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Influence of different drip irrigation strategies on irrigation water use efficiency on chufa (*Cyperus esculentus* L. var. *sativus* Boeck.) crop

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Abstract

Chufa is a typical crop in Valencia, Spain, where it is cultivated in ridges with furrow irrigation. It uses large volumes of water, and thus, different studies have been undertaken to maximize irrigation water use efficiency to obtain important water savings. Particularly, different values for turning water on, considering the basis of volumetric soil water content were analysed in drip irrigation. It was reported that starting each irrigation event when the volumetric soil water content dropped to 90% of the field capacity resulted in the best yield, and the best irrigation water use efficiency was obtained when it dropped to 80% of the field capacity. However, these results may be improved by defining the optimum criteria for turning water off, which is the aim of the present research. This investigation, conducted in 2015, 2016 and 2017, analises the productive response of the drip irrigated chufa crop, determining the yield and the irrigation water use efficiency. The volumetric soil water content was monitored using multi-depth capacitance probes, with sensors at 0.10, 0.20 and 0.30 m below the top of the ridge. Each irrigation event started when the volumetric soil water content at 0.10 m dropped to 85% of field capacity. Three irrigation strategies were considered. T1: each event resulting in water being turned off when the sum of the volumetric soil water content values that were measured at 0.10, 0.20 and 0.30 m reached the corresponding field capacity value; T2: turning water off in each event when the volumetric soil water content values that were measured at 0.20 m reached the corresponding field capacity value; and T3: each irrigation event applying 8.5 mm in 2015 and 2016, as well as 9.8 mm in 2017. Overall, the T2 strategy resulted in the largest yield, and

T3 resulted in the highest irrigation water use efficiency in 2015 and 2016. The average tuber weight and dry matter content did not differ between the irrigation strategies.

Keywords: Tuber, yield, volumetric soil water content, capacitance sensors, automatic drip irrigation.

1. Introduction

Chufa is the botanical var. *sativus* of *Cyperus esculentus* L. and it is also known as tiger nut, tigernut or yellow nutsedge. It is a common crop in the Valencia region of Spain, where chufa tubers are used to produce a milk-like non-alcoholic beverage called “*horchata*” or “*horchata de chufas*” (tiger nut milk or orgeat). This refreshing and wholesome beverage continues to be the subject of research in Spain (Bosch et al., 2005; Sánchez-Zapata et al., 2012; Sebastiá et al., 2010), and it has recently become popular in other countries, such as France, the UK, the US and Argentina. Recent studies have reported increasing interest in chufa cultivation, mostly for food technology and biodiesel production in Brazil, Cameroon, China, Egypt, Hungary, Niger, the Republic of Korea, Poland, Turkey, the US, and particularly Nigeria (Glew et al., 2006; Pascual-Seva et al., 2016). Different aspects related to chufa cultivation have been deeply studied, such as crop management techniques (Pascual et al., 1999), cultivar selection and plant characterization (Pascual et al., 1999, Pascual-Seva et al., 2013a), and nutrition and fertilization (Pascual-Seva et al., 2009).

Traditionally, chufa has been furrow irrigated, and the effect of this traditional irrigation method on chufa yield was addressed in Pascual-Seva et al. (2013b). Pascual-Seva et al. (2012) compared the productive response of the chufa crop cultivated in the traditional one plant row to other planting configurations, using flat raised beds with two or three plant rows with irrigation conducted by furrows, and lately, Pascual-Seva et al. (2016) compared those planting configurations under drip irrigation. In Valencia, there is currently a ready supply of water, and it is relatively inexpensive. However, due to significant periods of drought and the shift of water usage from irrigation to environmental, industrial and municipal applications, the use of irrigation water may soon become subject to regulation, and agriculturalists will need to adapt the rate, frequency, and duration of water supplies to successfully allocate limited water, as well as other inputs, to crops, as Evans and Sadler (2008) have globally indicated.

Therefore, it is important to increase the productivity of irrigation water. In this sense, Howell (2006) indicated that a way to enhance water use efficiency in irrigated agriculture is to increase the output per unit of water and to reduce losses of water due to unusable sinks. Evans and

Sadler (2008) pointed out that agricultural advances should include the implementation of crop location strategies, and the conversion to crops with higher economic value or productivity per unit of water consumed. In this sense, chufa is most likely the crop with the highest economic value of those grown in the area, representing nearly 19% of the surface dedicated to horticultural crops (Generalitat Valenciana, 2017). It produces 16,800 kg ha^{-1}, resulting in an annual average production, of 8,250,000 kg (MAPAMA, 2017), representing 6,600,000 € (0.80 € kg^{-1}; Regulatory Council of Denomination of Origin *Chufa de Valencia* personal communication).

It is globally known that soils of different textures present different abilities to retain water (Israelsen and Hansen, 1962; Keller and Bliesner, 1990); therefore, irrigation schedules based on the volumetric soil water content (VSWC) implicitly consider the specific soil texture and are applicable to different soil textures. Soil moisture sensors allow irrigation in accordance with the unique characteristics of a given crop in a given set of conditions, and they can be used as a “stand-alone” method (Thompson et al., 2007a). Pascual-Seva et al. (2015) compared the productive response of the chufa crop with drip irrigation and traditional furrow irrigation, monitoring the VSWC with capacitance probes. They considered three drip irrigation strategies, maintaining the soil water content between field capacity (FC) and three different refill points (VSWC values for turning water on), using the same criterion to turn water off in each irrigation event in the three strategies. The highest yield corresponded to starting each irrigation event when the VSWC value at a soil depth of 0.10 m dropped to 90% of the FC value, and the highest irrigation water use efficiency (IWUE) was obtained when each irrigation event began when the VSWC value dropped to 80% of the FC value. Then, to improve the irrigation performance the authors decided to analyse different criteria for turning water off, which is the aim of the present study. The yield and water volumes applied were determined, and the IWUE, which is a common indicator employed to assess the efficiency of the use of irrigation water in crop production (Tolk and Howell 2003), was calculated.

2. Materials and Methods

2.1. Cultivation methods

The study was conducted over three consecutive years (2015, 2016, and 2017) in a research field next to the campus of the *Universitat Politècnica de València*, Spain (39º38´N, 0º22´W) within the main chufa-producing area. To avoid soil replant disorders resulting from serial chufa cropping, the northern and southern areas of the research plot were alternately used.

The climate in the area is subtropical Mediterranean (Su, Me) according to Papadakis's agro-climatic classification (Verheye, 2009), with hot, dry summers and an average annual rainfall of approximately 450 mm, irregularly distributed throughout the year (approximately 40% in autumn). Figure 1 shows the most significant climatological data: temperature, precipitation and evapotranspiration of the reference crop (ETo) calculated by the FAO Penman-Monteith formulation (Allen et al, 1998) from the weather information obtained from an automated meteorological station located on the research field. Planting was performed on the 23rd and 24th of April in 2015 and 2016, respectively, as well as on the 12th of May in 2017. Tubers were planted in ridges that were 0.20 m high, and the ridge top centres were spaced 0.60 m apart. In all three seasons, the ridge length was 30 m, and its slope was 0.1%. The soil at the site was deep with a coarse texture and classified as Anthropic Torrifluvents according to the USDA Soil Taxonomy (Soil Survey Staff, 2010). The soil presented a moderately alkaline pH and was highly fertile (high organic matter content and high available phosphorous and potassium concentrations; Table 1). The soil was apparently uniform in depth throughout the plot because of the seedbed preparation, which entails several crossed passes with a rotary tiller after incorporating 400 m^3 ha^{-1} of sandy-textured soil from an industrial chufa laundry before the 2015 season and after sieving the soil when the tubers were harvested. Nevertheless, as shown in Table 2, the textural characteristics of the soils at different depths for each growing season ranged from sand to sandy loam. In each season, the soil texture was relatively uniform, but the top layer presented larger percentages of sand in 2015 than in the other seasons, initially due to the non-uniform distribution of the sandy soil incorporated in the plot, which resulted in the application of less sandy soil in the north than in the southern part of the plot, and lately due to the incorporation in depth of the sandy soil supplied, as a consequence of the sieving of the soil when the tubers were harvested.

The irrigation water was pumped from a well (EC=1.6 dS m^{-1}; $SAR_{(adjusted)}$=2.9; pH=7.4). The water did not show any restriction in terms of salinity for non-sensitive crops, such as chufa, or infiltration rate of water into the soil (Ayers and Westcot 1994).

Standard cultivation practices were followed during the crop period, as described in Pascual et al. (1997). Nutrient management was performed according to local practices, and both basal and top dressings were applied as described in Pascual-Seva et al. (2016). Straw-burning took place on the 20th, 17th, and 6th of November in 2015, 2016 and 2017, respectively; the tubers were harvested and washed on the 14th and 17th of December in 2015, respectively, and the 23rd and 27th of November in 2017, respectively. Due to significant precipitation in November and December 2016, harvesting during the 2016 season was delayed until the 17th of January 2017, and tubers were washed on the 18th of January 2017. The yield was obtained from tubers harvested in the whole unit plots, after washing, while the average tuber weight was obtained from tubers harvested within 2 m of the plant row, after washing and counting. Because the crop coefficient (K_c) of chufa is unknown, the IWUE was calculated as the relationship between the marketable yield (fresh tuber) and the irrigation water applied ($I_{applied}$), as presented by Cabello et al. (2009). For each event, the application efficiency (AE) was estimated as the ratio between the amount of water that could be stored in the root zone and $I_{applied}$.

2.2. Irrigation management

Plants were irrigated by a lateral line per ridge using a turbulent flow dripline (AZUDRIP Compact; Sistema Azud S.A., Murcia, Spain) with emitters, with 2.2 L h^{-1} flow, and spaced 0.25 m apart. The VSWC was continuously monitored with capacitance probes. In each irrigation strategy, one multi-depth capacitance probe (Cprobe; Agrilink Inc. Ltd., Adelaide, Australia) was installed inside a PVC access tube and placed in a ridge. The probe had sensors installed with midpoints at 0.10, 0.20 and 0.30 m below the top of the ridge, and each sensor was connected to a radio telemetry unit, which read the value of each sensor every 5 min and recorded an average value every 15 min, as reported in Pascual-Seva et al. (2016). The stored raw data were sent by radio through a relay station and then to a gateway connected to a computer for data analysis using the addVANTAGE software from ADCON telemetry GMbH (Vienna, Austria) (Vera et al. 2009). Before installation in the field, each sensor inside the PVC access tube was normalised by taking voltage readings while exposed to air (Va) and water (Vw) at ≈ 22ºC (Abrisqueta et al. 2012). Once the crop was established, the probes were calibrated in the field by the gravimetric method, and readings were obtained from each sensor and non-disturbed soil samples in the same ridge as the probes, at a maximum distance of 0.40 m. An undisturbed soil sample core (100 mL) was taken periodically using a soil sample ring kit (Eijkelkamp; Giesbeek, The Netherlands). Soil samples were dried at 105ºC in a forced-air oven (Model UF 260 Memmert, Büchenbach, Deutschland) to obtain the sample water content (%), which was compared with the corresponding scaled voltage value.

Variations in the VSWC were used to determine the *in situ* FC (Veihmeyer and Hendrickson 1931) and the corresponding turning on and off values for each irrigation event. Three different irrigation strategies were analysed (T1, T2 and T3). In all three strategies, each irrigation event began when the VSWC value at a soil depth of 0.10 m [corresponding to the maximum root density and water uptake by chufa plants (Pascual-Seva et al., 2013c)] dropped to 85% of the FC value; however, the irrigation strategies differed in the irrigation stop signal.

In T1, each irrigation event stopped when the sum of the VSWC values at 0.10, 0.20 and 0.30 m reached the corresponding FC value. In T2, each irrigation event stopped when the VSWC values at 0.20 m (maximum root depth) reached the corresponding FC value. In T3, each irrigation event applied a fixed irrigation dose, based on previously carried out experiments (Pascual-Seva et al. 2016). This dose was set at 8.5 mm (corresponding to 35 min) in 2015 and 2016, but in view of the low productive results of the firsts two seasons, the irrigation dose of this strategy was increased to 9.8 mm (40 min) in 2017. The rainfall and emitter flow rate for all three irrigation strategies were recorded using automatic tipping bucket gauges connected to a radio telemetry unit.

2.3 Experimental design and statistical analysis

Each irrigation strategy was replicated four times in a split plot design; each replication consisted of two ridges, which were surrounded by a similar ridge to eliminate border effects. The productive response results were analysed by a multifactorial analysis of variance using Statgraphics Centurion XVII (Statistical Graphics Corporation, 2014), considering as factors the growing season and the irrigation strategy. Differences between the means were compared using an LSD test at $P \leq 0.05$.

3. Results and Discussion

3.1. Irrigation management

Table 3 shows the linear calibration equations for the diverse multi-depth capacitance probes, which showed high correlation coefficients (r: 0.80-0.99) and significance levels ($P \leq 0.01$). These significance and correlation coefficients are consistent with those presented by Varble and Chávez (2011) and could therefore be considered appropriate, taking into account both the fact that the soil core samples were collected outside the sensor influence area and the errors associated with obtaining and processing the samples (Quemada et al., 2010). Although, the relationship between VSWC and the corresponding scaled voltage is not linear (Bell et al., 1987; Vera et al., 2009), the calibration curves may be regarded as linear over the relatively restricted range of soil moisture changes normally experienced for a given soil, as reported by Bell et al. (1987) and as shown in this study and in previous ones (Pascual-Seva et al., 2015). The VSWC that made each irrigation event turn on and off for each strategy and season is shown in Table 4. The differences are fundamentally related to the different texture of the soil profile (Table 2). The highest stop value for T1 in 2015 resulted in larger volumes of $I_{applied}$ per event (13.6 mm; Table 5) and therefore in a lower number of events (30) than those in 2016 (11.9 mm and 39 events) and 2017 (9.7 mm and 49 events). Regarding T2, the highest VSWC for irrigation stop corresponded to 2017, being the VSWC at 0.20 m higher than in the other seasons throughout the cycle, showing a lower variation with each irrigation event, as shown in Figures 2-4. These figures show the VSWC throughout the growth period for all depths and irrigation strategies during the three growing seasons, as well as the daily rainfall. Overall, the VSWC at a depth of 0.30 m was higher than that at shallower depths. The VSWC throughout the growth period for the three strategies was more irregular in 2015 than in 2016 and 2017, and was most likely related to the sandier textures, particularly in the top layer.

T1 led to more irrigation events in 2017 (49; Table 5), with lower $I_{applied}$ in each of the events (9.7 mm) compared to previous years (30 events and 13.6 mm in 2015; 39 events and 11.9 mm in 2016). T1 considers the sum of the VSWC at 0.10, 0.20, and 0.30 m for stopping each irrigation event. In 2017, the VSWC at 0.30 m depth represented 38.6% of the sum of the values corresponding to the three depths (Figure 4), while it represented 44.9% in 2015 (Figure 2) and 47.4% in 2016 (Figure 3). Thus, its influence in the sum is lower, increasing the effect of the shallower depths, thus arriving to the corresponding FC earlier, and consequently leading to shorter irrigation events.

In 2015, T2 irrigation events were shorter (9.2 mm) and more frequent (55 events, Figure 2) than in 2016 (18.6 mm and 28 events; Figure 3) and similar to 2017 (8.3 mm and 59 events; Figure 4). Irrigation water reached a higher depth in 2016, most likely because the surface soil layer (0.10 and 0.20 m deep) was less sandy in 2016, and therefore, the corresponding FC at these depths were higher, leading to a delay in both the irrigation turning on and off, and applying higher irrigation doses with a lower frequency. In 2017, the soil at 0.10 m was sandier than that in 2016, leading to more frequent irrigation events and maintaining VSWC at 0.20 m in values close to FC; therefore the irrigation events were shorter.

In 2015 and 2016, T3 irrigation events applied 8.5 mm, and the water did not reach the 0.30 m sensors (Figures 2 and 3). Considering the low yield obtained in these years, authors decided to increase it to 9.8 mm in 2017, when the irrigation water reached the 0.30 m layer (Figure 4), thus decreasing the AE in this strategy compared with T1 and T2 (Table 5). Most of the AE values could be considered low (down to 48% for T1 in 2016), but the shallowness of the roots (approximately 0.20 m) is a factor that should be noted and taken into account.

Table 5 presents the ETo and effective precipitation [Pe; calculated from rainfall data using the method of the U.S. Bureau of Reclamation (Stamm, 1967) as presented by Montoro et al. (2011)

and Pascual-Seva et al. (2016)] from planting to the 1st of November of each year (day that the harvest process starts). The K_c for chufa is unknown; thus, actual irrigation water requirements cannot be estimated, and the difference between ETo and Pe has been considered in water requirements. Larger amounts of water were required in 2015 and 2016 (751 and 763 mm, respectively) than in 2017 (695 mm), since in the last year, planting was delayed (21 days from 2015 and 17 days from 2016).

T3 resulted in the lowest $I_{applied}$ throughout the season in 2015 and 2016 (346 and 415 mm, respectively) and in the largest $I_{applied}$ in 2017 (562 mm). This outcome may have occurred as a consequence of both the increase in irrigation dose from the previous years, as previously mentioned, and of the larger number of irrigation events. The greatest $I_{applied}$ in 2015 and 2016 corresponded to T2 (506 and 520 mm, respectively) in 2015, due to the large number of events (55), and in 2016, due to the large depth applied in each of the events (19 mm).

On average, $I_{applied}$ represented 56% of the estimated water requirements in 2015, 61% in 2016 and 73% in 2017 (Table 5). These values, below 100%, led to the belief that the K_c for chufa should be below 1 for the entire crop cycle, which is in agreement with studies of the K_c that are currently being performed using a lysimetric station.

3.2. Productive response

The yield, average tuber weight, tuber dry matter content and IWUE corresponding to the moment of commercial harvest are given in Table 6. Both the growing season and irrigation strategy significantly affected ($P\leq0.01$) the tuber yield, as well as their interaction ($P\leq0.05$). Differences in growing season (2.06, 2.03, and 2.30 kg m^{-2} on average in 2015, 2016 and 2017, respectively) could be expected, since in addition to irrigation, yield depends on other factors such as climatic conditions, planting date, soil characteristics, fertilization, pest and disease incidence, etc. It has been reported that obtaining different chufa yields for different years in any given plot is common (Pascual-Seva et al., 2015). The average yield obtained in 2015 and 2016 (2.0 kg m^{-2}) could be considered as a good yield in a grower's fields; thus, the average yield obtained in 2017 (2.30 kg m^{-2}) can be considered high. The average yield for all three years (2.13 kg m^{-2}) is similar to that reported for drip irrigation by Pascual-Seva et al. (2015; 2.11 kg m^{-2}) and is greater than that obtained using furrow irrigation in the same study (1.75 kg m^{-2}).

The yield obtained with T3 (2.12 kg m^{-2}) is statistically similar to that obtained with T1 (1.96 kg m^{-2}), and both are lower ($P \leq 0.01$) than the yield obtained with T2 (2.31 kg m^{-2}). The yield in T3 is similar to the yield reported by Pascual-Seva et al. (2015) for the drip irrigation strategy, which started each irrigation event when the VSWC dropped to 80% of its FC (2.13 kg m^{-2}) and is similar to the yield presented by Pascual-Seva et al. (2016; 2.14 kg m^{-2}) for similar conditions. All strategies in Pascual-Seva et al. (2015) were automated to stop each irrigation event when the sum of the VSWC at 0.10, 0.20, and 0.30 m reached the corresponding FC value, as T1 in the herein presented study. In Pascual-Seva et al. (2016), the refill point corresponded to 85% of the FC, and each irrigation event applied, on average, 9.83 mm. When the refill point was fixed at 90% of FC (Pascual-Seva et al, 2015), the yield was 2.58 kg m^{-2}, and therefore, the yield obtained in T2 (2.31 kg m^{-2}) was between the results obtained in the previous studies, with refill points at 80% and 90% of FC. In the present study, it was considered appropriate to set the refill point at 85% of FC to obtain both a high yield and IWUE. T3 resulted in a similar yield as T1 in 2015 (1.92 and 1.94 kg m^{-2}, respectively) and 2016 (1.94 and 1.92 kg m^{-2}, respectively), when each irrigation event applied 8.5 mm. However, the yield increased to levels similar to T2 in 2017 (2.52 and 2.37 kg m^{-2} for T3 and T2, respectively) when the $I_{applied}$ per event was increased.

Howell (2001) reported both linear and curvilinear relationships between yield and $I_{applied}$ for potatoes, as demonstrated in this study, since both adjustments were significant ($P \leq 0.01$). Considering all three years, the yield increased linearly with $I_{applied}$ [$y = 0.771 + 0.029x$ ($r = 0.65$); y= yield in kg m^{-2}; $x = I_{applied}$ in mm], and followed a second-order polynomic equation [$y = 4.15 - 0.012x + 0.000017x^2$ ($R^2 = 49\%$)]. Pascual-Seva et al. (2015) presented a linear relationship for each growing season when considered separately but curvilineal when all of the data were considered together [$y = -1.9183 + 0.0138x + 1 \cdot 10^{-5}x^2$ ($R^2 = 93.45\%$)]. The two curvilinear relationships obtained in both studies are different, since in the last one, the irrigation strategies resulted in higher $I_{applied}$ (up to 763 mm) compared to the present study (with maximum $I_{applied}$ of 562 mm). These differences are due to the fact that at a high $I_{applied}$, a considerable fraction of this water is not consumed by ET, and does not lead to an increase in yield, as reported by Tolk and Howell (2003).

The average tuber weight and tuber dry matter content were only affected ($P \leq 0.01$; Table 6) by the growing season, with higher values in 2017; thus, in 2017, in addition to producing the greatest yield, the best tuber quality (average tuber weight and tuber dry matter content) was obtained. The average tuber weight for 2015 and 2016 (0.65 and 0.64 g tuber^{-1}, respectively) is consistent with the results presented in Pascual-Seva et al. (2015; 0.65 g tuber^{-1}) and Pascual-Seva et al. (2016; 0.66 g tuber^{-1}). In 2017, the tubers were larger than usual (0.73 g tuber^{-1}), and this finding is consistent with the results obtained by chufa growers in the area in this season (Regulatory Council of Denomination of Origin *Chufa de Valencia* personal communication).

Tuber dry matter content is dependent on the degree of tuber maturity and on tuber water loss before harvest, which in turn is dependent on the VSWC. The greater dry matter content in 2017 is most likely due to the lower VSWC at harvest time, since there were no rainfalls during the autumn months. Given the existence of a positive linear increment in horchata production yield with tuber dry matter content, this parameter should be considered in chufa tuber trade relations.

The percentage of small tubers was affected by neither the growing season nor the irrigation strategy ($P \leq 0.05$; data not shown).

Both growing season ($P \leq 0.01$) and irrigation strategy ($P \leq 0.05$) influenced IWUE (Table 6), but their interaction was not significant. The highest IWUE was obtained in 2015 (4.96 kg m^{-3}), as the higher yield obtained in 2017 did not compensate for the larger $I_{applied}$. Regarding the irrigation strategies, T3 led to higher IWUE values than T1, particularly because of the low $I_{applied}$ in 2015 (346 mm) and 2016 (415 mm). These IWUE values are consistent with those reported by Pascual-Seva et al. (2015), which ranged from 4.47 to 4.86 kg m^{-3} for drip irrigation. The higher IWUE values were obtained with the lower $I_{applied}$, which are similar to the results obtained by Ghazouani et al. (2015) for potato and by Önder et al. (2015) for sweet potato, in which both crops are cultivated by their underground organs. Tolk and Howell (2003) indicated that maximum IWUE usually occurs at an ET that is generally less than the maximum ET, thereby suggesting that irrigating to achieve the maximum yield would not correspond to the most efficient use of irrigation water, as shown in this study.

Consistent with Ghazouani et al. (2016), to define the best irrigation strategy, it is recommended to consider the availability of water and to perform an economic analysis, taking into account the cost of the irrigation water and the related profit achievable by the grower.

In this sense, the price received by the growers in the seasons included in the study is approximately 0.80 € kg^{-1} of fresh tubers (Regulatory Council of Denomination of Origin *Chufa de Valencia* personal communication), and the estimated price for irrigation water is 0.066 € m^{-3} (Pascual-Seva et al., 2015). Considering that the other cultural practices are similar for all strategies, the greatest profit corresponded to T2 (18,127 € ha^{-1} on average) and to T3 when applying 9.8 mm (19,769 € ha^{-1} in 2017), while the greatest profit per water applied corresponded to the 8.5 mm irrigation events (4.08 € m^{-3} on average). If water is readily available and inexpensive, as it currently is and considering the type of soils used in the study, which are representative of those in the chufa cultivation area, the irrigation strategy that leads to a maximum yield may be the most profitable option. Therefore, irrigating with T2 strategy or with a fixed dose of approximately 10 mm would be recommended for chufa in the traditional cultivation area. If water is the limiting factor, then irrigating to achieve maximum IWUE might be a better option, and therefore, irrigation events with 8.5 mm would be recommended.

Proper irrigation programming can be a way to improve IWUE, hence reducing the amount of water applied to the crop (De Pascale et al., 2011). Scientific irrigation is defined as the use of ETc data and VSWC to accurately determine the initial irrigation threshold and the irrigation dose (Leib et al., 2002). The proper time for irrigation can be defined based on different criteria such as VSWC, plant water stress and micrometeorological parameters to determine ET_c (De Pascale et al., 2011). Soil moisture sensors allow irrigation according to the unique characteristics of a given crop in a given field (Thompson et al., 2007a). Most of the publications refer to the use of soil moisture sensors as instruments for determining when to start the irrigation events, while the irrigation dose is determined by determining the VSWC depletion (Tuzel et al., 2017) or the ETc (Thompson et al., 2007a, 2007b). As Thompson et al. (2007a) indicated, the most suitable methods to scientifically schedule irrigation for vegetable crops are the FAO Penman-Monteith equation (Allen et al., 1998) and the use of soil moisture sensors. Since irrigation water requirements based on ET_c, for chufa crops have not been defined, it was decided to establish the irrigation automation based on the VSWC. In the present study, considering the VSWC depletion, irrigation dose should range between 5 and 10 mm (depending on the soil texture), as applied in T3. As mentioned above, chufa yield increases with $I_{applied}$, as occurred in T3 when the irrigation dose increased from 8.5 to 9.8 mm. Lower irrigation doses lead to low yields, as obtained in prior studies (Pascual-Seva, 2011).

The refill point has already been studied (Pascual-Seva et al., 2015), particularly when all of the analysed strategies turned the water off when the sums of the VSWC that were determined at 0.10, 0.20 and 0.30 m reached their corresponding FC values, similar to the irrigation strategy T1 used in the present study. The authors hypothesized that the productive response of the crop could improve by turning the irrigation off when the VSWC at the maximum root depth (0.20 m) reached its FC, even though this outcome implied a larger $I_{applied}$, and, in turn, lower AE. This outcome resulted in an increment of the yield and, in two of the three growing seasons, in an increment of the IWUE. Due to this result, it can be stated that the increment in yield compensated the increment in $I_{applied}$. Overall, it can be asserted that establishing an irrigation schedule based on the VSWC is a reliable option.

If it is not possible to stop the irrigation events using VSWC sensors, the irrigation dose could be pre-fixed. Given this outcome in chufa, the crop yield increases with the irrigation dose, and given that slight dose increments could lead to important yield improvements, it is of great importance to establish the optimum amount to be applied to produce proper yields. In this sense, as the considered soils are representative of those in the chufa cultivation area, it could be stated that applying approximately 10 mm is an advisable option. Furthermore, these results could be applicable to other crops, with shallow root systems that are included in the traditional Valencian crop rotations, such as onions, cabbages, cauliflowers, endives, lettuces, radish and carrots, although these statetements should be verified by specific studies.

To adjust the $I_{applied}$ to actual irrigation water requirements, the authors are currently focused on determining the K_c of chufa, both single and dual, which would facilitate an ET-based irrigation management system in addition to further improvements in IWUE.

4. Conclusions

Traditionally, the objective of researchers and growers has been to increase either yields or profits. Currently, as irrigation water is becoming a limited resource, achieving high irrigation water efficiency is of great importance. The adoption of drip irrigation in chufa cultivation results in an increment in the irrigation water efficiency. When water availability is not a limiting factor, as it is currently in the chufa cultivation area, irrigating to achieve a maximum yield may be the most profitable option, and therefore, turning water off on the basis of soil moisture at the maximum root depth is recommended. If, in the future, water is to become a limiting factor, or the use of soil moisture sensors to turn water off is not possible, the application of a fixed dose should be recommended. In the traditional chufa cultivation area, applying 8.5 mm would lead to high irrigation water use efficiencies, while increasing this dose up to 10 mm may improve the yields.

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