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Evapotranspiration of horticultural crops in an unheated plastic greenhouse

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Abstract

Large unheated greenhouse areas are located in the coastal lands of the Mediterranean Basin, based on low-cost structures covered with plastic. Water is a scarce resource in these areas and therefore it is necessary to optimise irrigation practice by applying the crop water needs, thus avoiding waste. This work was undertaken to determine the water requirements of four major horticultural crops grown in an unheated plastic greenhouse located in Almería, Spain.

Drainage lysimeters were used to determine the seasonal evapotranspiration (ET) of four crops (melon, green beans, watermelon and pepper), which ranged from 170 to 371 mm and it was associated with the reference ET (ET_0). Compared to irrigated crops outdoors, the seasonal ET of the greenhouse horticultural crops is relatively low due to the lower evaporative demand inside the greenhouse and to a further reduction in solar radiation transmission by whitening in late spring and summer. Additionally, off-season greenhouse crops are grown during low evaporative demand periods, thus the low water requirements.

Crop coefficient (K_c) curves were obtained for the four crops under different conditions. The K_c values varied with the crop, stage of development, and with management practices. Measured peak K_c values for crops, which were not vertically supported (melon and watermelon) were between 1 and 1.1, similar to the measured values for the same crops under field conditions. By contrast, peak K_c values for vertically supported (VS) crops (melon, green bean and sweet pepper) varied between 1.3

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and 1.4, which are higher than those reported for outdoors. The tall and open canopy structures of the VS greenhouse crops, their high leaf area indices, along with the high proportion of diffuse radiation inside the greenhouse, allowed for more uniform light penetration within the canopies and ET rates in those crops higher than those of the short, non-supported crops.

Management and climatic conditions combined to define an unusual K_c curve for sweet pepper. The crop is transplanted in late summer and reaches the peak K_c in early winter. Because of the low temperatures, K_c decreased thereafter down to about 1.0, until climatic conditions inside the greenhouse improved. From late winter to the end of the season, K_c was either stable or increased steadily. A simple K_c model based on thermal time for greenhouse crops with and without pruning, was proposed and validated. The model gave accurate estimates of measured K_c values for melon and pepper.

Keywords: Crop coefficient; Crop evapotranspiration; Horticultural crops; Plastic greenhouse; Models

1. Introduction

Greenhouse cultivation is a steadily growing agricultural sector all over the world (Enoch and Enoch, 1999; von Eslner et al., 2000). In Europe, most greenhouses were originally located in the centre and the north and consisted of high-cost, glass-covered structures with climatic control systems. This situation has changed drastically in the last decades and, at present, extensive greenhouse areas are located in the coastal areas of the Northern and Southern rims of the Mediterranean (Briassoulis et al., 1997). The type of structure primarily used in those areas is the so-called Mediterranean greenhouse (Wittwer and Castilla, 1995); low-cost, unheated plastic-covered structures and with soil-grown crops. Large areas are devoted to intensive horticulture under plastic; for instance, in the coast of the Almería province, south-east Spain, there are approximately 25,000 ha of greenhouses dedicated to intensive horticultural production (Sanjuan, 2001), one of the largest concentrations of greenhouses around the world.

Water is a scarce resource in the coastal areas of the Mediterranean and Almería, with an average annual precipitation of 220 mm, is no exception. Irrigation is the major consumer of water in the area and therefore it must be carried out with high efficiency. One prerequisite for efficient irrigation is knowledge of the consumptive use of the major crops or their evapotranspiration (ET). Such information is required to minimise percolation losses and thus environmental pollution.

For outdoor conditions, the approach using the product of reference ET (ET_0) and a crop coefficient (K_c) as proposed by FAO (Doorenbos and Pruitt, 1977; Allen et al., 1998) is commonly used to calculate ET worldwide. Of the many approaches used to calculate ET_0, the FAO Penman–Monteith equation, based on meteorological data and a hypothetical reference crop, is now considered the standard reference (Allen et al., 1998). The K_c varies with crop characteristics and only to a limited extent with climate. This enables the transfer of standard K_c values among locations and climates (Allen et al., 1998).

In the glasshouses of northern Europe, most crops are growing in soil-less cultures where soil evaporative losses are minimal. In these growing mediums, transpiration models of different complexity have been developed for predicting irrigation requirements for these systems (Jollie, 1999). In practice, applied water is commonly controlled by a computer on the basis of real time solar radiation measurements, as affected by crop type and growth crop stage (Jollie, 1999).

Studies on the water requirements of horticultural crops in Mediterranean greenhouses are scarce and irrigation is mainly scheduled according to farmers experience, despite the water scarcity (Fernández, 2000). In France, Villele (1974) found a high correlation between ET_0 measurements and solar radiation above the crop, but the relationship varied with climate and greenhouse type. In Spain, Fernández et al. (2001) found that the four methods proposed by FAO (Doorenbos and Pruitt, 1977) gave estimates of similar precision of the ET_0 measured inside a plastic greenhouse. They also concluded that solar radiation was the main factor affecting ET_0 and developed a model for the estimation of greenhouse ET_0, which was locally calibrated and shown to perform correctly under different conditions.

Canopy development and management of some greenhouse horticultural crops is quite different than that of outdoors. Differences in plant spacing, crop height (use of vertical supports, pruning practices) and in aerodynamic properties may affect the K_c values. Moreover, the proportion of diffuse radiation in a greenhouse is higher than outdoors (Baille, 1999). Thus, it is questionable whether the standard K_c values, determined experimentally outdoors, can be used directly to determine the ET of the greenhouse crops. Additionally, there is a need to determine the duration of the major growth stages for the major crops. For estimating the time from planting to effective full cover, simple models using thermal time regression equations or more sophisticated plant growth models has been proposed (Ritchie and Johnson, 1990; Slack et al., 1996).

This work was performed to develop the crop coefficients and to compute the evapotranspiration of four of the major horticultural crops (melon, green pepper, green bean and watermelon) grown in unheated plastic greenhouses in south-east Spain.

2. Material and methods

2.1. Site, experiments and management

The experiments were carried out in 'Las Palmerillas' research station (Cajamar), located at El Ejido, Almería (latitude 36°48′N, longitude 2°3′W, altitude 155 m) on the coastal area of south-east Spain. The climate is Mediterranean with a mild winter (mean monthly temperature of 12.9 °C at winter) and a mean annual precipitation of 220 mm.

The experiments were conducted in two typical Mediterranean greenhouses (Wittwer and Castilla, 1995). They were low-cost structures, 58 m long × 24 m wide, covered with a 0.2 mm thick thermal polyethylene sheet. They were E–W oriented and passively ventilated by opening side panels and roof vents, and had metallic structures with symmetrical roofs of 12.5% slopes. Artificial layered soils, were used, consisting of a 30 cm layer of imported loamy soil placed above the naturally-occurring, gravely sandy-loam soil. Latter, a shallow (2 cm) layer of manure is placed on the imported soil surface and then a 10 cm layer of coarse sand is applied on top as mulch. This artificial soil is widely used in the greenhouses of the region. For the loamy soil, the upper and lower limits of soil water content were 0.30 and 0.10 cm cm^{-3} (Castilla, 1986).

Table 1
Dates of sowing or transplanting and harvest, and plant density of melon, green beans, pepper and watermelon crops grown in plastic greenhouses in Almería

Crop	Sowing or transplanting	Harvest	Plant density (plants m^{-2})
Melon	8 March 1993	5 July 1993	1
Melon	10 January 1994	25 June 1994	1
Melon	17 March 1999	14 June 1999	1
Green bean	17 September 1992	10 January 1993	6
Green bean	20 August 1993	12 December 1993	6
Sweet pepper	9 September 1996	25 May 1997	2
Sweet pepper	15 September 1997	20 May 1998	2
Watermelon	17 March 1999	6 June 1999	0.25

Melon, green bean and sweet pepper crops were grown from 1992/1993 to 1998/1999. Watermelon was grown in another greenhouse of similar characteristics in 1999. Irrigation water of 0.4 dS m^{-1} electrical conductivity was supplied through a drip system that had a distribution uniformity above 90%.

Another greenhouse (24 m × 20.5 m) was sown with perennial grass (*Cynodon dactylon* L.*)*, which was maintained at 0.1–0.2 m height by regular mowing. The grass greenhouse was irrigated with the same water used for the horticultural crops.

In each greenhouse we used two drainage lysimeters, 4 m length, 2 m width and 0.7 m depth, located on the southern side, which had 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 down to 0.6 m, where a layer of gravel was placed on top of the butyl rubber sheet. The lysimeter soil depth was adequate as most of the growth and activity of roots from greenhouse horticultural crops use to occur within the imported loamy soil layer (Castilla, 1986). Table 1 presents the planting and harvest schedules for all crops studied. Specific horticultural practices were as follows:

- **Melon** (*Cucumis melo* L.). Plants were grown during the winter-spring season of 1992/1993 (Spanish type, cv. Categoría), 1993/1994 (Spanish type, cv. Categoría) and 1998/1999 (Galia type, cv. Eros). For the 1992/1993 and 1993/1994 seasons, plants were not supported (NS) and the main stem was pruned leaving two secondary stems per plant. For the 1998/1999 season, the main stem was also pruned leaving two secondary stems per plant, which were vertically supported (VS) by wires up to a height of 2 m. During flowering, bees (*Apis mellifera*) were introduced in the greenhouse for pollination. Fertilisers were applied before planting, at a rate of 13 g N m^{-2}, 6 g P_2O_5 m^{-2} and 30 g K_2O m^{-2} in the 1992/1993 season, and at 12 g N m^{-2}, 6 g P_2O_5 m^{-2} and 22 g K_2O m^{-2} in the 1993/1994 season. Additional nutrients were added via irrigation through the season at a rate of 2 g m^{-2} of N in 1992/1993, and 9 g m^{-2} of N and 7 g m^{-2} of P_2O_5 in 1993/1994. During 1998/1999 all fertilisers were applied via irrigation at a rate of 27 g m^{-2}, 12 g P_2O_5 m^{-2} and 30 g K_2O m^{-2}.
- **Green bean** (*Phaseolus vulgaris* L.). Plants of cv. Helda were grown during the autumn-winter season of 1993/1994 and were vertically supported with wires up to a height of 2 m. All fertilisers were applied before planting at a rate of 9 g P_2O_5 m^{-2} and 22 g K_2O m^{-2}.

- **Sweet pepper** (*Capsicum annuum* L.). Plants of cv. Drago, Lamuyo type, were grown during 1996/1997 and 1997/1998. Plants were vertically supported using the Dutch system in which three stems per plant are vertically supported by guides, and lateral stems are removed. Fruits were mostly red when harvested. Each cropping season, fertilisers were applied before planting at a rate of 5 g N m^{-2}, 10 g P_2O_5 m^{-2} and 30 g K_2O m^{-2}. Fertilisers were also added through the irrigation at a rate of 70 g m^{-2} of N, 12 g P_2O_5 m^{-2} and 46 g K_2O m^{-2} in 1996/1997, and at 86 g m^{-2} of N, 13 g P_2O_5 m^{-2} and 48 g K_2O m^{-2} in 1997/1998.
- **Watermelon** (*Citrullus lanatus* L.). Plants of seedless watermelon (cv. Reina de Corazones) grafted on *Cucurbita maxima* × *Cucurbita moschata* rootstocks were grown during the winter-spring season of 1998/1999. During flowering, bees (*A. mellifera*) were introduced for pollination. All fertilisers were applied through the irrigation at a rate of 21 g m^{-2} of N, 22 g m^{-2} of P_2O_5 and 48 g m^{-2} K_2O.

2.2. Measurements

2.2.1. Greenhouse climate

An automatic agro-meteorological station (AWOS 7770, Thies Clima, Gottingen, Germany), mounted at 1.5 m height, and a class A evaporation pan were placed in the southern part of the greenhouse that had the grass cover. Air temperature was measured with a hair hydrothermograph from January 1988 to September 1990, and with a ventilated aspiro-psychcrometer from October 1990 to December 1999. Evaporation rate (E_0) was measured daily from 1985 to 1999. The relation between E_0 and ET_0 values was experimentally determined by Fernández et al. (2001).

The temperature and relative humidity of the greenhouse where the crops were grown was measured daily with a hair hydrothermograph. Analysis of weather parameters (temperature and humidity) in both greenhouses indicated that the climate in the crop and grass greenhouses was very similar.

2.2.2. Evapotranspiration

Horticultural crop evapotranspiration (ET) and grass or reference evapotranspiration (ET_0) were weekly measured in the lysimeters by the soil water balance approach using the following equation:

$$\mathrm{ET} = (\mathrm{SWC}_{t0} - \mathrm{SWC}_{t1}) + I - D \quad (1)$$

where ($SWC_{t0} - SWC_{t1}$) is the change in volumetric soil water content between two measurement dates; *I* and *D* are, respectively, the total volumes of applied irrigation water and collected drainage for the period under consideration.

The volumetric soil water content in the lysimeters was measured with a TDR system (TRASE 6005X1, Soil Moisture Corp. Santa Barbara, CA, USA). Weekly TDR measurements were initially scheduled, but for not supported crops (melons and watermelon) the frequency of measurement was drastically reduced when crops covered most of the soil surface to avoid crop damage. In vertically supported crops measurements were, in general, carried weekly or biweekly. TDR probes were installed in each crop lysimeter at four locations: two within the wetted zones by the emitters and two halfway between drip lines. At each location, the soil water content was measured at 0–9, 10–29 and 30–59 cm. Soil water content was also measured in four locations inside the grass lysimeter. Drainage from the lysimeters was collected daily and applied irrigation water was measured with a water meter. Emitter discharge was frequently checked to ensure that the water applied to the lysimeters was in line with volumetric measurements. The K_c values were calculated for weekly periods as the ratio between ET and ET_0 values (Doorenbos and Pruitt, 1977; Allen et al., 1998).

The depth of applied irrigation water required was determined using pan evaporation data from the grass greenhouse, following general recommendations developed for Almería greenhouses (Castilla et al., 1990). To ensure that ET was not limited by excessive or reduced soil water content, irrigation was adjusted to allow for some drainage from the lysimeter most of the time.

2.2.3. Leaf area index

Plants were periodically collected throughout their growth cycles to measure leaf area index (LAI) with an electronic planimeter (Delta T Devices Ltd., Cambridge, England). LAI was calculated from four samples of 1 m^2 of each crop, except for the supported melon (four samples of 2 m^2) and the watermelon crop (four samples of 4 m^2).

2.3. Modelling K_c under partial cover

The K_c values of NS melons and green beans during partial crop cover (LAI less than 3) were estimated using the approach proposed by Ritchie and Johnson (1990). First, measured plant leaf area values were plotted as a function of cumulative thermal time (TT) and a Gomperzt function was adjusted to the data as follows:

$$A = A_0 \exp[-b \exp(K\,\mathrm{TT})] \quad (2)$$

where A is plant leaf area at time t, A_0 the maximum plant leaf area, TT the cumulative thermal time, and b and K the empirical parameters of the Gomperzt equation that are obtained by linear transformation of Eq. (2) using experimental data. Calculation of cumulative thermal time after emergence or planting of the crop requires daily data of maximum and minimum air temperature, and critical, crop-specific temperatures (Caudal et al., 1985; Fernández, 2000). Empirical parameters were determined for NS melon and green bean using measured LAI of both crops from the 1992/1993 season and assuming A_0 values of 15,000 cm^2 for bean and 40,000 cm^2 for melon. Thereafter, assuming a linear relationship between K_c and LAI values from crop's emergence (transplanting) to effective full cover, K_c values were determined as:

$$K_c = K_{c_{ini}} + \left[\frac{K_{c_{mid}} - K_{c_{ini}}}{3}\right] \times \mathrm{LAI} \quad (3)$$

where $K_{c_{ini}}$ and $K_{c_{mid}}$ are the K_c values for the initial and mid-season stages, respectively (Doorenbos and Pruitt, 1977; Allen et al., 1998).

For greenhouse crops frequently pruned such as pepper, the Ritchie and Johnson's method could not be used because their LAI values are clearly affected by pruning. Thus, for the partial cover stages of the pepper crop a linear relationship between K_c and TT was established using LAI, and TT data measured during partial cover in the 1996/1997 season. The use of this approach is, therefore, limited to pepper crops under similar canopy management.

3. Results

3.1. Crop evapotranspiration

Table 2 presents the measured seasonal ET values for melon, green bean, sweet pepper and watermelon. Seasonal ET ranged from 170 to 371 mm. The lowest values were 170 mm for watermelon and 174 mm for green bean. In melon, ET varied from 177 to 298 mm, while pepper had ET values of 353–371 mm. Fig. 1 shows the seasonal evolution of ET for the four crops in relation to the ET_0. In melons, there was a difference between the 2 years; in 1993, ET reached ET_0 values about 20 days earlier than in 1999. The changing evaporative demand from autumn towards spring dominated the ET patterns of each crop, but there were significant differences among crops in the evolution of ET (Fig. 1). In all cases, The ET values were clearly less than the ET_0 in the early developmental stages, but the ET increased with time until it until exceeded ET_0, clearly in bean, pepper, and in VS melons, but was close to ET_0 in watermelon (Fig. 1). Average daily values of ET ranged from 0.3 mm day^{-1} (sweet pepper of 1996/1997) to 4.5 mm day^{-1} (melon of 1999) while ET_0 ranged from values around 0.5 mm day^{-1} in the winter of 1996/1997 to values close to 4.0 mm day^{-1} in the springs of 1993, 1997 and 1999 (Fig. 1).

3.2. Crop coefficients

Fig. 2 shows the seasonal evolution of measured K_c and LAI values for melon, green bean and watermelon crops. For the three melon crops (two NS and one VS), the K_c was around 0.2 during the crop establishment or initial stage ($K_{c_{ini}}$) when LAI values were close to zero (Fig. 2). Thereafter, the K_c increased almost linearly, reaching a maximum value when LAI exceeded 2.5–3. The maximum or mid-season K_c value ($K_{c_{mid}}$) was around 1.0–1.1 for the NS melon crop in both seasons, but reached 1.2–1.3 for the VS crop (Fig. 2). As melons were approaching the end of the 1994 and 1999 crop cycles, their K_c values decreased somewhat, a decline that was also observed for the LAI values. The K_c curves of

Table 2
Crop duration (days) and seasonal values of crop reference evapotranspiration (ET_0, mm) and evapotranspiration (ET, mm) of melon, green bean, pepper and watermelon crops grown in plastic greenhouses in Almería

Crop	Seasons	Length	ET_0	ET
Melon	1992/1993	119	307	298
Melon	1993/1994	135	206	219
Melon	1998/1999	90	229	177
Green bean	1993/1994	114	174	174
Sweet pepper	1996/1997	258	445	371
Sweet pepper	1997/1998	248	407	353
Watermelon	1998/1999	90	228	170

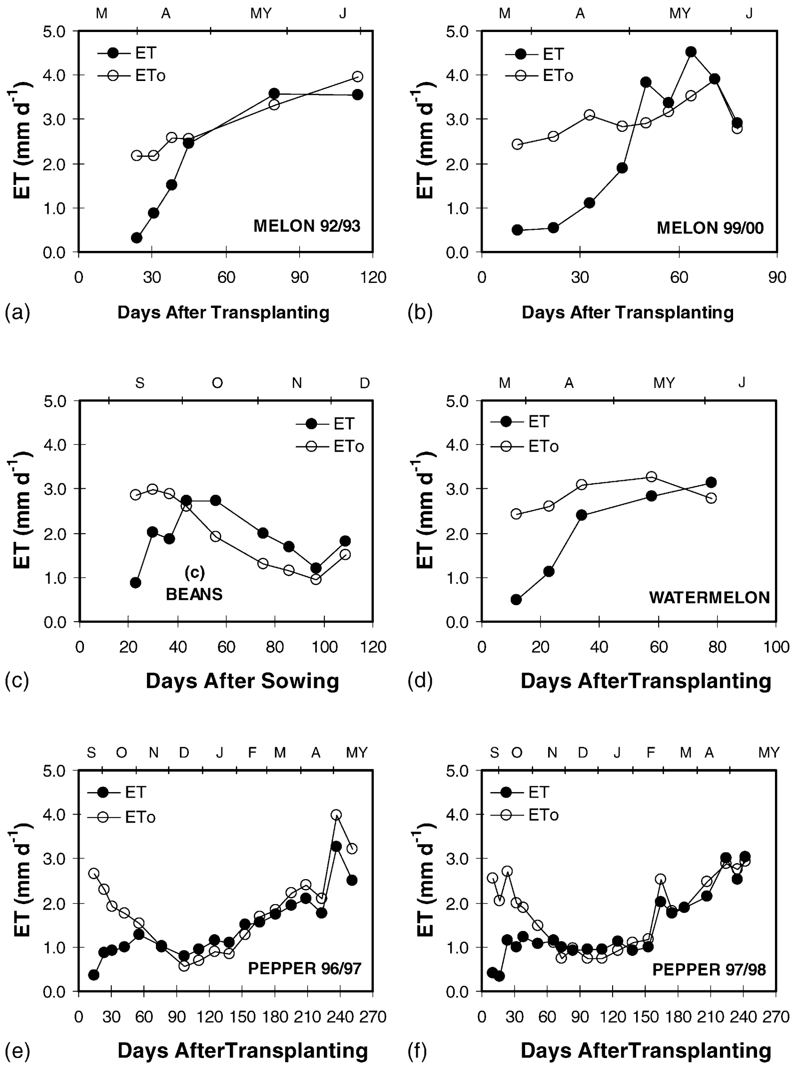

Fig. 1. Greenhouse reference crop evapotranspiration (ET_0) and crop evapotranspiration (ET) values of: (a) a no supported melon (winter-spring season of 1992/1993); (b) a vertically supported melon (winter-spring season of 1998/1999); (c) a vertically supported green bean (autumn-winter season of 1992/1993); (d) a no supported watermelon (winter-spring season of 1998/1999); and (e) and (f) two supported sweet pepper (1996/1997 and 1997/1998 seasons) (at El Ejido, Almería).

the NS melons differed between growing seasons (Fig. 1) because the initial and crop development stages were longer in 1994 than in 1993.

The initial K_c value of watermelon during the spring of 1999 was 0.2 ($K_{c_{ini}}$) when the LAI values were close to zero (Fig. 2). Thereafter, the K_c increased almost linearly to a maximum value of 1.1 ($K_{c_{mid}}$) at the end of the crop cycle. A similar evolution was observed for LAI that reached a maximum value of 3.2.

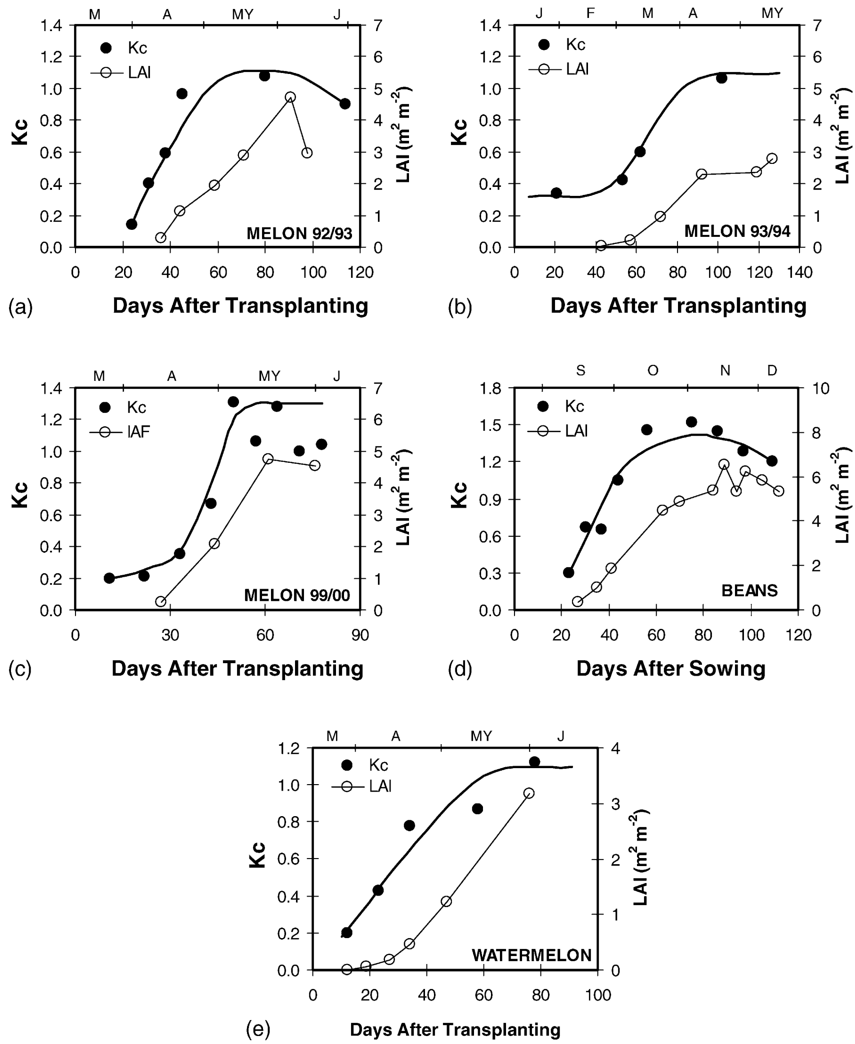

Fig. 2. Curves of crop coefficient (K_c) and leaf area index (LAI) values of: (a) a no supported melon (winter-spring season of 1992/1993); (b) a no supported melon (winter-spring season of 1993/1994); (c) a vertically supported melon (winter-spring season of 1998/1999); (d) a vertically supported green bean (autumn-winter season of 1992/1993); and (e) a no supported watermelon (winter-spring season of 1998/1999). Crops grown in plastic greenhouses at El Ejido, Almería.

The seasonal evolution of LAI and K_c values for the vertically supported green bean crop was similar throughout most of the green bean growth cycle (Fig. 1). Initially, the K_c was slightly higher than 0.2. Later, the K_c increased almost linearly to reach a maximum average value of 1.4 ($K_{c_{mid}}$) when LAI was above 3. Finally, K_c decreased slightly down to 1.2 at the end of the season, which was associated to a decline in LAI (Fig. 2).

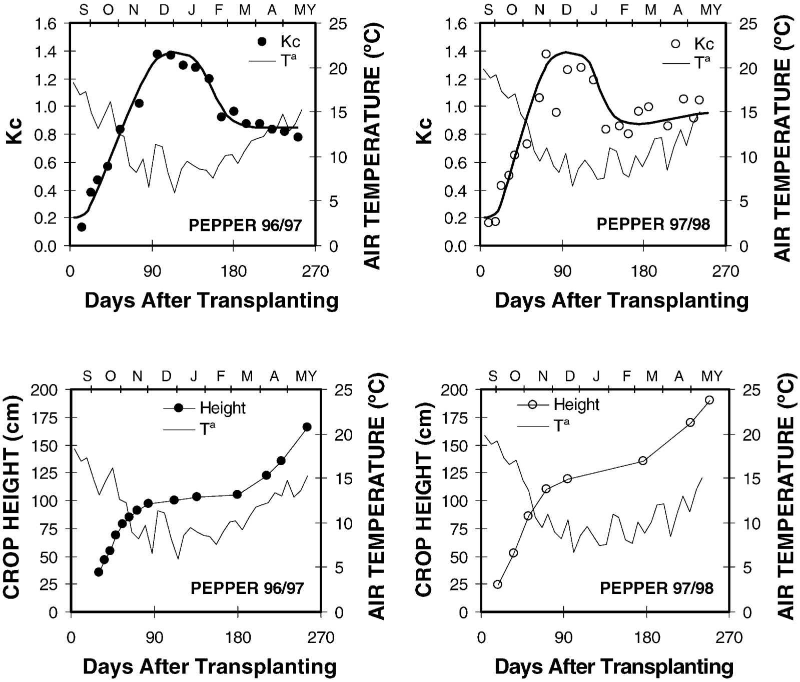

Fig. 3. Crop coefficient (K_c), crop height and inside air temperature values of a supported sweet pepper crop grown in a plastic greenhouse during the 1996/1997 and 1997/1998 growing seasons (at El Ejido, Almería).

Measured values of K_c for a pepper crop are shown in Fig. 3 for two cropping seasons. The K_c rapidly increased from an initial value of 0.2 ($K_{c_{ini}}$) to a maximum average value of 1.3–1.4 ($K_{c_{mid}}$), as the crop grew in autumn (Fig. 3). Later, during the coldest part of winter, when daily minimum air temperatures were below 10 °C (Fig. 3), the K_c values decreased progressively to a value around 0.9. Thereafter, the evolution of K_c differed slightly between seasons. In the 1996/1997 season, The K_c declined steadily to a value of 0.8 during the last 3 months, whereas it showed a slight increase to 1.0 during the last 3 months of the 1997/1998 season (Fig. 3).

3.3. Modelling crop coefficients

To generalize the K_c values, it is necessary to simulate the K_c for the initial and crop development stages. We used the approach proposed by Ritchie and Johnson (1990) for predicting the LAI of green bean and NS melon crops during these stages. Thereafter, a linear relationship between K_c and LAI values from crop's emergence (transplanting) to effective full cover was assumed. The Ritchie and Johnson model was validated with data of the 1993/1994 season and gave good estimates of measured LAI values of both crops during the initial and crop development stages, when the K_c values are critically influenced by LAI (Fig. 4). In the stages approaching maximum LAI, model predictions were poorer (Fig. 4) but that had limited impact on K_c values as LAI does not affect K_c much after full

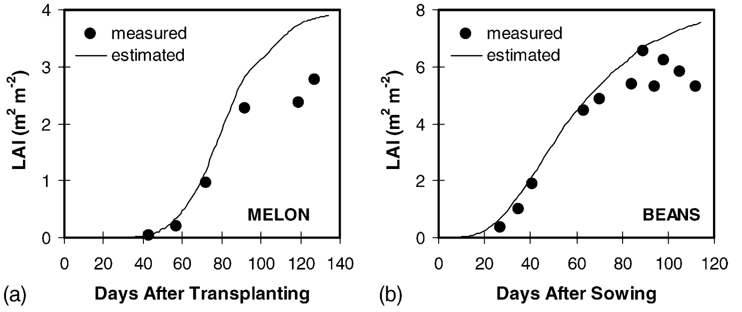

Fig. 4. Measured and estimated values of leaf area index (LAI) of a no supported melon (a) and a vertically supported green bean crop (b) during the 1993/1994 cropping season (at El Ejido, Almería).

radiation interception has been achieved. From effective full cover to final harvest, K_c values are considered equal to $K_{c_{mid}}$.

For the sweet pepper crop, the empirical regression equation obtained between K_c and TT values during the partial crop cover stage was:

$$K_c = K_{c_{ini}} + 0.00176 \times (\mathrm{TT} - 200) \quad (4)$$

This equation was used for estimating K_c for pepper during the initial and crop development stages, with the constraint that K_c values cannot be lower than $K_{c_{ini}}$ or higher than $K_{c_{mid}}$ during these stages. From effective full cover, the estimated K_c values for the sweet pepper crop are considered equal to the $K_{c_{mid}}$. At the onset of January, normally, starts a period of low vegetative growth and premature leaves ageing in pepper, which ends at the onset of March (Fig. 3). This period, caused by the low winter temperatures, produced a progressive K_c decline (falling phase). Hereafter, the estimated K_c values maintained a steady value of around 0.9 (Fig. 3).

Finally, Fig. 5 presents measured and estimated K_c values of melon (1993/1994) and pepper (1997/1998). Measured K_c values were correctly estimated using these models throughout the entire melon and pepper growth cycle (Fig. 5). When the calculated data was plotted against the measurements (Fig. 5) most data were closely distributed around the 1:1 line and the intercept and the slope of the regression equation were not significantly different from zero and unity, respectively ($P < 0.05$). The mean absolute error (Willmott, 1981) was 0.10. Thus, this model could be used for K_c estimations of greenhouse horticultural crops growing in soils. To generalize the K_c values, Table 3 presents the K_c values for the major crops grown under plastic greenhouses in Almería.

4. Discussion

The seasonal ET of four major Mediterranean greenhouse crops ranged from 170 to 371 mm whereas the seasonal ET_0 varied from 174 to 445 mm for the same period (Table 2). While there were considerable differences in the seasonal ET between and within crops, evaporative demand was the primary cause for such differences as the seasonal ET was clearly associated with the seasonal ET_0 (R^2 = 0.93, n = 7). In Mediterranean areas, the

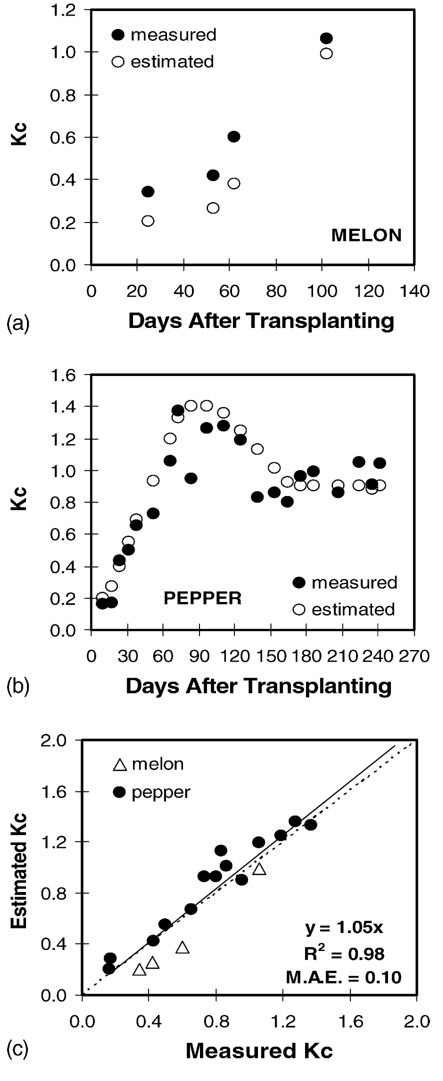

Fig. 5. Measured and estimated K_c values of melon (1993/1994) and pepper (1997/1998) grown in plastic greenhouses at El Ejido, Almería.

seasonal ET of greenhouse horticultural crops is quite low when compared to that of irrigated crops outdoors (Fabeiro et al., 2002 (melon); Barros and Hanks, 1993; Hegde and Srinivas, 1990 (green bean); Erdem and Yuksel, 2003 (watermelon); Beese et al., 1982 (sweet pepper)). This is due, firstly, to a lower evaporative demand inside a plastic greenhouse, which is 30–40% lower than outdoors throughout the entire greenhouse cropping season (Fernández, 2000). Secondly, greenhouse cultivation in the Mediterranean areas is mostly concentrated in periods of low evaporative demand (autumn, winter and spring), whereas irrigated crops outdoors are often grown during high evaporative demand

Table 3
Crop coefficients values for the initial ($K_{c_{ini}}$), mid-season ($K_{c_{mid}}$) and late-season ($K_{c_{end}}$) growth stages of the main horticultural crops grown in plastic greenhouses in Almería

Crop	$K_{c_{ini}}$	$K_{c_{mid}}$	$K_{c_{end}}$
Not supported melon	0.2	1.1	1.0[a]
Vertical supported melon	0.2	1.3	1.1[a]
Green bean	0.2	1.4	1.2[a]
Sweet pepper	0.2	1.3	0.9
Not supported watermelon	0.2	1.1	1.0[a]

[a] Values used for crops harvested more than once; otherwise $K_{c_{mid}}$ values are used form effective full cover to crop harvest.

periods. Moreover, the whitening of the external plastic cover as temperatures increase in Spring, is common in most Mediterranean greenhouses to reduce the air temperature inside. This practice also reduces the greenhouse transmission coefficient for solar radiation, and, therefore, it decreases further the evaporative demand indoors. The low ET and the high value of the crops grown off-season, combine to yield values of water productivity of the order of 10–15 \$ m^{-3}, a value amongst the highest reported for irrigated agriculture (Postel, 1998).

The seasonal K_c curves of four major Mediterranean greenhouse crops under different management conditions were experimentally determined. K_c values varied by crop, developmental stage, and management. There was a clear association between K_c and LAI, particularly during the development stage (Fig. 2), reflecting the effects of crop growth and development on ET (Doorenbos and Pruitt, 1977; Allen et al., 1998). The evolution of K_c in greenhouse crops followed a pattern similar to those described for most herbaceous crops grown outdoors (Doorenbos and Pruitt, 1977; Allen et al., 1998). After crop establishment, when the crop starts its lineal growth phase, both K_c and LAI values increased rapidly and reached maximum K_c values, which define the mid-season stage, as crop LAI approached values above 2.5–3 (Fig. 2). Finally, a slight decline of K_c was observed at the end of some crop cycles (late-season stage), which was also associated to an LAI decline, normally attributed to leaf senescence. Nevertheless, many off-season crops, such as the melons, are terminated due to marketing reasons before plants age enough to induce a reduction in K_c (Fig. 2).

Mid-season stage value of K_c for NS greenhouse crops (melon and watermelon) was about 1.1 (Fig. 2). This value coincides with the maximum K_c value measured in France in a melon crop grown in a heated greenhouse (Caudal et al., 1985), and it is similar to the mid-season K_c values reported for melon and watermelon grown outdoors (Allen et al., 1998; Grattan et al., 1998). In Mediterranean areas, crops with prostrate growth habit, such as melon and watermelon, are usually managed similarly in greenhouses and outdoors and, consequently, they present similar canopy characteristics (ground cover, crop height, leaf area, etc.). Thus, for such greenhouse crops, the mid-season K_c values proposed for outdoor crops (Allen et al., 1998) appear reasonable for use. By contrast, mid-season K_c values for vertically supported greenhouse crops (melon, green bean and sweet pepper) were around 1.3 (Figs. 2 and 3). These values are similar to those reported for similar crops of tomato, sweet pepper and green bean (Castilla et al., 1990), grown in plastic greenhouses of Almería, and for tomato grown in a plastic greenhouse in southern Italy (Quaglietta-

Chiaranda and Zerbi, 1986). However, these K_c values are higher than those reported for the same crops in Mediterranean areas of Italy (Rubino et al., 1986) and in California (Snyder et al., 1987; Grattan et al., 1998), and those proposed for Allen et al. (1998) for subhumid climates, all grown outdoors. The values reported here were obtained under a wide range of climatic conditions from winter to late spring, but in all cases there were no significant differences in the relative humidity and air temperatures of the greenhouses used for the ET and ET_0 measurements, respectively. It appears that, in greenhouses, supported vegetable crops with tall canopies have greater maximum K_c values than the same crops with prostrate growth habits. Allen et al. (1998) concluded that tall crops, such as maize or sugar cane, had maximum K_c values 15–20% greater that those of short crops. They also recommend mid-season K_c values of 1.15–1.20 for vegetable crops such as bean, pepper, cucumber or tomato when grown on stalks reaching 1.5–2 m in height, instead of the 1.00–1.05 values when they are grown without support. The higher K_c values of the VS greenhouse crops, usually reaching 1.5–2 m in height, is probably due their net radiation being greater that that of short crops, because of the morphological features of their canopies. The taller greenhouse crops could intercept more radiation (Rosenberg et al., 1983). Moreover, the greater LAI and the more open canopy structures of VS canopies, combined with an increase in the diffuse radiation component inside the greenhouse (Baille, 1999), enables better radiation absorption and hence increased transpiration from those canopies. All this resulted in tall greenhouse crops having their entire canopy actively contributing to the enhanced transfer of heat and water vapour, thus the high K_c values found experimentally.

The pepper crop K_c curve in the greenhouse did not follow those described by Doorenbos and Pruitt (1977) and Allen et al. (1998) for pepper outdoors. After a short initial stage, the K_c increased rapidly to reach the maximum value in early winter (Fig. 3). Thereafter, however, the K_c decreased during the colder part of winter in both seasons. This decline in K_c coincided with a period of low vegetative growth (crop height maintained steady) and premature leaf ageing, possibly caused by the low temperatures (Fig. 3). Low temperatures have been reported to cause premature ageing of new cucumber leaves in Almería greenhouses (Lorenzo, 1994). This phase also coincided with the first harvests and assimilate competition between vegetative and reproductive organs (Lorenzo, 1994) could have also contributed to the low vegetative growth. Subsequently, as temperatures increases, pepper K_c values stayed stable or had a slight increase (Fig. 3). The K_c values for the last phase of greenhouse pepper differ from the K_c decline phase, commonly reported for pepper and most agronomic crops (late-season stage). This can be attributed to the crop re-growth observed in spring when the greenhouse climatic conditions improve (Fig. 3). A similar seasonal evolution of K_c values was reported by Castilla et al. (1990) and Fernández (2000) for tomatoes grown under greenhouse conditions in Almería.

In the Almería region, planting and harvest dates of greenhouse crops vary substantially from year to year depending on agronomic, weather and, especially, on market conditions. As a result, the length of the four growth stages considered in the K_c–ET_0 approach (Doorenbos and Pruitt, 1977; Allen et al., 1998) could differ significantly between seasons (Fig. 2) and growers. Therefore, the use of the K_c–ET_0 approach in greenhouse crops requires an estimate of the length of the main growth stages. Two approaches were followed to estimate K_c values during the initial and crop development stages, both based on TT data. For greenhouse crops slightly or not pruned, the Ritchie and Johnson method was used giving good estimations of LAI values for NS melon and green beans (Fig. 3). For greenhouse crops frequently pruned, such as pepper, a linear relationship between K_c and TT was determined that would need calibration in other environments. The K_c values reported in Table 3 should enable growers to determine the water requirements of greenhouse crops and to schedule their irrigation to meet the crop demands with minimum waste.

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References

Allen, R.G., Pereira, L.S., Raes, D., Martín, M., 1998. Crop evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome, 300 pp.

Baille, A., 1999. Energy cycle in greenhouses. In: Stanhil, G., Enoch, H.Z. (Eds.), Greenhouse Ecosystems. Ecosystems of the World 20. Elsevier, Amsterdam, pp. 214–245.

Barros, L.C.G., Hanks, R.J., 1993. Evapotranspiration and yield of beans affected by mulch and irrigation. Agron. J. 85, 692–697.

Beese, F., Horton, R., Wierenga, P.J., 1982. Growth and yield response of chile pepper to trickle irrigation. Agron. J. 34, 30–34.

Briassoulis, D., Waaijenberg, D., Gratraud, J., von Eslner, B., 1997. Mechanical properties of covering materials for greenhouses. Part 1. General overview. J. Agric. Eng. Res. 67, 81–96.

Castilla, N., 1986. Contribución al estudio de los cultivos enarenados en Almería: Necesidades hídricas y extracción de nutrientes del cultivo de tomate de crecimiento indeterminado en abrigo de polietileno. Doctoral Thesis. Universidad de Madrid, España.

Castilla, N., Elías, F., Fereres, E., 1990. Evapotranspiración de cultivos hortícolas en invernadero en Almería. Invest. Agr.: Prod. Prot. Veg. 5 (1), 117–125.

Caudal, Y., Dumoulin, J., Fourel, A., Joubert, G., Leteinturier, J., Moreau, B., Musard, M., Odet, J., Pelletier, J., Thicoipe, J.P., Veschambre, D., Wacquant, C., Zuang, H., 1985. Melón. Marché et techniques de production. C.T.I.F.L., p. 270.

Doorenbos, J., Pruitt, W.O., 1977. Guidelines for Predicting Crop Water Requirements. FAO Irrigation and Drainage Paper 24. FAO, Rome, 194 pp.

Enoch, H.Z., Enoch, Y., 1999. The history and geography of the greenhouse. In: Stanhil, G., Enoch, H.Z. (Eds.), Greenhouse Ecosystems. Ecosystems of the World 20. Elsevier, Amsterdam, pp. 1–15.

Erdem, Y., Yuksel, A.N., 2003. Yield response of watermelon to irrigation shortage. Sci. Hortic. 98, 365–383.

Fabeiro, C., Martín de Santa Olalla, F., De Juan, J.A., 2002. Production of muskmelon (*Cucumis melo* L.) under controlled deficit irrigation in a semi-arid climate. Agric. Water Manage. 54, 93–105.

Fernández, M.D., 2000. Necesidades hídricas y programación de riegos en los cultivos hortícolas en invernadero y suelo enarenado de Almería. Doctoral Thesis. Universidad de Almería, España.

Fernández, M.D., Orgaz, F., Fereres, E., López, J.C., Céspedes, A., Pérez-Parra, J., Bonachela, S., Gallardo, M., 2001. Programación del riego de cultivos hortícolas bajo invernadero en el sudeste español. Cajamar (Caja Rural Intermediterránea), Almería, España, 78 pp.

Grattan, S.R., George, W., Bowers, W., Dong, A., Snyder, R.L., Carrol, J., 1998. New crop coefficients estimate water use of vegetables row crops. Calif. Agric. 52 (1), 16–20.

Hegde, D.M., Srinivas, K., 1990. Plant water relations and nutrient uptake in French bean. Irrig. Sci. 11, 51–56.

Jollie, O., 1999. The water cycle. In: Stanhil, G., Enoch, H.Z. (Eds.), Greenhouse Ecosystems. Ecosystems of the World 20. Elsevier, Amsterdam, pp. 303–326.

Lorenzo, P., 1994. Interceptación de la luz, bioproductividad e intercambio gaseoso durante la ontogenia del cultivo de pepino (*Cucumis sativus* L.) en invernadero. Doctoral Thesis. Universidad de Barcelona, España.

Postel, S.L., 1998. Water for food production. Bioscience 48, 629–637.

Quaglietta-Chiaranda, Q.F., Zerbi, G., 1986. Water requirements of eggplant grown under a greenhouse. Acta Hortic. 191, 149–156.

Ritchie, J.T., Johnson, B.S., 1990. Soil and plant factors affecting evaporation. In: Stewart, B.A., Nielsen, D.R. (Eds.), Irrigation of Agricultural Crops. Agronomy Series 30. American Society of Agronomy, pp. 363–390.

Rosenberg, N.J., Blad, B.L., Verma, S.B., 1983. Microclimate: The Biological Environment. Wiley, New York.

Rubino, P., Tarantino, E., Miglionico, M., 1986. Distribuzione dei consumi idrici durante il ciclo colturale del fagiolo da sgusciare misutati con lisimetro a pesata. Irrigazione 33 (2), 23–29.

Sanjuan, J.F., 2001. Análisis de la evolución de la superficie invernada en la provincia de Almería mediante teledetección de imágenes thematic mapper (TM) del satelite landsat desde la campaña 1984/1985 hasta la campaña 1999/2000. F.I.A.P.A, Almería, España, 46 pp.

Slack, D.C., Martin, E.C., Sheta, A.E., Fox, F., 1996. Crop coefficients normalized for climatic variability with growing-degree-days. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Proceedings of the International Evapotranspiration and Irrigation Scheduling Conference. ASAE, San Antonio, TX, USA, pp. 892–898.

Snyder, R.L., Lanini, B.J., Shaw, D.A., Pruitt W.O., 1987. Using reference evapotranspiration (ET_0) and crops coefficients to estimate crop evapotranspiration (ETc) for agronomic crops, grasses, and vegetable crops. University of California, Division of Agricultural and Natural Resources, Leaflet 21427, 12 pp.

Villele, O., 1974. Besoins en eau des cultures sous serre- essai de conduite des arrosages en fonction de l'ensoleillement. Acta Hortic. 35, 123–129.

von Eslner, B., Briassoulis, D., Waaijenberg, D., Mistriotis, A., von Zabeltizt, Chr., Gratraud, J., von Eslner, 2000. Mechanical properties of covering materials for greenhouses. Part 1. General overview. J. Agric. Eng. Res. 67, 81–96.

Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 2 (2), 184–194.

Wittwer, S.H., Castilla, N., 1995. Protected cultivation of horticultural crops worldwide. HortTechnology 3, 6–19.