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Consumptive water use in pecan trees in the Hermosillo Coast

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ABSTRACT

Objective: To estimate the consumptive use of water for pecan trees (*Carya illinoinensis*).

Design/methodology/approach: In this study, the consumptive use of water for pecan trees was estimated by applying the water balance equation ($Irrigation+rainfall-ET_c=0$).

Results: The results obtained from the 2020 to 2023 cycles show that an average irrigation depth of 1,365 mm should be irrigate per cycle, similar to the ET_c estimated in situ by the Eddy Covariance Method.

Limitations on study/implications: Regional scope.

Findings/conclusions: The water balance is positive and shown a water surplus of 369 mm per cycle. This means that, considering only irrigation, savings of 147 mm per season could be achieved, representing an average of 1,470 m^3 ha^{-1} per agricultural cycle, without causing water stress for pecan trees.

Keywords: Water-balance, Soil-Water-depletion, Pecan.

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INTRODUCTION

The pecan tree (*Carya illinoinensis* K.) is one of the most profitable crops in the Hermosillo Coast. It currently occupies 51.2% (10,878 ha) of the total production in Sonora, with an average yield of 2.0 t ha^{-1} (Retes *et al.*, 2021; SIAP, 2023). The pecan tree has adapted well to this region, as it prefers arid and semi-arid climates. However, it has a long phenological cycle and high canopy coverage (Rodríguez *et al.*, 2022), which leads to high annual evapotranspiration (Brown, 2010; Rodríguez *et al.*, 2018; Rodríguez *et al.*, 2022).

Sammis *et al.* (2004), Brown (2010), and Valdez *et al.* (2010) report a seasonal and annual evapotranspiration (ETc) value of 1,200 to 1,450 mm in pecan orchards. Rodríguez *et al.* (2022) have measured ETc in pecan trees on the Hermosillo Coast using the Eddy Covariance (EC) method and report an average ETc of 1,469 mm. They have also recorded irrigation and rainfall, obtaining an annual average of 1,718 mm.

Valdez *et al.* (2010) recommended annual irrigation depths ranging from 1,360 to 2,100 mm for mature pecan trees. These irrigation depths were estimated using the reference evapotranspiration (ETo) recorded at agroclimatological stations located on the Hermosillo Coast. Rodríguez *et al.* (2010) reported an annual irrigation depth of 2,020 mm applied in a mature orchard on the Hermosillo Coast. Additionally, Rodríguez *et al.* (2022) observed a reduction in irrigation from 1,898 mm to 1,536 mm year^{-1}. This decrease in irrigation depths is attributed to the practice of burying irrigation lines.

Valdez *et al.* (2013) and Vieira *et al.* (2013) indicate that irrigation in pecan orchards in the region exceeds actual demand by 30%. Valdez *et al.* (2010 and 2018) mention that applying irrigation depths of 1,360 to 1,430 mm has resulted in average yields of 2.02 to 2.7 t ha^{-1} of high-quality pecans. Furthermore, daily irrigation depths applied in the region range from 8 to 10 mm day^{-1}, which is similar to atmospheric demand (Brown, 2010). Valdez *et al.* (2013) also point out that monthly requirements during the summer months can reach approximately 220 mm.

The differences between applied and evapotranspired irrigation depths indicate a potential reduction of approximately 200 mm per cycle for pecan trees. Therefore, it can be speculated that the annual irrigation depths for mature pecan orchards should range from 1,200 to 1,300 mm. However, there is still ongoing debate regarding the actual annual irrigation requirements.

Furthermore, the common practice in pecan irrigation management is to replenish soil water to field capacity (FC) after the available moisture, defined by FC and the critical irrigation point, has been depleted. However, the water content at FC is rarely determined in situ for each agricultural cycle. This often leads to a misperception of the water available for crops and, consequently, to poor irrigation management. Many agricultural soils are not uniform and may include horizons that restrict internal flow and drainage. Therefore, it is difficult to estimate the water retained in the soil that needs to be replenished through irrigation.

The latter necessitates the search for strategies to improve irrigation efficiency, such as drip irrigation, as well as determining the correct irrigation scheduling by estimating crop water requirements using precise *in situ* techniques like the Eddy Covariance method (turbulent techniques) and soil moisture monitoring, among others. Therefore, the objective of this study was to determine the monthly and annual irrigation depth required for pecan trees on the Hermosillo Coast by applying the water balance concept during the 2020 to 2023 cycles.

MATERIALS AND METHODS

The study has been conducted in a mature pecan orchard covering 108 ha in the Viñas de la Costa de Hermosillo plot (28° 55’ 25”, −111° 17’ 59”). The pecan trees are planted with a spacing of 6 m between plants and 12 m between rows (139 plants ha^{-1}), and the orchard was established between 1999 and 2000. A 21-meter-tall micrometeorological tower was installed at the site. At the top of the tower, sensors are installed to measure net radiation (Rn), temperature (T), precipitation (P), and relative humidity (Rh). Additionally, an Eddy Covariance System (LI7550RS and WindMaster Pro Sonic Anemometer) is installed. The data recorded by the micrometeorological tower are used to calculate the daily reference evapotranspiration (ET_o) and hourly *in situ* evapotranspiration (ET_c) of the pecan trees.

Time domain reflectometry sensors (TDR 315L, ACClima) were installed in the soil at 0.30, 0.60, 0.90 and 1.2 m, at 0.20 m from the irrigation line to measure the moisture content. These sensors were connected to a Datalogger DataSnap SDI-12 (Table 1). Data logging is done at 10 min intervals, and average values are stored every 30 min.

The soil moisture content at field capacity (FC) for the 0.3 and 0.6 m strata was determined according to the standard method, using the Richards' pressure extractor (Soil moisture Corp, USA) and drying the samples at 105 °C for 24 hours in a convection oven. The bulk density was measured using the Uhland cylinder method (Gabriels and Lobo, 2006).

Irrigation is applied through a drip system using RAM-type irrigation pipes, with a dripper flow rate of 1.6 L h^{-1} spaced 0.6 m apart. Two irrigation lines were placed on each side of the pecan tree row. The first irrigation line is located 1.5 m from the trunk, and the second line is positioned 1.5 m from the first, resulting in an average of 40 drippers per tree. Beneath one of the drippers, a rain gauge (Texas Electronics) was installed to record the irrigation depth applied and the duration of each irrigation event.

Evapotranspiration

Reference evapotranspiration (ET_o) was calculated using daily meteorological data recorded and the FAO56 approach (Allen et al., 1998) (Equation 1).

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{1}$$

where: ET_o is the reference evapotranspiration (mm·d^{-1}), R_n is net radiation (MJ m^{-2} d^{-1}), G is soil heat flux (MJ m^{-2} d^{-1}), T is the average daily air temperature (°C), Δ is the slope of the saturation vapor pressure curve at T (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), e_s is saturation vapor pressure at T (kPa), e_a is average daily vapor pressure (kPa), and u is average daily wind speed (m s^{-1}).

Meanwhile, the calculation of ET_c was performed using the general equation (2) (Burba, 2022) with the EddyPro ver. 6.0 software (LI-COR), utilizing the averaged data recorded at 30-minute intervals with the Eddy Covariance System equipment.

$$F \approx \underline{\rho_\alpha}\,\underline{W'S'} \tag{2}$$

where: F represents the latent heat flux (LE; W m^{-2}), sensible heat (H; W m^{-2}), and CO_2 (mg m^{-2} s^{-1}); ρ_α is the air density (kg m^{-3}), $W'_2$is the vertical wind velocity (m s^{-1}), and S'_2represents the covariance of fluctuations in water, heat, carbon dioxide, methane, etc., respectively.

By expressing equation 2 in terms of the energy balance (equation 3), equation 4 is obtained.

$$LE + H = R_n - G \tag{3}$$

where R_n represents net radiation (W m^{-2}), and G represents the soil heat flux (W m^{-2}). From equation 3, LE is expressed in equivalent energy $ET\lambda$, and then the corrected $ET\lambda$ in the Eddy Covariance System is converted into an equivalent water depth ET (mm h^{-1}) (Wang *et al.*, 2020), expressed as:

$$ET = \frac{3600 * \lambda ET}{\lambda * \rho_W} \tag{4}$$

where the value of λ is $2.501-0.00236\ Ta$ (Ta=air temperature, °C), and ρ_W is the density of water vapor (103 kg·m^{-3}), with 3600 being the conversion factor from hours to seconds.

Water balance

Pereira *et al.* (2010) recommend using the concept of water balance (WB) (Equation 5) to estimate the water inputs and outputs in the soil over a time interval Δt, considering a soil layer of thickness Z, bounded at the top by the soil surface and at the bottom by the depth Zn, as previously defined.

$$\theta_i = \theta_{i-1} + \frac{\left(P_i - Q_{ri}\right) + I_{ni} - ET_{ci} - DP_i + GW_i}{1000\, z_{ri}} \tag{5}$$

where: θ_i is the soil water content in the root zone (mm·mm^{-1}) on day i; θ_i-1, is the soil water content in the root zone (mm·mm^{-1}) on day i^{-1}; P_i, is the precipitation on day i (mm); Q_{ri}, is the surface runoff on day i (mm); I_{ni} is the irrigation depth on day i (mm), or the amount of irrigation water that actually infiltrates for storage in the root zone; ET_{ci} is the crop evapotranspiration on day i (mm); DP_i is the percolation on day i (mm); and GW_i is the accumulated capillary rise flow on day i (mm).

However, Equation 5 considers the variables Q_{ri}, DP_i, and GWi, which are difficult to record, measure, or estimate on a daily basis. Therefore, in this study, the water balance (WB) was calculated considering the input variables (irrigation and rainfall) and the output variable (ET_c), ($WB = Irrigation + Rainfall - ET_c$) for a daily time interval for the cycles from 2020 to 2023.

RESULTS AND DISCUSSION

Under the concept of the water balance ($WB = Irrigation + Rainfall - ET_c = 0$), it was determined that an excess of water exceeding 300 mm per cycle is applied in the pecan

Table 1. Sensors installed in the micrometeorological tower of the pecan walnut orchard in Viñas de la Costa de Hermosillo, Sonora.

Measured factors	Sensor	Measurement height (m)
Sensitive heat flux (H, W m^{-2})	3D Sonic anemometer (CSAT3, Campbell Scientific Ltd. USA)	21.0
Latent heat flux (LE, W m^{-2})	IRGA 7500Rs (LICOR, USA) and 3D Sonic anemometer	21.0
Soil heat flux (G, W m^{-2})	Plate HFP01SC (Hukseflux)	−0.1
Carbon flux (CO_2, μmol m^{-2} s^{-1})	IRGA 7500Rs (LICOR, USA) and 3D Sonic anemometer	21.0
Temperature and air humidity (°C and %)	HMP60 (Vaisala, Finland)	15.0
Wind speed and direction (m s^{-1}, degrees)	3 D Sonic anemometer (CSAT3, Campbell Scientific Ltd. USA)	21.0
Soil temperature (°C)	TDR315L (Acclima, USA)	−0.30, −0.60, −0.90, − 1.20
Soil moisture (m^{3} m^{-3})	TDR315L (Acclima, USA)	−0.30, −0.60, −0.90, − 1.20
Precipitation (mm)	Rain gauge (Texas Electronics, USA)	12.0
Irrigation (mm)	Rain gauge (Texas Electronics, USA)	0.5
Net radiation (W m^{-2})	Net Radiometer (Kipp & Zonen, Netherlands)	19.2
Incident solar radiation (W m^{-2})	Albedometer (Kipp & Zonen, Netherlands)	19.2
Reflected solar radiation (W m^{-2})	Albedometer (Kipp & Zonen, Netherlands)	19.2

walnut orchard at the study site (Table 2). If rainfall is disregarded, this excess due to irrigation is between 60 to 235 mm, considering that an annual irrigation application of over 1500 mm is applied (Table 2).

This indicates that appropriate adjustments are not made to the applied irrigation amounts during the rainy season (July and August). Table 2 also shows that the average actual evapotranspiration of the pecan (ET_c) is around 1365 mm per cycle. The ET_c does not show significant differences between cycles, and the trend is similar across all four cycles (Figure 3).

This allows us to indicate that average irrigation amounts of 1,365 mm per cycle should be applied, similar to the ET_c determined *in situ*. If rainfall is not considered, this would represent a reduction of 147 mm in the annual irrigation amount applied, which means that savings of approximately 2000 m^{3} ha^{-1} per cycle (2.0 thousand m^{3} ha^{-1}) could be achieved (Table 2). These results support the proposals by Valdez *et al.* (2010, 2018) and Vieira *et al.* (2013), which indicate that by applying irrigation amounts of 1360 to 1430 mm to mature trees, average yields of 2.02 to 2.7 t ha^{-1} of high-quality pecans can be achieved. Furthermore, this aligns with what Sammis *et al.* (2004) and Rodríguez *et al.* (2010) mention,

Table 2. Water Balance in Pecan Orchard in the Costa de Hermosillo, Sonora.

Crop Season	Water balance					Thousand m^{3} ha^{-1}
	Irrigation (mm)	Rain (mm)	ETc (mm año^{-1})	R+Ll−ETc	m^{3} ha^{-1}	
2020	1594	153	1445	(+) 300	1446	1.45
2021	1528	267	1293	(+) 500	2410	2.41
2022	1415	246	1356	(+) 305	1463	1.46
2023	1370	140	1356	(+) 150	736	0.74
Average	1476	201	1362	(+) 315	1514	2.0

that a pecan orchard in production can consume an amount of approximately 1.4 m of water per year.

The annual ET_c is also consistent with the values of 1200 to 1450 mm reported by Sammis *et al.* (2004), Brown (2010), Valdez *et al.* (2010), and Rodríguez *et al.* (2022). Furthermore, Figure 3 shows that the maximum daily ET_c values between 8 and 9 mm during the spring-summer season are similar to those observed by Sammis *et al.* (2004) and Djaman *et al.* (2018) for arid and semi-arid climates. On the other hand, analyzing the soil moisture content (θv) and its variation due to the frequencies and amounts of irrigation applied (Figure 1), values close to field capacity (FC) are observed. The figure shows that in some periods, the moisture remained above FC, even in the layers of 60, 90, and 120 cm. This means that the applied amounts exceed the soil's retention capacity and the plants' demand through evapotranspiration.

Soil moisture exhibited the same behavior across the four cycles. This moisture reaches values of 28 to 31% (θv) from March to September. It then shows a decrease to between 22 and 27% (θv) from September to November, due to the reduced frequency of irrigation. It is also observed that in all four layers, there is movement of water and soil moisture, indicating a redistribution towards deeper layers, as well as extraction by the roots of the pecan tree and possibly some percolation.

As previously mentioned, the common practice in irrigation management for pecan trees is to replenish soil water to field capacity (FC) after the readily available moisture has been consumed. However, FC is not necessarily achieved in the field, as shown in Figure 1. This leads to a misperception of the irrigation requirements, as well as the available water for the crop, and consequently results in poor irrigation management.

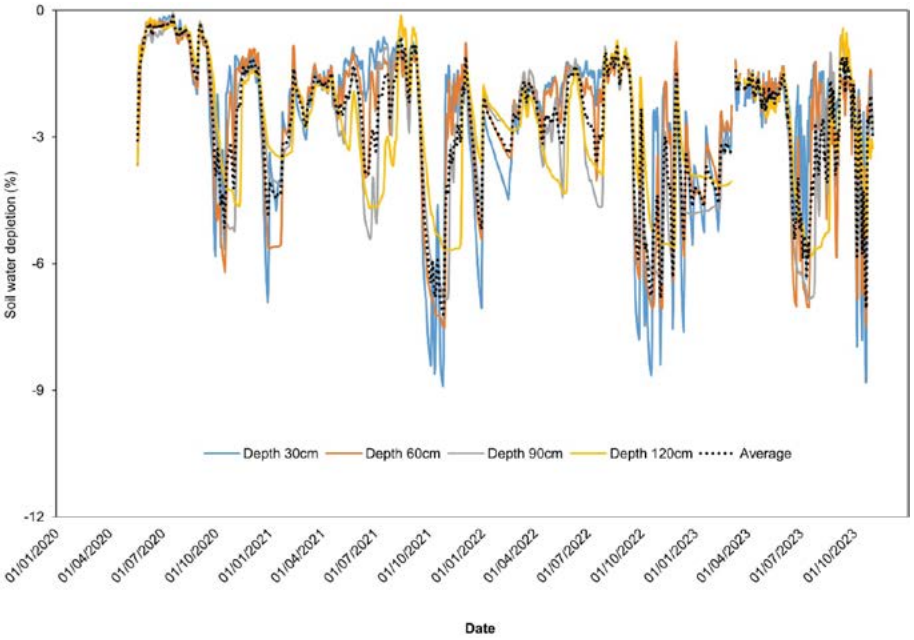

Figure 1. Irrigation depths applied in the pecan orchard in the Costa de Hermosillo, Mexico, and variation of soil moisture content (θv) in the soil profile.

To reduce ambiguity regarding the available water in the soil profile, the concept of "soil water depletion" proposed by Evett *et al.* (2019) was used. The maximum soil water content was utilized as a reference point, and depletion was determined for each stratum. The water content values were converted into equivalent values for each depth to minimize ambiguity concerning the soil's water storage and retention capacity (Figure 2).

This approach reveals a more consistent representation of the soil's response to the application and removal of water. In Figure 2, it is observed that in the 30, 60, and 90 cm strata, there was greater depletion, between 5 to 8.5% (θv), equivalent to 65% of the total soil moisture. It is also noted that the greatest depletions of water in the soil profile occur from the second week of September to the third week of November across all four cycles. This coincides with the decrease in irrigation frequency, as this stage corresponds to the opening of the husk, harvesting, and leaf drop of the pecan trees in the area.

The use of sensors, such as the TDR 315L, and the implementation of the concept of "soil water depletion" allow for a more precise estimation of the amount of water that needs to be replenished during each irrigation event. This approach eliminates the influence of factors such as texture, bulk density, and organic matter content on the recorded values. Furthermore, the TDR 315L sensors have a margin of error of about 2% of θv (Acclima, Inc. 2017).

If the depletion of water in the soil profile is expressed in terms of depth (mm d^{-1}), the retention and removal capacity of water is further clarified (Figure 3). This figure clearly shows the applied irrigation depths (mm d^{-1}) and the amount of water stored and removed in the soil profile (mm d^{-1}) from 30 to 120 cm. The figure also displays the amount of water transpired (mm d^{-1}). In this figure, it is observed that the soil can retain up to 12

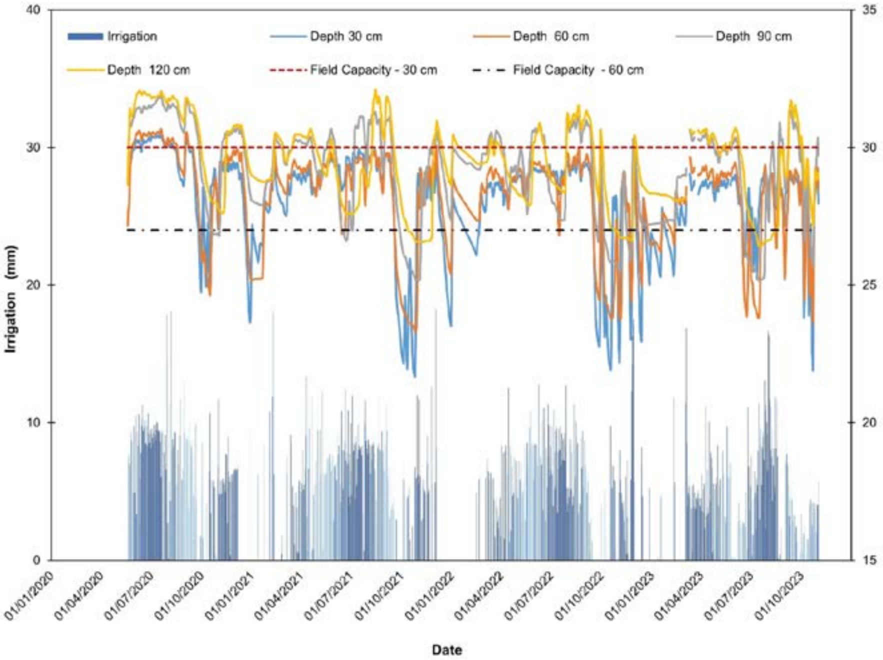

Figure 2. Maximum soil water content and depletion by strata, equivalent values, applying the concept of "soil water depletion".

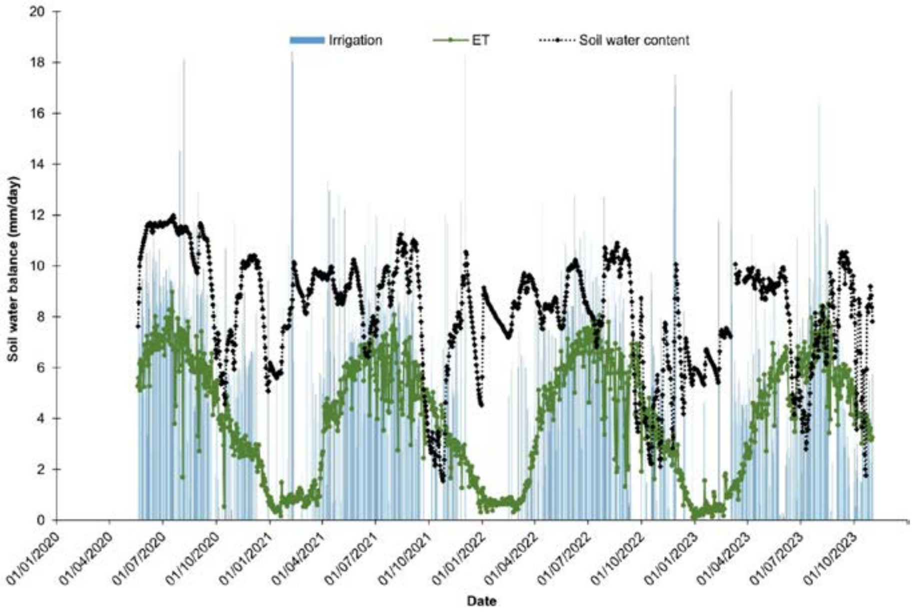

Figure 3. Irrigation, crop evapotranspiration, and available water in the soil profile in a pecan orchard in the Costa de Hermosillo, Sonora.

mm d^{-1}. It is also noted that the amount of water removed from the soil profile can reach up to 9.5 mm (from 12 to 2.5 mm), indicating that total depletion is not reached. This removed amount, during certain periods of the pecan cycle, is equivalent to the maximum ET_c observed in the crop. Conversely, the applied irrigation depths per event are always greater than the ET_c, and in some cases, they reach up to 18 mm per day (Figure 3).

This causes the soil to have available moisture for most of the pecan cycle. Only during the period from the second week of September to the third week of November does the greatest depletion occur. However, with the decrease in the evapotranspirative rate due to the senescence of the pecan tree, and subsequent irrigations, the available moisture is restored to between 5 and 8 mm for the next cycle. This reinforces the recommendation that irrigation depths of 8 to 10 mm per event should be applied, as previously indicated. These irrigation depths are related to the water retention capacity in the soil profile and the evapotranspirative rate of the pecan tree in the study site (Figure 3).

With the results shown in Figure 3, it is possible to generate and recommend an irrigation schedule. In this regard, a calendar with monthly irrigation amounts for pecans is proposed in Table 3. These monthly amounts can be applied according to the crop demand (ET_c) and the suggested irrigation amounts of 8 to 10 mm per event. Generally, irrigation calendars for most crops are reported on a monthly basis.

This calendar considers applying at least one irrigation in January to complement the residual soil moisture of around 5.5 mm (Figure 3). In February, it is proposed to apply two irrigations. In the following months, the frequency of irrigation increases due to the sprouting of the pecan tree foliage, fruit formation, and dry matter accumulation. By implementing this irrigation calendar, the consumptive use of the pecan tree would be around 1368 mm by the end of the production cycle (Table 3). This annual calendarization

Table 3. Recommended irrigation amounts for pecan trees at the Viñas de la Costa site, Hermosillo, Sonora.

Month	Crop season				Monthly irrigation (cm)	Standard deviation
	2020	2021	2022	2023		
January	1.0	1.5	1.5	1.5	1.4	0.3
February	3.1	1.4	1.6	3.1	2.0	0.9
March	4.5	4.4	4.7	4.5	4.5	0.2
April	12.3	9.4	13.4	12.3	11.7	2.1
May	16.8	17.0	17.5	16.8	17.1	0.4
June	20.6	18.5	20.3	16.8	19.8	1.1
July	22.9	18.8	20.1	18.8	20.6	2.1
August	18.6	17.8	17.6	20.5	18.0	0.5
September	17.2	14.9	14.3	16.5	15.5	1.5
October	11.9	12.4	12.5	12.1	12.3	0.3
November	8.6	8.5	9.1	8.2	8.7	0.3
December	6.8	5.4	3.5	5.0	5.2	1.7
Total	144.2	130.0	136.0	136.0	136.8	

and consumptive use is similar to that recommended by Valdez (2010, 2015, and 2018). Although the same author mentions that the irrigation amount for March includes a moisture reservoir corresponding to an additional amount of 42 mm. However, as shown in Figure 3, the soil has available moisture for the crop during that period.

CONCLUSIONS

The results presented in this study indicate that the consumptive use of the pecan tree for the study site is approximately 1365 mm per year. Therefore, it is feasible to reduce the current irrigation amounts by 150 mm without causing water stress to the pecan tree, reinforcing the proposal by Rodríguez *et al.* (2022). This reduction represents a savings of around 1470 m^3 ha^{-1} per cycle per hectare (1.47 thousand m^3 ha−1). This strategy will allow for efficient water use without significantly impacting yields, considering that, in most cases, as shown in this work, there is a general trend toward over-irrigation.

On the other hand, the use of the water balance, soil moisture sensors, and the "soil water depletion" concept allows for a more accurate estimation of the amount of water that should be replenished in each irrigation event.

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