Science of the Total Environment 768 (2021) 144975

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Determination of crop coefficient for chufa crop (*Cyperus esculentus* L. var. *sativus* Boeck.) for sustainable irrigation scheduling

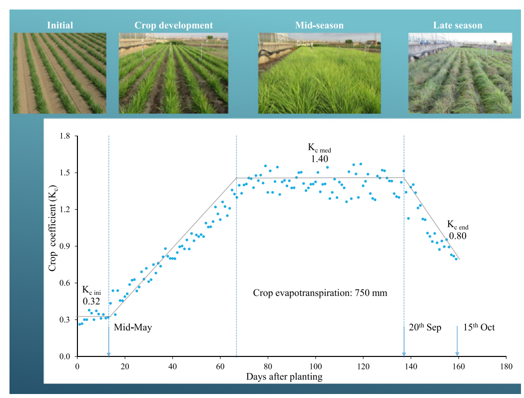
Nuria Pascual-Seva *, Bernardo Pascual

*Centre Valencià d'Estudis sobre el Reg. Universitat Politècnica de València, Camí de Vera s/n, 46022 València, Spain*

## HIGHLIGHTS

- Seasonal $ET_c$ for the chufa crop is approximately 750 mm.
- Chufa single crop coefficients ($K_c$) are determined using a smart field lysimeter.
- $K_{c\ ini}$, $K_{c\ med}$ and $K_{c\ end}$ are 0.32, 1.4 and 0.8, respectively, for local conditions.
- For standard conditions, $K_{c\ med}$ and $K_{c\ end}$ are 1.24 and 0.73, respectively.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 15 October 2020
Received in revised form 22 December 2020
Accepted 30 December 2020
Available online 30 January 2021

Editor: LEONOR RODRIGUEZ-SINOBAS

*Keywords:*
Tuber
Evapotranspiration
Irrigation water requirements
Smart field lysimeter
Water savings

## ABSTRACT

Chufa is a traditional crop in *L'Horta de València* (Spain), a historical agricultural system that has been recognised in the register of Globally Important Agricultural Heritage Systems, managed by the Food and Agriculture Organization of the United Nations (FAO), and is one of the six protected Mediterranean and metropolitan horticultural fields as per the European Environment Agency. Chufa is a horticultural crop cultivated for its tubers. Our team has carried out different studies to improve the sustainability of chufa crop, particularly the efficiency of irrigation water use; however, the complete irrigation water requirements remain unknown. Therefore, the main aim of this study was to determine the crop coefficient values for chufa crop along its crop cycle using a smart field weighing lysimeter for three consecutive seasons and to determine its irrigation water requirements. The single crop coefficient values are 0.32, 1.40, and 0.80 for the initial stage, mid-season stage, and end of the late season stage, respectively for local conditions and 1.24 and 0.73 for mid- and late season stages, respectively for standard conditions. FAO segmented and second-order polynomial functions are presented to describe the crop coefficient evolution throughout the cycle, and could be used for irrigation scheduling and may lead to important water savings. The average seasonal net irrigation water requirement for chufa crop was approximately 640 mm, representing around 57% of the irrigation depth usually applied by chufa growers. The water savings that may be achieved by the adjustment of irrigation water with irrigation water requirements, using the crop coefficient, would improve, to a great extent, the sustainability of the *L'Horta de València* historical agricultural system, in view of the water scarcity resulting from climate change. This sustainable irrigation scheduling will improve the ecosystem indices, which have been altered by the application of over-irrigation, in the area.


* Corresponding author.
*E-mail address:* nupasse@upv.es (N. Pascual-Seva).

https://doi.org/10.1016/j.scitotenv.2021.144975

## 1. Introduction

Chufa (*Cyperus esculentus* L. var. *sativus* Boeck.), also known as tiger nut, tigernut, or yellow nutsedge, is a traditional crop in *L'Horta de València,* Spain (hereafter referred to as L'Horta). L'Horta is a historical agricultural system that was recognised in November 2019 on the register of Globally Important Agricultural Heritage Systems (GIAHS), managed by the Food and Agriculture Organization of the United Nations (FAO), and recognised as one of the six protected Mediterranean and metropolitan horticultural fields by the European Environment Agency (FAO, 2020a). L'Horta covers an area of 28 $km^2$, of which 546 ha (approximately 19.5% of the L'Horta area) is dedicated annually to chufa cultivation (MAPA, 2020). It is a traditional peri-urban irrigated agricultural landscape located around the Valencia city boundaries. This area is made up of many micro-plots, with an average size of 0.4 ha, and its maximum size does not exceed 0.8 ha [Regulatory Council of Denomination of Origin Chufa of Valencia (RCDOCV), personal communication]. This smallholding system comprises the existence of many roads, paths, and irrigation ditches, constituting an integral element of L'Horta, general configuration of which must be maintained (Generalitat Valenciana, 2016). To avoid soil replant disorders, crop rotation is practiced; hence, chufa plots are usually surrounded by other crops with different crop cycles. Therefore, micro-plot structure and crop rotation lead to small expanses of vegetation surrounded by shorter or dry cover. L'Horta encompasses an ancient and complex irrigation system that performs environmental and food functions, making it a symbol of life and sustainability (Romero and Melo, 2015). This irrigation system originated in the 8th century, when Muslims built eight irrigation channels along the Turia River, and since then, the irrigation applied in the area has been regulated by the Tribunal of Waters (*Tribunal de les Aigües*), which has been recognised as a UNESCO world immaterial heritage since 2009 (Angelakis et al., 2020; Sala, 2012). In spite of these recognitions, some authors have reported the crisis of L'Horta landscape (Francés and Romero, 2014) owing to the combination of different pressures, such as high water demand and the progressive socio-economic dissociation between citizens and L'Horta (increasing the perception that agriculture "wastes" water).

Water scarcity and drought are spreading worldwide, and climate change suggests further increase in aridity and frequency of extreme events, such as low rainfall amounts, long drought periods, and high temperatures (WWAP, 2016). Currently, agriculture uses large amounts of water [about 65% of the available freshwater in Spain and 69% worldwide (FAO, 2020b)]; therefore, the European Water Framework Directive 2000/60 (The European Parliament and the Council of the European Union, 2000), currently in force, encourages the use of water-saving tools in agriculture to avoid water shortages.

Chufa is an herbaceous plant cultivated for its tubers, which are mainly used to produce a non-alcoholic beverage called "horchata" or "horchata de chufa" (tiger nut milk or orgeat). In recent years, "horchata" and chufa tubers, have become popular in other countries, such as France, the United Kingdom, the United States of America, and Argentina (da Costa Neto et al., 2019). On a small scale, traditionally, chufa tubers have also been consumed fresh, and recently, they have been introduced into signature cuisine and in the production of modern spirit drinks and high quality oil, used in both food and cosmetics (Pascual-Seva, 2011).

Locally, the economic impact is rather important because it represents a retail market value of 60 million euros (da Costa Neto et al., 2019). Chufa is also cultivated in Burkina Faso, China, Egypt, Ghana, Ivory Coast, Mali, Niger, Nigeria, Senegal, Sudan, Turkey, and the United States of America (De Castro et al., 2015; Duman, 2019; El-Shenawy et al., 2019; Liu et al., 2019).

Chufa is considered an unconventional crop (Pascual et al., 2000), although it is not included in the lists of minor crop. Nonetheless, the high added value of chufa justifies the publication of many articles on its use in food technology (Adebayo-Oyetoro et al., 2019; Duman, 2019; Zhu et al., 2019), medicine, and pharmacology (Badejo et al., 2020; El-Shenawy et al., 2019; Oluwajuyitan and Ijarotimi, 2019), and other industries (Okoro et al., 2019; Tian et al., 2019), evidencing the increasing interest in its cultivation.

Our team has carried out different studies to increase the sustainability of chufa crop (Pascual et al., 2000), particularly by improving irrigation and irrigation water use efficiency, both in furrow and in drip irrigation (Pascual-Seva et al., 2018, 2013). It is noteworthy that chufa cultivation extends from April to November, and as a summer crop, it requires large amounts of irrigation water. Although important improvements in water management were reported in those studies, their findings were not conclusive because the evapotranspiration ($ET_c$) of the chufa crop remains unknown. Therefore, a research line aiming to determine the irrigation water needs of chufa crop was initiated in 2016, with preliminary results presented by Pascual-Seva et al. (2019).

Estimation of $ET_c$ and consequently crop irrigation water requirements (Pereira et al., 2020) is of great importance in agricultural water management (Hashim et al., 2012) at the regional level. The standard method for estimating $ET_c$ was reported in FAO56 (Allen et al., 1998) and involves the calculation of a grass reference evapotranspiration ($ET_o$) and a specific crop coefficient ($K_c$). This approach has recently been updated by Pereira et al. (2021a, 2021b). $ET_o$ is routinely calculated using the FAO-Penman-Monteith equation, as suggested in FAO56. Daily local $ET_o$ values are available for Valencian chufa growers through the SIAR (Spanish Agro-climatic Information System for Irrigation) network (IVIA, 2011). The objective of the $K_c$ is to transfer costly evapotranspiration (ET) measurements by normalising them with the $ET_o$ (Jensen and Allen, 2016). The $K_c$ value for a variety of crops grown under different climatic conditions was initially suggested by Doorenbos and Pruitt (1977) and updated in FAO56. These values are commonly used in places where local data are not available (Groh et al., 2015); however, chufa has not been reported among these crops. It is noteworthy that a reliable calculation of $ET_c$ strongly depends on the appropriate estimation of $K_c$ values**,** which may vary by ecosystem, climatic conditions, and crop growth stage development (Groh et al., 2015). Doorenbos and Pruitt (1977) and Allen et al. (1998) emphasised the strong need to develop $K_c$ values for specific climatic conditions (Tyagi et al., 2000).

Currently, $K_c$ values are based on $ET_c$ measurements, using sensitive weighing lysimeters or micrometeorological related methods (e.g., eddy covariance system) (Jensen and Allen, 2016). Weighing lysimeters, which are blocks of soil that are covered by vegetation and placed back into the soil with their surface exposed to the atmosphere (Doležal et al., 2018), directly determine the ET of a crop using a water balance at the block level and measuring changes in its mass. This technique has been employed for measuring crop water use since its first deployment in Coshoctan (Ohio, USA) in 1937 (Bryla et al., 2010). There are different types of lysimeter in terms of size, bottom boundary conditions, and technology applied, each with their corresponding advantages and disadvantages. The present experiment used a smart field lysimeter (SFL), which considers a small representative soil volume that does not require a large, and expensive, supporting structure (Doležal et al., 2018).

The objective of this study was to determine the single crop coefficient of chufa crop using an SFL, which would be used in irrigation scheduling for adjusting the irrigation water applied with the irrigation water requirements, to improve chufa crop sustainability.

## 2. Materials and methods

The study was conducted for three consecutive years (2017, 2018, and 2019) in a research field (0.24 ha) located next to the campus of the Universitat Politècnica de València, Spain (39°29′N, 0°20′W), within the main and traditional chufa production area in L'Horta of approximately

242 ha, including the northeastern part of the peri-urban area of Valencia city.

Planting was performed on 12th May 2017, 19th April 2018, and 8th May 2019 as soon as it was possible in each year, using, as customary today, tubers acquired from local traders and that has not been subjected to any pre-sowing treatment. Tuber planting was traditionally carried out on the first fortnight of May, but Pascual et al. (1997) reported the advantage of planting in advance, when allowed by crop rotation and rain, because it led to an increase in yield. The end of the irrigation period was considered for all the three years to be the 15th day of October, which is consistent with the typical practice by local growers, to accelerate the natural drying of the leaves that are removed on the second week of November, when the RCDOCV allows harvesting process to begin. At the end of the irrigation period, all plants had reached their full maturity in all three seasons. Tubers were harvested on the last week of November. Fig. 1 presents an estimate of the plant height and the ground cover fraction for the chufa crop.

According to the UNESCO-FAO classification (Gaussen et al., 1963), the climate in the area is Warm temperate: Mediterranean xeric type and accentuated sub-desert subtype, with hot, dry summers, and an average annual rainfall of approximately 450 mm, irregularly distributed throughout the year.

Next to the SFL, tubers were planted in ridges measuring 0.20 m high and spaced 0.60 m apart at a spacing of 0.10 m within the ridge (corresponding to 120 kg tubers $ha^{-1}$), with three tubers planted (equally spaced at 0.10 m apart) in the SFL. The soil at the site was deep, classified as Anthropic Torrifluvents according to the USDA Soil Taxonomy (Soil Survey Staff, 2014). At the beginning of this study, the soil presented a moderately alkaline pH and was highly fertile [pH = 8.07; EC (1:5; 0.22 dS $m^{-1}$), organic matter = 2.01%, total calcium carbonate = 23.01%, active calcium carbonate = 2.90%, phosphorous (sodium bicarbonate) = 232 ppm, and potassium (ammonium acetate) = 345 ppm]. The soil texture was sandy loam in the most superficial 0.50 m (analysed every 0.10 m depth).

Cultural operations (planting, weeding, harvesting, etc.) were manually performed on the SFL and on the immediate surrounding area to simulate field practices (Pascual and Pascual-Seva, 2017) and ensure that crop development was similar to that in the surrounding field, as reported by Howell et al. (1991), and as close as possible to standard conditions [the crops grown in large fields under excellent agronomic and soil water conditions (Allen et al., 1998)]. Thus, no differences were detected between the plants cultivated in the SFL and those grown in the surrounding field. Fertigation was based on Hoagland's No. 2 nutrient solution (Maynard and Hochmuth, 2006) [EC: 2.31 dS $m^{-1}$; pH adjusted to 6.1; macronutrient concentrations (all in mM): $NO_3^-$, 14.0; $H_2PO_4^-$, 1.0; $SO_4^{2-}$, 2.45; $K^+$, 6.0; $Ca^{2+}$, 4.0; $Mg^{2+}$, 2.0; micronutrient concentrations (all in μM): $Fe^{2+}$, 15; $Mn^{2+}$, 10; $Zn^{2+}$, 5; $B^{3+}$, 30; $Cu^2+$, 0.75; $Mo^{6+}$, 0.5] applied throughout the crop cycle. The irrigation water [EC = 1.6 dS $m^{-1}$; SAR (adjusted) = 2.9; pH = 7.4] was pumped from a well, not showing any restriction in terms of salinity for non-sensitive crops such as chufa or permeability (Ayers and Wescott, 1994), thus leaching was not required.

Irrigation water management in the SFL was automated jointly with the surrounding area, as reported by Pascual-Seva et al. (2018). The volumetric soil water content in the field was continuously monitored with a multi-depth capacitance probe (Cprobe; Agrilink Inc. Ltd., Adelaide, Australia), installed inside a PVC access tube and placed on a ridge. The probe had a sensor installed at 0.10 m below the top of the ridge and 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. Each irrigation event started when the soil moisture at 0.10 m soil depth had decreased to 85% of its field capacity [15.4%, 13.7%, and 13.3%, in 2017, 2018, and 2019, respectively; determined in situ as Pascual-Seva et al., 2018 reported]. At that point, a dose of 10 mm was applied over 40 min in the field. The field was 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 SFL was irrigated using a dripper (Navia, Sistema Azud S.A., Murcia, Spain) with flow identical to those used in the surrounding area (2.2 L $h^{-1}$).

To determine the chufa $ET_c$, a monolithic lysimetric station (SFL-600E; METER Group Inc., München, Germany; Fig. 2) was acquired and installed at a minimum of 15 m from the experimental field borders. This SFL consists of a stainless-steel cylinder (height 600 mm, inner diameter 300 mm, volume of soil 42 L), placed over a weighing platform (PL100, resolution ±1 g, accuracy ±14 g; UMS GmbH, 2014) inside a stainless-steel field enclosure. The cylinder is connected to a leachate tank, which is located above another weighing platform (PL10; resolution ±1 g, accuracy ± 1.7 g; UMS GmbH, 2014) to record deep percolation losses. The system includes a pumping system for bidirectional regulation of the lower hydraulic boundary, which is controlled by the field matric potential that automatically maintains true field conditions within the lysimeter. In this study, the SFL recorded the weights of the cylinder and that of the leachate tank every minute. Both weighting platforms were mechanically tested at the start of each season using calibrated weights.

To avoid the small weight fluctuations produced by wind, insects, etc. (Howell et al., 1995), we decided to determine the water balance every hour according to the expression (UMS GmbH, 2014):

$$ET_c = P - L - DS$$

where P is the precipitation plus irrigation (mm); L is the leachate (mm); DS is the lysimeter weight change (mm). P was determined as the increase in mass of the lysimeter plus L, and this quantity was only considered when the value was greater than 0.21 mm because values less than this could not be classified as either precipitation or irrigation

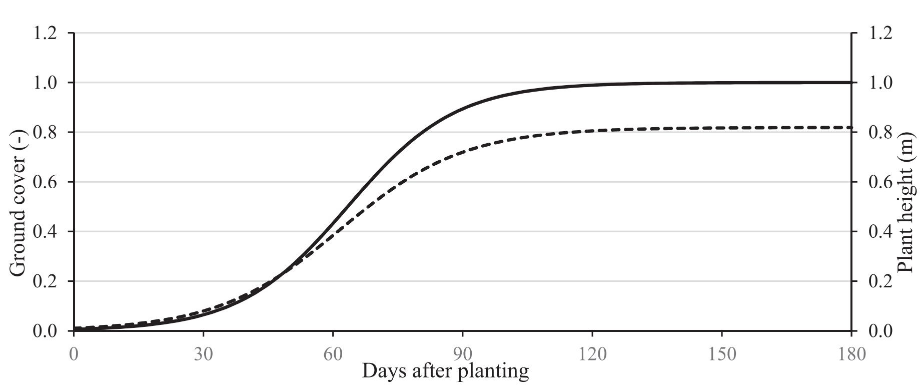



**Fig. 1.** Chufa ground cover fraction (straight line) and plant height (dashed line) along the growing season. Average values.


**Fig. 2.** Smart field lysimeter used in the study without (A) and with chufa plants (B). View of the experimental plot with the landscape surrounding it (C).

(UMS GmbH, 2014). L was determined hourly by the weight differences between the leachate tank. DS was directly calculated as the hourly difference of the lysimeter weight. For the different parameters, the weight units were transformed into water depth units (mm) by taking the specific gravity of water as 1 g cm$^{-3}$ and the cylinder surface as 0.07 m$^2$ (based on a 300 mm diameter). Once P, L, and DS were known, and neglecting the plant biomass increment as reported by Vaughan and Ayars (2009), the $ET_c$ was determined. The SFL readings were checked daily to identify individual readings that could not be explained by natural processes of water input and loss (Vaughan and Ayars, 2009) and by the assumption that no ET occurs during precipitation and irrigation events (Groh et al., 2015). This procedure was done according to Allen et al. (2011) for data quality assessment and quality control. Hourly $ET_c$ values were added to determine the daily $ET_c$ values.

An agro-meteorological station (Decagon Devices Inc., Washington, USA) was installed next to the SFL over a reference grass surface within the experimental field. This station included the sensors needed to obtain the data required for the $ET_o$ calculation: a VP-4 sensor, for monitoring vapour pressure, humidity, temperature, and atmospheric pressure; an ECRN-100 High-Resolution Rain Gauge; a Davis Cup anemometer; and a PYR pyranometer. These sensors were distributed between 1.75 and 2 m from the ground, to which the anemometer was placed. Sensors were calibrated by the supplier before each season started. Furthermore, a data logger, which transfers the data through GPRS, was incorporated into the setup, and the data were downloaded with the software DataTrac 3 version 3.13 (Decagon Devices Inc., Washington, USA). Daily $ET_o$ (mm day$^{-1}$) was determined using the FAO-56 Penman-Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where Δ is the slope of the saturation vapour pressure–temperature relationship at mean air temperature (kPa °C$^{-1}$), $R_n$ is the net radiation at the crop surface (MJ m$^{-2}$ d$^{-1}$), G is the soil heat flux (MJ m$^{-2}$ d$^{-1}$), T is the average air temperature (°C), $u_2$ is the wind speed at 2 m height (m s$^{-1}$), ($e_s$-$e_a$) is the vapour pressure deficit (kPa), and γ is the psychrometric constant (kPa °C$^{-1}$).

The quality of weather data were assessed before their use in the equation, following that reported by Allen (2008) and Allen et al. (2011). Solar radiation ($R_s$) measurements were plotted against theoretically derived solar radiation for clear sky ($R_{so}$), and the higher measured $R_s$ values did not differ by more than 5% from $R_{so}$. All the relative humidity values recorded during the experiment were reasonable, ranging from 35% to 85%. Temperature records did not exceed the recorded extremes for the region in any case, and the average of the daily extremes ($T_{max}$ and $T_{min}$) coincides with the average of the data logger for the day. In relation to wind speed, most of the daily mean values are greater than 1 m s$^{-1}$, and they are very close to those reported by SIAR (IVIA, 2011) for the nearest station (30 km apart).

After the $ET_c$ and $ET_o$ values were determined, daily $K_c$ values for each season were calculated by dividing the $ET_c$ values by the $ET_o$ estimates (Allen et al., 1998).

$$Kc = \frac{ET_c}{ET_o}$$

The four growth stages of the chufa crop, which include initial, crop development, mid-season, and late season stages, were established from the FAO-segmented $K_c$ curve in accordance with Allen et al. (1998). This curve presents the daily $K_c$ value versus the day after planting (DAP) for each year. The duration of the growing stages was first approximated from on-site inspection of the ground surface area covered by vegetation (López-Urrea et al., 2009) for the initial and crop development stages, and to the phenological stage for the mid- and late-season stages (Allen et al., 1998). The initial stage starts at planting and continues until 10% of the soil surface is covered by the crop. The crop development stage runs from that moment to full effective cover (when the leaves in adjacent rows start to intermingle); the mid-season stage covers the period from full cover to the start of leaf senescence, and the late season stage runs until the end of the irrigation period (15th October). After the first approximation, growth stages were established based on the change in the slope of the $K_c$-DAP function, as stated by Abdelhadi et al. (2000). Analyses were performed using the method of Muggeo (2003) as implemented in the R package segmented v1.2–0 (Muggeo, 2020).

## 3. Results and discussion

### 3.1. Agro-meteorological conditions during the three growing seasons

A summary of monthly agro-meteorological conditions (average temperature, wind speed, solar radiation, and minimum relative humidity) during the three growing seasons are shown in Table 1. These values are representative of those reported in the area in the last few years. The different seasonal rainfall values registered in the three seasons are not extraordinary in the area. Fig. 3 presents the average daily air (at 2 m height) and soil (at 0.05 m soil depth; measured inside the lysimeter) temperature during each growing season.

**Table 1**
Average temperature, wind speed (at 2 m height), solar radiation, minimum relative humidity, and total rainfall during the three growing seasons. Daily average values for each month of each growing season.

| | Temperature (°C) | | | Wind speed ($m\ s^{-1}$) | | | Solar radiation ($MJ\ m^{-2}\ day^{-1}$) | | | Relative humidity (%) | | | Rainfall (mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2019 | 2017 | 2018 | 2019 | 2017 | 2018 | 2019 | 2017 | 2018 | 2019 | 2017 | 2018 | 2019 |
| April | 15.68 | 16.54 | 15.84 | 1.31 | 1.66 | 1.76 | 15.87 | 18.49 | 16.34 | 49.50 | 48.06 | 50.39 | 21.40 | 17.40 | 58.00 |
| May | 20.07 | 19.13 | 18.82 | 1.51 | 1.43 | 1.53 | 24.91 | 22.80 | 22.96 | 51.53 | 49.91 | 50.86 | 8.20 | 25.30 | 20.00 |
| June | 24.54 | 23.22 | 22.32 | 1.44 | 1.52 | 1.39 | 26.58 | 24.88 | 25.95 | 51.83 | 53.66 | 50.52 | 24.40 | 90.60 | 0.00 |
| July | 25.90 | 26.48 | 26.46 | 1.38 | 1.50 | 1.33 | 23.29 | 25.04 | 23.70 | 58.60 | 56.20 | 55.05 | 1.00 | 1.80 | 5.40 |
| August | 26.05 | 27.10 | 26.45 | 1.25 | 1.38 | 1.25 | 19.31 | 20.73 | 20.70 | 61.20 | 55.48 | 55.94 | 22.40 | 15.20 | 4.80 |
| September | 23.26 | 24.35 | 23.92 | 1.32 | 1.07 | 1.19 | 16.17 | 14.61 | 14.36 | 51.61 | 63.53 | 57.21 | 4.80 | 120.40 | 78.60 |
| October | 20.55 | 19.12 | 20.65 | 0.98 | 1.17 | 1.04 | 10.14 | 9.37 | 9.35 | 57.14 | 55.09 | 52.28 | 12.60 | 182.60 | 23.20 |
| Seasonal[a] | 24.20 | 23.20 | 23.70 | 1.32 | 1.35 | 1.31 | 20.91 | 20.63 | 20.56 | 56.19 | 55.47 | 53.67 | 62.20 | 263.40 | 126.40 |

[a] from planting (12th May 2017, 19th April 2018 and 8th May 2019) to 15th October.

### *3.2. Reference evapotranspiration, crop evapotranspiration, net irrigation requirements, and number of irrigation events*

The daily values for $ET_o$, $ET_c$, and precipitation in 2017, 2018, and 2019 are shown in Fig. 4. The peak $ET_o$ values were closed to 9.5, 8, and 7 mm $d^{-1}$ in 2017, 2018, and 2019, respectively, owing to days with high temperature, high wind speed, and low relative humidity. The lowest $ET_o$ values were related to cloudy days with low solar radiation and low temperature. Daily oscillation was greater for the $ET_c$ than that for the $ET_o$ because after each irrigation event (in particular, 2 h after the irrigation ended), the $ET_c$ increased significantly, and then decreased over time until the next event. The seasonal $ET_o$, $ET_c$, and effective precipitation values (registered in the SFL) are presented in Table 2. The highest $ET_c$ (782 mm) occurred in 2018, although this year presented the overall lowest net irrigation requirements (602 mm) owing to its greater effective precipitation compared to that of the other years.

In each growing season in the SFL and in the surrounding field, irrigation was carried out 53, 43, and 34 times in 2017, 2018, and 2019, respectively. Table 3 shows the date of each irrigation event during the three growing seasons.

### *3.3. Crop coefficient for the chufa crop according to FAO segmented curve*

The crop cycle was divided into the four growing stages, for which the last day [in dates, day of the year (DOY), DAP, and growing degree days (GDD, °C-d; calculated by taking the integral of average daily temperatures above a base temperature of 10 °C; Elias and Castellví, 1996)] is presented in Table 4.

Following a three-year study, Pascual et al. (2000) stated that chufa tuber sprouting increased (in terms of percentage and earliness) with increasing temperatures, with 30 °C being the approximate optimum temperature. This study reported higher sprouting percentages at 30 °C than at 20 °C, which in turn were higher than at 15 °C. Delaying of planting makes tubers to establish at higher temperatures, increasing sprouting (Pascual et al., 2000) and growth rate (Jansen, 1971), thus reducing the duration of the initial stage. Planting was carried out on different dates each year; 2017 and 2019 could be considered as late-planting seasons, while 2018 was an early planting season. The planting dates depended on many factors, such as harvesting of the previous crop in crop rotation and soil moisture, owing to rainfall. In all three seasons, 10% soil coverage was achieved on similar dates (between 15th and 21st May; Table 4) when the average soil temperature at 0.05 m soil depth reached 25 °C, which corresponds to an average air temperature of 19 °C; thus, the initial stage was longer in 2018 than in 2017 or 2019. The initial stage in 2018 comprised three irrigation events, whereas only one was carried out in the other years during this stage. Considering that irrigation was implemented with a nutrient solution, the plants in 2018 received three times the amount of fertiliser than those in 2017 or 2019 and may have led to faster crop development and a consequent reduction in the development stage (by as many as 27 days compared to 2019). In all the three years, senescence started around the Autumnal equinox (18th – 23th September; Table 4), when day and night were of equal length with temperature decline (as is well known and recorded in the agro-meteorological station), leading to a longer mid-season stage in 2018. The duration of the late season was similar in all the three years, lasting from 22 to 27 days, owing to their similar date of initialisation and the establishment of the end of the crop cycle on a fixed date (15th October) to accelerate the natural process used for drying of the leaves.

The seasonal initial, mid-season, and end of the late stage $K_c$ values are presented in Table 5. These average values are, 0.32, 1.40, and 0.80, respectively, which are similar to those obtained in the preliminary study [0.25, 1.43, and 0.75, respectively; Pascual-Seva et al., 2019].

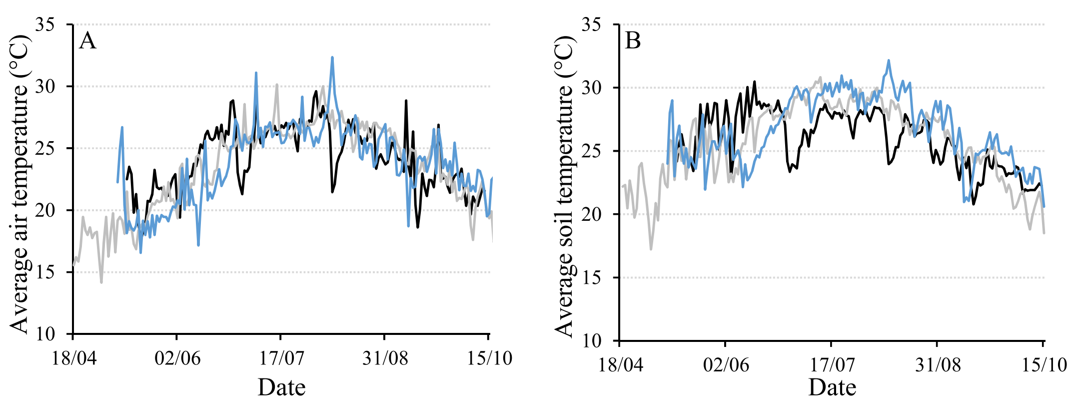



**Fig. 3.** Average air (at 2 m height; A) and soil (at 0.05 m soil depth; B) daily temperature during the study periods in 2017 (black), 2018 (grey), and 2019 (blue).

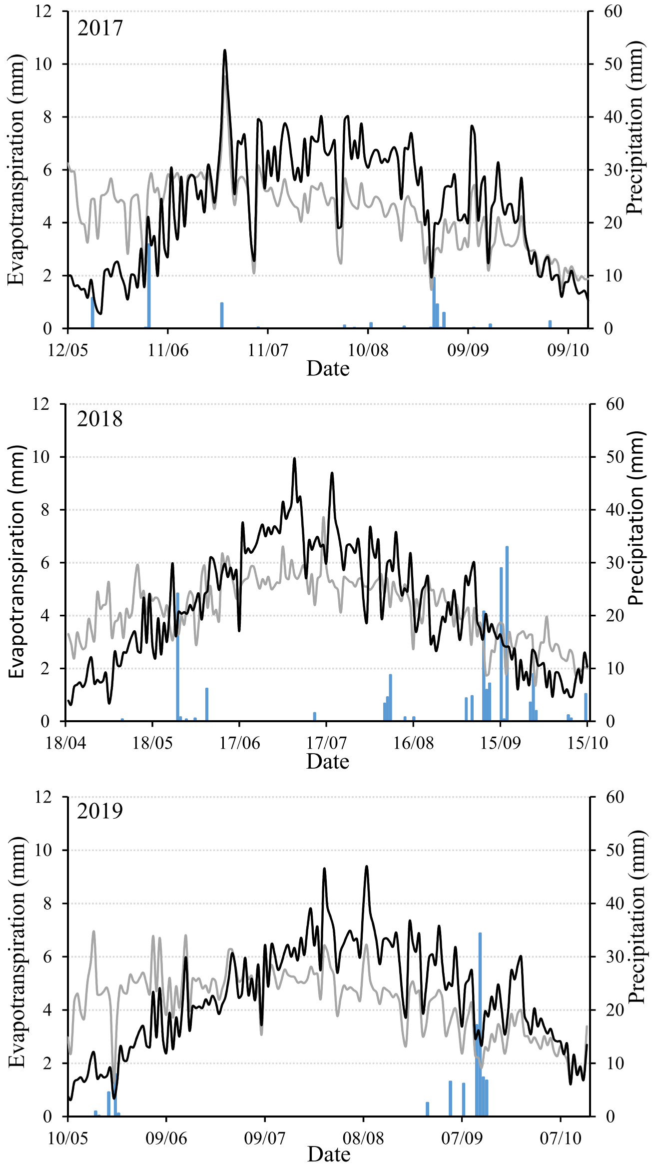



**Fig. 4.** Daily reference ($ET_o$; grey) and crop ($ET_c$; black) evapotranspiration during the experimental periods. Vertical bars represent the daily precipitation.

**Table 2**
Reference evapotranspiration ($ET_o$), crop evapotranspiration ($ET_c$), effective precipitation (Pe), and net irrigation requirements (NIR = $ET_c$-Pe) according to study year.

| Year | $ET_o$ (mm) | $ET_c$ (mm) | Pe (mm) | NIR (mm) |
|---|---|---|---|---|
| 2017 | 680.45 | 724.58 | 48.52 | 676.06 |
| 2018 | 773.07 | 781.92 | 179.80 | 602.12 |
| 2019 | 710.86 | 737.16 | 95.60 | 641.56 |

The initial $K_c$ ($K_{c\ ini}$) was consistent over the three years, as expected, given that the crop management practices were equally applied. This low value is in accordance with the fact that the crop was drip-irrigated, with only a small fraction of the area being wetted, and therefore having reduced evaporation (the main component of ET in this stage). During the late season stage, $K_c$ decreased from 1.40 to 0.80 ($K_{c\ end}$), which corresponded to an intermediate senescence stage because the end of this stage is considered to occur when irrigation is no longer applied to allow for the natural drying of the plants. Thus, this approach accelerates the senescence process to allow the aerial part to be removed, which is necessary before tuber harvesting (Pascual and Pascual-Seva, 2017). The mid-season $K_c$ ($K_{c\ mid}$) value was 1.4, which is generally considered too high; nevertheless, to understand this value, both climatic and smallholding characteristics must be considered. According to Allen et al. (2011) and Pereira et al. (2021a), under arid and semiarid conditions, differences in aerodynamic and surface resistances coupled with potentially strong regional advection may cause the $K_c$ value to be as high as 1.2. Even exceptionally high values can reach values of 1.4 for tall, dense, healthy, and well-watered vegetation. This is the case of the present study, in which chufa plants were subjected to a Mediterranean xeric climate type, are tall, reaching 0.80 m in height, and were maintained healthy and well irrigated.

Smallholding structure and crop rotation imply that fields are surrounded by other crops and traditional paths, which may increase the $K_c$ value owing to advection effect. As Allen et al. (2011) stated, small expanses of vegetation surrounded by shorter or dry cover may cause a "clothesline effect" and ET may be significantly greater than the corresponding $ET_o$. According to Loomis and Connor (2002), most of the microclimatic transition are considered a few meters from the edge of the crop, but the necessary distance for a true stationary regime in the wind profile and in the value of the microclimatic factors can be several hundred meters, which may not be reached within the normal size of cultivated fields of mot agricultural systems, particularly in L'Horta.

Allen et al. (1998) emphasised the strong need to develop $K_c$ values for specific crop conditions, and given that the experimental field is a representative of the chufa crop cultivation area in L'Horta (characterised by micro-plots, crop rotations, and many historical paths), the obtained values are representative of the crop in the area, even though its size does not meet the standard condition of large fields. To transfer to other regions with standard climate conditions and large fields, $K_{c\ mid}$ and $K_{c\ end}$ values were adjusted as reported by Pereira et al. (2021a), resulting in values of 1.46 and 0.86, respectively. Considering that these values can be affected by micro-scale advection or clothesline effect, and following the criteria to correct the excess $K_c$ indicated by Pereira et al. (2021a), they can be reduced by 15% to result in $K_{c\ mid}$ in 1.24 and $K_{c\ end}$ in 0.73.

Following the report of Allen et al. (1998), $K_{c\ ini}$, $K_{c\ med}$ and $K_{c\ end}$ may be fixed in a graph. Diagonal lines are drawn from $K_{c\ ini}$ to $K_{c\ mid}$ within the crop development stage and from $K_{c\ mid}$ to $K_{c\ end}$, within the late season stage. The daily 4-stage $K_c$ values (derived from the data measured by the SFL) and best-fit lines for each growing stage plotted against the DAP values are shown in Fig. 5. The expression that

**Table 3**
Date of each irrigation event during the three growing seasons.

| | 2017 | 2018 | 2019 |
|---|---|---|---|
| April | – | 20 | – |
| May | 21,26,31 | 2,11,21,26 | 8,23,30 |
| June | 8,11,14,17,18,20,22,24,27,28,29 | 2,14,17,19,21,23,25,27,29 | 5,7,13,16,20,23,25,28,29 |
| July | 1,3,5,8,10,12,14,16,18,20,22,25,27,29,31 | 1,4,6,8,11,14,16,18,20,23,25,27,29,31 | 2,4,10,12,15,17,19,22,24,26,28,30 |
| August | 3,4,6,8,10,11,13,15,17,19,21,23,25,27 | 3,5,8,11,14,17,20,22,25,27,30 | 2,5,8,11,14,17,20,25,31 |
| September | 1,3,5,8,10,12,15,18,22,25,29 | 2 | 26 |
| October | 5 | 2.7 | – |

**Table 4**
Final day of each growth stage in dates, day of the year (DOY), days after planting (DAP), and growing degree days (GDD; °C-d) for each growing stage according to study year.

| | Initial | | | | Development | | | | Mid-season | | | | Late season | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Date | DOY | DAP | GDD | Date | DOY | DAP | GDD | Date | DOY | DAP | GDD | Date | DOY | DAP | GDD |
| 2017 | 21-May | 141 | 9 | 104 | 16-Jul | 197 | 65 | 905 | 18-Sep | 261 | 129 | 1893 | 15-Oct | 288 | 156 | 2219 |
| 2018 | 15-May | 135 | 26 | 213 | 20-Jun | 171 | 62 | 617 | 21-Sep | 264 | 153 | 2090 | 15-Oct | 288 | 177 | 2382 |
| 2019 | 21-May | 141 | 13 | 113 | 21-Jul | 202 | 74 | 916 | 23-Sep | 266 | 138 | 1912 | 15-Oct | 288 | 160 | 2197 |

**Table 5**
Initial, mid-season, and end of the late season single crop coefficient values according to study year.

| Year | Initial | Mid-season | End |
|---|---|---|---|
| 2017 | 0.32 | 1.40 | 0.8 |
| 2018 | 0.32 | 1.39 | 0.8 |
| 2019 | 0.32 | 1.42 | 0.8 |

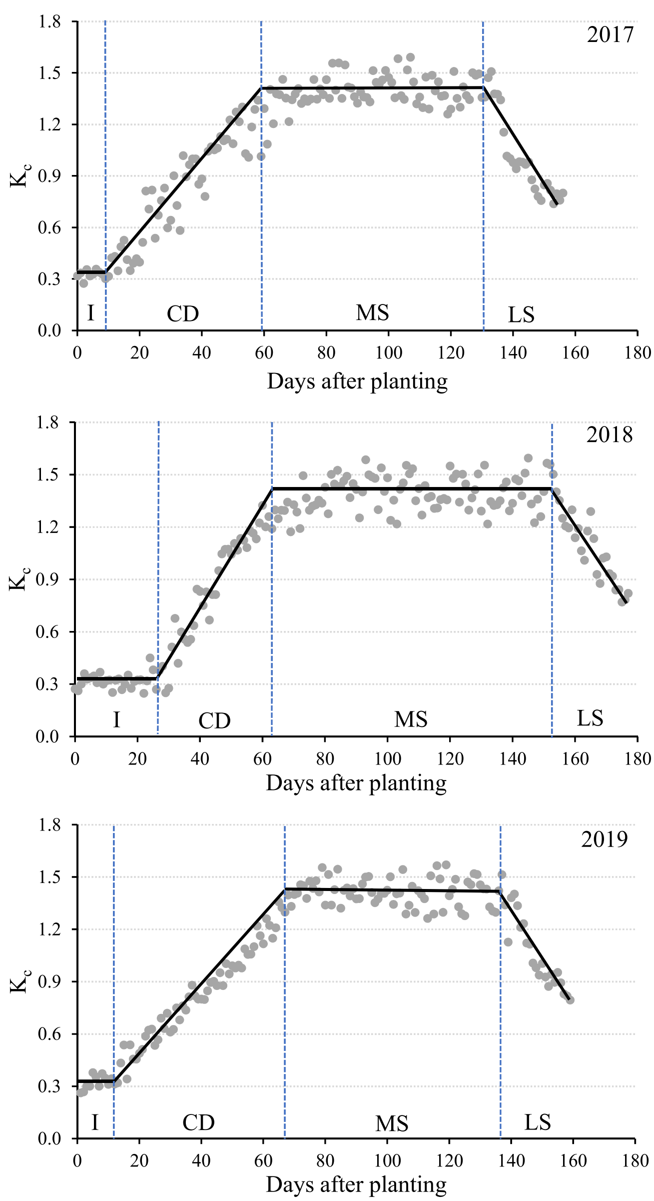



**Fig. 5.** Daily crop coefficient ($K_c$) values and their best-fit lines in relation to days after planting for each growth stage: initial (I), crop development (CD), mid-season (MS), and late season (LS) stages according to study year.

defines the $K_c$ values in relation to the DAP during these stages for each season and their corresponding adjustment are presented in Table 6.

The slope of the crop development stage for 2018 was greater than that for the other years, although the initial and final $K_c$ values for this stage were similar for all the three years; however, plant growth was faster in 2018, accelerating the increment of $K_c$ value. The slope in the late season stage is rather similar for all the three years, owing to the similarities in both the $K_c$ values and stage length. Therefore, a general relationship that considers the data for all the three years has also been considered:

Crop development stage: $K_c = 0.0183\ \text{DAP} + 0.1164$ (r: 0.91; $P \leq 0.01$)

Late stage: $K_c = -0.0083\ \text{DAP} + 2.3172$ (r: 0.49; $P \leq 0.01$)

The low correlation coefficient obtained for the late season stage is related to the duration of the different seasons. When DOY is considered instead of DAP, the relationships are as follows:

Crop development stage: $K_c = 0.016\ \text{DOY} + 1.7883$ (r: 0.86; $P \leq 0.01$)

Late stage: $K_c = -0.0261\ \text{DOY} + 8.2642$ (r: 0.89; $P \leq 0.01$)

From these relationships, it can be stated that $K_c$ is better related to DAP during the crop development stage, whereas it is better related to DOY during the late season stage.

### *3.4. Crop coefficient for chufa crop according to polynomial functions*

Crop coefficient values have been presented for the four stages of the growth cycle, but other methods are currently recommended for the estimation of $K_c$ value for annual crops as a function of DAP, DOY, or GDD (Pereira et al., 2021a). Thus, polynomial functions were adjusted to describe the evolution of $K_c$ throughout the cycle, in relation to DAP, DOY, and GDD. The best fit corresponds to second-order polynomial functions, both for each year and for the entire study period (Fig. 6). Considering the positive adjustments for all data, these polynomial functions can be used to determine the daily $K_c$, and in turn, the daily $ET_c$ for chufa crop.

### *3.5. Recommendations for irrigation scheduling*

The use of the presented $K_c$ values and the local $ET_o$ available through the SIAR (IVIA, 2011) would allow chufa growers to schedule irrigation and adjust irrigation depth to the irrigation requirements. Given that the seasonal $ET_c$ and the net irrigation requirements for the chufa crop are approximately 750 and 640 mm, respectively and that the latter represents between 53% and 61% of the irrigation depth usually applied by chufa producers (ranging from 1050 to 1200 mm; Pascual-Seva et al., 2013), this irrigation management would allow water savings greater than 40%, and therefore, increase crop sustainability in L'Horta in view of the water scarcity owed to climate change.

Our team has started the procedures to include, after publication, the $K_c$ values presented in this study in the SIAR (IVIA, 2011). Thus, growers can directly obtain the net irrigation requirements for sustainable irrigation water management. The RCDOCV will also spread these results among chufa producers. Furthermore, the $K_c$ adjusted to standard climate conditions could be applied to chufa cultivated under different conditions. Although these $K_c$ values are readily usable for chufa crop, future studies will focus on determining the dual $K_c$, which will be one step for the assessment of the ecosystems in the area.

**Table 6**
Linear regression of crop coefficient ($K_c$) and days after planting (DAP) for crop development and late season stages according to study year.

| Year | Crop development | | Late season | |
|---|---|---|---|---|
| 2017 | $K_c = 0.019DAP + 0.1575$ | (r: 0.95; $P \leq 0.01$) | $K_c = -0.0309DAP + 5.4309$ | (r: 0.92; $P \leq 0.01$) |
| 2018 | $K_c = 0.028DAP - 0.3982$ | (r: 0.96; P ≤ 0.01) | $K_c = -0.0245DAP + 5.1224$ | (r: 0.91; P ≤ 0.01) |
| 2019 | $K_c = 0.017DAP + 0.1557$ | (r: 0.99; P ≤ 0.01) | $K_c = -0.0272DAP + 5.0862$ | (r: 0.92; P ≤ 0.01) |

## 4. Conclusions

In this study, the single crop coefficient for chufa was obtained, and the values are 0.32, 1.40, and 0.80 for the initial stage, mid-season stage, and end of the late season stage, respectively for local conditions and 1.24 and 0.73 for mid- and late season stages, respectively for standard conditions. The FAO segmented and second-order polynomial functions are presented to describe the evolution of $K_c$ throughout the cycle. The

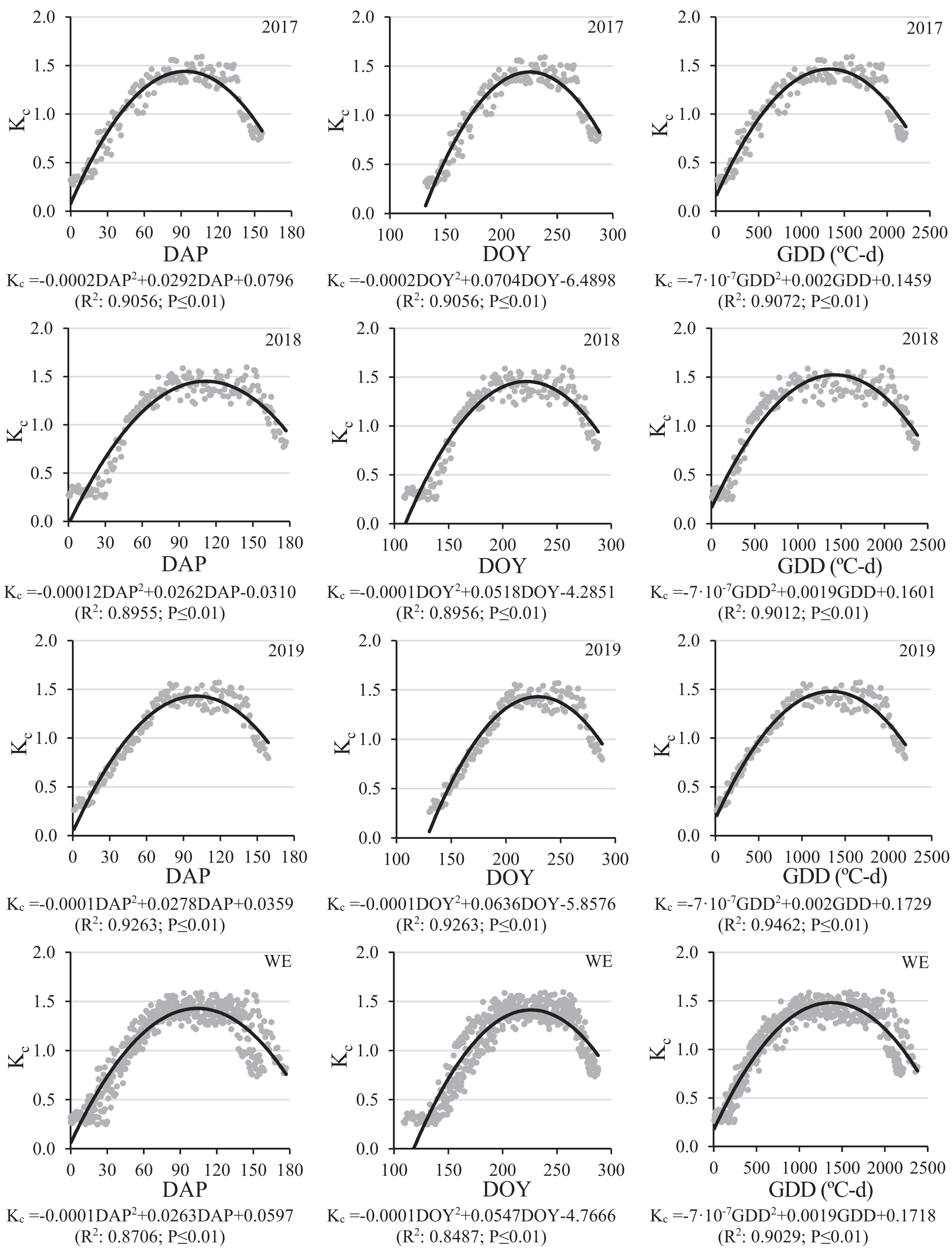



**Fig. 6.** Second-order polynomial functions correlating crop coefficient to the number of days after planting (DAP), days of the year (DOY), and growing degree-days (GDD) for each growing season and for the whole experiment (WE).

use of the presented $K_c$ in irrigation scheduling may allow the adjustment of irrigation depth to meet irrigation requirements, saving water by up to nearly 50%, and increasing crop sustainability in the *L'Horta de València* historical agricultural system in view of water scarcity resulting from climate change. This irrigation scheduling may also be applied in other areas where chufa is cultivated, improving their agroecosystems.

## Aknowledgements

This work was supported by the Generalitat Valenciana [GV/2017/037]. Authors would like to thank Dr. Palero for introducing them to R software.

## CRediT authorship contribution statement

**Nuria Pascual-Seva:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Bernardo Pascual:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References


Abdelhadi, A.W., Hata, T., Tanakamaru, H., Tada, A., Tariq, M.A., 2000. Estimation of crop water requirements in arid region using Penman-Monteith equation with derived crop coefficients: a case study on Acala cotton in Sudan Gezira irrigated scheme. Agric. Water Manag. 45, 203–214. https://doi.org/10.1016/S0378-3774(99)00077-3.

Adebayo-Oyetoro, A.O., Ogundipe, O.O., Adeyeye, S.A.O., Akande, E.A., Akinyele, A.B., 2019. Production and evaluation of tigernut (*Cyperus esculentus*) milk flavoured with *moringa oleifera* leaf extract. Curr. Res. Nutr. Food Sci. 7, 265–271. https://doi.org/10.12944/CRNFSJ.7.1.26.

Allen, R.G., 2008. Quality assessment of weather data and micrometeorological flux- impacts on evapotranspiration calculation. J. Agric. Meteorol. 64, 191–204.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop requirements. FAO Irrigation and Drainage Paper nº 56. FAO, Rome, Italy.

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting: II. Recommended documentation. Agric. Water Manag. 98, 921–929. https://doi.org/10.1016/j.agwat.2010.12.016.

Angelakis, A.N., Zaccaria, D., Krasilnikoff, J., Salgot, M., Bazza, M., Roccaro, P., Jimenez, B., Kumar, A., Yinghua, W., Baba, A., Harrison, J.A., Garduno-Jimenez, A., Fereres, E., 2020. Irrigation of world agricultural lands: evolution through the Millennia. Water (Switzerland) 12. https://doi.org/10.3390/W12051285.

Ayers, R.S., Wescott, D.W., 1994. Water quality for agriculture. FAO Irrigation and Drainage Paper nº 29. FAO, Rome, Italy.

Badejo, A.A., Nwachukwu, U., Ayo-Omogie, H.N., Fasuhanmi, O.S., 2020. Enhancing the antioxidative capacity and acceptability of Kunnu beverage from gluten-free pearl millet (*Pennisetum glaucum*) through fortification with tigernut sedge (*Cyperus esculentus*) and coconut (*Cocos nucifera*) extracts. J. Food Meas. Charact. 14, 438–445. https://doi.org/10.1007/s11694-019-00305-2.

Bryla, D.R., Trout, T.J., Ayars, J.E., 2010. Weighing lysimeters for developing crop coefficients and efficient irrigation practices for vegetable crops. HortScience 45, 1597–1604. https://doi.org/10.21273/hortsci.45.11.1597.

da Costa Neto, J.J.G., Gomes, T.L.M., Justo, T.F., Pereira, K.S., Amaral, P.F.F., Rocha Leão, M.H.M., Fontes Sant'Ana, G.C., 2019. Microencapsulation of tiger nut milk by lyophilization: morphological characteristics, shelf life and microbiological stability. Food Chem. 284, 133–139. https://doi.org/10.1016/j.foodchem.2019.01.110.

De Castro, O., Gargiulo, R., Del Guacchio, E., Caputo, P., De Luca, P., 2015. A molecular survey concerning the origin of *Cyperus esculentus* (Cyperaceae, Poales): two sides of the same coin (weed vs. crop). Ann. Bot. 115, 733–745. https://doi.org/10.1093/aob/mcv001.

Doležal, F., Hernandez-Gomis, R., Matula, S., Gulamov, M., Miháliková, M., Khodjaev, S., 2018. Actual evapotranspiration of unirrigated grass in a smart field lysimeter. Vadose Zo. J. 17, 170173. https://doi.org/10.2136/vzj2017.09.0173.

Doorenbos, J., Pruitt, W.O., 1977. Crop water requirements. FAO Irrigation and Drainage Paper nº 24. FAO, Rome, Italy.

Duman, E., 2019. Some physico-chemical properties, fatty acid compositions, macro-micro minerals and sterol contents of two variety tigernut tubers and oils harvested from east mediterranean region. Food Sci. Technol. 39, 610–615. https://doi.org/10.1590/fst.28018.

Elias, F., Castellví, F., 1996. Agrometeorología. Mundi-Prensa, Madrid, Spain.

El-Shenawy, M., Fouad, M.T., Hassan, L.K., Seleet, F.L., El-Aziz, M.A., 2019. A probiotic beverage made from tiger-nut extract and milk permeate. Pakistan J. Biol. Sci. 22, 180–187. https://doi.org/10.3923/pjbs.2019.180-187.

FAO (Food and Agriculture Organization of the United Nations), 2020a. Historical Irrigation System at l'Horta de València, Spain [WWW Document]. URL. http://www.fao.org/giahs/giahsaroundtheworld/designated-sites/europe-and-central-asia/historical-waterscape-of-lhorta-de-valencia/detailed-information/en/. (Accessed 1 September 2020).

FAO (Food and Agriculture Organization of the United Nations), 2020b. Aquastat [WWW Document]. URL. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en. (Accessed 4 September 2020).

Francés, M., Romero, J., 2014. La Horta de Valencia: un paisaje cultural con futuro incierto. Universitat de València, València.

Gaussen, H., Emberger, M., Berger, L., Philipis, A., 1963. Carte bioclimatique de la zone méditerranéenne. Notice explicative. UNESCO-FAO, Paris, France.

Generalitat Valenciana, 2016. Plan de acción territorial de ordenación y dinamización de la Huerta de Valencia. [Normativa PATODHV]. URL. http://politicaterritorial.gva.es/documents/20551069/163286955/04.+Normativa/0cd75aa8-fa39-4400-8d40-0b6175ca521f. (Accessed 12 July 2020).

Groh, J., Pütz, T., Jülich, F., Vanderborght, J., Vereecken, H., 2015. Estimation of evapotranspiration and crop coefficient of an intensively managed grassland ecosystem with lysimeter measurements. 16th Gumpensteiner Lysimetertagung, Raumberg-Gumpenstein, Austria, pp. 107–112.

Hashim, M.A.A., Siam, N., Al-Dosari, A., Asl-Gaadi, K.A., Patil, V.C., Tola, E.H.M., Rangaswamy, M., Samdani, M.S., 2012. Determination of water requirement and crop water productivity of crops grown in the Makkah region of Saudi Arabia. Aust. J. Basic Appl. Sci. 6, 196–206.

Howell, T., Schneider, A., Jensen, M., 1991. History of lysimeter design and use for evapotranspiration measurements. In: American Society of Civil Engineers (Ed.), Lysimeters for Evapotranspiration and Environmental Measurements. New York, USA, pp. 1–9.

Howell, T.A., Schneider, A.D., Dusek, D.A., Marek, T.H., Steiner, J.L., 1995. Calibration and scale performance of Bushland weighing lysimeters. Trans. ASAE 38, 1019–1024.

IVIA (Instituto Valenciano de Investigaciones Agrarias), 2011. El sistema de información agroclimática para el regadío. [WWW Document]. URL. http://riegos.ivia.es/red-siar. (Accessed 12 July 2020).

Jansen, L.L., 1971. Morphology and photoperiodic responses of yellow nutsedge. Weed Sci. 19, 210–219.

Jensen, M.E., Allen, R.G., 2016. Evaporation, evapotranspiration, and irrigation water requirements. Evaporation, Evapotranspiration, and Irrigation Water Requirements. American Society of Civil Engineers (ASCE), New York, USA https://doi.org/10.1061/9780784414057.

Liu, X.X., Liu, H.M., Li, J., Yan, Y.Y., Wang, X., De Ma, Y.X., Qin, G.Y., 2019. Effects of various oil extraction methods on the structural and functional properties of starches isolated from tigernut (*Cyperus esculentus*) tuber meals. Food Hydrocoll. 95, 262–272. https://doi.org/10.1016/j.foodhyd.2019.04.044.

Loomis, R.S., Connor, D.J., 2002. Ecología de cultivos. Mundi-Prensa, Madrid, Spain.

López-Urrea, R., Martín de Santa Olalla, F., Montoro, A., López-Fuster, P., 2009. Single and dual crop coefficients and water requirements for onion (*Allium cepa* L.) under semiarid conditions. Agric. Water Manag. 96, 1031–1036. https://doi.org/10.1016/j.agwat.2009.02.004.

MAPA (Ministerio de Agricultura Pesca y Alimentación), 2020. Anuario de estadística. Avance 2019. Madrid.

Maynard, D.N., Hochmuth, G.J., 2006. Knott's Handbook for Vegetable Growers. Fifth edition. Wiley, New York, USA https://doi.org/10.1002/9780470121474 Knott's Handbook for Vegetable Growers: Fifth edition.

Muggeo, V.M.R., 2003. Estimating regression models with unknown break-points. Stat. Med. 22, 3055–3071. https://doi.org/10.1002/sim.1545.

Muggeo, V.M.R., 2020. Segmented package V1.2-0 [WWW Document]. R Doc. URL. https://www.rdocumentation.org/packages/segmented/versions/1.2-0. (Accessed 8 July 2020).

Okoro, E.E., Igwilo, K.C., Ifeka, K., Okafor, I.S., Sangotade, I., 2019. Cellulosic *Cyperus esculentus* L. as a filtrate loss modifier in field applicable aqueous and non-aqueous drilling fluids. J. Pet. Explor. Prod. Technol. 9, 1331–1337. https://doi.org/10.1007/s13202-018-0580-y.

Oluwajuyitan, T.D., Ijarotimi, O.S., 2019. Nutritional, antioxidant, glycaemic index and Antihyperglycaemic properties of improved traditional plantain-based (*Musa AAB*) dough meal enriched with tigernut (*Cyperus esculentus*) and defatted soybean (*Glycine max*) flour for diabetic. Heliyon 5. https://doi.org/10.1016/j.heliyon.2019.e01504.

Pascual, B., Pascual-Seva, N., 2017. Chufa. In: Maroto, J., Baixauli, C. (Eds.), Cultivos Hortícolas Al Aire Libre. Cajamar Caja Rural, Almería, SPain, pp. 85–109.

Pascual, B., Maroto, J.V., López-Galarza, S., Alargada, J., Castell-Zeising, V., 1997. El cultivo de la chufa. Estudios realizados. Valencia, Spain.

Pascual, B., Maroto, J.V., López-Galarza, S., San Bautista, A., Alagarda, J., 2000. Chufa (*Cyperus esculentus* L. var. *sativus* Boeck.): unconventional crop. Studies related to applications and cultivation. Econ. Bot. 54, 439–448. https://doi.org/10.1007/BF02866543.

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. Universitat Politècnica de València, Valencia, Spain.

Pascual-Seva, N., San Bautista, A., López-Galarza, S., Maroto, J.V., Pascual, B., 2013. Furrow-irrigated chufa crops in Valencia (Spain). I: productive response to two irrigation strategies. Spanish J. Agric. Res. 11, 258–267. https://doi.org/10.5424/sjar/2013111-3385.

Pascual-Seva, N., San Bautista, A., López-Galarza, S., Maroto, J.V., Pascual, B., 2018. Influence of different drip irrigation strategies on irrigation water use efficiency on chufa (*Cyperus esculentus* L. var. *sativus* Boeck.) crop. Agric. Water Manag. 208, 406–413. https://doi.org/10.1016/j.agwat.2018.07.003.

Pascual-Seva, N., San Bautista, A., López-Galarza, S., Maroto, J.V., Pascual, B., 2019. Using a lysimetric station to determine the irrigation water requirements for chufa crop (*Cyperus esculentus var. sativus*). Acta Hortic. 1251, 101–108. https://doi.org/10.17660/ActaHortic.2019.1251.13.

Pereira, L.S., Paredes, P., Jovanovic, N., 2020. Soil water balance models for determining crop water and irrigation requirements and rrigation scheduling focusing on the FAO56 method and the dual Kc approach. Agric. Water Manage. 241, 106357.

Pereira, L.S., Paredes, P., López-Urrea, R., Hunsaker, D.J., Mota, M., Mohammadi Shad, Z., 2021a. Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach. Agric. Water Manage. 243, 106196.

Pereira, L.S., Paredes, P., Hunsaker, D.J., López-Urrea, R., Mohammadi Shad, Z., 2021b. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agric. Water Manage. 243, 106466.

Romero, J., Melo, C., 2015. Spanish Mediterranean Huertas: theory and reality in the planning and management of peri-urban agriculture and cultural landscapes. WIT Trans. Ecol. Environ. 193, 585–595. https://doi.org/10.2495/sdp150501.

Sala, D., 2012. El Tribunal de las Aguas de la Vega de Valencia. Valencia.

Soil Survey Staff, 2014. Keys to soil taxonomy. 12th ed. USDA-NRCS, USDA-NRCS, Washington, DC, USA https://doi.org/10.1109/TIP.2005.854494.

The European Parliament and the Council of the European Union, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Off. J. Eur. Union.

Tian, Y., Wang, F., Xie, L.F., Xu, Y.P., Duan, P.G., 2019. Lewis acid-catalyzed in situ transesterification/esterification of tigernut in sub/supercritical ethanol: an optimization study. Fuel 245, 96–104. https://doi.org/10.1016/j.fuel.2019.02.038.

Tyagi, N.K., Sharma, D.K., Luthra, S.K., 2000. Determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter. Agric. Water Manag. 45, 41–54. https://doi.org/10.1016/S0378-3774(99)00071-2.

UMS GmbH, 2014. SmartField-Lysimeter User Manual. Munich, Germany.

Vaughan, P., Ayars, J., 2009. Noise reduction methods for weighing lysimeters. J. Irrig. Drain. Eng. 135, 235–240. https://doi.org/10.1061/(ASCE)0733-9437(2009)135.

WWAP (United Nations World Water Assessment Programme), 2016. The United Nations World Water Development Report 2016: Water and Jobs. UNESCO, Paris, France.

Zhu, Y., Elbrhami, A.A., Popovic, V., Koutchma, T., Warriner, K., 2019. Comparative effects of thermal, high hydrostatic pressure, and UV-C processing on the quality, nutritional attributes, and inactivation of *Escherichia coli*, *Salmonella*, and *Listeria* introduced into tiger nut milk. J. Food Prot. 82, 971–979. https://doi.org/10.4315/0362-028X.JFP-18-493.