

# DETERMINATION OF THE PRACTICAL CULTIVATION COEFFICIENT OR IRRIGATION FACTOR IN CHERIMOLIA ORCHARDS (*Annona cherimola* Mill.) USING SOIL SENSORS

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## ABSTRACT

Given the growing water scarcity and the need to make cherimoya (*Annona cherimola* Mill.) cultivation more sustainable, this study proposes using soil sensors to increase irrigation water use efficiency (EUAr) without compromising fruit yield or quality. The objective was to determine the practical crop coefficient (KcS) or irrigation factor by using capacitance probes to continuously determine the dynamics of water absorption from the soil by the crop. To this end, a completely randomized block design trial was conducted over two seasons, incorporating two irrigation treatments: the control (To) and cherimoya trees irrigated according to the FAO-56 Penman-Monteith (Kc-ETo) methodology, as established by the Food and Agriculture Organization of the United Nations (FAO). This approach utilized data obtained from soil sensors and the interpretation of management guidelines for efficient irrigation. Crop productivity and resource use efficiency were assessed. Likewise, relationships between crop phenology and changes in the normalized difference vegetation index (NDVI) were explored to determine curves that estimate the optimal KcS for the season. The use of sensors resulted in a notable increase in EUAr in both seasons, reaching a maximum of 68 % compared to the methodology proposed by FAO. No significant differences were detected between treatments in terms of yield or fruit size. The optimal mean and 70th percentile values of the crop coefficient (KcS) obtained were 0.43–0.47 for the flowering stage, 0.66–0.73 for the fruit set stage (start of fruit growth), and 0.43 for the fruit growth stage until harvest. Likewise, when reference evapotranspiration exceeded 2.25 mm per day, there was a clear difference in soil water depletion between levels above and below the irrigation threshold. Finally, it was observed that the crop absorbed the most water between 13:00 and 16:00 hours.

**Keywords:** Efficient irrigation, capacitance, water use efficiency, sustainability.

## INTRODUCTION

Spain and Peru are the world's leading producers of cherimoya (*Annona cherimola* Mill.), producing 104 835 290 and 20 505 Mg annually, respectively (Larranaga *et al.*, 2017; SIEA, 2018; MAPA, 2019; Vallejo, 2024). In Chile, annual production is around

**Citation:** Gárate-Cortés EJ, Reyes-Sánchez RI, Callejas-Rodríguez RH. 2025. Determination of the practical cultivation coefficient or irrigation factor in cherimolia orchards (*Annona cherimola* Mill.) using soil sensors. *Agrociencia*. <https://doi.org/10.47163/agrociencia.v59i5.3257>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: January 01, 2025.  
Approved: August 04, 2025.  
**Published in Agrociencia:**  
August 11, 2025.

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3734.4 Mg per year, and the main production area is the Coquimbo Region in the north of the country, destined for export to the United States and the domestic market. However, due to the effects of climate change, this region has been subject to structural drought for more than 10 years (Pizarro *et al.*, 2022a), prompting the need to develop strategies and adopt technological tools to reduce water consumption for irrigation in agriculture.

In technified orchards, crop water requirements are determined using the methodology proposed by the Food and Agriculture Organization of the United Nations (FAO) (Allen *et al.*, 1998). In this way, crop evapotranspiration (ET<sub>c</sub>) can be obtained in millimeters per day (mm d<sup>-1</sup>) from the product of reference evapotranspiration (ET<sub>o</sub>), determined using the Penman-Monteith method, and the crop coefficient (K<sub>c</sub>), obtaining a dimensionless value (ET<sub>c</sub> = ET<sub>o</sub> × K<sub>c</sub>). However, the value of K<sub>c</sub> is not clearly defined for the soil and climate conditions of Chile's main production area.

In this context, Gardiazábal and Rosenberg (1993) proposed K<sub>c</sub> values for orchards located in the Quillota area (central Chile, with a Mediterranean climate), establishing a minimum value of 0.2 for the period of lowest water consumption by the tree and a maximum value of 0.8 during its peak growth phase. Meanwhile, in Almuñécar, Spain, Rodríguez-Pleguezuelo *et al.* (2011) and Durán-Zuazo *et al.* (2019) estimated K<sub>c</sub> values for cherimoya cultivation under conventional management in Mediterranean climate conditions. Both studies reported average K<sub>c</sub> values between 0.62 and 0.63 during flowering, between 0.65 and 0.68 during fruit set, and between 0.5 and 0.55 during fruit growth. These studies confirm that the K<sub>c</sub> value must be determined for each agroclimatic zone and even consider the existence of specific agronomic management practices, as these can significantly affect the ET<sub>c</sub> estimate (Calera *et al.*, 2017; Domínguez-Niño *et al.*, 2020).

Agriculture 4.0 is defined as the collection of technologies (equipment, sensors, and software) focused on the digitization of agricultural processes, big data analysis, and the use of the Internet of Things (IoT) to improve the production process from start to end, making it faster, cost-effective, and sustainable. The use of continuous reading soil sensors, such as capacitance probes or frequency domain reflectometry probes, has made it possible to generate more efficient irrigation strategies than those achieved using the FAO-56 Penman-Monteith methodology. These probes are currently considered one of the major technological advances for irrigation control in agriculture (Abioye *et al.*, 2020; Hardie, 2020; Martínez-Gimeno *et al.*, 2020).

The sensors continuously assess the volumetric water content in the soil at different depths, allowing the hourly or daily depletion caused by the root system to be determined. In addition, the information obtained from these measurements allows water balances to be calculated and deep percolation below the active root zone to be estimated (Coelho *et al.*, 2021; Pizarro *et al.*, 2022b), thus optimizing irrigation efficiency (da Silva, 2020). This approach also allows the determination of the so-called practical crop coefficient 'K<sub>c</sub> probe' (K<sub>c</sub>S, dimensionless) (Callejas-Rodríguez and Seguel, 2021) or irrigation factor (IF) (Vera *et al.*, 2019), which integrates variables such as vegetation

cover, location coefficient ( $K_r$ ), and the efficiency of the irrigation system used. This strategy is particularly relevant at the farm level, as it represents a more practical and less costly alternative to the use of weighing lysimeters to obtain the  $K_c$  coefficient for the species.

In addition,  $K_cS$  facilitates rational access to technology on medium-sized or large farms, characterized by a high number of irrigation sectors. Through categorized grouping (clustering) that considers variables such as variety, rootstock, soil types, and foliage expression (Callejas-Rodríguez and Seguel, 2021), and by determining the  $K_cS$  or  $FI$ , it is feasible to manage multiple irrigation sectors belonging to the same cluster. This can be achieved from a single sector equipped with soil sensors and by adjusting the criteria using complementary technologies (satellite images, Scholander pressure pump, dendrometry, and other indicators), which reduces the investment in technology.

Given the limited information available to determine the water requirements of cherimoya cultivation, and considering the need to implement sustainable irrigation management systems to address water scarcity, the hypothesis was proposed that the use of soil sensors and the implementation of the concept of Agriculture 4.0 would increase irrigation water use efficiency ( $EUAr$ ). In this context, the objective of the research was to determine a practical crop coefficient that maximizes water productivity without affecting the yield or export quality of the fruit.

## MATERIALS AND METHODS

The study was conducted in northern Chile, in La Serena, Coquimbo Region, on commercial plots owned by HC Ltda., Fundo Corazón de María ( $29^{\circ} 58.844' S$ ,  $71^{\circ} 13.486' W$ , at an altitude of 100 m), during the 2019 and 2020 seasons. The study area has a climate classified as 'BMk' according to the Köppen-Geiger classification, corresponding to the coastal steppe or cloudy type, with an average annual temperature of  $16^{\circ}C$  and approximate precipitation of 104 mm per year concentrated in the winter. The study was conducted with 10-year-old cherimoya trees (*Annona cherimola* Mill.), "Concha Lisa" cultivar, planted at  $5 \times 2.5$  m and formed into a cup shape. The irrigation system was located with two lines of emitters per tree and drippers every 0.5 m on the line with a flow rate of  $2.8 L h^{-1}$ , whose precipitation from the equipment corresponded to  $2.3 mm h^{-1}$ , with irrigation efficiency and a uniformity coefficient of 90 % each. The bulb was well defined, with a root system located mainly in the first 50 cm of the soil profile (Figure 1), with a high presence of fine and medium roots that decrease in depth, where the thick roots are located. The soil, with a high degree of evolution, has a sandy loam texture in the first 50 cm, a pH of 7.5, an electrical conductivity (CE) of  $0.85 dS m^{-1}$ , an organic matter content of 0.97 %, and a stoniness of 3.7 %.

A completely randomized block design was used with two irrigation treatments and five replicates per treatment, considering four trees as the experimental unit. The first treatment was the control field ( $T_0$ ), where trees were irrigated using the



**Figure 1.** Soil profile of “Concha Lisa” cherimoya trees (*Annona cherimola* Mill.) observed through a trial pit dug in the row, 50 cm from the tree trunk and in the area corresponding to the irrigation bulb.

methodology proposed by FAO (Allen *et al.*, 1998). Crop evapotranspiration was obtained in millimeters per day ( $\text{mm d}^{-1}$ ) using the expression  $ET_c = ET_0 \times K_c$ , where  $ET_0$  corresponds to reference evapotranspiration ( $\text{mm d}^{-1}$ ), determined using the Penman-Monteith method, and  $K_c$  to the crop coefficient (dimensionless) proposed by Gardiazábal and Rosenberg (1993). Furthermore, a second treatment was considered, using capacitance probes with multisensors (Ts). The irrigation criterion was based on the evaluation of the dynamics of soil water content and its relationship with plant extraction, adjusting the frequency and timing of irrigation in accordance with the management guidelines for the use of soil sensors (Vera *et al.*, 2019; Callejas-Rodríguez and Seguel, 2021).

The management lines used in the Ts treatment corresponded to: i) full level (NLL), which is the maximum water capacity that the soil can hold without producing deep percolation and where the sensor located at greater depth should not show activity (daily depletion); ii) probe field capacity (CCs), which refers to the water content in the soil evaluated with the probe after a heavy rainfall or irrigation event and being left to drain freely for 24 to 48 h (Zotarelli *et al.*, 2019); and iii) recharge point (PR), equivalent to the irrigation threshold based on the capacitance probe technique, where, for the same atmospheric demand, a decrease in daily depletion is observed compared to the previous day, indicating that plants face greater difficulties in extracting water due to the progressive depletion of water resources (increased tension). The management

guidelines described and the data obtained by the sensors were interpreted in real time using the Irrimax Live platform (Sentek Technologies, Australia).

In both treatments, an SF model volumetric line meter (Arad, Israel) was installed to determine the volume of irrigation water used. An EnviroscaMR frequency domain reflectometry capacitance probe (Sentek Technologies, Australia) was also installed. The probe was calibrated for the study site and set 30 cm from the trunk of a representative plant, next to a dripper. Each probe had five sensors located at depths of 10, 20, 30, 50, and 80 cm in the soil profile. The readings from each sensor were recorded every 15 min. A Davis Vantage weather station (Davis Instruments, California, USA) was installed in the area to obtain temperature, reference evapotranspiration ( $ET_o$ ), and degree days (10 °C-based), with the biofix being the time of pruning (°DG).

To determine the apparent daily consumption of the trees ( $ET_c$ ), a water balance was performed, quantifying the inputs and outputs of the system according to the following equation:

$$ET_c = R + P_{ef} + Ac - Es - P_{prof} - \Delta S$$

where  $ET_c$  is crop evapotranspiration (mm),  $R$  is irrigation quota (mm),  $P_{ef}$  is effective precipitation (mm),  $Ac$  is capillary rise (mm),  $Es$  is surface runoff (mm),  $P_{prof}$  is deep percolation (mm), and  $\Delta S$  is the change in volumetric water content in the soil in the root zone (mm). Surface runoff was considered zero, as the orchard did not have a prominent slope, as was capillary rise, which was deemed insignificant for the balance. Deep percolation was calculated as the volume of water infiltrated below the last sensor in reference to NLL.

To calculate the practical crop coefficient ( $KcS$ ), the 70th percentile of the data was used, and two assumptions were made: 1) The water content in the soil was adequate and not limiting for the plant; and 2) Outside irrigation periods,  $ET_c = \Delta S$ , because the daily variation in soil water content was due solely to evapotranspiration, with no percolation or water inputs, these values being zero. Finally,  $KcS$  was calculated from  $ET_c$  and its relationship with  $ET_o$ , using the formula:

$$KcS = \frac{ET_c \text{ or effective irrigation}}{ET_o}$$

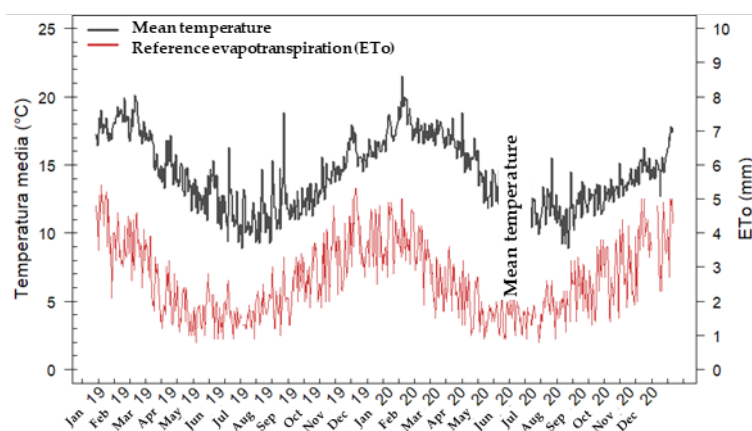
Additionally, the following production variables were determined: i) fruit load, expressed as the total number of fruits harvested per tree; ii) average fruit weight, estimated from a subsample of 20 fruits per tree; and iii) total yield per tree. Likewise, vegetative growth was evaluated as the increase in trunk cross-sectional area ( $\Delta ASTT$ ) and the evolution of the normalized difference vegetation index (NDVI), based on images obtained with a multispectral imaging sensor (MSI) mounted on the Sentinel 2A and 2B satellites, with a spatial resolution of 10 m and a temporal resolution of

10 days. The bands used were B2, B3, B4, B8, B8a, and B11. The download format was L1-C from the top of the atmosphere (TOA), so the images were transformed to background surface reflectance (BOA) based on the two-step atmospheric correction method (Chávez, 1988). Moreover, to extrapolate irrigation protocols, the relationships between  $KcS$  obtained with NDVI and the accumulation of  $^{\circ}DG$  for different periods in the season were explored. Finally, irrigation water use efficiency (EUAr) was determined as the ratio between yield and the volume of irrigation water used per hectare.

The data were analyzed using mixed linear models. The fixed effects are the irrigation treatments, and the random effects are the number of fruits harvested, fruit weight, yield per tree, and increase in trunk cross-sectional area. In cases where differences were detected between treatments, a Fisher's multiple comparison test was performed with  $p \leq 0.05$ , after verifying the assumptions of homogeneity of variance and normality of errors. Infostat and RStudio software were used.

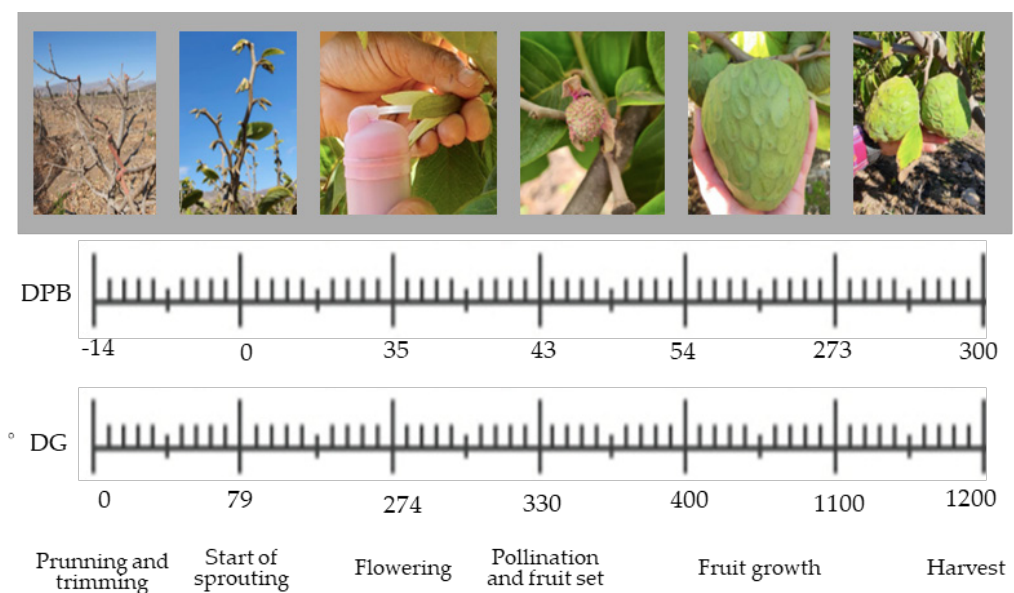
## RESULTS AND DISCUSSION

The evolution of the mean temperature and reference evapotranspiration in the trial sector was marked by the seasons of the year. In the case of temperature, the average maximum was  $22^{\circ}C$  in January and the minimum was  $7^{\circ}C$  in June. The maximum  $ET_o$  rose to  $4.8 \text{ mm d}^{-1}$  in summer and a minimum of  $1.8 \text{ mm d}^{-1}$  in winter (Figure 2). The total annual  $ET_o$  was equivalent to  $896.96 \text{ mm}$ .



**Figure 2.** Evolution of the average ambient temperature ( $^{\circ}C$ ) and reference evapotranspiration ( $ET_o$ ) in the test area (southern hemisphere, La Serena, Coquimbo Region, Chile).

From pruning, it took approximately 314 calendar days to reach harvest, equivalent to around  $1100^{\circ}DG$  for the fruit to ripen properly (Figure 3). Due to possible variations in mean temperatures in the area during the autumn and winter months (April, May,



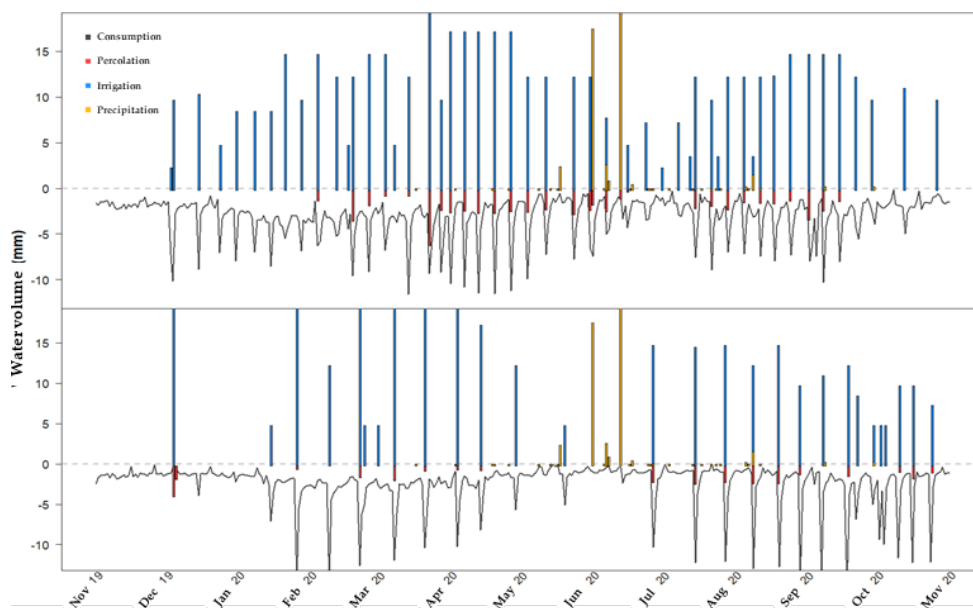
**Figure 3.** Estimation of duration (days after bud break, DAB) and accumulation of degree days ( $^{\circ}\text{DG}$ ), based on  $10^{\circ}\text{C}$ , of phenological stages for the entire period (mean of both seasons), from the date of pruning of cherimoya plants (*Annona cherimola* Mill.).

June, and July), the harvest date for the same pruning date can vary between 20 and 15 calendar days. Pruning begins in late November (southern hemisphere, spring), with harvesting taking place in July-August of the following year (winter).

### Water balance

The 2019 season saw low rainfall, with only 10.79 mm between the end of May and mid-June. These volumes did not exceed 80 cm in depth or NLL in the treatments, with the entire amount being considered effective precipitation. The percolation amounts attributed to irrigation management were higher in  $T_0$ , reaching 183.4 mm, while in  $T_s$ , 90.8 mm of percolation were recorded, distributed throughout the season. During the 2020 season, rainfall was 52 mm in two events in winter, with deep percolation observed only in  $T_0$ . The percolated amounts in the treatments were 167 mm and 28.7 mm for  $T_0$  and  $T_s$ , respectively (Figure 4), demonstrating more accurate programming, as pointed out by Gasque *et al.* (2016).

Treatment  $T_0$  showed greater inaccuracy in determining irrigation water requirements, with significant variations in  $\text{ET}_c$  reported in many cases when comparing the results against the original unit in which it was developed (Pereira *et al.*, 2021). Throughout the study, the  $T_s$  method allowed for a 65.9 % saving in deep percolation.

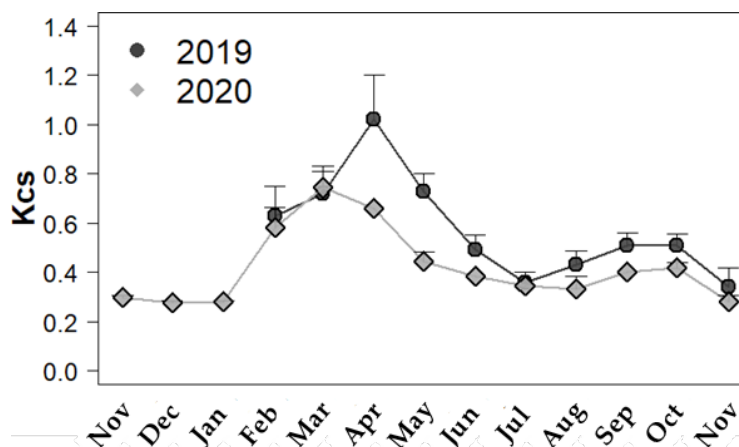


**Figure 4.** Temporal course of irrigation, precipitation, change in volumetric water content, and percolation in the control treatment (To, upper) and the treatment with capacitance probes (Ts, lower) during the 2020 season.

#### Practical crop coefficient (KcS) or irrigation factor

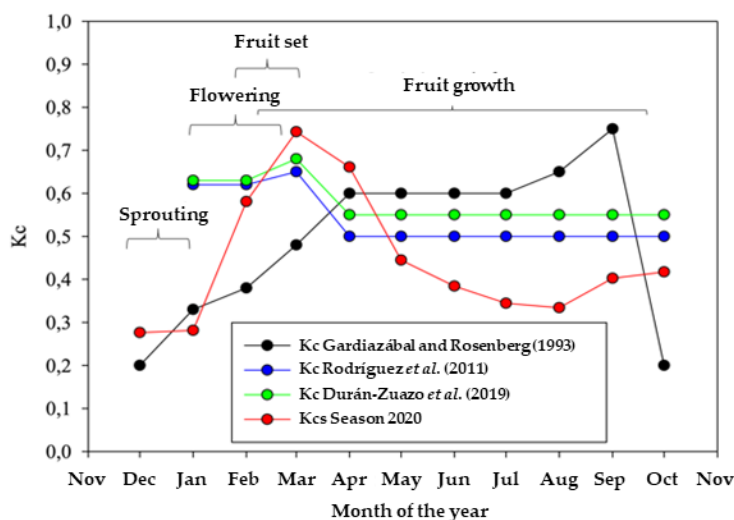
Using the information generated with Ts, KcS was calculated, from which three well-defined stages can be highlighted (Figure 5). For the 2019 season, the range of average values for the 70th percentile for the flowering, fruit set, and fruit growth stages evaluated was 0.63–0.75, 0.67–0.79, and 0.59–0.66, respectively. For the 2020 season, the average value ranges for the aforementioned stages were 0.43–0.47, 0.66–0.73, and 0.43, respectively, which were adjusted to a better definition of irrigation time and frequency based on the experience of the previous year. The possibility of continuously measuring irrigation water inflows and outflows at various intervals between irrigations for the estimation of KcS allows the equation to be simplified to the variation in daily water content, achieving results similar to the work carried out on peach trees by Vera *et al.* (2019), who also used capacitance probes.

The optimization of irrigation water use in the 2020 season is due to factors relevant to implementing this methodology: a) one year of experience allows for the stabilization of the initial variability of the data associated with the process of installing capacitance probes in the soil; and b) the optimization of irrigation criteria, after one year of information, is related to the adjustment of irrigation management lines. Moreover, irrigation criteria must be validated with optimal yield results, as well as the quality of export fruit. It is advisable to use other water status indicators to evaluate the irrigation schedule for the season, such as the water potential of the stem at solar noon (Vera *et*



**Figure 5.** Average practical crop coefficient (Kcs) of the 70th percentile per month for the 2019 and 2020 seasons, determined using information obtained from irrigation treatment with capacitance probes (Ts) in a cherimoya orchard (*Annona cherimola* Mill.). Vertical bars correspond to the 70th percentile.

*al.*, 2019; Callejas-Rodríguez and Seguel, 2021). However, for the cherimoya crop, this was not feasible due to the thickness of the petiole and the excessive size of the leaves. The estimated Kcs values for the 2020 season were compared with the Kc values proposed by other authors for this species in its different phenological stages obtained by other authors (Rodríguez-Pleguezuelo *et al.*, 2011; Durán-Zuazo *et al.*, 2019), and the means for the flowering, fruit set, and fruit growth stages were plotted (Figure 6).

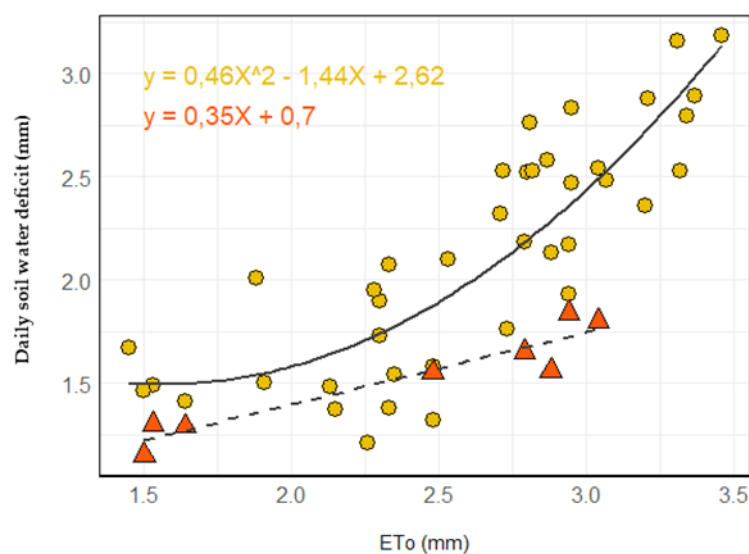


**Figure 6.** Estimation of the practical crop coefficient (Kcs) for the 2020 season compared with different values proposed for the cultivation of cherimoya (*Annona cherimola* Mill.).

During the summer (January and February),  $E_{To}$  ranged between 3.16 and 4.35  $\text{mm d}^{-1}$ , dropping in winter to values between 0.56 and 2.26  $\text{mm d}^{-1}$ . Devi and Reddy (2018) point out that, in autumn and winter, temperature and vapor pressure deficit decrease, and with them plant transpiration, generating low  $E_{Tc}$  values. This condition was observed in the dynamics of soil water content measured with capacitance probes, coinciding with Kirkham (2005), who points out that tree transpiration (water absorption by active roots) depends fundamentally on the volumetric water content in the soil when atmospheric demand is high. However, when it is very low, as in the study area, trees maintain a low transpiration rate regardless of the water content in the soil.

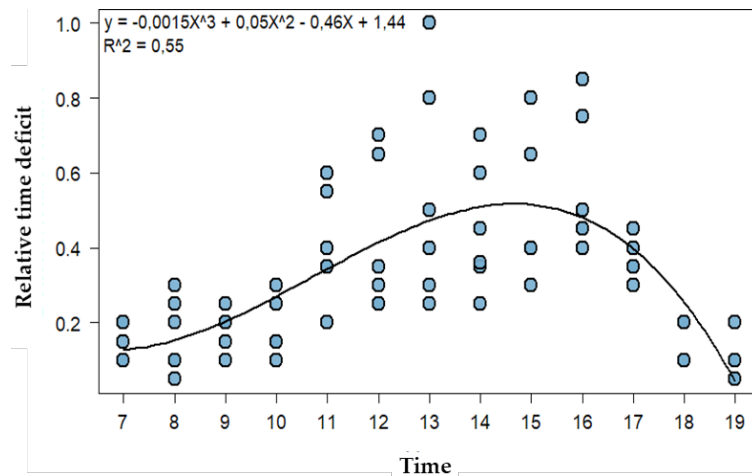
For cherimoya, an  $E_{To}$  below 2.25  $\text{mm d}^{-1}$  does not have a clear effect on the daily moisture deficit monitored in the soil, both for optimal and suboptimal water availability conditions (Figure 7). However, once demand exceeds 2.5  $\text{mm d}^{-1}$ , it is clear that low irrigation water availability (below the recharge point) is insufficient to compensate for this increase in atmospheric demand, a situation that occurs when the crop is not subject to limiting soil water conditions.

According to Higuchi *et al.* (1998), stomatal conductance in cherimoya leaves under 12 hours of daylight conditions shows two peaks according to the traditional schedule: one at 8:00 a.m. and another at 6:00 p.m., with the former being higher in the early morning. Considering that stomatal opening depends on solar radiation (Allen *et al.*, 1998), it is important to note that in the test area, due to permanent cloud cover in the mornings, solar radiation values were low from sunrise until midday. Subsequently,



**Figure 7.** Relationship between reference crop evapotranspiration ( $E_{To}$ ) and daily water deficit caused at root level in the area monitored with an Enviroscan sensor (depths of 20, 30, and 50 cm) for two soil moisture conditions: a) content between field probe capacity (CCs) and recharge point (PR) (yellow circles), and b) below PR or irrigation threshold (red triangles).

they increased (from 40 to 60 %) and remained so until 3:00 p.m., gradually decreasing thereafter. Therefore, it could be assumed that, as a result of low radiation and stomatal opening, the expected morning maximum did not occur, which would be reflected in the absorbent activity of the roots (Figure 8). This increased late, around midday, maintaining higher consumption until 4:00 p.m., the time when the production area traditionally clears up.



**Figure 8.** Hourly water deficit in the soil caused by cherimoya trees in the area monitored with an Enviroscan sensor (at depths of 20, 30, and 50 cm), according to the time of day.

These conditions contrast with those found in Andalusia, Spain, where the flowering-to-harvest period occurs in spring and summer with higher solar radiation, a mean annual temperature of 20 °C, high relative humidity (Rodríguez-Pleguezuelo *et al.*, 2011), and up to 11 mm d<sup>-1</sup> of ETo (Durán-Zuazo *et al.*, 2019). With these climatic characteristics and proper irrigation, hypothetical explanations could be given for the possibilities of a higher transpiration rate and greater production potential, with yields of up to 40 Mg ha<sup>-1</sup> (González and Cuevas, 2008) or fewer calendar days to harvest. Another determining factor that could partially explain the low KcS values in winter is the percentage of ground cover by trees, which would affect the location coefficient (Allen *et al.*, 1998). An orchard with 70 % coverage by mature trees can result in a Kc value of less than one, as occurred in the trial, where the trees reached 59 % coverage. One of the commercial objectives of generating the practical crop coefficient on medium-sized or large farms is the possibility of extrapolating the experience of one irrigation sector to others that meet categorical criteria (cluster formation) (Callejas-Rodríguez and Seguel, 2021) that do not have soil sensors. With the information obtained from this study, two functions are proposed to define KcS (Table 1): function A, using days post-sprouting, and function B, using °DG as a cumulative predictor from pollination.

**Table 1.** Functions to determine the practical crop coefficient ( $KcS$ ) based on the accumulation of degree days since pollination ( $^{\circ}DG$ ) or based on the days after sprouting (DPB) for the 2020 season.

Function	Variable		Equation	$R^2$
	Dependent	Independent		
A	$KcS$	DPB	$y = 9 \cdot 10^{-8}x^3 - 5 \cdot 10^{-5}x^2 + 0.0082x + 0.2303$	0.60
B	$KcS$	$^{\circ}DG$	$y = 3 \cdot 10^{-9}x^3 - 6 \cdot 10^{-6}x^2 + 0.0032x + 0.2379$	0.77

Additionally, for the relationship between NDVI and  $KcS$ , three periods were identified, each with a different function (Table 2). The first period (C) ran from the start of the season to the beginning of autumn (590 accumulated  $^{\circ}DG$ ); the second (D) ran from autumn to the end of winter (750 accumulated  $^{\circ}DG$ ); and the third (E) ran from the start of spring (770 accumulated  $^{\circ}DG$ ) to the end of the season.

**Table 2.** Functions for determining the practical crop coefficient ( $KcS$ ) from the normalized difference vegetation index (NDVI) for the periods from the start of the season to autumn (C), from autumn to the end of winter (D), and from the start of spring to the end of the season (E).

Funtion*	Variable		Equation	$R^2$
	Dependent	Independent		
C (590 $^{\circ}DG$ )			$y = 0.8928x + 0.0213$	0.80
D (750 $^{\circ}DG$ )	$KcS$	NDVI	$y = 0.8185x + 0.2844$	0.86
E (770 $^{\circ}DG$ )			$y = 0.3474x + 0.2043$	0.36

\*The values in brackets indicate the cumulative degree days since pollination ( $^{\circ}DG$ ) for the start of each period.

The  $KcS$  values showed a high correlation with the NDVI values. As pointed out by Pôças *et al.* (2020), the use of vegetation indices may be a useful tool for irrigation management in the context of precision agriculture. A high correlation was also found with the accumulated  $^{\circ}DG$  since pollination, which would allow for more efficient irrigation in areas without soil sensors.

In general, no significant differences were detected that could indicate that irrigation treatments would cause problems in fruit yield and quality (Table 3). An increase in the cross-sectional area of the trunk was only detected in the second season for  $T_s$  compared to  $T_o$ .

The use of soil sensors allowed for a significant reduction in irrigation water volumes compared to the FAO-56 Penman-Monteith ( $Kc-ET_o$ ) methodology (Table 4). In cherimoya orchards in Spain, the irrigation volume used was similar to that obtained with  $T_s$  ( $3970 \text{ m}^3 \text{ ha}^{-1}$ ) (Durán-Zuazo *et al.*, 2019), but clearly lower than that used

**Table 3.** Production parameters and increase in trunk cross-sectional area ( $\Delta$  ASTT) obtained for each treatment and season.

Season and treatment	Fruit load	Fruit weight	Yield	$\Delta$ ASTT
	(Number of fruits per tree)	(g)	(kg tree <sup>-1</sup> )	(cm <sup>2</sup> tree <sup>-1</sup> )
<i>2019</i>				
To	75.4	305.0	21.5	3.23
Ts	79.7	312.9	24.4	3.28
<i>2020</i>				
To	44.5	549.4	24.9	2.06b
Ts	45.1	600.2	26.6	5.32a

Different letters indicate significant differences between treatments for the same parameter and season ( $p < 0.05$ ). To: control treatment; Ts: irrigation treatment with capacitance probes.

**Table 4.** Irrigation water volume, irrigation water use efficiency (EUAr), and resource savings achieved for each treatment.

Season and treatment	Irrigation	EUAr	Water saving compared to To	Energy saving compared to To
	(m <sup>3</sup> ha <sup>-1</sup> )	(kg m <sup>-3</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	USD ha <sup>-1</sup>
<i>2019</i>				
To	5916	2.9		
Ts	4255	4.6	1661 (28.1 %)	315.4
<i>2020</i>				
To	5169	3.8		
Ts	3360	6.4	1823 (35.3 %)	346.1

Different letters indicate significant differences between treatments for the same parameter and season ( $p < 0.05$ ). To: control treatment.

by To. However, other studies in the same country have recorded volumes between 6000 and 7160 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> (González and Cuevas, 2008; Soler and Cuevas, 2008), which are higher than both treatments. These results are consistent with authors who worked on other species, reporting that, when restoring water volumes lower than ETc, yields were the same as when 100 % of it was replaced (Centofanti *et al.*, 2018). Optimizing irrigation programming made it possible to increase EUAr by 63.5 % compared to the To treatment during the study period, thus validating it as a tool for addressing water stress situations without affecting crop yield. The value was higher than those recorded in Spain by Rodríguez-Pleguezuelo *et al.* (2011) and Durán-Zuazo *et al.* (2019), with 1.4 and 3.3 kg ha<sup>-1</sup> m<sup>-3</sup>, respectively. In addition, cost savings were

generated by reducing the amount of electricity used by about 300 USD ha<sup>-1</sup> (Kaptein *et al.*, 2019; Vera *et al.*, 2019) (Table 4).

Finally, one of the difficulties in further analyzing the results is the limited availability of published information on this crop. The generation of the KcS, or irrigation factor, during two seasons of work made it possible to provide a new irrigation management tool for an area with particular conditions in Chile, whose final validation will be possible after several years of use and the correct categorization (clustering) of those irrigation sectors that do not have soil sensors.

### CONCLUSIONS

The use of soil sensors, compared to the FAO-56 Penman-Monteith method (Kc-ET<sub>o</sub>), allowed for savings in irrigation water and electricity of up to 30 %, improving irrigation water use efficiency by up to 68 % without affecting yield or fruit size. By calculating a water balance, the use of probes made it possible to obtain values for the practical crop coefficient or irrigation factor, which vary between 0.27 and 0.74 for periods of lower and higher consumption, respectively.

Water depletion in the soil could only be clearly detected by the sensors when reference evapotranspiration (ET<sub>o</sub>) exceeded 2.25 mm per day, under conditions without water restrictions. Furthermore, the greatest relative hourly depletion by plants occurred between 1:00 p.m. and 4:00 p.m. This type of irrigation optimization strategy, which is site-specific and cost-effective, utilizes new technologies within the framework of Agriculture 4.0 to enable the development of more efficient irrigation management schemes in areas with particular conditions that differ from those under which the ET<sub>o</sub>-Kc methodology's parameters were established.

### ACKNOWLEDGEMENTS

To Mr. Roberto Hernández Codoceo and Ismael Plácido Tomieli, from HC Ltda., La Serena, for their support in conducting the study.

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