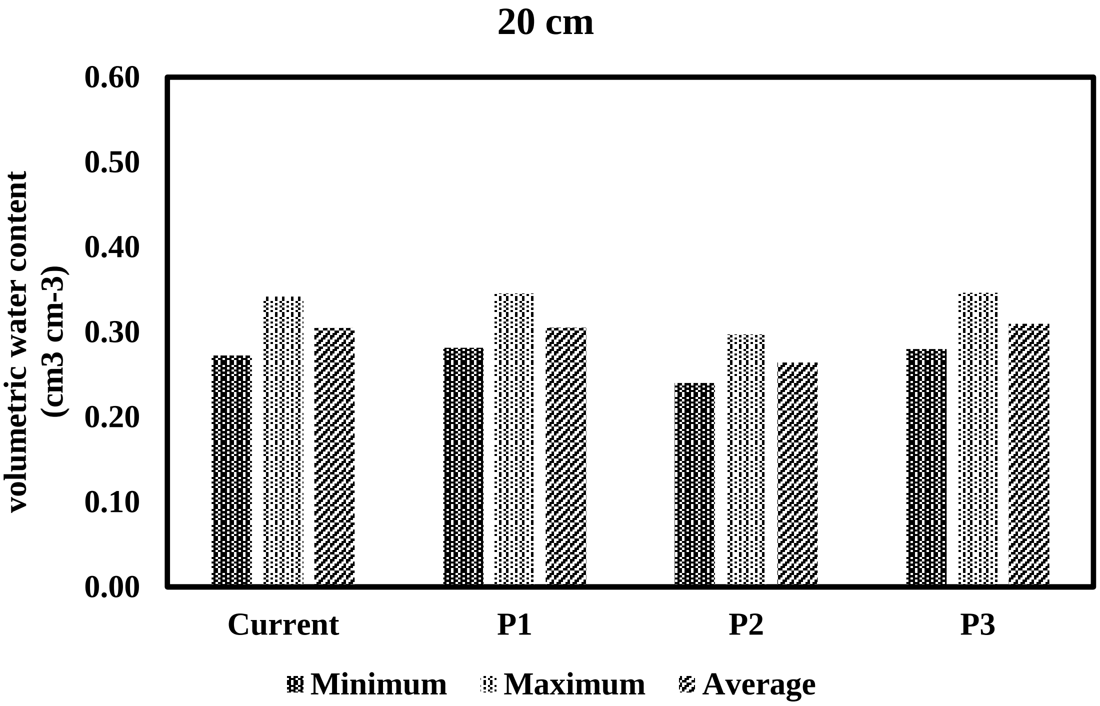
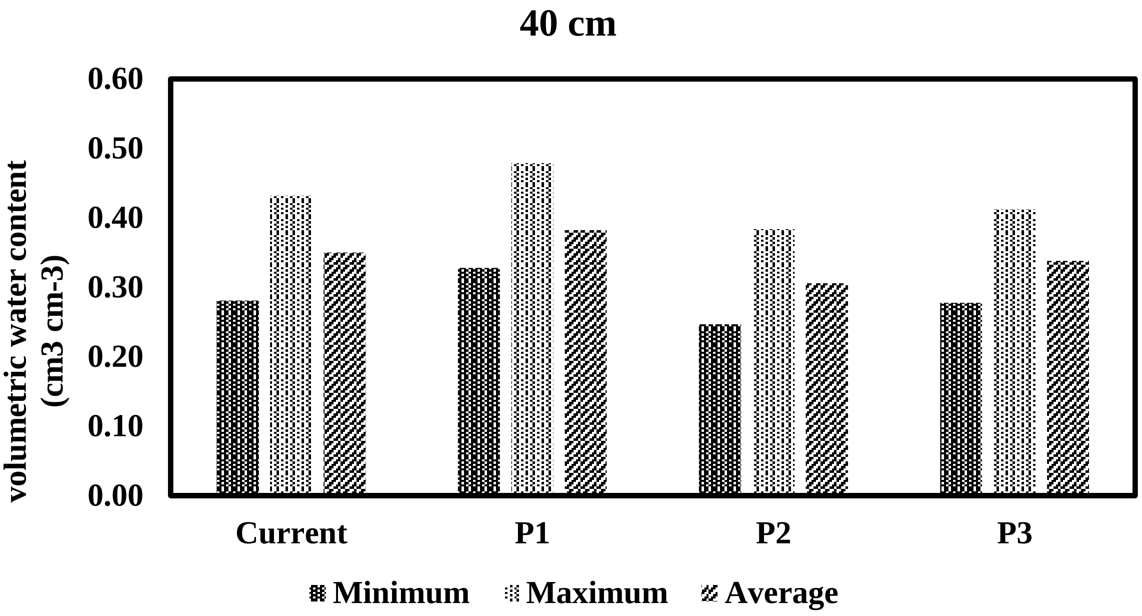


Figure 11 Bottom flux simulated by HYDRUS-1D for different irrigation scenarios

a.)



b.)



c.)

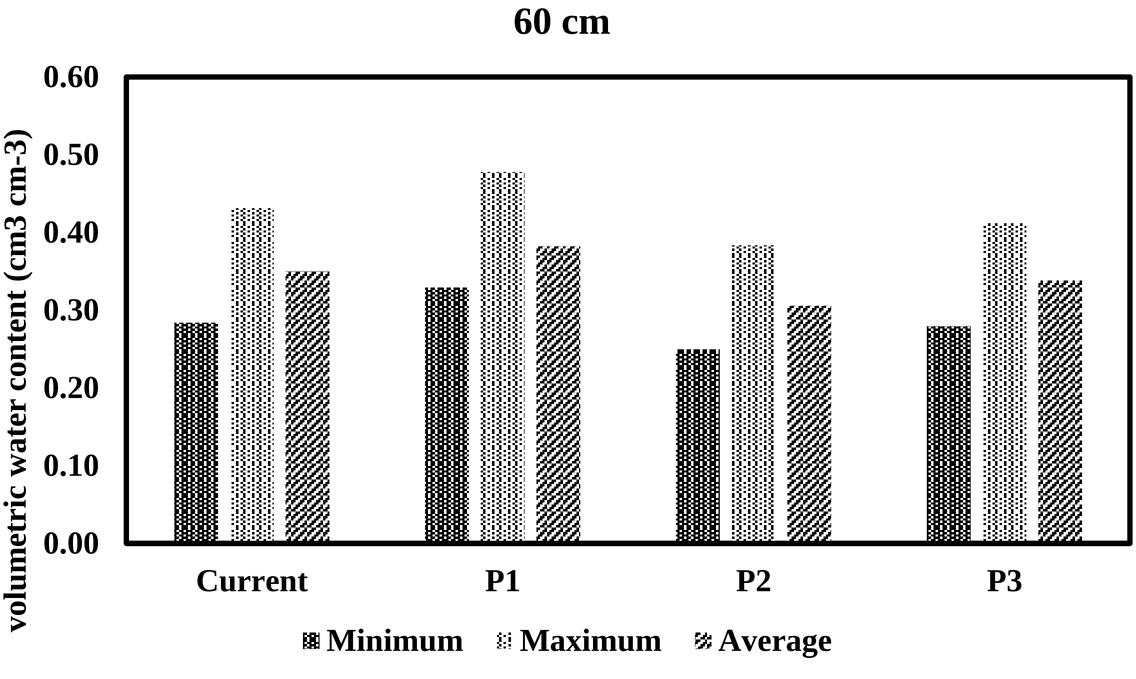


Figure 12 The simulated minimum, maximum and mean daily θv for three different irrigation scenarios for three different depths a.), b.) and c.).

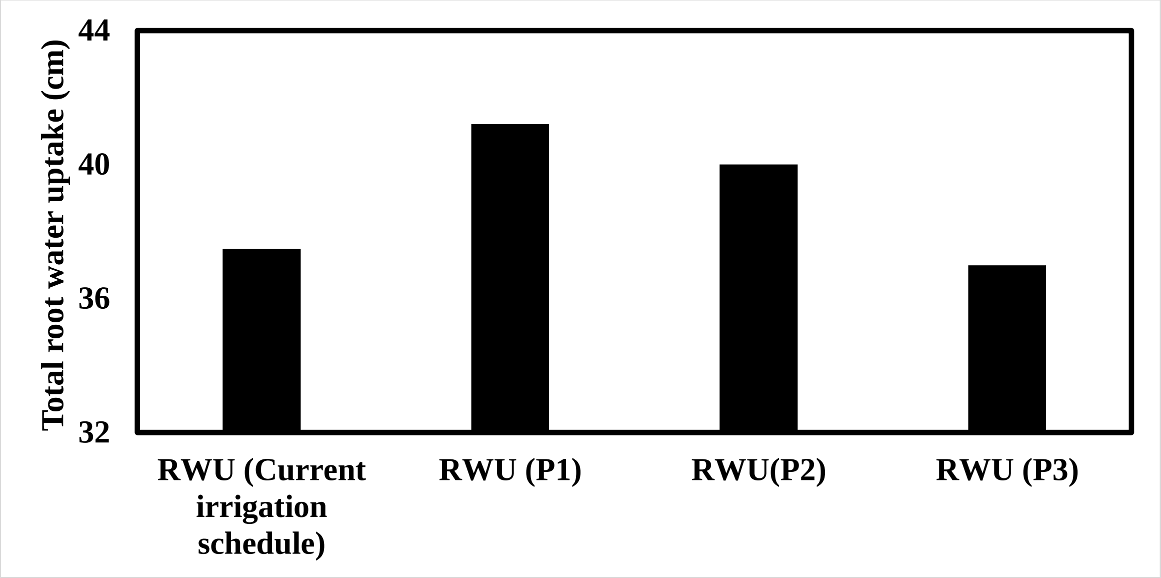


Figure 13 Cumulative root water uptake for current irrigation schedule and three prediction scenarios

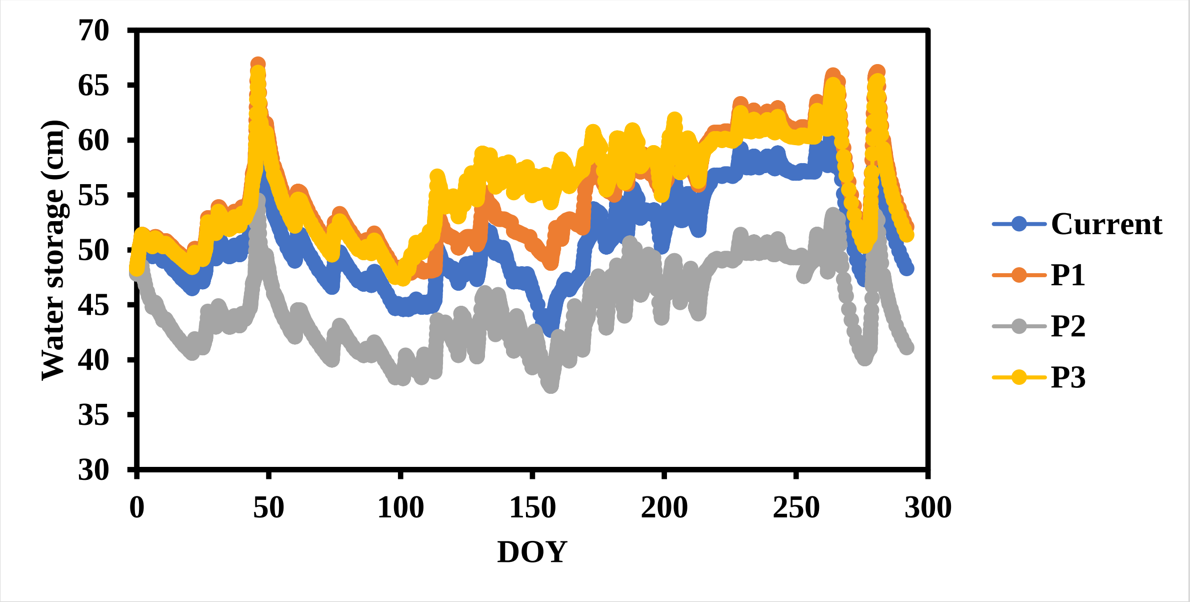


Figure 14 Total water storage in the soil profile for different scenarios

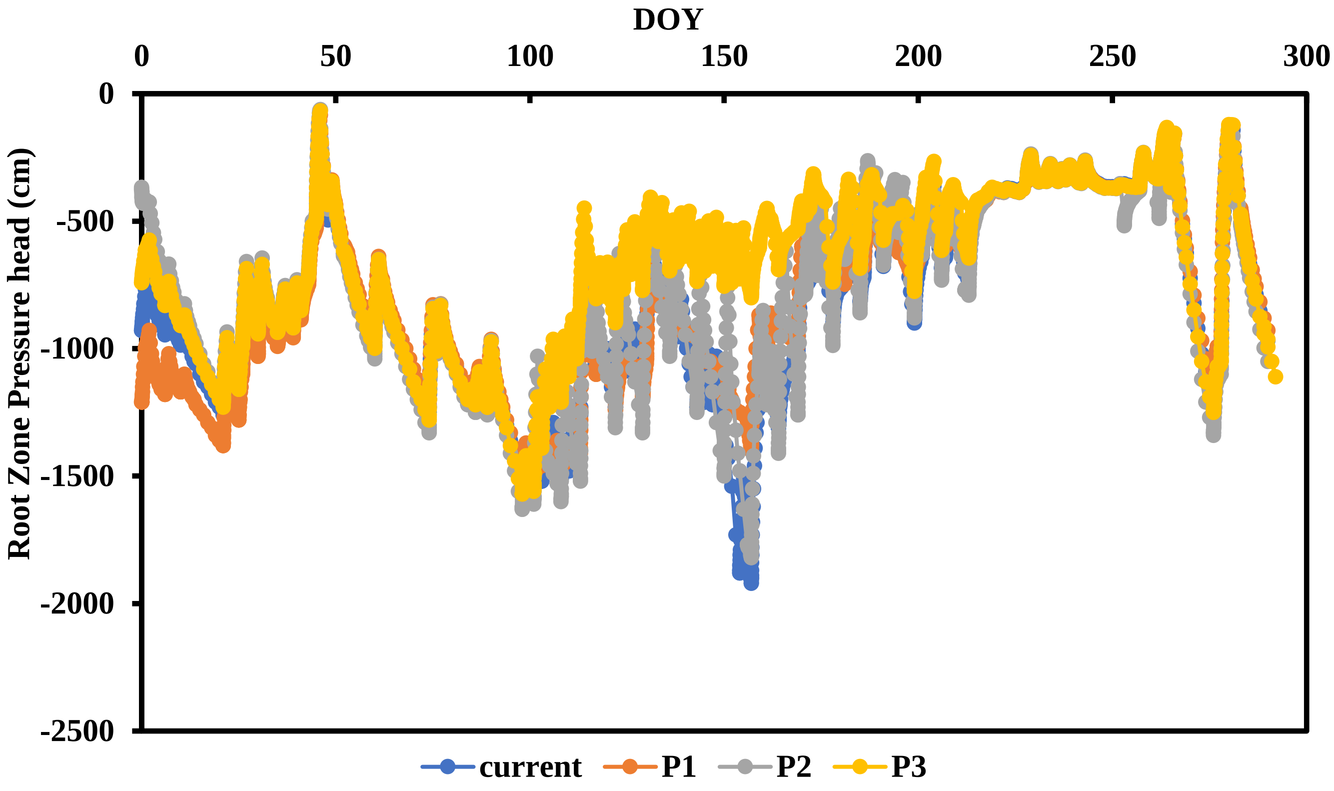


Figure 15 Root zone pressure head for different irrigation scenarios

3. CONCLUSION

Pecan requires an ample amount of water during growing season to produce a successful and acceptable yield. To fulfill that water requirement, various irrigation events are needed to supplement the rainfall during the peak growing season. Both time and amount of irrigation water is important for producing good quality nuts. The water requirement of trees depends on soil type, tree age and climatic conditions. Therefore, HYDRUS 1-D model was used to simulate the water movement through different soil layers. The model was successfully calibrated and validated during this study period. After validation, the model was used to predict soil water content RWU, and water loss by drainage and evapotranspiration under three different irrigation scenarios compared to current irrigation schedules. The results of this study indicated that the P1 irrigation scenario was the best irrigation strategy among three preformed scenarios. The simulations indicated that water loss was lower, and soil water storage was maximized in P1 as compared to the other two and the current irrigation schedule. However, there is a need to validate these findings at the field level and the evaluate the effectiveness of this strategy on quality and yield of nuts. This study can serve as a basis for future studies in evaluating the effect of reduced irrigation during pre-kernel filling stage.