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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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A B S T R A C T

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.

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

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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 (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (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 (39°38´N, 0°22´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). Fig. 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 Westcott, 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 ≈22 °C (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