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Furrow-irrigated chufa crops in Valencia (Spain).
I: Productive response to two irrigation strategies

N. Pascual-Seva, A. San Bautista, S. López-Galarza, J. V. Maroto and B. Pascual*

Departamento de Producción Vegetal. Universitat Politècnica de València.
Camino de Vera, s/n. 46022 Valencia. Spain

Abstract

Chufa (*Cyperus esculentus* L. var. *sativus* Boeck.) is an important vegetable crop in Valencia (Spain), where its tubers are used to produce a refreshing drink called 'horchata'. Water is relatively inexpensive, there are no data regarding the volumes of water used to grow chufa, and the irrigation water use efficiency (*IWUE*) has neither been determined. The aim of this research was to compare the productive responses of the chufa crop to two irrigation strategies (IS). The volumetric soil water content (*VSWC*) was monitored with capacitance sensors. Trends in *VSWC* were used to determine the *in situ* field capacity (*FC*), beginning each irrigation event when the *VSWC* reached either approximately 45% (H1) or 60% (H2) of the *FC* at a soil depth of 0.10 m. The experiments were conducted over three consecutive seasons. An area velocity flow module measured the water flow. The yields, the water volumes used, and the *IWUE* were calculated. Plants were periodically sampled and the harvest index and relative growth rate were determined. The yield was affected by the year and by the IS. The greatest yields were obtained with the H2 strategy (on average 2.18 kg m^{-2} for H2 *vs.* 1.94 kg m^{-2} for H1; $p \leq 0.01$), and the average tuber weight (*ATW*) was affected ($p \leq 0.01$) by the year and IS interaction. *IWUE* was affected by the year, and none of the considered factors affected the harvest index ($p \leq 0.05$). It can be concluded that maintaining a higher *VSWC* would increase both yield and *ATW* without affecting *IWUE.*

Additional key words: capacitance sensors; harvest index; irrigation water use efficiency; tuber; volumetric soil water content.

Introduction

Chufa, also known as tigernut, is the botanical var. *sativus* of *Cyperus esculentus* L., and it is an important vegetable crop in the Huerta Norte area of the Valencia Region (Spain). The land surface area dedicated to the chufa crop annually is approximately 500 ha (the total surface area of the municipalities where chufa is cultivated is approximately 5,000 ha). Traits of commercial tubers are specified by the Regional Administration Legislatica: unit weight 0.45 y 0.80 g (fresh matter); length 0.9-1.6 cm; width 0.7-1.1 cm; proximate composition (on a dry matter basis): fats ≥ 23%, proteins ≥ 6.5%, starch ≥ 25%, and sugars ≥ 11.0% (CAPA, 2010).

Chufa tubers are used to produce a beverage called 'horchata', which is a popular, refreshing, and wholesome drink in Spain. Horchata has recently become popular in other countries, such as France, the UK, the USA, and Argentina. A recent study has reported increasing interest in chufa cultivation, mostly for food technology and biodiesel production, in Brazil, Cameroon, China, Egypt, Hungary, the Republic of Korea, Poland, Turkey, and the USA (Pascual-Seva *et al.*, 2009).

The traditional cropping pattern in the region consists of a rotation of chufa with other crops such as potato, onion, lettuce, escarole, and red cabbage. The chufa is planted in April or May, depending on the previous crop and spring rainfall. Seedbed preparation entails two crossed passes with a rotary tiller. Tubers (120 kg

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* Corresponding author: bpascual@prv.upv.es
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Abbreviations used: *ATW* (average tuber weight); DAP (days after planting); DOY (day of the year); DW (dry weight); EY (experimental year); *FC* (field capacity); H1 (irrigation strategy starting at 45% FC); H2 (irrigation strategy starting at 60% FC); *HI* (harvest index); IS (irrigation strategy); *IWA* (irrigation water applied); *IWP* (irrigation water productivity); *IWUE* (irrigation water use efficiency); K_c (crop coefficient); *RGR* (relative growth rate); *RP* (refill point); *TDMC* (tuber dry-matter content); *WP* (water productivity); *WUE* (water use efficiency).

tubers ha^{-1}) are planted on ridges, which are normally 0.20 m high, and the spacing between ridge top centers is 0.60 m. Tuber formation starts in June. The aboveground biomass is burned around the beginning of November, when it has dried, and the chufa tubers are then mechanically harvested when the soil water content is adequate. Laser technology is used to achieve a leveled field surface after harvesting. Therefore, the leveling of the land for chufa cultivation depends upon the crop management of the other plants grown between chufa in the crop rotation.

C. esculentus is an abundant weed in all temperate and tropical zones (Wills, 1987). Therefore, studies on its morphology, physiology, and control strategies when it is seen as a weed do exist, but little research has been performed regarding its cultivation. Nevertheless, two autochthonous clones and one clone of African origin were selected and characterized (Pascual *et al.*, 2000); the accumulation of macronutrients was measured (583, 109, 355, 295, and 58 kg ha^{-1} of N, P, K, Ca, and Mg, respectively; Pascual-Seva *et al.*, 2009); diverse agronomic studies were made – including a study of the influence of the planting date on tuber yield (Pascual *et al.*, 1999). This study showed that planting in mid-April rather than May extends the cultivation cycle and increases yield; however, planting in April is not always possible as previous crops are often awaiting harvest. Moreover, in Valencia, April is generally a rainy month and this may impede the preparation of the land for planting.

As reported by Stegman *et al.* (1980), water management objectives typically lead to some form of timing criteria for water application. In the study region, the decision to irrigate also considers other factors, such as plant and soil appearance, while parameters such as soil matric potential or root zone water content are not measured. Growers use their experience to decide when to stop irrigating. They usually block the furrows at the downstream ends, thereby eliminating surface runoff, but growers occasionally leave the downstream ends open.

There are no data on the volumes of water used, application efficiencies (*AE*), or water productivity for chufa or the other crops cited. Most of the crops in the area have shallow root systems. In the case of chufa, the root depth does not exceed 20 cm. This property (in addition to the lack of parameters such as soil matric potential or root zone water content) makes it difficult to obtain good *AE*, especially in sandy soils.

Water use efficiency (*WUE*) and irrigation water use efficiency (*IWUE*) are commonly used indicators for assessing the efficiency of the use of irrigation water in crop production (Bos, 1980; Tolk & Howell, 2003). Water use efficiency is generally defined in agronomy as the ratio of crop yield (usually the economic yield) to the volume of water consumed by the crop [evapotranspiration (*ET*) = evaporation + transpiration] (Tolk & Howell, 2003), although *WUE* can also be calculated as the ratio of economic yield to the volume of water applied (irrigation + rainfall; Ko & Piccinni, 2009). *IWUE* is defined as the increase in yield under irrigated production compared to that under dryland production (Bos, 1980). This expression has also been used to relate yield to the volume of irrigation water applied (*IWA*; Tolk & Howell, 2003).

Playán & Mateos (2006) stated that the increase of *IWUE* can be achieved by both the increase of crop yield and the reduction of gross water use through improvements in irrigation efficiency, which has been studied in the companion paper (Pascual-Seva *et al.,* 2013, this issue).

In order to acquire an estimate of the volume of water applied by growers during chufa cultivation a preliminary study was carried out in 2005 (Ballester, 2006). First, a representative opinion survey was carried out among the growers of the region to determine typical irrigation frequencies. With these results, two strategies (which combined the grower's solutions) were assayed: irrigating with summer frequencies of 10 days (F2), and 14 days (F1). Irrigation at the F2 frequency provided 20% higher total irrigation (804 mm in F1 and 966 in F2), leading to a yield increment of 36.6% (F2 with regard to F1). While the yield obtained for F2 (2.2 kg m^{-2}) was considered to be good, the corresponding yield for F1 (1.61 kg m^{-2}) was considered low.

The objective of this paper was to analyze the productive response (tuber yield and tuber unit weight) of the chufa crop to two irrigation strategies (IS) and to establish a schedule of irrigation for growers. In a companion paper (Pascual-Seva *et al.,* 2013, this issue), the current irrigation performance is analyzed and management recommendations are proposed to improve irrigation efficiency.

Material and methods

Experimental plot conditions

Field studies were conducted over three consecutive years (2006, 2007, and 2008) on two adjacent plots on a commercial farm. This farm is near the Valencia Polytechnic University campus in Spain (39° 29' N and

0° 20' W) and is representative of the plots in the region. One plot was used in 2006 and 2008, and the other plot was used in 2007 to avoid soil exhaustion problems related to crop repetition. According to the Papadakis' agroclimatic classification system (Elías & Ruiz, 1977), the climate is subtropical Mediterranean, with hot, dry summers and an average annual rainfall of approximately 450 mm, which is irregularly distributed throughout the year, with 40% of the rainfall occurring in the autumn.

The soil textural type is loamy sand in the 2006 and 2008 plot, and sand in the 2007 plot. The soils are deep, and they are classified as anthropic torrifluvents according to the USDA's Soil Taxonomy (Soil Survey Staff, 2010). The analyses performed in this study indicated that the soils had slightly or moderately alkaline *pH* levels and that they were fertile (moderate organic matter content and high available phosphorus and potassium concentrations). Their chemical characteristics are presented in Table 1.

In the study area, water comes from the Rascanya Canal, which flows from the Turia River (EC = 1.38 dS m^{-1}; $SAR_{(adjusted)}$ = 1.21; pH = 7.2). The irrigation water has no use restrictions due to salinity for non-sensitive crops, as chufa, or permeability (Ayers & Westcott, 1994). However, there are certain restrictions with regards to water delivery because the water delivery policy only allows irrigation from Monday through Thursday.

Standard cultivation practices described in the Introduction and in detail by Pascual *et al.* (1997) were followed throughout the crop period. Planting was performed on April 12th in 2006 (102nd day of the year; DOY), May 8th in 2007 (128th DOY), and April 11th in 2008 (102nd DOY). Delayed planting in 2007 experiment (in relation to those 2006 and 2008) was due to spring rainfall events. The furrow length was 66 m in 2006 and 2008, and 82.5 m in 2007.

Capacitance sensors were used for determining the beginning of each irrigation event [when the volumetric soil water content (*VSWC*) reached a set value (refill point; *RP*)]; while the irrigators choose the termination moment based on their own experience – which in turn reflects regional practices.

Table 1. Chemical soil characteristics at the beginning of the three experiments: pH, electrical conductivity (*EC*), organic matter (*OM*), available phosphorus (P), and exchangeable potassium (K)

Experimental year	pH	*EC* (dS m^{-1})	*OM* (%)	P (mg kg^{-1})	K (mg kg^{-1})
2006	7.89	0.550	1.74	196	438
2007	7.88	0.592	0.79	241	293
2008	7.98	0.460	1.41	113	399

Basal dressing that consisted of 2 kg m^{-2} of sheep manure [57.2% dry weight (DW); 60.9% organic matter DW] and 90 g m^{-2} of 15:15:15 ($N:P_2O_5:K_2O$) was applied on the day before planting. The top dressing consisted of 3.12 g m^{-2} of N in the form of NO_3K, and it was applied along with the first two irrigation sessions of July in each season.

Treatments and measurements

The irrigation strategies were defined according to *VSWC*. In each IS, three ECH_2O EC-5 capacitance sensors with ECH_2O Utility software (Decagon Devices Inc., Pullman, WA, USA) were placed at a depth of 0.10 m [Pascual-Seva (2011) stated that the maximum root density and water uptake by chufa plants occurred at 10 cm depth] and they were connected to an Em50 data-logger (Decagon Devices Inc., Pullman, WA, USA) to monitor the *VSWC*. Variations in the *VSWC* were used to determine the *in situ* values corresponding to field capacity (*FC*), which is defined as the amount of water held in the soil after excess water has drained away and the rate of the downward movement of water has materially decreased (Veihmeyer & Hendrickson, 1931), reaching a plateau. Irrigation was scheduled so that each irrigation event began (*RP*) when the *VSWC* at the sensor that presented the values nearest to the average evolution, reached approximately 45% (H1) or 60% (H2) of the *FC*, considering that water delivery was restricted to a four-day on/three-day off schedule.The water flow was continuously measured by a flow meter (ISCO 2150 area velocity flow module; Teledyne ISCO Inc., Lincoln, NE, USA) located where the water entered the experimental plots.

Plants within a 1 m^2 area were periodically sampled from each experimental plot during the cultivation cycle. The plants were divided into three parts and analyzed separately: (i) shoots with all of their leaves (herein referred to as leaves), (ii) roots and rhizomes as a whole, given the difficulty of separating them (herein referred to as roots), and (iii) tubers. The plant height was measured and the shoots and tubers were counted at each sampling. After washing, each sampled plant part (leaves, roots, or tubers) was dried at 65°C in a forced-air oven until its weight remained constant to obtain the dry weight (DW). At harvest, the average tuber weight (*ATW*) was determined by counting and weighing tubers from a sample of approximately 500 g, and then tubers were oven-dried at 65°C to a constant weight for calculating the tuber dry-matter content (*TDMC*) on a fresh matter basis (%).

The end of the chufa irrigation period was considered to be the time when the straw was burned, before tuber harvesting. In this study, the dates of straw burning were November 2nd in 2006, November 6th in 2007, and November 7th in 2008. The tubers were harvested and washed on 22 and 23 November 2006, 18 and 19 December 2007, and 24 and 25 November 2008.

The harvest index (*HI*) was calculated for each sampling as the ratio of tuber yield to total biomass, including the root system, on a dry matter basis (g g^{-1}; Van der Veeken & Lommen, 2009).

By using data regarding the DW of each part of the plant, it was possible for the exponential growth phase to determine the mean relative growth rate (*RGR*; g g^{-1} d^{-1}) between samplings

$$RGR = \frac{\ln W_2 - \ln W_1}{(t_2 - t_1)} ,$$

where W_2 and W_1 were the total biomasses at sampling times t_2 and t_1, respectively (Williams, 1946; Radford, 1967; Causton, 1991).

Because the crop coefficient (K_c) of chufa is unknown, *WUE* was calculated as the relationship between fresh tuber yield and total water input (irrigation + rainfall; Ko & Piccinni, 2009), and *IWUE* was calculated as the relationship between fresh tuber yield and *IWA* (Cabello *et al.*, 2009; Ko & Piccinni, 2009).

Each IS (H1: $RP = 45\%$ of the *FC*; H2: $RP = 60\%$ of *FC*) was replicated four times in a split-plot design. Data were analyzed by analysis of variance (Statgraphics 5.1 plus; Statistical Graphics Corporation, 2005). Differences between means were compared by the LSD test at $p \leq 0.05$.

Results and discussion

The *FC* values were 0.28, 0.27, and 0.28 m^3 m^{-3} for 2006, 2007, and 2008, respectively. The corresponding *RP* values for each strategy and experiment are shown in Table 2. Considering that the root zone depth was estimated as the maximum development of root mass (20 cm based on phenological estimates), the average water depth required to fill the root zone was determined to be 22 mm for all irrigation sessions in H2, while in H1 31 mm were required in 2006 and 2008, and 30 mm in 2007.

Planting in 2007 was delayed relative to the plantings in 2006 and 2008 due to climatic conditions, causing a reduction in the cultivation cycle. The seasonal rainfall water input was 158, 498, and 438 mm in 2006, 2007, and 2008, respectively, the average annual rainfall in the area being 450 mm. In 2006, the measured rainfall was scarce (158 mm); in 2007, most of the rainfall (470 mm) occurred at the end of the cultivation period (Fig. 1) and therefore was not available to the plants. In 2008, there were two rainfall periods, one at the beginning of the growing period (145 mm), which led to a reduction in the number of irrigation events, and another one at the end of the cycle (240 mm).

Fig. 1 shows the *VSWC* during the vegetative stage in the three experimental years, as well as the water input from each rainfall event. Although water delivery was restricted to the four-day on/three-day off schedule, the *VSWC* value at the beginning of each session coincided closely with the scheduled irrigation programmes. For the three experimental years, *VSWC* showed similar evolution during the growing period, their values being within the 0.1-0.5 m^3 m^{-3} interval. There were 11 irrigation events for H1 in each experiment, while there were 14, 15, and 13 irrigation events for H2 in 2006, 2007, and 2008, respectively. The seasonal *IWA* for each IS and experimental year (EY) ranged from 937 to 1,200 mm for H1, and from 1,041 to

Table 2. Volumetric soil water content at field capacity (*FC*), refill point (*RP*), irrigation event number (No.) and irrigation water applied (*IWA*), for the two irrigation strategies (H1 and H2) in each experimental year (EY)

EY	*FC* (m^3 m^{-3})	H1			H2		
		RP (m^3 m^{-3})	No. events	*IWA* (mm)	*RP* (m^3 m^{-3})	No events	*IWA* (mm)
2006	0.28	0.126	11	937	0.168	14	1,041
2007	0.27	0.122	11	1,008	0.162	15	1,201
2008	0.28	0.126	11	1,200	0.168	13	1,320

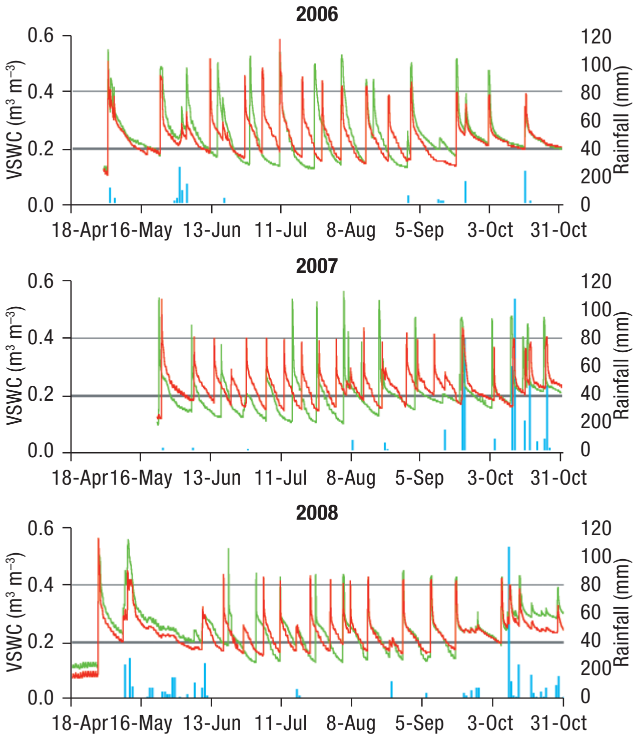

Figure 1. Volumetric soil water content (*VSWC*) and water input for each rainfall event, along the cultivation stage, corresponding to the sensors used to schedule the irrigation strategies H1 and H2, in 2006, 2007, and 2008 experiments, initiating each irrigation event when the *VSWC* at 0.10 m rose to 45 and 60% field capacity for the H1 (——) and H2 (——) strategies, respectively. | Rainfall.

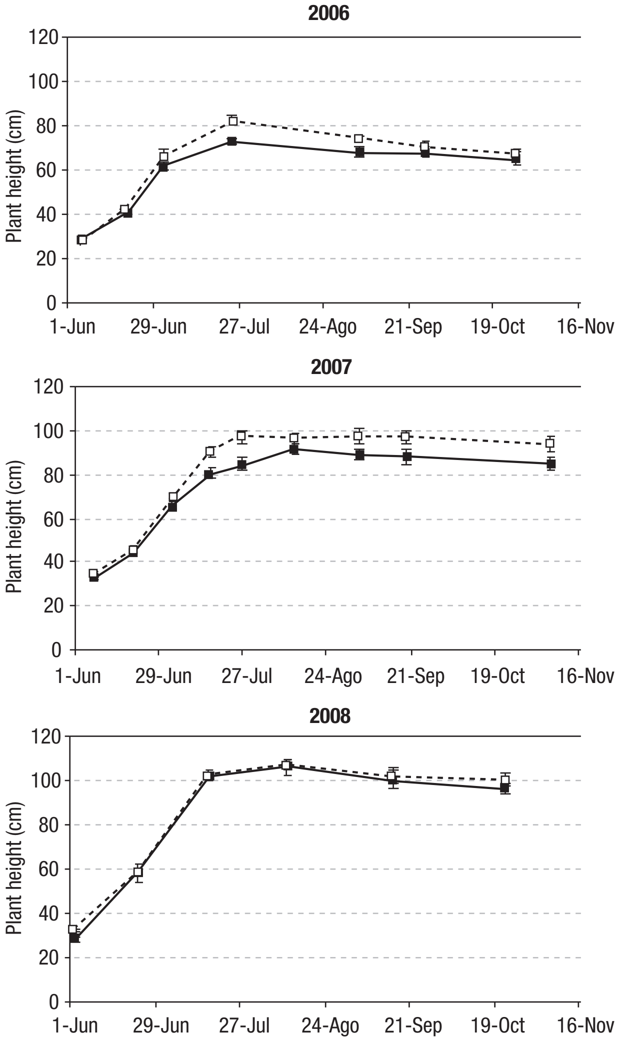

Figure 2. Changes in the plant height (cm) for the cultivation cycles in the 2006, 2007, and 2008 experiments. Each irrigation event started when the *VSWC* at 0.10 m rose to 45% (■ H1) and 60% (□ H2) field capacity. Vertical bars represent the standard error.

1,320 mm for H2, the last measurement being 13% (on average) higher than for H1 (Table 2). Values for H1 were similar to those obtained for F2 in 2005 (11 irrigation events and 965 mm; Ballester, 2006), when the irrigation schedule was based on frequency, and the seasonal rainfall water input was 135 mm, since the irrigation schedules were similar in practice.

Plant height increased in line with a seasonal sigmoid curve (Fig. 2); in two of the three experiments (2006 and 2007) plant height increased when the frequency of irrigation had been increased. Plants in the 2007 experiment were taller than those of 2006 and slightly shorter than those of the 2008 experiment – despite having been planted around a month later (planting performed on 102nd DOY, 128th DOY, and 102nd DOY of 2006, 2007, and 2008, respectively).

The DW of the plants increased during the cultivation phases up to approximately 1.5 kg m^{-2} (Fig. 3). Initially the aboveground biomass accounted for most of the plant biomass, but from a certain date (specifically at the beginning of September in 2006, the beginning of August in 2007, and at the end of August in 2008) the aboveground biomass was exceeded by the tuber biomass due to translocation processes in the tubers, as well as leaf senescence. On these dates EY had a greater impact than IS. There were no consistent differences in the response in biomass production to IS, however a trend can be seen of greater biomass production with higher water content threshold (greater aboveground biomass in 2008 and greater tuber biomass in the 2007 and 2008 experiments). These results agree with those obtained in drip irrigation studies (Pascual-Seva *et al.*, 2010) where a positive linear increase in biomass with *IWA* was observed. Greater tuber yield

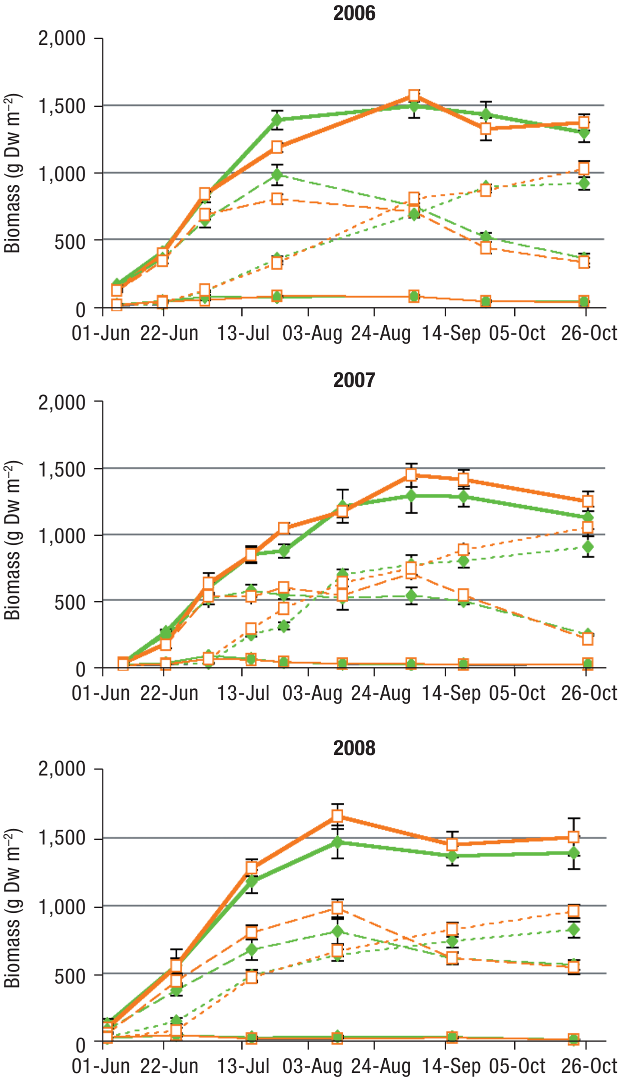

Figure 3. Biomass accumulation (——) and partitioning in leaves (- - -), roots (—), or tubers (····), corresponding to irrigation strategies H1 and H2, in 2006, 2007, and 2008 experiments, initiating each irrigation event when the *VSWC* at 0.10 m rose to 45 and 60% field capacity for the H1(■) and H2 (□) strategies, respectively. Vertical bars represent the standard error. The equations fitting ($p \leq 0.01$) the corresponding biomass accumulation for the whole plant [WP (g DW plant^{-1}); d: number of days after planting] for the exponential growing period (103, 97, and 98 days after planting for 2006, 2007, and 2008, respectively) were: 2006 [(H1: $WP = 40.971 \cdot e^{0.0344 \cdot d}$; $R^2 = 0.9707$), (H2: $WP = 49.561 \cdot e^{0.0313 \cdot d}$; $R^2 = 0.9238$)]; 2007 [(H1: $WP = 142.876 \cdot e^{0.0225 \cdot d}$; $R^2 = 0.9148$); (H2: $WP = 148.845 \cdot e^{0.0223 \cdot d}$; $R^2 = 0.8585$)]; 2008 [(H1: $WP = 25.187 \cdot e^{0.0412 \cdot d}$; $R^2 = 0.9728$), (H2: $WP = 19.279 \cdot e^{0.0313 \cdot d}$; $R^2 = 0.9923$)].

with higher water content threshold was confirmed at plot level ($p \leq 0.01$; Table 3).

Although plants in the 2007 experiment were taller than those of 2006 and slightly shorter than those of the 2008 experiment (as above mentioned and shown in Fig. 2) these plants produced a smaller aboveground biomass (Fig. 3) given that they had the fewest shoots (average maximum values of 1,284, 593, and 1,010, for 2006, 2007 and 2008, respectively). Consequently, it can be stated that delayed planting of chufa corresponds with less prolific tillering.

Growth of the whole plant, until approximately 100 days after planting (DAP; 103 for 2006, 97 for 2007, and 96 for 2008; for both IS), followed an exponential function over time (Fig. 3 legend), enabling the use of the *RGR* expression (Williams, 1946) as derived from this exponential relationship. The changes in the *RGR* values during these periods are presented in Fig. 4. The highest *RGR* value in each EY and IS (0.107 and 0.101 g g^{-1} d^{-1} for 2006 in H1 and H2, respectively; 0.153 and 0.142 g g^{-1} d^{-1} for 2007 in H1 and H2; 0.100 and 0.107 g g^{-1} d^{-1} for 2008 in H1 and H2) corresponded to the period between the first and second samplings, and it decreased afterwards. Delayed planting in 2007 caused a reduction in the cultivation cycle length, and consequently increased the *RGR* values. The *RGR* values were slightly higher than those determined for chufa in a soilless culture (0.09 g g^{-1} d^{-1}; Pascual-Seva *et al.*, 2009).

The yield, *ATW*, *TDMC*, *IWUE*, and *WUE* values, corresponding to the moment of commercial harvest, and *HI*, for the different irrigation strategies and experiments, are shown in Table 3. For all of the experiments, the last sampling demonstrated nearly complete root senescence and considerable leaf senescence. For this reason, the *HI* values presented in Table 3 correspond to the last sampling carried out in September (26th in 2006, 19th in 2007, and 15th in 2008).

The EY had a greater impact than IS on all analyzed parameters (higher % total sum of squares; Table 3). The EY affected ($p \leq 0.01$) both tuber yield and *ATW*, producing the highest yield in 2008 and the lowest value in 2006 (2.41 kg m^{-2} and 0.66 g for 2008 *vs.* 1.82 kg m^{-2} and 0.60 g for 2006, respectively). Both experiments were carried out in the same plot, and it has been reported that obtaining different yields for different years in any given plot is common (Pascual-Seva *et al.*, 2008). In 2007, when planting was delayed, the obtained yield (1.95 kg m^{-2}) was lower ($p \leq 0.05$) than that obtained in 2008 (2.41 kg m^{-2}). Pascual *et al.* (1997) reported a consistent increase in yield with an advance of planting from May to April.

The IS affected ($p \leq 0.01$) tuber yield; the H2 strategy resulted in the highest yield (on average 2.18 kg m^{-2}

Table 3. Influence of experimental year (2006, 2007 and 2008) and irrigation strategies (initiating each irrigation event when the volumetric soil water content at 0.1 m soil depth rose to 45% or 60% field capacity, in H1 and H2, respectively) on yield, average tuber weight (*ATW*), tuber dry-matter content (*TDMC*), irrigation water use efficiency (*IWUE*), water use efficiency (*WUE*), and harvest index (*HI*)

	Yield (kg m^{-2})	***ATW*** **(g)**	***TDMC*** **(%)**	***IWUE*** **(kg m^{-3})**	***WUE*** **(kg m^{-3})**	***HI*** **(–)**
Experimental year (EY)						
2006	1.82^{c}	0.60^{c}	58.02^{a}	1.84^{ab}	1.59^{a}	0.617
2007	1.95^{b}	0.64^{b}	55.04^{b}	1.77^{b}	1.22^{c}	0.611
2008	2.41^{a}	0.66^{a}	55.26^{b}	1.91^{a}	1.42^{b}	0.579
Irrigation strategy (IS)						
H1	1.94^{b}	0.62^{b}	55.41^{b}	1.84	1.39	0.602
H2	2.18^{a}	0.64^{a}	56.80^{a}	1.84	1.42	0.603

ANOVA Parameters (degrees of freedom)	**% Total sum of squares**					
EY (2)	74.3**	61.6**	52.3**	41.6*	86.7**	22.55 ns
IS (1)	17.1**	11.7**	13.9**	0.1 ns	1.1 ns	0.0002 ns
EY× IS (2)	2.3 ns	16.9**	5.1 ns	2.6 ns	1.5 ns	8.82 ns
Residuals (12)	6.4	9.9	28.7	55.7	10.8	68.62
SD	0.09	0.01	1.23	0.09	0.06	0.036

HI corresponds to the penultimate sampling (September: 26th in 2006, 19th in 2007, and 15th in 2008). Different letters in the same column indicate significant differences ($p \leq 0.05$) according to the LSD test. All weight values are on fresh weight basis. ns: no significant difference. ** (*): significant at $p \leq 0.01$ ($p \leq 0.05$). SD: standard deviation.

vs. 1.94 kg m^{-2} for H1). The difference represented 12% of the value, on average. As with the tuber yield, the *ATW* was affected ($p \leq 0.01$) by the IS, but it was also affected ($p \leq 0.01$) by the EY-IS interaction, exhibiting differences ($p \leq 0.05$) among IS only in 2007 and 2008 (not in 2006), with higher values for H2 (0.66 and 0.68 g for 2007 and 2008, respectively) than for H1 (0.61 and 0.65 g for 2007 and 2008, respectively). These results agree with those obtained by Shock *et al.* (1998) in a study carried out on onions (a vegetable grown for its underground organs) that compared the effect of different water potential thresholds (ranging from –12.5 to –100 kPa) for furrow irrigation. Shock *et al.* (1998) reported increases in marketable yields and percentages of large bulbs with increasing irrigation thresholds. The incremental increase in yield with increasing *IWA* agrees with the results obtained in a concurrent study carried out on drip irrigation (Pascual-Seva *et al.*, 2010), which demonstrated a positive linear increment in yield with *IWA* and is also in accordance with those reported by Leskovar *et al.* (2011) who obtained a modest decline in onion yield (8%) when using water-conserving practices (75% ETc rate) with a subsurface drip. Leskovar *et al.* obtained a larger decline (23%) after adopting more restrictive irrigation rates (50% ETc). This increase also agrees with studies by Clemmens & Molden (2007) and Fereres (2008), who reported that, for many crops, marketable yield is often directly related to water consumption. However, in those studies, the authors cited relationships between the yield and consumed water, while in this study the tuber yield has been correlated with the *IWA* because the unknown K_c of the chufa crop prevented calculation of the water consumption.

The incremental increase of yield with increasing *IWA* lead to similar *IWUE* (*WUE*) values in both IS. There were differences in *IWUE* ($p \leq 0.05$) and *WUE* ($p \leq 0.01$) between EY, with values of *IWUE* ranging from 1.77 kg m^{-3} (2007) to 1.91 kg m^{-3} (2008) and *WUE* values from 1.42 kg m^{-3} (2007) to 1.59 kg m^{-3} (2006). These results demonstrate the different behavior of *IWUE* and *WUE* in different years (the highest *WUE* value in 2006 and the highest *IWUE* value in 2008), which supports the results presented by Payero *et al.* (2008) who stated that opposite results can be found. During the 2007 and 2008 experiments, only a small fraction of the rainfall was used in evapotranspiration because most of the rainfall occurred at the end of the growing season, when it did not contribute to increasing the yield, as Tolk & Howell (2003) indicated.

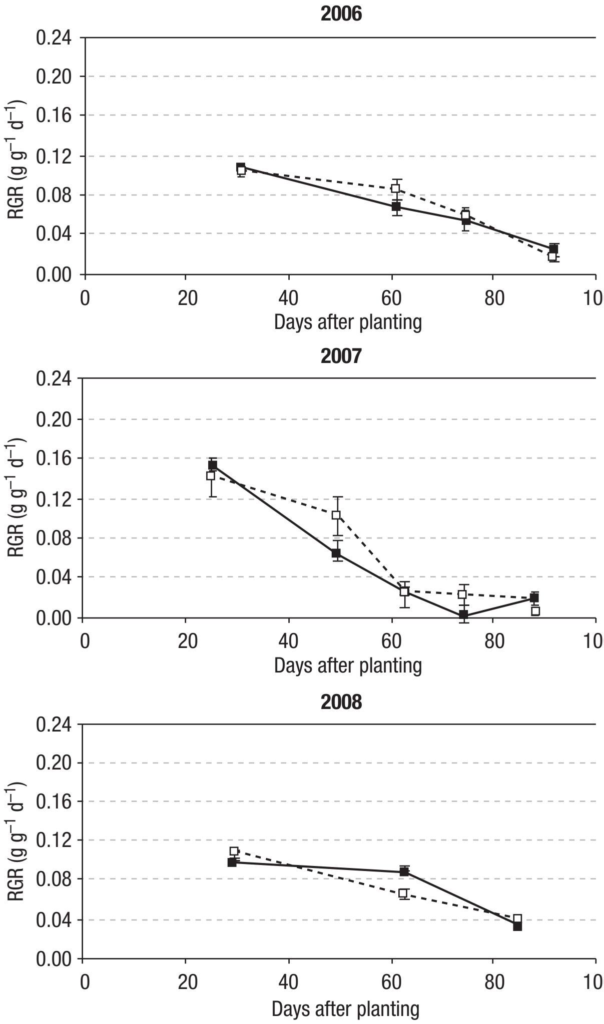

Figure 4. Changes in the relative growth rate (*RGR*, g g^{-1} d^{-1}) values for exponential growth phase (103, 97, and 98 days after planting for 2006, 2007, and 2008, respectively). Each irrigation event started when the *VSWC* at 0.10 m rose to 45% (■ H1) and 60% (□ H2) field capacity. Vertical bars represent the standard error.

Given the current price of tubers and the cost of irrigation, the profit that increase irrigation thresholds generates (with increased yields) is greater than the associated cost increase. If water delivery restrictions or price increases were imposed then lower irrigation thresholds could represent an adequate strategy.

The EY also affected *TDMC* ($p \leq 0.01$), showing the highest value in 2006 (58.0%) and the lowest in 2007 (55.0%). This result supports those obtained in the study on bed cultivation that was simultaneously conducted (Pascual-Seva, 2011). The *TDMC* value depends on the degree of tuber maturity and on tuber water loss before harvest, which in turn depend on the *VSWC*. Due to the scarce measured rainfall at the end of the 2006 growing cycle, the lowest *VSWC* occurred, favoring drying of the tubers, which consequently produced the highest *TDMC* value. The *TDMC* was also affected by the IS ($p \leq 0.01$); H2 resulted in the highest value (56.8% *vs.* 55.4% for H1), which was most likely related to the higher maturation degree of the H2 tubers at harvesting. In fact, H1 demonstrated higher percentages of small tubers (≤ 6 mm; 5.45%) than did H2 (4.34%), which is related to a delay in tuber growth and maturation. Given the existence of a positive linear increment in horchata production yield with *TDMC*, this parameter should be considered in chufa tuber trade relations

The *HI* values ranged, on average, from 0.58 (for 2008) to 0.62 (for 2006; Table 3), and they were not affected ($p \leq 0.05$) by the experimental year, although there were notable differences among the values obtained in the different experiments. Since the first studies carried out on chufa crops by the research group (Pascual, 1981), important differences have been detected among the values obtained in different years [with average *HI* values (tubers/leaves + tubers, on a dry-weight basis) of 0.56 and 0.64, for 1979 and 1980, respectively]. The *HI* values were slightly lower than those obtained in soilless culture (0.67; Pascual-Seva, 2011). The IS also had no repercussions on *HI*. This result agrees with Fereres (1998), who reported that, in most cases the *HI* was not more strongly affected by irrigation deficits than biomass production, and he concluded from a review of numerous experiments carried out on different crops that the *HI* value was not affected by drought until biomass production was reduced below 60-70% of the value obtained without water limitations, which did not occur in either of the two experimental irrigation strategies.

As final conclusions, considering the thresholds assessed, it can be stated that maintaining a higher *VSWC* would increase both yield and *ATW* without affecting the *IWUE* due to the parallel increase in *IWA*. Yields obtained with the highest assayed water content threshold exceeded the absolute maximum yield in grower's fields.

The *TDMC* may vary considerably with the rainfall at the end of the growing cycle, and with the harvesting date. Therefore, this difference could be reflected in the sale price of tubers because this parameter directly affects horchata production yield.

Although great performance improvements are not expected due to high yields obtained with the less restrictive strategy and because of the lack of a drop in *IWUE*, further research would be advisable to evaluate other irrigation schedules, such as those using higher *VSWC* thresholds, or the use of other irrigation systems such as drip irrigation.

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References

Ayers RS, Westcott DW, 1994. Water quality for agriculture. FAO Irrig Drain Paper 29. FAO, Rome. 97 pp.

Ballester R, 2006. Influencia de la frecuencia y del manejo de los riegos en la nutrición, crecimiento y rendimiento de la chufa (*Cyperus esculentus* L. var. *sativus* Boeck.). Thesis. Escuela Técnica Superior de Ingenieros Agrónomos, Univ Politécnica de Valencia, Valencia, Spain. 76 pp. [In Spanish].

Bos MG, 1980. Irrigation efficiencies at crop production level. International Commission on Irrigation and Drainage 29: 18-25.

Cabello MJ, Castellanos MT, Romojaro F, Martínez-Madrid C, Ribas F, 2009. Yield and quality of melon grown under different irrigation and nitrogen rates. Agric Water Manage 96: 866-874.

CAPA, 2010. Orden 17/2010, de la Conselleria de Agricultura, Pesca y Alimentación, por la que se aprueba el texto del reglamento de la Denominación de Origen Protegida Chufa de Valencia y su consejo regulador. Diari Oficial de la Comunitat Valenciana, Spain. Num. 6273/24.05.2010:21055-21069. [In Spanish].

Causton DR, 1991. Plant growth analysis: the variability of relative growth rate within a sample. Ann Bot 67: 137-144.

Clemmens AJ, Molden DJ, 2007. Water uses and productivity of irrigation systems. Irrig Sci 25: 247:261.

Elías F, Ruiz L, 1977. Agroclimatología de España. Cuadernos INIA No. 7. INIA, Madrid. 565 pp. [In Spanish].

Fereres E, 1998. El agua y la productividad de los cultivos. In: Agricultura sostenible (Jiménez Díaz RM, Lamo de Espinosa J, eds). Mundi-Prensa, Madrid. pp: 213-225. [In Spanish].

Fereres E, 2008. The future of irrigation in horticulture. Chron Hortic 48(3): 9-11.

Ko J, Piccinni G, 2009. Corn yield responses under crop evapotranspiration-based irrigation management. Agric Water Manage 96: 799-808.

Leskovar DI, Agehara S, Yoo K, Pascual-Seva N, 2011. Crop coefficient-based deficit irrigation and planting density for onion: growth, yield, and bulb quality. HortScience 46: 1-7.

Pascual B, 1981. Estudio para la mejora de las técnicas de fertilización y cultivo de la chufa (*Cyperus esculentus* L.) en la provincia de Valencia. Doctoral thesis. Univ Politécnica de Valencia, Valencia, Spain. 345 pp. [In Spanish].

Pascual B, Maroto JV, López-Galarza S, Alagarda J, Castell Zeising V, 1997. El cultivo de la chufa. Estudios realizados. Generalitat Valenciana, Conselleria de Agricultura, Pesca y Alimentación, Valencia, Spain. 95 pp. [In Spanish].

Pascual B, Maroto JV, López-Galarza S, San Bautista A, Alagarda J, 1999. Chufa (*Cyperus esculentus* L. var. *sativus* Boeck): an unconventional crop. Studies related to applications and cultivation. Econ Bot 54: 439-448.

Pascual B, López Galarza S, Alagarda J, San Bautista A, Maroto JV, Castell-Zeising V, 2000. Selection and characterization of "chufa" cultivars (*Cyperus esculentus* L. var. *sativus* Boeck.). Acta Hortic 523: 33-41.

Pascual-Seva N, 2011. Estudios agronómicos sobre el cultivo de la chufa (*Cyperus esculentus* L. var. *sativus* Boeck.): estrategias de riego, tipos de plantación, absorción de nutrientes, y análisis fitoquímico. Doctoral thesis. Univ Politécnica de Valencia, Valencia, Spain. 353 pp. [In Spanish].

Pascual-Seva N, San Bautista A, López-Galarza S, Maroto JV, Pascual B, 2008. El manejo del riego en el cultivo de la chufa (*Cyperus esculentus* L. var. *sativus* Boeck.). Agrícola Vergel 314: 53-57. [In Spanish].

Pascual-Seva N, Pascual B, San Bautista A, López-Galarza S, Maroto JV, 2009. Growth and nutrient absorption in chufa (*Cyperus esculentus* L. var. *sativus* Boeck.) in soilless culture. J Hort Sci Biotech 84: 393-398.

Pascual-Seva N, San Bautista A, López-Galarza S, Maroto JV, Pascual B, 2010. Application of FDR probes for evaluation of chufa (*Cyperus esculentus* L. var. *sativus* Boeck.) response to drip and furrow irrigation. In: Transactions The third international symposium on soil water measurement using capacitance, impedance and TDT, (Paltineanu IC, Vera J, eds). Ioan Caton Paltineanu & Juan Vera Muñoz. Murcia, Spain. pp: 2.2:1-14.

Pascual-Seva N, San Bautista A, López-Galarza S, Maroto JV, Pascual B, 2013. Furrow-irrigated chufa crops in Valencia (Spain). II: Performance analysis and optimization. Span J Agric Res 11(1): 267-277.

Payero JO, Tarkalson DD, Irmak S, Davison D, Petersen JL, 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield water use efficiency and dry matter production in a semiarid climate. Agric Water Manage 95: 95-908.

Playán E, Mateos L, 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric Water Manage 80: 100-116.

Radford PJ, 1967. Growth analysis formulae. Their use and abuse. Crop Science 7: 171-175.

Shock CC, Feibert EB, Saunders LD, 1998. Onion yield and quality affected by soil water potential as irrigation threshold. HortScience 33: 1181-1191.

Soil Survey Staff, 2010. Keys to soil taxonomy, 11th ed. USDA-NRCS, Washington DC, USA. 338 pp.

Statistical Graphics Corporation, 2005. Statgraphics Plus for Windows 5.1. Statistical Graphics, Rockville, MD, USA.

Stegman EC, Muxick JT, Stewart JI, 1980. Irrigation water management. In: Design and operation of farm irrigation systems (Jensen ME, ed). ASAE, St Joseph, MI, USA. pp: 763-816.

Tolk JA, Howell T, 2003. Water use efficiencies of grain sorghum grow in three USA southern Great Plains soils. Agric Water Manag 59: 97-111.

Van der Veeken AJH, Lommen WJM, 2009. How planting density affects number and yield of potato minitubers in a commercial glasshouse production system. Potato Res 52: 105-119.

Veihmeyer FJ, Hendrickson AH, 1931. The moisture equivalent as a measure of the field capacity of soils. Soil Sci 32: 181-193.

Williams RF, 1946. The physiology of plant growth with special reference to the concept of net assimilation rate. Ann Bot 10: 1-72.

Wills GD, 1987. Description of purple and yellow nutsedge (*Cyperus esculentus* and *C. rotundus*). Weed Technol 1: 2-9.