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Dynamics of Moisture and Nutrients in the Root Zone, Actual Evapotranspiration (ETr), and Irrigation Efficiency in Avocado Trees of Highland and Midland Orchards of Michoacán, México

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Abstract: The objective of this research was to study the dynamics of moisture and nutrition at the root zone and to quantify the variables linked to efficient water management in avocado orchards of mid and high-lands of Michoacán, México, in typical Andisols of low fertility with (A)C(w2) and C(w2) climates, respectively. Using the FDR (Frequency Domain Reflectometry) technology, the dynamics of soil moisture and salinity were recorded daily at four depths: 0-15, 15-30, 30-45, and 45-60 cm. The soil moisture balance model was used to determine actual evapotranspiration (ETr), crop coefficient (Kc), and water use efficiency (WUE). Results indicated that ETr is 66-73% of the total water at 0-30 cm depth; the fertilizer absorption is limited to 0-30 cm, being negligible at deeper layers. The water use efficiency is 4.4 to 5.6 kg of fruit m-3 of applied water, and the ratio of the water use index (ETr/irrigation sheet applied, ISA) is 0.65-0.70; while the annual avocado Kc is 0.72 in Cutzato and 0.78 in Tiamba. We concluded that avocado has a low water requirement, it does not cause leaching of nutrients and/or water, the absorption of water and nutrients mostly occurs at 30 cm depth, and from a hydrological point of view, the crop is environmentally friendly.

Keywords: avocado water requirement; water use efficiency; temperate climate avocado; semi-warm climate avocado

1. Introduction

The Mexican avocado agro-industry is the most important activity linked to fruticulture in the country since it generates more than 3,7 billion dollars annually, and 74% of this income corresponds to the State of Michoacán [1,2]. However, this condition could change since the opening of the North American market to other countries with favorable production conditions, and a more competitive workforce, which could displace the avocado from Michoacán [3]. Despite the exponential growth of the avocado cultivation area, which grew from 77,000 ha in 1990 to 157,000 ha in 2015 [4], the average fruit yield has remained stable for more than 50 years, about 11 T ha^{-1}, which may be due to diverse causes regarding crop management and external factors such as meteors in general [5]. To produce avocado sustainably, this fruit crop should be cultivated in light, permeable, and deep soils [6], however, in México these edaphic characteristics are found and are particular to unstable soils, with low fertility and accelerated mineralization of organic matter [7]. In addition, in the case of Michoacán, soils have been brought under intense washing for millennia due to the occurrence of high-intensity rainfall events during the summer, where more than 1000 mm $year^{-1}$ occur in the growing season; moreover, the regional soils have high permeability, with a hydraulic conductivity > 70 mm hour^{-1} [8]. Among other cultivation practices, nutrition and irrigation are essential for achieving productivity and fruit quality without alternation; currently, the price of fertilizers has increased by 300% [9]. With the presence of climate change and under the current regional environmental conditions, the efficient use of water is an agricultural priority [10] even more in this Mexican region, which is aiming to keep being one of the most important avocado producers all over the world [11]. The water use efficiency for the production-consumption process provides a new perspective for water management in regional agriculture [12]. Reducing water use by increasing its use efficiency, contributes to enhancing production and consolidating a sustainable regional socioeconomic development [13]. To reach this goal, knowledge concerning the relationships among soil, water, nutrition, and nutrient absorption in avocados provides valuable information for the efficient management of irrigation and nutrition in this crop [14]. In fertigation, nutrients, as well as water, are supplied in avocados with low doses and high frequency to counteract the low natural fertility of the soil and maximize fruit quality and production [15], evenly, nutrients and water are temporally and spatially available on time, immediately in the root zone of the crop, to favor fruit setting and maximum production [16]. There is a general belief that avocado has a high water requirement [17], however, avocado hardly reaches or exceeds ETo values because its mature leaves are leathery and have a waxy cuticle that limits leaf water loss. An application to generate information to optimize irrigation, based on the reference evapotranspiration measurement (ETo) and climate factors with savings up to 68% of water, while electronic technology FDR (Frequency Domain Reflectometry), enables online and real-time visualization of soil moisture as well as nutrition at the root level, which can be a tool to improve efficiency on both inputs [18], however, in the case of the avocado tree this type of management has not been documented. The objective of this research was to assess the dynamics of moisture and nutrition in the avocado tree root zone and also to quantify the variables linked to efficient water management.

2. Materials and methods

Two orchards of 10-year-old Hass avocado trees were considered as assessment sites. Trees were planted at high density, 7 x 4 m (360 trees ha^{-1}). The orchards are located in Tiamba (19°29′49.4″ N; 102°03′43″ W) and Cutzato (19°21′15″ N; 102°07′44″ W) in the municipality of Uruapan, Michoacán, in C(w$_2$) and (A)C(w$_2$) climates, at elevations of 2060 and 1660 m, respectively. The annual average precipitation is 2,100 and 1,500 mm for Tiamba and Cutzato. Both soils are typical Andisols, with low fertility, very permeable, and lacking in structure, aggregation, stability, and consistency. For evaluating the variables irrigation requirement (ETo) and rainfall, an online real-time automated climatic station was installed (Brand iMetos v.3.3 Pessl Instruments), with FDR capacitive probes, and volumetric moisture sensors and soil salinity inserted each 15 cm. The equipment transmits climate information, soil moisture (Hs), and salinity through the data service and 4G SMS messages. The FDR capacitive probe is based on the response to changes in the dielectric constant of the medium (ε), using a frequency domain reflectometry technique through capacitors and variable frequency oscillators [19]. The probes include salinity sensors that measure the volumetric content ions (VCI) that were converted to dS m^{-1} units, with a calibration equation. The orchards were equipped with a drip fertigation system with drippers of 0.004 m^3 h^{-1}, inserted 0.50 m apart in a hose with 18 mm diameter, 16 gauge. The assessment of the two orchards took place over three years, from 2020 to 2022, recording Hs and VCI, with sensors in four soil depths 0-15, 15-30, 30-45, and 45-60 cm. The soil moisture balance model was applied to determine the average evapotranspiration sheet (mm) by the crop, in the three years of observation, as well as the dynamics of soil salinity due to the application of commercially balanced fertilizers in each irrigation to ensure optimal production [16]. Through the moisture balance [20], the crop evapotranspiration (ETr) was calculated according to the expression:

$$ETr = Wf + Pe + R \pm \Delta S \quad (1)$$

Where:

ETr= crop evapotranspiration (mm)

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Wf= available water at the beginning of the period

Pe= effective precipitation (mm)

R= applied irrigation (mm)

ΔS= change in stored soil moisture

The contribution of rain, due to its high intensity during summer until the beginning of autumn, was not taken into consideration in the balance model [21], so the equation is reduced to only the study of changes in soil moisture due to irrigation (ΔS):

$$\Delta S = \sum_{i=0}^{n}(\theta_i - \theta_{i-1})\Delta zi \qquad (2)$$

(2)

Where:

ΔS = annual average soil moisture variation (mm)

$\theta_i - \theta_{i-1}$ = volumetric water content of a soil stratum in two periods between irrigations ($cm^3\ cm^{-3}$)

Δzi = thickness of each soil depth (m)

n= number of soil depths studied

To determine the variables of irrigation efficiency, the following concepts were calculated [22]: volume of water applied (Va), the emitter referred to 1:00 ha:

$$Va = n\ q_e \frac{m^3}{hr\ m}\ x\ \frac{100\ m}{dh}\ x\ 100m \qquad \frac{m^3}{hr} \qquad (3)$$

Where:

n= number of irrigators per tree row (2 irrigators separated by 80 cm in both locations)

qe = emitter flow rate ($8\ L\ hr^{-1}\ m^{-1}$)

dh= distance between trees row (m)

The volume of water required by the crop (Vr) referred to as 1:00 ha and 100% ETo is calculated as:

$$Vr = [ETo\ x\ A]\ c \qquad \frac{m^3}{day} \qquad (4)$$

Where:

ETo= daily reference evapotranspiration (mm day^{-1}), taken from the climatic station

A= 10,000 m^2 (1:00 ha)

C= fraction of soil effectively spread in drip irrigation (c= 0.33, [23]):

The irrigation time (Tr) to apply the amount of water that the crop requires is:

$$Tr = \frac{Vr}{Va} \qquad (hr\ day^{-1}) \qquad (5)$$

Finally, the applied irrigation sheet (AIS), according to the net applied volume (VAN), was calculated with:

$$Lr = \frac{VAN}{10000\ m^2\ x\ c} \qquad (m) \qquad (6)$$

Where:

$$VAN = Va\ x\ Tr\ x\ N \qquad (m^3) \qquad (7)$$

N= number of days each month

According to the crop coefficient approach [24], the actual crop evapotranspiration ETr is calculated as the product of the reference evapotranspiration ETo and the crop coefficient Kc:

ETr = Kc ETo, then:

$$Kc = \frac{ETr}{ETo} \qquad (8)$$

Where Kc is dimensionless.

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Water use efficiency (WUE) was calculated considering the relationship between fruit yield (YF) and crop evapotranspiration water (ETr) [25]; while the water use index (WUI) was calculated according to [26], through the relationship between ETr and irrigation sheet applied:

$$WUE = \frac{YF}{ETr} \qquad WUI = \frac{ETr}{ISA} \tag{9}$$

Where:

YF= Fruit yield (kg/tree)
ETr= Crop actual evapotranspiration (mm)
ISA= Irrigation sheet applied (mm)

3. Results and Discussion

According to the average of the climatic variables during the three years of study (2020-2022), in the Cutzato and Tiamba locations, it can be identified that in Tiamba the climate is cooler than in Cutzato, and the annual accumulated precipitation exceeds 52% the precipitation at Cutzato (Table 1), which confirms the negative gradient precipitation on the municipality of Uruapan in a North-South direction [27]. The annual mean temperature is lower in Tiamba (15.0 °C) than in Cutzato (20.3 °C), while ETo is higher in Cutzato (3.7 mm day^{-1}) than in Tiamba (3.5 mm day^{-1}) even though, these values are similar, the annual difference is 183 mm, which indicates more irrigation in Cutzato than in Tiamba, equivalent to two months of ETo in Tiamba and greater stress for the crop due to the increased demand for water by the environment. The highest temperatures occur from March through May, registering a decrease in temperature during summer due to the effect of rain that coincides with the end of the spring season each year, continuing the decrease in temperatures in autumn and winter, and restarting the cycle in March.

Table 1. Average monthly values (2020-2022) of temperature and precipitation and average daily values of evapotranspiration in two experimental avocado locations in Uruapan, Michoacán México.

Month	Cutzato			Tiamba		
	Mean Temperature (°C)	Precipitation (mm)	ETo (mm)	Mean Temperature (°C)	Precipitation (mm)	ETo (mm day^{-1})
January	18.4	0.7	2.7	12.1	10.6	2.6
February	19.4	17.3	3.1	12.0	50.8	3.0
March	21.3	0.3	4.8	14.8	1.7	4.3
April	22.3	0.1	5.1	15.9	0.4	4.6
May	22.4	44.6	4.7	16.9	51.9	4.4
June	20.7	196.7	4.1	16.5	319.2	3.0
July	20.1	273.3	3.6	16.6	529.8	2.9
August	20.0	359.8	3.7	16.5	502.3	2.9
September	19.7	407.7	3.1	16.2	504.1	2.6
October	20.0	132.9	3.2	16.2	198.3	3.1
November	20.0	9.7	3.3	13.5	12	2.9
December	19.1	2.0	2.8	12.8	15.1	2.5
Average	20.3	1444.9	3.7	15.0	2196.2	3.2

ETo: Reference evapotranspiration (mm).

3.1. Soil Moisture Evaluation

Average annual soil moisture values for Cutzato (years 2020-2022) are shown in Figure 1. In the four depths studied, it is seen that the actual evapotranspiration (ETr) is maximum at the 0-15 cm depth, which demonstrates that the greatest amount of water absorbed by the crop is in the upper layer of the soil and there are also conditions to affirm that the avocado roots are very superficial, therefore, the water and the nutrients must be present as superficial as possible. At this depth (0-15 cm), it is important to consider that in the dry months from November to May, soil moisture drops very rapidly to levels even lower than 50% of field capacity, a variable that is only reached in the rainy season from June to October, but the high water consumption at this time of the year, despite the heavy rains, depletes water up to 60% of the field capacity, proving the high absorption power of the avocado root system in this stratum (0-15 cm) and a negative gradient of absorption as it goes deeper into the soil; in the next stratum (15-30 cm), the absorption is at least 25.4% lower. In the case of Cutzato, the desirable scenario would be to have around 50% soil moisture, to not affect avocado productivity. Also, in the lower layers (15-30, 30-45, and 45-60 cm), there is no significant water consumption, remaining almost constant at 40 cm³ cm⁻³, which proves that avocado is a crop with low water consumption. According to the previous descriptions, it is in the first 15 cm of soil, where water and fertilizer inputs must be present, for good development of the tree.

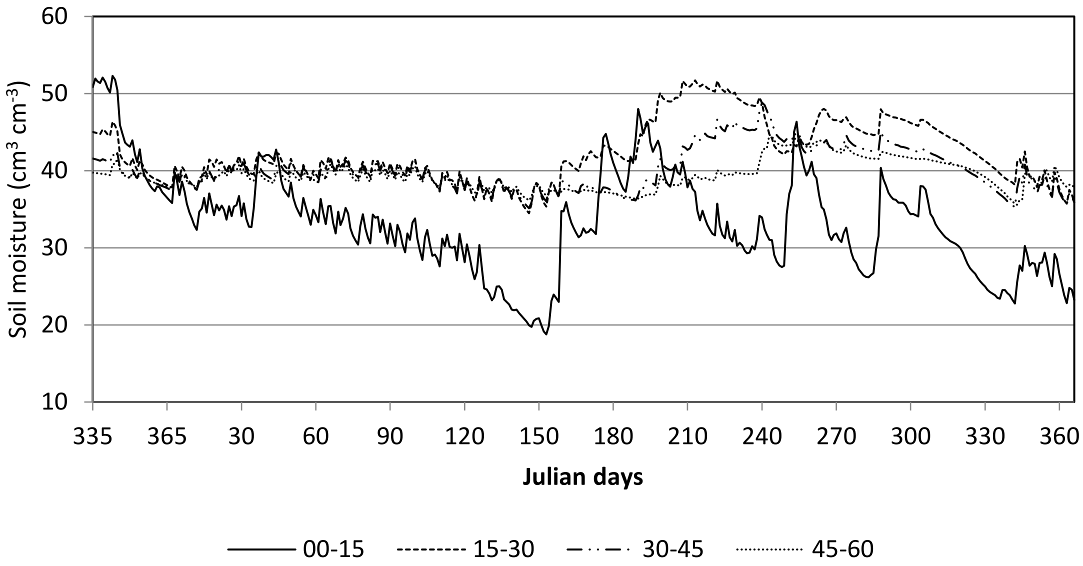

Figure 1. Annual average volumetric soil moisture (cm³ cm⁻³) in the avocado root zone on the depths measured in Cutzato location, municipality of Uruapan, Michoacán, México.

Figure 2 presents the assessment of the volumetric soil moisture in Tiamba, results that immediately reflect a different type of soil than that of the Cutzato location, since this soil is lighter with a higher sand content and a lower value of field capacity, around 44 cm³ cm⁻³; nevertheless, the trend of higher crop water consumption in the upper layer (0-15 cm) is evident, but there is a strong negative gradient of water absorption of lower rates in the lower layers, reaching the lowest at 60 cm depth. Also, Tiamba because of being a region with more rainfall, soil moisture in all strata remains close to field capacity from the beginning of the rainy season to the end (May-October, Julian days 150 through 300), and from November, soil moisture drops quickly until inducing resumption of irrigation in December. Therefore, although to a lower extent than in Cutzato, the most superficial layer in Tiamba is also the most important for quick water absorption.

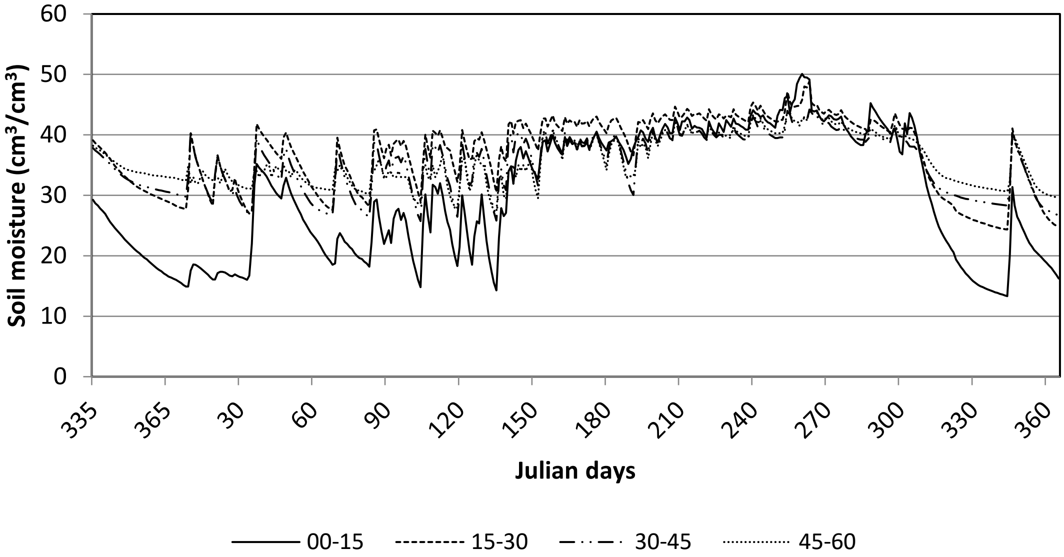

Figure 2. Volumetric soil moisture at 4 sampling depths (cm) in Tiamba location over an average of three years.

3.2. Actual Evapotranspiration (ETr) of Avocado

Table 2 reports the results of the avocado actual water consumption (ETr) in the two locations. Despite the difference in climate in both sites, similarity in ETr is observed, such similitude in two climatic contrasting locations (Table 1) indicates the presence of constraints for leaf water transpiration; it also seems to exhibit that the avocado tree water consumption is not affected by the prevailing climate since despite Cutzato is warmer than Tiamba, the ETr of Cutzato is 110 mm less than Tiamba's. It is remarkable too that in the upper layer (00-15 cm) the ETr is at least 57% and 20% higher than in the lower layers of Cutzato. In addition, the months with the highest ETr are from December to May in both locations, with a total of 617 mm in Cutzato and 592 mm in Tiamba, which corresponds to the time of fertigation in both orchards. Finally, the total annual ETr of avocado in the two most important climate types of the producing regions in Michoacán is 921.6 mm in temperate climates C(w) such as Tiamba and 965.3 mm in semi-warm climates (A)C(w) as in Cutzato.

Table 2. Three-year average avocado actual evapotranspiration (ETr) for locations Cutzato and Tiamba, municipality of Uruapan, Michoacán, México.

Month	Cutzato					Tiamba				
	Soil depth (cm)				ETr	Soil depth (cm)				ETr
	0-15	15-30	30-45	45-60	(mm)	0-15	15-30	30-45	45-60	(mm)
Dec	27.1	13.2	7.3	55.7	103.3	18.6	20.9	19.3	17.0	75.8
Jan	15.9	16.3	15.0	8.7	55.8	25.5	24.8	28.9	10.2	89.4
Feb	55.4	20.6	15.3	12.1	103.4	22.1	10.2	26.8	6.3	65.3
Mar	36.2	14.5	18.2	14.4	83.4	16.3	47.5	25.1	16.8	105.6
Apr	76.5	30.3	17.9	16.5	141.2	35.6	54.1	42.2	16.3	148.2
May	61.1	25.7	25.5	19.0	131.2	23.2	32.0	34.7	17.9	107.8
Jun	21.3	8.3	9.3	1.6	40.5	7.8	18.6	14.8	7.8	49.1
Jul	31.3	3.9	5.5	2.5	43.2	9.7	14.2	10.4	3.4	37.7
Aug	23.0	15.1	9.0	1.4	48.5	12.4	18.5	13.1	8.6	52.5
Sep	28.8	3.5	8.4	5.3	45.9	165.2	16.5	12.8	9.2	50.2

Oct	20.0	6.1	4.1	3.3	33.5	12.1	14.4	12.9	11.5	50.8
Nov	23.1	11.0	8.8	5.7	48.5	8.3	10.9	9.0	9.1	37.3
Dec	28.2	25.4	19.7	13.5	86.7	14.7	16.7	11.9	8.6	51.9
Total (mm)	447.8	194.0	163.9	159.7	965.3	371.5	299.1	261.7	142.8	921.6

3.3. Avocado Nutrition

Figure 3 shows the effect of fertilizers on soil salinity in Cutzato. As can be observed, fertilization also begins in December simultaneously with irrigation, the doses of complex soluble fertilizer are around 10 to 15 kg ha^{-1} in each event, and, as can be seen, the consumption of nutrients is very fast in avocado, since the drop in salinity levels is extremely fast, despite 12 fertilization events occur, for instance, between December and mid-February, high consumption of salts is observed, hence, the salinity records drops in two months at levels of 0.4 dS m^{-1}, which is the natural salinity of this soil. This consumption accelerates from the month of March when practically, as the fertilizer is applied, the crop rapidly absorbs it. It is also noticeable that more than 90% of the applied fertilizer remains in the 0-15 cm layer, without trespassing deeper layers in a significant way.

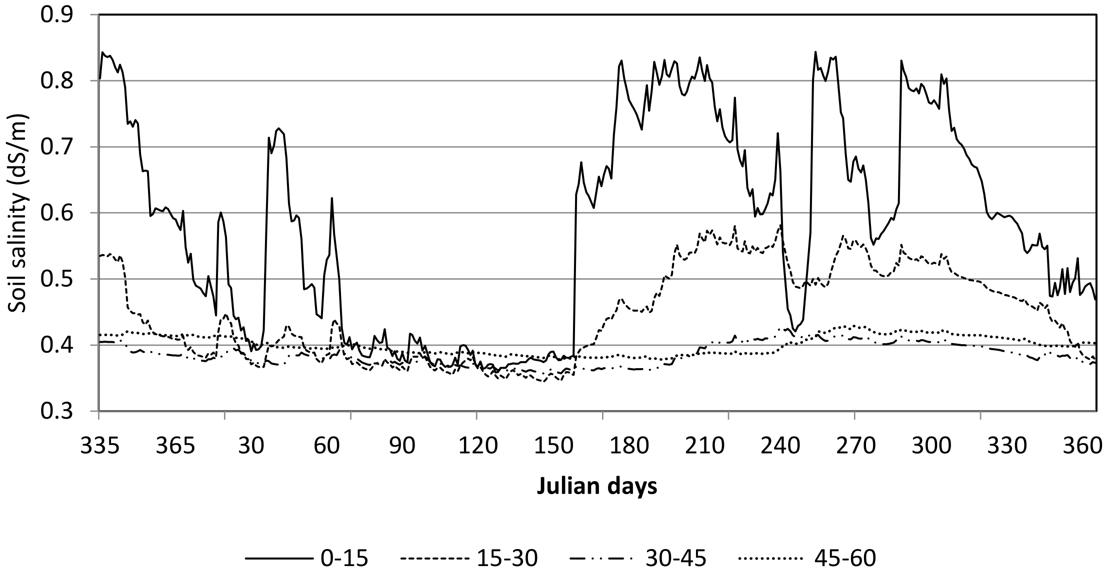

Figure 3. Soil salinity at four sampling depths after fertilizers assimilation on avocado in a midland orchard of Uruapan, Michoacán, México.

In Tiamba (Figure 4), the soil salinity was also evaluated, as a result of the nutritional management applied to the avocado tree with fertigation. Since it was a different soil than that in Cutzato, salinity changes are seen in all strata because it is a more permeable soil, fertilizer applications show greater appreciable variation in the most superficial layer (00-15) and the rest of the strata variation presents a lesser degree. Also, it is necessary to mention that the leaching of nutrients to deep layers is minimal since the content of salts in the last layer hardly changes and remains asymptotic throughout the year.

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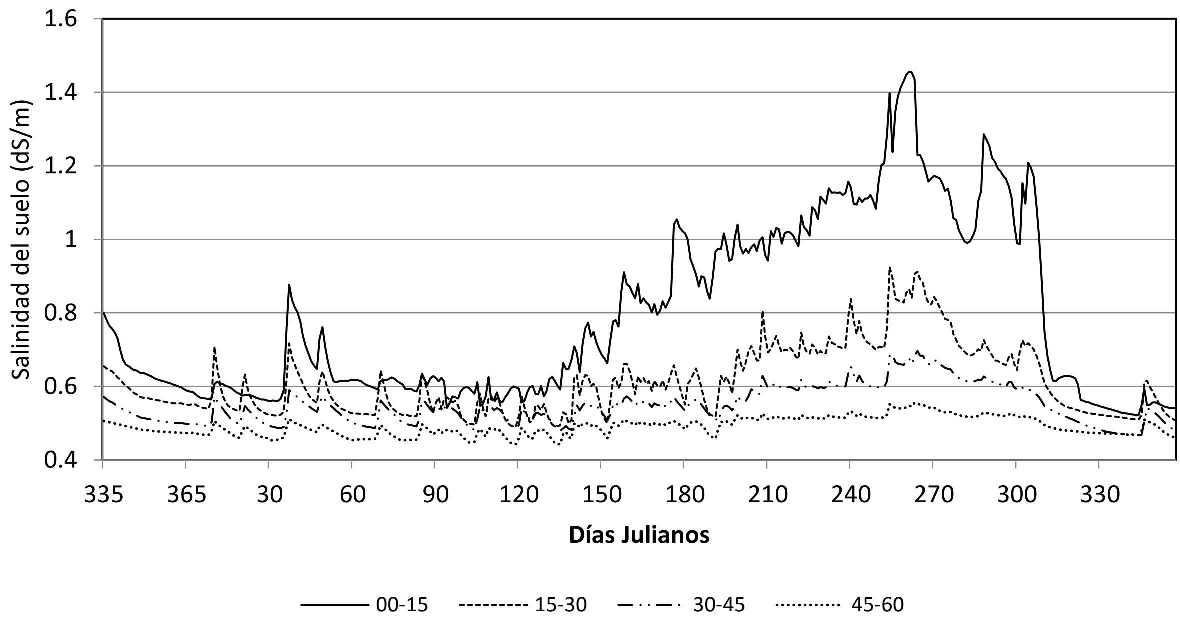

Figure 4. Soil salinity at four avocado sampling depths in Tiamba, Michoacán.

3.4. Water Use Efficiency

The variables related to water use efficiency WUE, WUI, and Kc of avocado, are unknown to date in the state of Michoacán and at a national level. In Table 3, it is observed that the cultivation coefficient was obtained by applying 100% of the ETo of each locality, which gives guidelines to consider that the avocado can be managed at a lower rate of ETo without affecting the performance of the avocado, however, it can be observed that in Tiamba, despite having less evapotranspiration demand from the environment, the water use efficiency(WUE) is 9% greater, but also the WUI is greater by 22%. Regarding Kc, the values obtained varied between locations, in Cutzato despite being warmer the Kc value was 0.72, whereas in Tiamba it reached 0.78; this difference can be explained because of 12% more yield in Tiamba, which caused a higher water demand.

Table 3. Annual average values for water use efficiency parameters in avocado cultivated in two locations of Michoacán, México.

Site	ETo (mm year^{-1})	ETr (mm year^{-1})	Kc	NWV (m^3 ha^{-1})	ISA (mm)	Yield (kg tree^{-1})	WUE (kg m^{-3})	IUA (ETr ISA^{-1})
Cutzato	1341.5	965.3	0.72	4426.9	1490.0	54.6	4.4	0.65
Tiamba	1180.7	921.0	0.78	3896.3	1311.9	61.2	5.6	0.70

ETo: reference evapotranspiration; ETr: actual evapotranspiration; Kc: crop coefficient; NWV: net water volume; ISA: Irrigation sheet applied annually; WUE: water use efficiency; WUI: water use index.

4. Discussion

Crop water requirements differ from one location to another because of differential altitude and climatic conditions; this is why more irrigation water must be supplied in Cutzato (Table 3) to avoid affecting crop productivity [28]. Monitoring data showed that in both locations, the maximum rate of water uptake occurs in the upper soil layer (0-15 cm); in Cutzato (Figure 1), this layer registered 46.3% of a total rate of 65% (four soil layers) for the water use index ETr/ISA, whilst in Tiamba it was 34.5% of a total rate of 70% of the rate ETr/ISA (Figure 2. Soil texture can mean the difference in the amount of ETr, being the soils with higher clay content those with higher ETr [29]; in this regard, our results

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showed the opposite, because the lighter soil of Tiamba induced a higher ETr than that from the heavier Cutzato soil. Avocados can consume water and nutrients up to 60 cm depth [30], since most of the absorbing roots are at this limit, the results documented here verify these data, since, at greater depths, this is from 45 to 60 cm from the surface, the absorption rate is less than that at superficial layers. In this deeper layer evaluated, 16.4% of water uptake was obtained in Cutzato and 13.2% in Tiamba, which demonstrates that at greater depths, the extraction rate may be lower. In this sense, the highest root density is up to 50-60 cm depth [29], which is related to the results of this research. Knowledge of moisture distribution in the avocado root zone can improve other management practices, such as nutrition or the application of agrochemicals [31], to optimize the inputs of this fruit. In both locations, the ETr exceeds 900 mm year^{-1} (Table 2), which indicates a significant water consumption that reflects the water needs that include both evaporation and transpiration [32], which can be highly variable within the time, influenced by climate change and the prevailing climate. This statement seems not to be confirmed in this research because, despite the sites' climatic differences (Table 1), ETr is similar in both locations; this seems to prove that avocado has ETr regulatory mechanisms to compensate for climatic differences from one region to another since a higher ETr would be expected in hot climates. This performance of avocados concerning ETr in two climatically contrasting locations could limit any water-saving program for avocados in temperate climates. A possible economic and productive affectation of water-saving programs can emerge [33]. Knowing the area of water uptake by the roots, also guarantee the absorption of nutrients, as can be appreciated in Figures 1 to 4. The importance of this knowledge lies in the fact that roots assimilate nutrients along with water [31]; reducing water uptake in avocados is the main cause of yield reduction [34]. The presence of nutrients inside the soil is evident in both locations, this condition is essential for the fruit to have a high concentration of nutrients, and thus, increase the benefits for human consumption [35]. In Cutzato as well as in Tiamba the consumption of fertilizers was slow at the end and at the beginning of the year (Figures 3 and 4), however, early nutrition at this season results in a greater number of fruits [16]; later a higher absorption rate is observed from the end of January to mid-May, this may be due to the exponential growth of the fruit and the high demand from winter vegetative shoots, which do not produce photosynthates and are rather a sink of nutrients [36]. Regarding fertigation in avocados, although a sudden increase of salts in the root zone is caused, they do not reach deeper soil layers, thus avoiding leaching and contamination; This result matches with a previous report [34]. In both locations, there is less crop water consumption than the environmental evapotranspiration demand, with 60% in Cutzato and 64% in Tiamba. For California avocado, a consumption of 86% of ETo has been reported [37]. The higher consumption of Tiamba concerning Cutzato may be explained because of sandier soil, thus, there is a greater moisture distribution in the soil profile and hence a greater root density; in this sense, a direct relationship between water availability and root growth was observed in avocado [17]. Regarding the Kc obtained in the two locations (0.72 and 0.78), they are similar to the value 0.73 previously obtained for adult trees [39]; however, they are slightly higher than those obtained in the interval 0.40-0.60 in other research [30]. According to the WUE and ISA values for the locations studied, the avocado orchards of Tiamba produce more with less water because of a WUE of 27.3% higher than Cutzato's and an ISA 12% lower than the Cutzato's. Nevertheless, the WUE of both sites is higher than 2 Kg m^{-3}, the value reported for other production zones [30].

4. Conclusions

The greatest amount of water absorbed by the crop occurs in the upper layer of the soil, thus water and nutrients must be present in the 00-15 cm layer of the soil profile. The crop actual evapotranspiration is similar in temperate climates C(w) and semi-warm climates (A)C(w), although slightly higher in these last ones. The avocado water use efficiency is greater in temperate climates than in semi-warm climates. Fertilizer application in low doses and high frequency does not produce excess of leachate and therefore is not a cause of water pollution. In general, avocado can be considered as a crop with low water requirements with more than 4.45 kg of fruit m^{-3} of applied water. The values obtained for water use efficiency indices WUE, WUI, and Kc, represent valuable

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reference parameters for future research and/or regional planning in the context of promoting high avocado yields with less water and fertilizers consumption.

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