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## Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data

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**Abstract** Irrigation scheduling based on the daily historical crop evapotranspiration ( $ET_h$ ) data was theoretically and experimentally assessed for the major soil-grown greenhouse horticultural crops on the Almería coast in order to improve irrigation efficiency. Overall, the simulated seasonal  $ET_h$  values for different crop cycles from 41 greenhouses were not significantly different from the corresponding values of real-time crop evapotranspiration ( $ET_c$ ). Additionally, for the main greenhouse crops on the Almería coast, the simulated values of the maximum cumulative soil water deficit in each of the 15 consecutive growth cycles (1988–2002) were determined using simple soil-water balances comparing daily  $ET_h$  and  $ET_c$  values to schedule irrigation. In most cases, no soil-water deficits affecting greenhouse crop productivity were detected, but the few cases found led us to also assess experimentally the use of  $ET_h$  for irrigation scheduling of greenhouse horticultural crops. The response of five greenhouse crops to water applications scheduled with daily estimates of  $ET_h$  and  $ET_c$  was evaluated in a typical *enarenado* soil. In tomato, fruit yield did not differ statistically between irrigation treatments, but the spring green bean irrigated using the  $ET_h$  data presented lower yield than that irrigated using the  $ET_c$  data. In the remaining experiments, the irrigation-management method based on  $ET_h$  data was

modified to consider the standard deviation of the inter-annual greenhouse reference ET. No differences between irrigation treatments were found for productivity of pepper, zucchini and melon crops.

### Introduction

The greenhouse industry has expanded in many parts of the world (Enoch and Enoch 1999), and in particular throughout mild winter coastal areas in the Mediterranean basin (Briassoulis et al. 1997; Pardossi et al. 2004). The adjacent Mediterranean coastal areas of Almería, Murcia and Granada, in the Southeast of Spain, are one of the largest concentrations of greenhouses in the world with approximately 37,500 ha mainly dedicated to intensive vegetable production (Castilla and Hernández 2005). Most of these are low-cost structures covered with plastic film, without climatic control systems and with soil-grown crops (Pérez-Parra et al. 2004). The use of this low-technology greenhouse has spread to several other countries (South America, Morocco) during the last decade, and it represents the archetype of low-cost plastic greenhouses (Pardossi et al. 2004). These are mainly used in developing countries under other denominations (Canarian-type, Moroccan-type, Sicilian-type, etc.).

Water is a scarce resource in areas with low annual precipitation, such as South-eastern Spain (average annual precipitation below 250 mm). Irrigation is the major consumer of water in this area and, therefore, it must be carried out with high efficiency to minimise percolation losses and environmental pollution, and increase water productivity. Considerable scope remains for improving irrigation management practices at the farm level in the Almería greenhouse area. Current irrigation practices are generally based on local farmers' experience and most of them irrigate without monitoring the soil- or plant-water status. High variations in irrigation water supplies to each of

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the main vegetable crops have been reported (Caja Rural 1997) and over-irrigation has been detected for some crops and periods (González 2003). In order to improve greenhouse irrigation efficiency, evapotranspiration (ET) for the main vegetable crops of the region has been determined (Orgaz et al. 2005) using the worldwide  $K_c$ - $ET_o$  method as proposed by the FAO (Doorenbos and Pruitt 1977; Allen et al. 1998) and current or real-time meteorological data. Based on this method, daily irrigation water requirements for the major greenhouse crops can be estimated with a computer program (<http://www.laspalmerillas.cajamar.es>), which requires daily solar radiation and temperature data (Fernández et al. 2001b). At present, however, it appears unlikely that greenhouse farmers will adopt this method of irrigation scheduling, as real-time meteorological data are required daily and water represents only 2–4% of total crop cost.

Use of average or historical evapotranspiration ( $ET_h$ ) for irrigation scheduling has been proposed for areas or periods where the inter-annual variability of the reference evapotranspiration ( $ET_o$ ) is low (Feres et al. 1981; Hanson 1996; Hill and Allen 1996; Hanson and Keita 1999). The  $ET_h$  values are calculated from historical meteorological data as historical crop coefficients ( $K_{ch}$ ) times historical reference evapotranspiration ( $ET_{oh}$ ). This method could be used to calculate  $ET_h$  values throughout the whole crop cycle before it starts if planting date and density are known, and can, therefore, be easily applied by farmers. In greenhouses on the Mediterranean coast of South-east Spain inter-annual variability of weekly  $ET_o$  values is relatively low (Fernández 2000). The highest variation occurs during winter and autumn seasons (with variation coefficients of 18 and 16%, respectively), due to the low  $ET_o$  values and the higher probability of rainfall. Thus, in these agro-systems the use of  $ET_h$  for irrigation scheduling of soil-grown crops could be of interest (Fernández et al. 2001a).

This work aims to provide both theoretical and experimental evaluation of the use of  $ET_h$  data for irrigation scheduling of greenhouse vegetable crops in a Mediterranean area in order to improve irrigation efficiency.

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## Materials and methods

### Theoretical studies

Seasonal values of irrigation water use of major soil-grown greenhouse crops from 41 farmers were measured over six consecutive cropping seasons: 1993/1994–1998/1999 (González 2003). Greenhouses were located in the main irrigation districts within the *Campo de Dalías* area (Almería), the largest and oldest greenhouse area on the Spanish Mediterranean coast with approximately 20,511 ha of plastic greenhouses (Sanjuan 2004). For each crop cycle, seasonal values

of current evapotranspiration ( $ET_c$ ) and historical evapotranspiration ( $ET_h$ ) were calculated and compared. Real-time meteorological data required for determining  $ET_c$  values were taken from a nearby weather station located in *Las Palmerillas-Cajamar* research station (2° 43' W; 36° 48' E; and 155 m elevation).

Additionally, the use of daily  $ET_h$  values for irrigation scheduling of major greenhouse crops over the 15 consecutive seasons (1988–2002) was compared with daily  $ET_c$  values using simple soil-water balances. The most common planting or sowing date of each vegetable crop was considered. The readily available water (RAW) of a representative *enarenado* soil (see following section) of 0.30 m thickness was calculated using a value of 0.40 for the fraction of total available water that can be depleted from the vegetable root zone before moisture stress occurs (Allen et al. 1998; Fernández et al. 2005). Daily  $ET_c$  and  $ET_h$  values were then compared for each crop cycle: when  $ET_h$  was lower than  $ET_c$  the soil-water content was depleted, and the cumulative soil-water deficit was calculated if the soil-water content was below field capacity.

The  $ET_c$  was calculated by the  $K_c$ - $ET_o$  method (Doorenbos and Pruitt 1977; Allen et al. 1998).  $ET_o$  (in  $\text{mm day}^{-1}$ ) was calculated with a locally calibrated radiation method (Eqs. 1 and 2) that requires daily solar radiation outside the greenhouse ( $G_o$ , in  $\text{mm day}^{-1}$ , available from 1983 to 2002) and greenhouse transmissivity data ( $\tau$ , in %). The latter, which changes slightly during the cropping season, was determined monthly from solar radiation measurements carried out outside and inside the greenhouse. This radiation method was verified using the  $ET_o$  data measured from 1999 to 2002 in another greenhouse (24×20.5 m) sown with perennial grasses (Orgaz et al. 2005). The agreement between estimated and measured  $ET_o$  data was very good as most data were narrowly distributed around the 1:1 line. The coefficient of determination ( $r^2$ ) of the best-fit line was 0.98 and values of the intercept and the slope of the regression line were not significantly different from zero and unity, respectively, at the 0.05 probability level. Simple regression formulas relating ET to solar radiation for estimating daily water requirements of greenhouse crops have previously been used by de Villèle (1974) and Baille (1999). The  $K_c$  values for major greenhouse horticultural crops were determined by Fernández (2000) and Orgaz et al. (2005). Daily  $K_c$  values from sowing/planting to effective full cover were determined as a function of thermal time, calculated using greenhouse air temperature (available from 1988 to 2002). Greenhouse air temperatures were measured within the greenhouse sown with perennial grasses and maintained at 0.1–0.2 m height by regular cutting. A more detailed description can be found in Fernández (2000) and Orgaz et al. (2005).

For Julian days (JD)  $\leq 220$

$$ET_o = (0.288 + 0.0019 \times JD)G_o \times \tau \quad (1)$$

For Julian days (JD)  $> 220$

$$ET_o = (1.339 - 0.00288 \times JD)G_o \times \tau \quad (2)$$

The  $ET_h$  was calculated as the product of the historical reference evapotranspiration ( $ET_{oh}$ ) and the historical crop coefficient ( $K_{ch}$ ). Daily  $ET_{oh}$  values were calculated as the average of daily reference evapotranspiration ( $ET_o$ ) values from a data set of 20 years (1983–2002). Daily  $K_{ch}$  values from sowing/planting to effective full cover were determined as a function of thermal time, calculated using the average air temperatures from a data set of 15 years (1988–2002). A more detailed description can be found in Fernández (2000).

## Experimental studies

### Site and experiments

The use of  $ET_h$  for irrigation scheduling of major soil-grown greenhouse crops (autumn–spring tomato, spring green bean, autumn–winter sweet pepper, autumn–winter zucchini and spring melon) was also evaluated in five greenhouse experiments (one per crop) carried out from 1999 to 2002 at *Las Palmerillas-Cajamar* research station (El Ejido, Almería). Experiments were conducted in two typical Mediterranean greenhouses: low-cost structures covered with plastic film (0.2-mm thick thermal polyethylene sheet), without heating equipment and passively ventilated by opening side panels and roof vents (Pérez-Parra et al. 2004). Artificially layered soils, typical of the region and known as *enarenados*, of similar water-retention characteristics were used in both greenhouses. These soils consist of the naturally occurring, gravelly sandy-loam soil covered with a 0.3-m layer of loamy soil, a 0.02-m layer of manure, and, finally, a 0.1-m mulch layer of coarse sand. Irrigation water of  $0.4 \text{ dS m}^{-1}$  electrical conductivity mixed with fertilizers was applied through a drip system (aboveground tape) with over 90% distribution uniformity. The upper limit of drained water content (field capacity) was  $0.31 \text{ cm}^3 \text{ cm}^{-3}$  for the loamy soil, and the lower limit (wilting point) was  $0.11 \text{ cm}^3 \text{ cm}^{-3}$  (González 2003). One greenhouse had four drainage lysimeters (4 m length, 2 m width and 0.7 m depth) located on the southern side with the bottom and walls covered with a butyl rubber insulation sheet. The soil profile in the lysimeter reproduced that of the outside area described above to a depth of 0.6 m, with a layer of gravel placed on top of the butyl rubber sheet. The lysimeter soil depth was adequate as most of the root growth from greenhouse crops occurs within the loamy soil layer (Orgaz et al. 2005). Green bean, sweet pepper and melon experiments were conducted in the greenhouse with four drainage lysimeters, whereas tomato and zucchini experiments were conducted in the greenhouse without lysimeters.

Two irrigation treatments were studied per experiment: crop irrigated using the current evapotranspiration values ( $ET_c$ ) and crop irrigated using the historical evapotranspiration ones ( $ET_h$ ). Treatments were arranged in a randomised complete-block design with four replications and means were compared with a Least Squares Means procedure. The experimental plot per replicate and treatment was  $54 \text{ m}^2$  for green bean, sweet pepper and melon, and  $74 \text{ m}^2$  for tomato and zucchini. For each crop, the amount of water applied per treatment was determined from the daily estimates of  $ET_h$  and  $ET_c$ , respectively, which were calculated as described in the theoretical studies section. However, in the experiments carried out on sweet pepper, zucchini and melon crops, the treatment irrigated using the  $ET_h$  estimates was slightly different. A confidence interval of historical evapotranspiration values was calculated daily as  $ET_h = (ET_{oh} \pm nSD) \times K_{ch}$ ; where SD is the standard deviation of daily  $ET_o$ ; and  $n$  is equal to 2 for autumn–winter cycles and to 3 for spring crop cycles. Daily  $ET_o$  data during the 1988–2002 period were assumed to be normally distributed and the 95 and 99% confidence interval was approximately constructed as  $\pm 2$  and  $\pm 3SD$ , respectively. Then, the amount of water applied to the treatment irrigated using  $ET_h$  in each of these three crops was chosen within the calculated  $ET_h$  confidence interval in order to keep the soil matric potential (SMP) approximately between the locally recommended values of  $-20$  and  $-30 \text{ kPa}$ .

Local crop practices were applied to each crop. Table 1 presents variety, planting and harvest schedules and plant density for all crops studied.

### Measurements

Soil matric potential (SMP) was measured with manual tensiometers (four per treatment and depth), installed at 0.12 and at 0.27 m below the sand layer near the plant (Fernández 2000).

Volumetric soil-water content was measured fortnightly with a TDR system (TRASE 6005X1, Soil Moisture Corp., Santa Barbara, CA, USA) in all crops except zucchini. In sweet pepper, melon and green bean crops, TDR probes were installed in three locations (0.10, 0.25 and 0.45 m from the drip line and in line with the plant) within each lysimeter (two lysimeters per irrigation treatment). At each location, the soil-water content ( $H_v$ , mm) was measured at 0–45 cm. In tomato, TDR probes were installed in four locations (0.05, 0.18, 0.37 and 0.75 m from the drip line and in line with the plant) in each plot. Drainage from lysimeters was collected daily and applied irrigation water per treatment was measured with a water meter. Emitter discharge rate was periodically checked per replication and treatment to ensure the uniformity of the applied water distribution and the accuracy of the volumetric measurements.

**Table 1** Crop, variety, date of sowing (S) or transplanting (T) and end of the cycle, and plant density of the greenhouse experiments carried out at EL Ejido, Almería

Crop	Variety	Sowing/transplanting	End of cycle	Plant density
Tomato ( <i>Lycopersicon esculentum</i> L.)	Daniela	20/09/1999 (T)	30/05/2000	1.5×0.5 m <sup>2</sup>
Green bean ( <i>Phaseolus vulgaris</i> L.)	Donna	04/02/2002 (S)	28/05/2002	2×0.5 m <sup>2</sup>
Sweet pepper ( <i>Capsicum annuum</i> L.)	Salamanca	24/07/2000 (T)	29/01/2001	1×0.5 m <sup>2</sup>
Zucchini ( <i>Cucurbita pepo</i> L.)	Cónsul	25/08/2000 (S)	22/01/2001	1.5×0.75 m <sup>2</sup>
Melon ( <i>Cucumis melo</i> L.)	Aitana	22/02/2001 (T)	26/05/2001	2×0.5 m <sup>2</sup>

Plants within an area of 6 (tomato, green bean and melon), 7 (sweet pepper) and 9 m<sup>2</sup> (zucchini) were monitored per plot to determine crop biomass and marketable and non-marketable productivity. Additionally, an area of 2 m<sup>2</sup> of plants were collected at three different stages of the pepper, melon and green bean cycle to measure the leaf-area index (LAI) with an electronic planimeter (AM7626, Delta T Devices Ltd, Cambridge, England).

Air temperature in the greenhouse with the grass cover was measured with a hair hydrothermograph from January 1988 to September 1990, and with a ventilated aspirator-psirometer (mod. 1.1130, Thies Clima, Germany) from October 1990 to December 2002. Air temperature (H08-032-08, HOBO, Onset Compute Corp., MA, USA) and global radiation (H08-008-04, HOBO, Onset Compute Corp) within the greenhouses, where the vegetable crops were grown was measured daily. Finally, global radiation at 1.5 m above one experimental greenhouse was measured daily with a pyranometer (CM21, Kipp&zonen, Delft, Netherlands).

Water-use efficiency (WUE) was calculated for total shoot biomass (WUE<sub>b</sub>) and total fresh fruit production (WUE<sub>f</sub>) as the ratio of total shoot dry matter or total fresh fruit weight to seasonal water use (Sinclair et al. 1984).

## Results

### Theoretical studies

Figure 1 compares seasonal values of ET<sub>c</sub> and ET<sub>h</sub> for different crop cycles (autumn–winter cycles of sweet pepper, cucumber and green bean, and spring cycles of melon, watermelon and green bean) from 41 commercial greenhouses located on the Almería coast and evaluated over six cropping seasons (González 2003). The ET<sub>h</sub> estimated correctly the seasonal ET<sub>c</sub> values for the major greenhouse crops on Almería coast: most data were closely distributed around the 1:1 line for each crop cycle (Fig. 1), and the intercept and the slope of the regression equation were not significantly different from zero and unity, respectively ( $P < 0.05$ ), except for cucumber.

Table 2 shows the predicted values of the maximum cumulative soil-water deficits (MCSWD) in each of the 15 consecutive growth cycles for the main greenhouse crops on the Almería coast in a typical *enarenado* soil: tomato, sweet pepper, melon, watermelon and autumn–winter

and spring green bean. The MCSWD values were determined with simple soil-water balances by a comparison of the daily ET<sub>h</sub> and ET<sub>c</sub> values to schedule irrigation. Soil-water deficits beyond the calculated RAW value of 25 mm were not detected in short-cycle crops grown during autumn and winter periods, such as the autumn–winter green bean (Table 2), whereas in short-cycle crops grown in spring periods (such as melon, watermelon and green bean) and long-cycle crops (such as tomato and sweet pepper), soil-water deficits clearly above RAW were found in only 3 or 4 of the 15 years (Table 2).

### Experimental studies

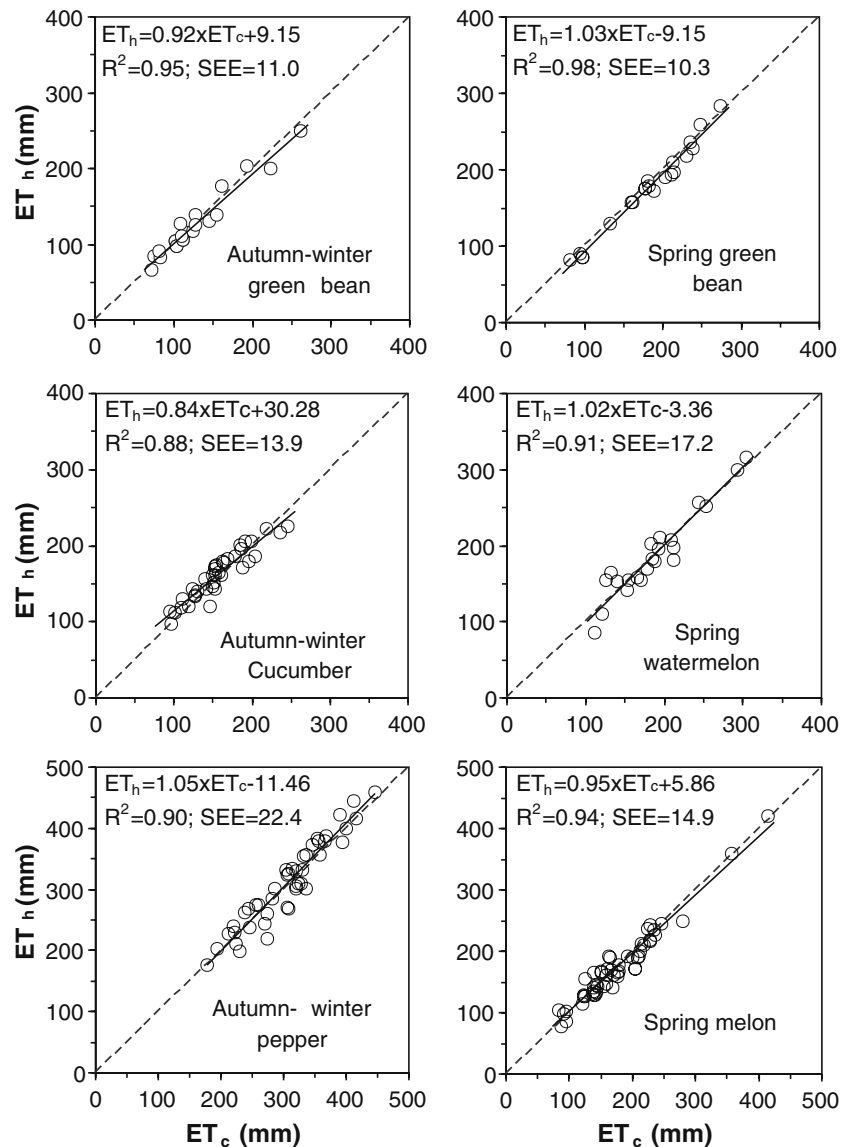
#### Tomato and green bean

The response of two greenhouse crops (autumn–spring tomato and spring green bean) to water applications scheduled by the estimates of ET<sub>h</sub> and ET<sub>c</sub> was evaluated experimentally.

Figure 2 shows the seasonal evolution of the SMP at 0.12 m below the sand layer near the plant for both irrigation treatments (ET<sub>h</sub> and ET<sub>c</sub>). In both the crops irrigated using the ET<sub>c</sub> values, the SMP varied between –15 and –30 kPa during most of the respective growth cycles (Fig. 2). The tomato crop irrigated using the ET<sub>h</sub> values presented similar SMP values to the one irrigated using the ET<sub>c</sub> values (Fig. 2), although they were slightly lower (–40 to –45 kPa) for short time intervals. In contrast, the green bean crop irrigated using ET<sub>h</sub> showed clearly lower SMP values, reaching around –75 kPa during flowering and fruit setting, than the one irrigated using ET<sub>c</sub> values. Similar behaviour between irrigation treatments was observed for the SMP at 0.27 m (data not shown) and for the volumetric soil-water content in the wetted soil zone (Fig. 2). The differences observed in soil-water status between irrigation treatments for the green bean crop (Fig. 2) were due to the higher values of real-time greenhouse reference ET (Fig. 3) and, especially the higher greenhouse temperatures during spring 2002, which resulted in faster growth and development of green bean (González 2003) and earlier maximum K<sub>c</sub> values (Fig. 3).

Shoot biomass and yield of both the crops are shown in Table 3 together with the seasonal irrigation water applied, which was slightly higher for the crop irrigated using the current ET data in both crops. No significant

**Fig. 1** Seasonal values of historical ( $ET_h$ ) versus real-time evapotranspiration ( $ET_c$ ) of the main greenhouse vegetable crops in the Campo de Dalías, Almería. Data from 41 commercial greenhouses monitored during six cropping seasons. *SEE*: Standard error of estimates



**Table 2** Maximum cumulative soil-water deficits (mm) occurred during each of the 15 consecutive cycles (1988–2002) for the main greenhouse crops on the Almería coast

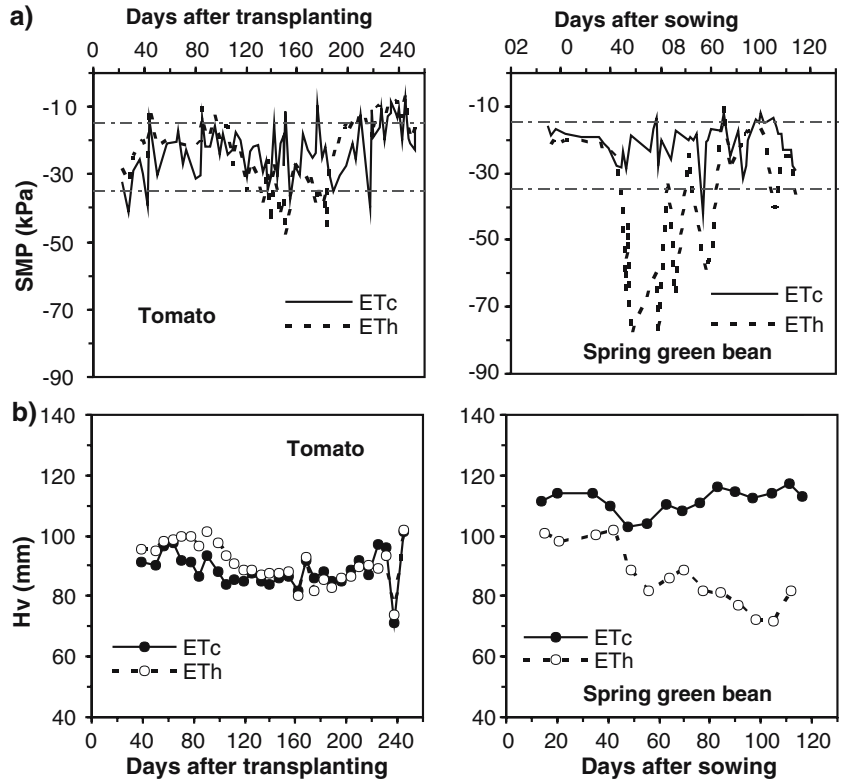
Year	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Green bean (A–W)	5	11	8	13	3	2	1	1	4	8	12	16	3	7	4
Green bean (S)	16	3	20	24	8	9	10	5	10	30	5	14	5	48	26
Melon (S)	7	4	10	22	8	9	12	4	8	29	5	22	10	54	47
Watermelon (S)	14	3	11	16	6	17	13	3	8	28	4	9	4	54	36
Sweet pepper (A–W)	5	5	5	38	4	3	1	3	23	20	32	34	34	8	25
Tomato (A–S)	8	12	13	15	8	5	4	7	25	12	41	32	31	24	10

S: Spring; A: Autumn; W: Winter

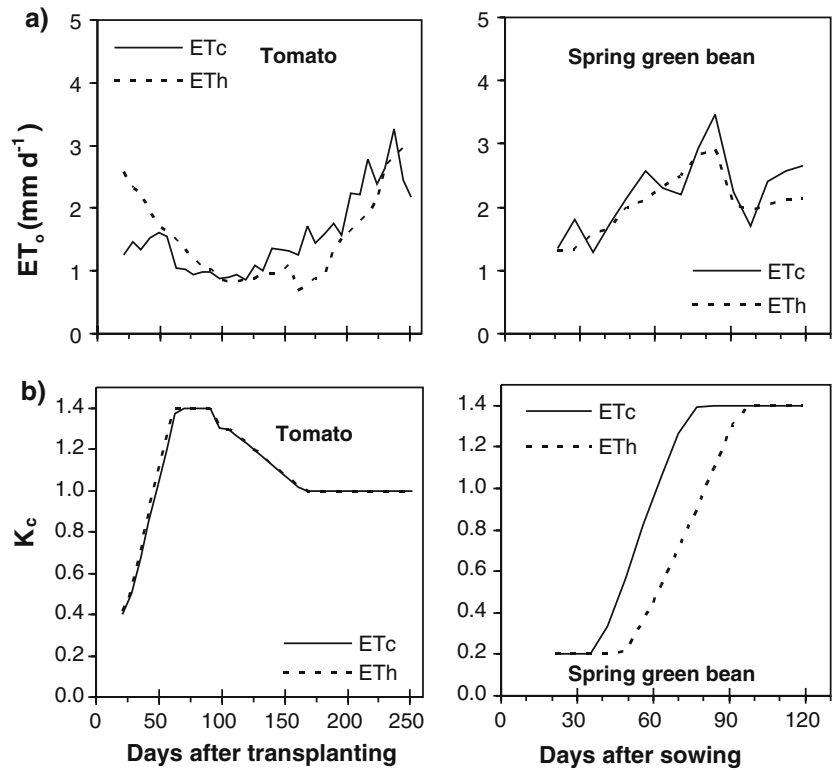
differences ( $P < 0.05$ ) between the irrigation treatments was found for tomato yield, although it was slightly lower for the crop irrigated using the  $ET_h$  values than that irrigated using the  $ET_c$  values. However, the green bean yield was significantly lower for the crop irrigated using the  $ET_h$  values. Similar behaviour between irrigation treatments was observed for shoot biomass.

There were no significant differences between irrigation treatments in tomato, but the generative and shoot biomass was significantly lower for the green bean crop irrigated using the  $ET_h$  values. Finally, no significant differences between irrigation treatments were observed in the harvest index for both crops (0.54 for tomato and 0.42–0.43 for green bean).

**Fig. 2** Seasonal evolution of **a** soil matric potential (*SMP*) measured before irrigation at 0.12 m below the sand layer near the plant; **b** Soil-water content (*H<sub>v</sub>*) measured in the wetted zone near the plant. Tomato and green bean crops irrigated using the *ET<sub>h</sub>* and *ET<sub>c</sub>* estimations, respectively



**Fig. 3** Seasonal evolution of: **a** greenhouse reference crop evapotranspiration (*ET<sub>o</sub>*) and **b** crop coefficient (*K<sub>c</sub>*) for two greenhouse crops (tomato and green bean) irrigated with current (*ET<sub>c</sub>*) and historical (*ET<sub>h</sub>*) crop evapotranspiration data



*Sweet pepper, zucchini and melon crops*

The use of *ET<sub>h</sub>* for irrigation scheduling was also experimentally evaluated in sweet pepper, zucchini and

melon crops, but in these experiments the amount of water applied at each irrigation event to the crops irrigated using the historical values of ET was chosen within the calculated *ET<sub>h</sub>* confidence interval

**Table 3** Total irrigation water applied, fresh weight of total and marketable fruits, vegetative, generative and shoot biomass and harvest index (HI) of tomato and green bean crops irrigated using the values of  $ET_h$  and  $ET_c$ , respectively

Crop and treatment		Irrigation water applied (mm)	Fresh fruits ( $g\ m^{-2}$ )		Shoot biomass ( $g\ m^{-2}$ )			HI ( $g\ g^{-1}$ )
			Total	Marketable	Vegetative	Generative	Total	
Tomato	$ET_c$	419	19,320	16,996	867	1,018	1,885	0.54
	$ET_h$	374	17,974	15,581	821	943	1,764	0.54
	LSD		NS	NS	NS	NS	NS	NS
Green bean	$ET_c$	187	5,021 a <sup>a</sup>	4,581 a	509	380 a	889 a	0.43
	$ET_h$	157	4,431 b	4,178 b	463	338 b	801 b	0.42
	LSD		354	269	NS	24	71	NS

LSD Least significant difference ( $P < 0.05$ ); NS No significant differences ( $P < 0.05$ )

<sup>a</sup>Values within a column followed by different letter are significantly different ( $P < 0.05$ )

$[ET_h = (ET_{oh} \pm nSD) \times K_{ch}]$  in order to maintain the SMP between the recommended values of  $-20$  and  $-30$  kPa.

For both irrigation treatments ( $ET_h$  and  $ET_c$ ) of pepper, zucchini and melon crops, the SMP values measured at 0.12 m varied between  $-15$  and  $-35$  kPa during most of the respective growth cycles (Fig. 4), except at the end of the melon crop when the soil-water availability was gradually lowered in both irrigation treatments. This final reduction is a common local practice aimed at increasing the fruit quality. Similar behaviour between irrigation treatments was observed for the SMP measured at 0.27 m (data not shown). Moreover, at both the depths, the SMP was slightly more variable for the crops irrigated using the  $ET_h$  data.

Table 4 shows the data of shoot biomass and fresh fruit production of pepper, zucchini and melon crops together with the seasonal irrigation water applied. The latter was slightly higher for the crop irrigated using the current ET values in the three experiments. No significant differences were found between irrigation treatments for total and marketable yield of sweet pepper, zucchini and melon crops (Table 4) or for the vegetative, generative and shoot biomass. The harvest index was about 0.60 for sweet pepper, 0.45 for zucchini and 0.68 for melon.

#### Water use efficiency

Table 5 shows the data of WUE based on shoot biomass ( $WUE_b$ ) and total fresh fruit weight ( $WUE_f$ ) for green bean, sweet pepper and melon crops. No significant

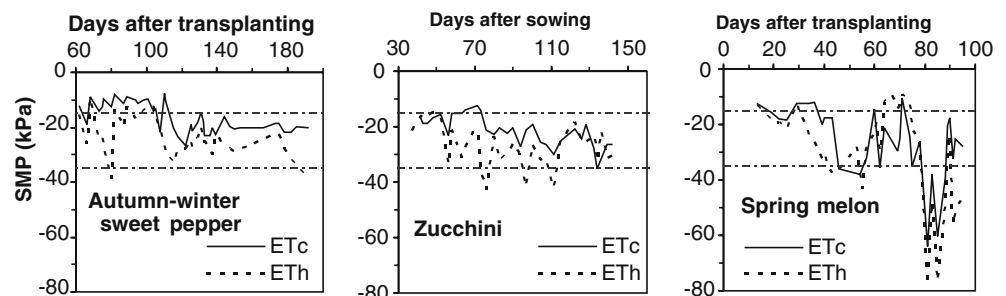
differences were found between irrigation treatments for  $WUE_b$  and  $WUE_f$  in any crop. Mean  $WUE_b$  values ranged from  $4.6\ g\ l^{-1}$  in green bean,  $5.7\ g\ l^{-1}$  in sweet pepper to  $7.3\ g\ l^{-1}$  in green bean, while  $WUE_f$  values ranged from  $26\ kg\ m^{-3}$  in green bean,  $40\ kg\ m^{-3}$  in sweet pepper to  $49\ kg\ m^{-3}$  in melon.

#### Discussion

Irrigation scheduling based on daily  $ET_h$  data was theoretically and experimentally assessed for the major soil-grown greenhouse vegetable crops on the Mediterranean coast of South-east Spain in order to improve irrigation WUE. The use of  $ET_h$  data for estimating the irrigation crop-water requirements is a simple method that can be easily adopted by farmers because it does not require real-time weather data (Hill and Allen 1996).

The potential use of  $ET_h$  data for irrigation scheduling of greenhouse vegetable crops was first evaluated theoretically. Overall, the simulated seasonal  $ET_h$  values for different crop cycles from 41 greenhouses monitored over six consecutive cropping seasons were not significantly different from the simulated seasonal  $ET_c$  values (Fig. 1). Therefore, the  $ET_h$  appears to be a useful tool for estimating seasonal crop-water requirements of greenhouse vegetable crops. However, differences between  $ET_h$  and  $ET_c$  values can occur throughout the crop cycle and induce transient soil-water deficits affecting crop productivity. In addition, the simulated values of MCSWD occurred in each of the 15 consecutive growth cycles were determined for the main greenhouse

**Fig. 4** Seasonal evolution of the soil matric potential (SMP) measured before irrigation at 0.12 m below the sand layer near the plant for sweet pepper, zucchini and melon crops, each irrigated using the  $ET_h$  and  $ET_c$  data, respectively



**Table 4** Total irrigation water applied, fresh weight of total and marketable fruits; vegetative, generative and total shoot biomass; and crop-harvest index (HI,  $\text{g g}^{-1}$ ) of sweet pepper, zucchini and melon crops, each irrigated using the values of  $\text{ET}_h$  and  $\text{ET}_c$ , respectively

Crop and treatment		Irrigation water applied (mm)	Fresh fruits ( $\text{g m}^{-2}$ )		Shoot biomass ( $\text{g m}^{-2}$ )			HI ( $\text{g g}^{-1}$ )
			Total	Marketable	Vegetative	Generative	Total	
Sweet pepper	$\text{ET}_c$	288	9,279	8,513	449 b	809	1,258	0.64 a <sup>a</sup>
	$\text{ET}_h$	248	8,807	7,881	571 a <sup>a</sup>	780	1,352	0.58 b
	LSD		NS	NS	122	NS	NS	0.06
Zucchini	$\text{ET}_c$	167	6,600	5,886	503	382	885	0.43
	$\text{ET}_h$	157	6,306	5,657	449	373	821	0.46
	LSD		NS	NS	NS	NS	NS	NS
Melon	$\text{ET}_c$	146	7,297	5,689	338	688	1,026	0.67
	$\text{ET}_h$	130	7,330	6,082	326	719	1,045	0.69
	LSD		NS	NS	NS	NS	NS	NS

LSD Least significant difference ( $P < 0.05$ ); NS No significant differences ( $P < 0.05$ )

<sup>a</sup>Values within a column followed by different letter are significantly different ( $P < 0.05$ )

**Table 5** Water-use efficiency ( $\text{g l}^{-1}$ ) based on shoot biomass ( $\text{WUE}_b$ ) and total fresh fruit weight ( $\text{WUE}_f$ ) of green bean, sweet pepper and melon crops irrigated using the values of  $\text{ET}_h$  and  $\text{ET}_c$ , respectively

Treatments	Green bean		Sweet pepper		Melon	
	$\text{WUE}_b$	$\text{WUE}_f$	$\text{WUE}_b$	$\text{WUE}_f$	$\text{WUE}_b$	$\text{WUE}_f$
$\text{ET}_c$	4.78	27.21	6.07	40.29	7.87	43.81
$\text{ET}_h$	4.44	25.23	5.27	39.36	6.68	54.38
LSD	NS	NS	NS	NS	NS	NS

LSD Least significant difference ( $P < 0.05$ ); NS No significant differences ( $P < 0.05$ )

crops on the Almería coast in a typical *enarenado* soil: simple soil-water balances were used comparing daily  $\text{ET}_h$  and  $\text{ET}_c$  values to schedule irrigation (Table 2). The calculated RAW value of 25 mm was very close to 27 mm, the threshold value of available soil-water content below which sweet pepper  $\text{ET}_c$  decreased in response to water stress in a typical *enarenado* soil on the Almería coast (Fernández et al. 2005). Soil-water deficits clearly affecting the greenhouse crop productivity ( $\text{MCSWD} > \text{RAW}$ ) were not detected in any of the short-cycle crops grown during autumn and winter periods (Table 2), whereas for short-cycle crops grown in spring periods and long-cycle crops, soil-water deficits clearly above RAW were found in 3 or 4 of the 15 years. The highest MCSWD values, which normally occurred at the end of the cycles and especially during the spring period, were associated to high differences between cumulative values of  $\text{ET}_o$  and  $\text{ET}_{oh}$  or between the dates of reaching maximum  $K_c$  values. The inter-annual variability of the daily crop evapotranspiration values during 1988–2002 was, in general, higher for short cycles during spring periods than for autumn–winter periods. In conclusion,  $\text{ET}_h$  values are useful for estimating irrigation-water requirements of soil-grown greenhouse vegetable crops on the Mediterranean coast of Southeast Spain as, on the whole, they do not produce excessive soil-water depletion (Fernández et al. 2001a). However, given the few cases of possible high crop-water deficits, it seems advisable to assess this method

experimentally before recommending its use for irrigation scheduling of high-value crops, such as greenhouse crops.

The response of five greenhouse crops (tomato, sweet pepper, zucchini, melon and green bean) to water applications scheduled with estimates of  $\text{ET}_h$  and  $\text{ET}_c$  was, therefore, evaluated in five experiments. In the tomato crop, SMP values were between  $-15$  and  $-35$  kPa during most of the growth cycle under both irrigation treatments (Fig. 2), although they varied more for the crop irrigated using the  $\text{ET}_h$  data. These values were close to the SMP of this soil at field capacity (Ritchie et al. 1999; González 2003). Consequently, shoot biomass and yield of tomato were not statistically different for the two irrigation treatments, although some productive parameters were slightly lower for the crop irrigated using the  $\text{ET}_h$  data. By contrast, the green bean crop irrigated using the  $\text{ET}_h$  data showed values of SMP and soil-water content clearly lower than that irrigated using the  $\text{ET}_c$  data, reaching values of SMP around  $-75$  kPa during crop flowering and fruit setting (Fig. 2). During these periods and the previous weeks, current values of green bean evapotranspiration were clearly higher than the corresponding historical values, because of higher  $\text{ET}_o$  values (Fig. 3) and especially higher greenhouse temperature during the spring 2002, which resulted in faster growth and development (González 2003) and earlier maximum  $K_c$  values (Fig. 3). In short cycles during spring periods,



relatively high values of greenhouse air temperature during the crop-development stage, compared to the historical climatic year, could induce major differences in  $K_c$  values between  $ET_c$  and  $ET_h$  treatments. Consequently, the crop irrigated using the  $ET_h$  data produced a lower LAI during the vegetative growth period ( $5.5 \text{ m}^2 \text{ m}^{-2}$  for the  $ET_h$  treatment vs.  $6.4 \text{ m}^2 \text{ m}^{-2}$  for the  $ET_c$  treatment at 87 days after sowing), lower total and marketable yield and lower vegetative and shoot biomass than the crop irrigated using the  $ET_c$  data (Table 3). Therefore, SMP values of  $-75 \text{ kPa}$  during flowering and fruit setting of green bean produced water stress and reduced growth and yield. Considering the water-retention curves for this soil (González 2003), SMP values of  $-75 \text{ kPa}$  may deplete about 35–40% of the total available water. These values of allowable depletion are slightly lower than those proposed by Doorenbos and Pruitt (1977) and Allen et al. (1998). The SMP values at which water stress occurred in the green bean crop were similar to those found by Mack and Varseveld (1982) and Hegde and Srinivas (1990) in loamy or finer soils, but clearly lower than those found by Stansell and Smittle (1980) in a loamy sandy soil.

Both theoretical studies and the two previous experiments have demonstrated that the use of daily values of  $ET_h$  for irrigation scheduling of greenhouse crops could be a useful irrigation tool in low-technology greenhouses, but it may occasionally induce crop-water deficit periods leading to yield reductions in a few years (3 out of 15) when the current climatic conditions lead to crop-water demands higher than those of the mean microclimatic year, such as that occurred in the green bean experiment during spring 2002. However, for high-value vegetables crops such as these (water-productivity values between 8 and  $16 \text{ € m}^{-3}$ , González 2003), the proposal of irrigation scheduling programmes which could occasionally lead to crop-water stress is not advisable, since most farmers would then probably apply much more water than recommended in order to avoid any possible reduction in yield or fruit quality. Thus, to optimise irrigation management of greenhouse horticultural crops based on  $ET_h$  data, three further experiments were conducted with sweet pepper, zucchini and melon crops, respectively. In these experiments, instead of using single  $ET_h$  values to estimate the amount of water applied at each irrigation event, values were chosen within the daily calculated  $ET_h$  confidence interval [ $ET_h = (ET_{oh} \pm nSD) \times K_{ch}$ ] in order to maintain the SMP close to the recommended values of  $-20$  and  $-30 \text{ kPa}$ . This method was applied simultaneously by monitoring the SMP with simple manual tensiometers. In the three crops evaluated, the SMP values varied between the recommended values during most of the respective growth cycles for both irrigation treatments ( $ET_h$  and  $ET_c$ ). No differences were found between irrigation treatments for crop growth, productivity or quality. Consequently, irrigation scheduling based on  $ET_h$  confidence interval data in combination with soil-water sensors covered the greenhouse crop-water

requirements and did not have a negative effect on biomass, yield or fruit quality. This method for scheduling irrigation could avoid the few cases of water deficit detected in the soil-water balance study (Table 2). It also allows ET values to be adjusted to the in situ greenhouse and crop conditions (i.e. variation in greenhouse structures and locations, and crop management). Finally, this method could even be used for greenhouses without soil-water sensors, which is usually the case in this area, although with less precision: farmers would have to decide how much water to apply at each irrigation event within the calculated  $ET_h$  confidence interval by observing the plant and/or weather conditions. In conclusion, the use of  $ET_h$  confidence interval data is recommended for estimating the crop-water requirements of soil-grown greenhouse vegetable crops on the Mediterranean coast of South-east Spain. This easily adoptable irrigation-scheduling method can be used to improve the irrigation water efficiency both in greenhouses without systems to monitor the soil- or plant-water status, and together with simple soil-water sensors such as manual tensiometers.

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