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 ≤ 0.01), and the average tuber weight (ATW) was affected (p ≤ 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 ≤ 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 Legislativa: 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
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 above-ground 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 \([\text{evapotranspiration} (ET) = \text{evaporation} + \text{transpiration}]\) (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.

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-P₂O₅-K₂O) was applied on the day before planting. The top dressing consisted of 3.12 g m⁻² of N in the form of NO₃K, and it was applied along with the first two irrigation sessions of July in each season.

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)

<table>
<thead>
<tr>
<th>Year</th>
<th>pH</th>
<th>EC (dS m⁻¹)</th>
<th>OM (%)</th>
<th>P (mg kg⁻¹)</th>
<th>K (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>7.89</td>
<td>0.550</td>
<td>1.74</td>
<td>196</td>
<td>438</td>
</tr>
<tr>
<td>2007</td>
<td>7.88</td>
<td>0.592</td>
<td>0.79</td>
<td>241</td>
<td>293</td>
</tr>
<tr>
<td>2008</td>
<td>7.98</td>
<td>0.460</td>
<td>1.41</td>
<td>113</td>
<td>399</td>
</tr>
</tbody>
</table>

Treatments and measurements

The irrigation strategies were defined according to VSWC. In each IS, three ECH₂O EC-5 capacitance sensors with ECH₂O 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 m² 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 (Kc) 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 m³ 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 m³ 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)

<table>
<thead>
<tr>
<th>EY</th>
<th>FC (m³ m⁻³)</th>
<th>H1</th>
<th></th>
<th>H2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RP (m³ m⁻³)</td>
<td>No. events</td>
<td>IWA (mm)</td>
<td>RP (m³ m⁻³)</td>
</tr>
<tr>
<td>2006</td>
<td>0.28</td>
<td>0.126</td>
<td>11</td>
<td>937</td>
<td>0.168</td>
</tr>
<tr>
<td>2007</td>
<td>0.27</td>
<td>0.122</td>
<td>11</td>
<td>1,008</td>
<td>0.162</td>
</tr>
<tr>
<td>2008</td>
<td>0.28</td>
<td>0.126</td>
<td>11</td>
<td>1,200</td>
<td>0.168</td>
</tr>
</tbody>
</table>
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
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 (26$^{th}$ in 2006, 19$^{th}$ in 2007, and 15$^{th}$ 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).

<table>
<thead>
<tr>
<th></th>
<th>Yield (kg m⁻²)</th>
<th>ATW (g)</th>
<th>TDMC (%)</th>
<th>IWUE (kg m⁻³)</th>
<th>WUE (kg m⁻³)</th>
<th>HI (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental year (EY)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>1.82a</td>
<td>0.60c</td>
<td>58.02a</td>
<td>1.84ab</td>
<td>1.59a</td>
<td>0.617</td>
</tr>
<tr>
<td>2007</td>
<td>1.95b</td>
<td>0.64b</td>
<td>55.04b</td>
<td>1.77b</td>
<td>1.22c</td>
<td>0.611</td>
</tr>
<tr>
<td>2008</td>
<td>2.41a</td>
<td>0.66a</td>
<td>55.26b</td>
<td>1.91a</td>
<td>1.42b</td>
<td>0.579</td>
</tr>
<tr>
<td><strong>Irrigation strategy (IS)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>1.94b</td>
<td>0.62b</td>
<td>55.41b</td>
<td>1.84</td>
<td>1.39</td>
<td>0.602</td>
</tr>
<tr>
<td>H2</td>
<td>2.18a</td>
<td>0.64a</td>
<td>56.80a</td>
<td>1.84</td>
<td>1.42</td>
<td>0.603</td>
</tr>
</tbody>
</table>

**ANOVA**

<table>
<thead>
<tr>
<th>Parameters (degrees of freedom)</th>
<th>% Total sum of squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>EY (2)</td>
<td>74.3**</td>
</tr>
<tr>
<td>IS (1)</td>
<td>19.1**</td>
</tr>
<tr>
<td>EY × IS (2)</td>
<td>2.3 ns</td>
</tr>
<tr>
<td>Residuals (12)</td>
<td>6.4</td>
</tr>
<tr>
<td>SD</td>
<td>0.09</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yield (kg m⁻²)</strong></td>
<td><strong>ATW (g)</strong></td>
</tr>
<tr>
<td><strong>TDMC (%)</strong></td>
<td><strong>IWUE (kg m⁻³)</strong></td>
</tr>
<tr>
<td><strong>WUE (kg m⁻³)</strong></td>
<td><strong>HI (–)</strong></td>
</tr>
<tr>
<td>EY (2)</td>
<td>74.3**</td>
</tr>
<tr>
<td>IS (1)</td>
<td>19.1**</td>
</tr>
<tr>
<td>EY × IS (2)</td>
<td>2.3 ns</td>
</tr>
<tr>
<td>Residuals (12)</td>
<td>6.4</td>
</tr>
<tr>
<td>SD</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**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 ≤ 0.05) according to the LSD test. All weight values are on fresh weight basis. ns: no significant difference. ** (*): significant at p ≤ 0.01 (p ≤ 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 ≤ 0.01) by the IS, but it was also affected (p ≤ 0.01) by the EY-IS interaction, exhibiting differences (p ≤ 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 IWUE because the unknown Kc of the chufa crop prevented calculation of the water consumption.

The incremental increase of yield with increasing IWUE lead to similar IWUE (WUE) values in both IS. There were differences in IWUE (p ≤ 0.05) and WUE (p ≤ 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 Payervo 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.
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 \((\leq 6 \text{ mm}; 5.45\%)\) 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.

**Figure 4.** Changes in the relative growth rate \((RGR, \text{ g g}^{-1} \text{ d}^{-1}\)) 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% \((\square H1)\) and 60% \((\Box H2)\) field capacity. Vertical bars represent the standard error.
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.

Acknowledgements

This study was funded by the Regulatory Council of Denomination of Origin Chufa of Valencia of Spain.

References


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.