Water use and production of a greenhouse pepper crop under optimum and limited water supply

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SUMMARY

Sweet pepper, grown from autumn to spring, is a major crop in greenhouse vegetable production systems of the Mediterranean coast in south-eastern Spain. Irrigation water is limited in this region, yet little information is available to assist in irrigation management at farm and regional levels. The aim of this work was to determine crop evapo-transpiration, water-use efficiency and the effect of continuous water deficits on crop growth and production of pepper grown in plastic greenhouses in two growing seasons. Three irrigation treatments were applied T1, watered with 100% of estimated crop water requirements; and T2 and T3 watered, respectively, with 50% and 20% of estimated crop water requirements. Seasonal crop evapo-transpiration (ETc) in treatment T1 was 346–362 mm. The effect of water deficit on crop growth was apparent approximately 80 d after transplanting. The contribution of soil water uptake to total ETc for treatments T2 and T3 was, respectively, 20–22% and 43–47%. The response of ETc to water stress was apparent at a threshold value of 55% of available water content (AWC), suggesting an allowable depletion of soil moisture equivalent to 27 mm. For treatments T2 and T3, reductions in total fruit production (relative to treatment T1) were 33 and 62%, respectively; and reductions in marketable fruit production were 47 and 67%, respectively. Water deficit had little effect on total fruit number, but substantially increased the proportion of unmarketable fruits due to small fruit size, and high incidences of sunburn and blossom-end rot. Linear relationships were found between both shoot biomass and marketable fresh fruit production with ETc. Mean water use efficiency values for shoot dry matter (WUE_b) were 4.5–4.7 g m^{-2} mm^{-1}, for total fresh fruit production (WUE_t) between 24–33 g m^{-2} mm^{-1} and for marketable fresh fruit production (WUE_m) between 16.9 and 25.9 g m^{-2} mm^{-1}. Water stress did not induce early fruit production, nor influence the relative distribution of assimilates within the plant.

The surface area of greenhouses used for vegetable production is expanding rapidly throughout the Mediterranean coast of Spain and other countries in the Mediterranean Basin (Wittwer and Castilla, 1995). The Mediterranean greenhouse vegetable production system is mostly based on simple, low technology greenhouses, which exploit the favourable climatic conditions of the region (mild winters, high number of sunshine hours) enabling vegetable production during late autumn to early spring (Castilla 1994), which is not possible in mainland Europe without high technology/cost greenhouse systems.

The favourable growing conditions of the Mediterranean coastal region are, however, often associated with low supplies of water. In south-eastern Spain where the greenhouse industry is currently most highly concentrated, with 25,000 ha of simple plastic greenhouses in the province of Almeria, the supply of water is a limiting factor for greenhouse vegetable production. Most irrigation water used in Almeria is obtained from local aquifers. Declining surface levels in supply wells indicate over-exploitation of aquifers (ITGME, 1991), which is associated with salt water intrusion in some coastal areas (ITGME, 1991).

Currently, 80% of cropping within greenhouses in Almeria is in soil, and drip irrigation is used in all greenhouses. The replacement of furrow irrigation with drip irrigation, during the 1980s, appreciably improved overall irrigation efficiency. However, given that current irrigation management is mostly based on experience (Thompson *et al.*, 2002a), considerable scope remains for improved irrigation management practices at the farm-level. Information that contributes to improved irrigation management practices will assist in maintaining both the supply and quality of aquifer water, which are essential for the sustainability of this industry in its present form.

Depending on market prices, pepper is either the major or the second major crop, on the basis of surface area, in the south-eastern spanish greenhouse industry. In the 1999/2000 season 8,500 ha (34% of the total area of greenhouses) were planted with pepper. In this region, depending on variety and market conditions, pepper is generally grown from late summer/early autumn to late winter/early summer.

Pepper is considered one of the vegetable crops most susceptible to water stress from insufficient irrigation (Doorenbos and Kasam, 1986). Additionally, in the Mediterranean coastal region there is a heightened risk of soil-borne fungal diseases when over-irrigation occurs, because the growing cycle includes the late autumn to late winter period when climatic conditions are cool and moist. Consequently, in order to maximise pepper production in this region, optimal irrigation management is essential. A recent survey of farm water use showed considerable variation, in the total volumes of water applied for similar levels of pepper production (Perez and Carreño, 1996). To optimise pepper production and profitability, and to ensure the most efficient use of limited water resources, there is a clear need for comprehensive information regarding crop water use of pepper grown in this horticultural system.

For pepper grown in open fields in spring to summer growing cycles, there is information available regarding crop water requirements, water use efficiency (WUE) and responses to inadequate irrigation (e.g. Beese *et al.*, 1982; Dalla-Costa and Gianquinto, 2002). This information has contributed to the development of irrigation strategies for optimal yield and maximum water use efficiency (Dalla-Costa and Gianquinto, 2002). However, this information is not applicable to pepper crops grown in greenhouses with an autumn to spring growing cycle.

For similar levels of production, crop water requirements are considerably less in greenhouses than in open fields (FAO, 1991). This is a consequence of the much lower evapotranspiration inside greenhouses on account of there being considerably less wind, reduced solar radiation, and higher atmospheric humidity (Montero *et al.*, 1985; Fernandez *et al.*, 1994). Therefore, greenhouse crops have appreciably higher water use efficiency (WUE). Additionally, the autumn to spring growing season of pepper grown in the plastic greenhouses of the Mediterranean coast will considerably modify the pattern of crop growth, which is likely to influence the effect of water on crop growth and production. There is very little published information available for pepper grown during an autumn to spring cycle in low technology greenhouses, with respect to optimal crop water requirements, WUE, and the effect of water deficit on crop growth and production.

This work was conducted to determine for pepper grown in plastic greenhouses in an autumn to spring season: (i) optimal crop water requirements, (ii) water use efficiency, (iii) the effect of continuous water deficits on growth and production, and (iv) extraction of soil water with time and from different depths. This information is necessary for the development of improved on-farm irrigation management.

MATERIAL AND METHODS

Water use, crop growth and fruit production in response to water deficit were characterized for two separate sweet pepper crops grown during the 1996/97 and 1997/98 growing seasons.

Experimental site

Experiments were conducted in a greenhouse at the Cajamar "Las Palmerillas" experimental station in El Ejido, Almeria province, in south-eastern Spain, (2º43'W, 36º48'N and 151 m elevation). The climate is Mediterranean with mild winters and low annual precipitation. Average annual temperatures and rainfall are 18ºC and 220 mm, respectively.

Two trials were conducted in an unheated plastic greenhouse (58 m long by 24 m wide). The greenhouse consisted of a metallic frame covered with a 0.2 mm-thick thermal polyethylene sheet. It had a symmetrical planar roof with the main axis oriented E–W. Each plane of the roof had a slope of 12.5%. The greenhouse was passively ventilated by opening side panels and roof vents.

The soil within the greenhouse was an "enarenado" artificial layered soil, typical of the region, which is used in 80% of the greenhouses in the Almeria region (Wittwer and Castilla, 1995). The "enarenado" soil was formed by placing a 20 cm layer of silty-loam soil, then a layer of dried farmyard manure (5 kg m^{-2}), and above that a 10 cm mulch layer of coarse river sand above the naturally-occurring soil. Relevant properties of the indigenous and imported soils are given in Table I. Irrigation was applied with a drip system with lines 1 m apart and one emitter per plant, with a discharge rate of 2 l h^{-1}, every 0.5 m. The irrigation water had an electrical conductivity of 0.4 dS m^{-1} and a sodium adsorption ratio (SAR) of 0.4.

The greenhouse had six drainage lysimeters located in the southern side (4 m long x 2 m wide, 0.7 m deep). The lysimeters were constructed with a 0.6 mm thick layer of butyl rubber and had a 10 cm layer of gravel placed at its bottom. The rest of the soil profile in the lysimeter reproduced that of the 'enarenado' described above.

Sweet pepper (Lamuyo type) (*Capsicum annuum*, L.; cv. Drago) was grown in both studies. Five- to 6 week-old seedlings were transplanted on 9 September 1996, and on 15 September 1997. Both crops were grown for 258 d until late May of the following year. Plants were grown in rows 1 m apart, with 0.5 m spacing between plants within rows, giving a plant population of 2 plants m^{-2}. Plants were vertically supported by nylon cord guides, and pruned to have three stems per plant. Harvesting of red fruits commenced 144 d after transplanting (DAT), with 8 harvests being conducted for each crop.

Before planting, 50 kg ha^{-1} N, 47 kg ha^{-1} P and 249 kg ha^{-1} K were applied. The following additional nutrients were applied with the irrigation water during the 1996/97 season, 705 kg ha^{-1} N, 52 kg ha^{-1} P and 386 kg ha^{-1} K; and, during the 1997/98 season, 860 kg ha^{-1} N, 59 kg ha^{-1} P and 396 kg ha^{-1} K.

Irrigation Treatments

The treatments were: T1 - watered with 100% of the estimated crop water requirements; T2 - watered with 50% of the water applied to T1; and T3 - watered with 20% of the water applied to T1. Irrigation treatments were maintained throughout the growing season. The crop water requirements were determined using data from an evaporation pan, surrounded by grass cover, which was located nearby in a similar greenhouse. The procedures used to estimate water requirements from evaporation pan data were those of Fernandez *et al.* (2001) who developed relevant calibrations for plastic greenhouses in Almeria. To ensure maximum crop evapotranspiration in treatment T1, irrigation was adjusted to ensure detectable drainage in the T1 lysimeters, from each irrigation. A fixed irrigation frequency was applied in all treatments, with irrigations being applied 2 and 3 times per week, respectively, during the period from november to january and from febrery to may.

Experimental design

The greenhouse was divided longitudinally along the central E–W axis into two areas, hereafter designated the northern and southern parts. Water use and fruit production measurements were conducted in the southern part of the greenhouse. Most of the detailed crop growth measurements were conducted in the northern part. The three irrigation treatments were applied in the southern part, but only the two most contrasting treatments (T1 and T3) were examined in the northern part.

The southern part (12 m width x 58 m long) was divided longitudinally along the E–W axis into two blocks. Within each block, there were six experimental plots of 54 m^2 (9.0 m x 6 m). The three irrigation treatments were randomly applied twice to each block, so that there were 4 replicate plots for each of the three treatments in the southern part of the greenhouse. Each plot in the southernmost block had centrally-located drainage lysimeters, giving two lysimeters per treatment.

The northern part of the greenhouse (10 m x 58 m) was also divided longitudinally along the main E–W axis into two blocks. Each block was divided into four experimental plots of 67.5 m^2 (13.5 m x 5 m). The two most contrasting treatments (T1 and T3) were randomly applied twice in each block, giving four replicate plots for both treatments T1 and T3 in the northern part of the greenhouse.

Separate analyses of variance were conducted for the southern and northern parts of the greenhouse, which were each analysed as a completely randomised block design with two blocks and two replications per block. Means were compared with a Least Significant Differences procedure. Statistical comparisons were considered significant at $P \leq 0.05$.

Soil water content and soil water extraction

Soil water content was measured gravimetrically in each plot in the southern part of the greenhouse, at the beginning (SWC_{to}) and end (SWC_{tl}) of both growing seasons, at three sampling points and three depths (0-20, 20-40 and 40-60 cm excluding the sand layer). Soil samples were oven-dried at 105ºC and weighed. At planting, the soil was at field capacity following the application of a large flood irrigation. Water extraction was calculated for 20 cm soil depth intervals as the difference between the initial and final volumetric soil water contents. Total crop water extraction was calculated for each plot as the mean of the 0-60 cm extraction of the three sampling points.

Volumetric soil water content, in all lysimeters, was measured once every 2 weeks with a TDR system (Trase 6005X1, Soil Moisture Corp., Santa Barbara, CA, USA). In each lysimeter, TDR probes were installed in each of four separate locations. Two locations were next to the emitters, and two were located mid-way between drip lines. In the lysimeters of treatment T1, 20 cm long buriable (3-prong) TDR probes were installed. In the 10 cm sand mulch layer, the probes were installed at a flat angle, and in both the imported silty-loam layer and original soil layer at a 45° angle. In the imported silty-loam layer, the probes were located at mid-depth, and in the original soil layer within the upper 15 cm. In the T2 and T3 lysimeters, 45 cm long non-buriable (2-prong) TDR probes were installed vertically, providing data on the 0–45 cm depth as measured from the sand surface. Soil water extraction to 45 cm depth was determined for each 2-week period from the difference in soil moisture measurements between consecutive TDR readings.

Available soil water content (AWC) for 0–45 cm soil depth, was calculated for each 2-week period, from the volumetric soil water content data determined by TDR measurements, for treatments T1 and T3 as:

$$AWC = \left(1 - \frac{SWC_{fc} - SWC_{a}}{SWC_{fc} - SWC_{pwp}}\right) \times 100$$

where SWC is the soil water content for the 0–45 cm soil depth, expressed in mm, and the subscripts *a, fc* and *pwp* correspond to the actual water content at sampling, field capacity and permanent wilting point. The SWC values at field capacity and permanent wilting point for 0–45 cm soil depth were calculated from volumetric soil water content data, determined with the TDR in treatment T3. SWC_{fc} was the SWC (0–45 cm depth) when the T3 lysimeters ceased drainage after the initial flood irrigation. SWC_{pwp} was the SWC (0–45 cm depth) when the crop in treatment T3 ceased to extract soil water. SWC_{fc} and SWC_{pwp} were determined to be 87 and 37 mm, respectively. Both values are means of 2 replicates.

Crop evapo-transpiration

Crop evapotranspiration (ETc) was determined for the complete growing season in 1996/97 and 1997/98, in the southern part of the greenhouse, using the following water balance calculation:

$$ET = \left(SWC_{t0} - SWC_{t1}\right) + I - D$$

where ($SWC_{t0} - SWC_{t1}$) is the change in volumetric soil water content between transplanting and the end of the season. I and D are, respectively, the total volumes of applied irrigation water and collected drainage for the growing season. The volumetric soil water content data used in these calculations were derived from the gravimetric water content data, obtained at the beginning and end of the growing seasons, as previously described, and site bulk density data (Table I). Applied irrigation water was measured volumetrically. Drainage from the lysimeters was manually collected and measured each day. For treatment T1, ETc was determined using data from the two lysimeters. In treatments T2 and T3, D was omitted from the water balance calculations because there was no drainage from the lysimeters of these treatments.

For the purpose of determining the threshold available soil water content at which crop water use was affected, ETc was calculated for all 2-weekly periods, for treatments T1 and T3, using the approach described above. For these calculations, the soil water balance was calculated from the 0–45 cm depth volumetric soil water content data measured with the TDR, at the beginning and end of each 2-week period.

Plant measurements

Measurements of dry matter accumulation and leaf area index (LAI) were conducted in the northern part of the greenhouse, for treatments T1 and T3. Once per month, 2 plants within a 1 m^2 area in each plot were harvested and the leaf area, total shoot dry matter, and the amount of dry matter in leaves, stems and fruits determined. Leaf area was measured with an electronic area meter (Delta-T Devices Ltd; Cambridge, England). Leaf area index (LAI, m^2 m^{-2}) was calculated as the area of leaves per unit of surface area of soil. Dry matter determinations of leaves, stems and fruits were made by weighing all of the fresh plant material immediately after separation, and then determining the dry matter content by oven-drying sub-samples (500 g fresh weight) at 80ºC for 48 h.

Determinations of both pruned shoot material and fruit production, during the season, were conducted in the northern part of the greenhouse. Fourteen plants were marked in each plot at the beginning of the season, and all pruned material was collected from these plants. Pruning was conducted 5 times in 1996/97 and 4 times in 1997/98. At each pruning, the dry matter was determined as described previously. Harvests of fruit from the same plants were conducted 8 times during each of the two crops. At each harvest, fruits were separated into marketable and non-marketable fruit; their fresh and dry weight were determined as previously described. Pruned material and harvested fruit were included in data describing the seasonal evolution of dry matter in leaves, stem, and fruit.

Crop height measurements were made in the southern part of the greenhouse, using four marked plants in each plot. Measurements were made 14-times, at regular intervals, in 1996/97, and 8-times, at regular intervals, in 1997/98. A flexible tape measure was used to measured the height as the distance between the soil and the insertion of the last developed fully-expanded leaf.

In each plot of the southern part of the greenhouse, 16 plants in a 8 m^2 surface area were marked, and the dry weight of pruned material and the number, fresh and dry weight of marketable and non-marketable fruits were determined for every harvest during the season. At the end of the season, the 16 marked plants were cut at ground level and removed. They were separated into vegetative material and fruit, which were weighed and the dry matter content determined. Dry matter content of the vegetative material was determined by drying a 1 kg sub-sample in a forced air oven at 80ºC for 48 h. For each plot, total shoot dry matter was determined from the vegetative dry matter at the final sampling, the combined dry weight of all pruned material, and the combined dry weight of total fruit production from all fruit harvests. Harvest index was determined, for each plot, as the ratio of total fruit dry matter to total shoot dry matter.

Water use efficiency (WUE) was calculated for total shoot biomass (WUE_b) and for both total fresh (WUE_t) and marketable fruit production (WUE_m) as the ratio of the total shoot dry matter or the total fresh fruit weight or marketable fruit weight to seasonal ETc.

RESULTS

Crop evapo-transpiration and soil water extraction

Total crop evapotranspiration (ETc) varied with the irrigation treatment in each growing season (Table II). The ETc for the 1996/97 and 1997/98 growing seasons was, respectively, 362 and 346 mm for T1, 239 and 246 mm for T2, and 137 and 160 mm for T3 (Table II). Relative to the well-watered treatment, the ETc for the two treatments under deficit irrigation, was 66–71% for T2 and in 38–46% for T3. For each treatment, there was little difference between seasons in either ETc or the total volume of irrigation water applied. During both seasons, small amounts of drainage were continuously collected from the lysimeters in the T1 treatment, confirming that ETc from this treatment was 100% of crop water requirements.

For the treatments under deficit irrigation, ETc exceeded applied water (Table II), because of soil water extraction, which increased with increasing water stress (Table III). Only 3–4% of seasonal ETc in the well-watered treatment (T1) was obtained from stored soil (Table III). For treatments T2 and T3, stored soil water (10–70 cm depth) provided, respectively, 20–23% and 43–47% of ETc. No differences between treatments were observed in the proportions of water extracted from individual soil depth increments, which were 45% from 10–30 cm, 34% from 30–50 cm and 22% from 50–70 cm soil depth (Table III).

Soil water extraction patterns from the 0–45 cm soil depth during 1996/97 are presented in Figure 1. Treatment T3 maintained a relatively constant extraction rate of 0.42 mm d^{-1} for 135 d, after which extraction was negligible. Total soil water extraction for T3 was 57 mm for 1996/97. Treatment T2 maintained an average extraction rate of 0.22 mm d^{-1} for 200 days in 1996/97, giving a total soil water extraction of 45 mm. Similar results were observed for T2 and T3 during the 1997/98 growing season.

To determine the threshold value for available soil water content (AWC) below which pepper ETc decreases in response to water stress, the ratio of ETc for two weeks periods of treatments T3 to T1 were plotted against relative AWC (Figure 2). The threshold AWC at which reductions in ETc of treatment T3 became apparent was approximately 55%, which is equivalent to a depletion of 27 mm (depth of 45 cm).

Seasonal evolution of crop growth and fruit production

Crop height followed a tri-phasic pattern in both cropping seasons. Firstly, it increased linearly during the first 80 days, then it remained relatively constant during winter (80 to 180 DAT), and then, with improved spring temperatures, crop height increased again (data not presented). Crop height was strongly affected by the irrigation treatments. Differences between treatments were significant from

84 and 71 DAT until the end of the season respectively, for 1996/97 and 1997/98. In 1996/97, the differences between T2 and T3 were significant only at the two last sampling dates. In contrast, in 1997/98, differences between T2 and T3 were significant from 71 DAT onwards. A more intense pruning in 1996/97, that reduced LAI differences between T1 and T3 (Figure 3), may explain this difference in crop height between the two growing seasons.

The seasonal evolution of leaf area index (LAI) of treatment T1 was very similar in both growing seasons (Figure 3 A, B), and was generally similar to that observed for crop height. Firstly, there was a linear increase until 80 DAT, then a second period (80–200 DAT), during winter, when there was a smaller rate of increase; and a final period, during spring, when LAI increased rapidly, reaching a final maximum value of 5–6 $m^2 m^{-2}$. Differences in LAI between treatments T1 and T3 were significant ($P \leq 0.05$) from 80 DAT onwards, and increased as the growing season progressed. At the end of the season, relative to treatment T1, the LAI of treatment T3 was 28 and 46%, respectively, for 1996/97 and 1997/98.

The seasonal evolution of shoot dry matter for T1 and T3 for both growing seasons is presented in Figures 3 C, D. In T1, dry matter accumulation was more rapid from 155 DAT, onwards in 1996/97, and from 200 DAT onwards, in 1997/98. There were significant differences in dry matter accumulation between treatments T1 and T3 after 155 DAT in 1996/97, and after 78 DAT in 1997/98.

Dry matter accumulation in leaves, stems and fruits for treatments T1 and T3, are presented in Figure 4. In T1, dry matter in vegetative organs increased slowly during autumn-winter (0–200 DAT), and then more rapidly in the spring. Dry matter in leaves, stems and fruit of T3 was reduced relative to T1 from 80 DAT onwards, although partitioning to the different plant parts was unaffected by water deficits (Figure 4). Initially, 50–60% of dry matter was allocated to leaves, and 40–50% to stems. As the crop grew, an increasing proportion of dry matter was allocated to fruit, reaching 50% at final harvest. The recovery in vegetative growth in spring observed for T1, did not occur in T3 in 1996/97 and was slight in 1997/98 (Figure 4).

Water deficits in T2 and T3 appreciably reduced total and marketable fresh fruit production (Table IV). In both seasons, the differences between T1 and T2, and between T2 and T3 were statistically significant (Table IV). Marketable fruit production was most sensitive to water stress, followed by total fruit production and total shoot dry matter production (Table IV). Averaged over the two seasons, the reductions in shoot biomass, total, and marketable fresh fruit production in T2 relative to T1 were, respectively, 20, 33 and 47%. The corresponding reductions for T3 compared to T1 were 44, 62 and 67%.

The total number of fruit was not affected by water deficit in 1996/97 (Table IV). In 1997/98, only T3 had significantly less total fruit than T1. Nevertheless, water deficit substantially increased the proportion of unmarketable fruits (Table IV). These fruits were considered unmarketable on account of sunburn or blossom-and-root (data not presented). Average marketable fruit size was not affected by water deficit (Table IV) because most of the marketable fruit came from the earlier harvests when fruit production was not affected by the water deficit (Figure 5). After 160 DAT, no marketable fruit was collected from T3, and only a relatively small amount from T2 (Figure 5). After 240 DAT, there was a large increase in fruit production in T1, and a smaller increase in T2 that may be attributed to the onset of improved climatic conditions in spring (Figure 5).

Mean water use efficiency for dry matter production (WUE_b) increased slightly with the water deficit treatments, with values of 4.5–4.7 g m^{-2} mm^{-1} for treatment T1, 5.2–5.5 for T2, and 5.5–6.4 for T3 (Table V). Mean water use efficiency for total (WUE_t) and for marketable (WUE_m) fresh fruit production was between 24 and 33 g m^{-2} mm^{-1} and between 17 and 26 g m^{-2} mm^{-1} for all treatments, respectively (Table V). There were no clear tendencies in the response of WUE_t and WUE_m to water deficit.

Discussion

Response of pepper to water deficit

Relative to the well-watered treatment, the ETc values from the water deficit treatments were proportionally appreciably higher than the proportions of crop water requirements provided as irrigation. This was because of appreciable crop uptake of soil water, which contributed approximately 20% and 45% of ETc, respectively, for treatments T2 and T3. The treatments receiving 50 and 20% of estimated crop water requirements (actually 66-71% and 38-46% of total ETc) had reductions in total fruit production of 33 and 62%, respectively. The reductions in marketable fruit production, in the deficit irrigated treatments, were much larger than those in total fruit production. A large increase in the proportion of small fruit after 170 DAT, was the main factor for the large reduction in marketable fruit production. These general responses to prolonged water deficit are consistent with observations for pepper crops grown in greenhouses (Chartzoulakis and Drosos, 1997) and in open fields (Pellitero *et al.*, 1993). In addition to their small size, the un-marketable fruit in the present studies had high incidences of sunburn and blossom-end rot. The sunburn was presumably caused by the combined effects of (i) the lower LAI in the stressed treatments, and (ii) the increasing levels of incoming radiation in spring. Increased incidences of blossom-end rot, in deficit-irrigated pepper crops, have been reported for open field conditions (Rubino *et al.*, 1993; vanDerwerken and Wilcox-Lee, 1998).

The reductions in total fruit production reported here are larger than those of Chartzoulakis and Drosos (1997) for greenhouse-produced pepper in Greece who reported reductions in total fruit production of 26% and 47% for treatments receiving 65 and 40% of ETc. The method of determining ETc used by Chartzoulakis and Drosos (1997) based on the use of tensiometers and the assumption of negligible drainage may explain the differences between our and their studies for irrigations of approximately 40% of ETc.

The application of water stress did not have any effect on the relative distribution of assimilate among plant parts. Consequently, harvest index (HI) did not increase with water stress, as has been reported for some vegetable species such as melon (e.g. Fernandez, 2000).

Thresholds values of available soil water

Data in figure 2 suggest the threshold value of available soil water, for a discernible reduction in ETc, was approximately 55%. These data suggest that for these soil types, which are common in the greenhouses of south-eastern Spain, and these climatic conditions, that soil provides a "buffer" of approximately 45% of available water content before ETc is affected. Doorenbos and Kassam (1986) reported that for pepper grown under conditions of low evaporative demand (rates of daily ETc of 2–3 mm d^{-1}) that maximum ETc is maintained until 42–50% of available soil water content is depleted. In the current studies, daily ETc was initially 1.0–1.5 mm d^{-1} which increased to 2.5–3 mm d^{-1} in spring (Fernandez *et al.*, 2000), indicating that the threshold value determined here is consistent with that reported by Doorenbos and Kassam (1986) for similar evaporative conditions.

This soil water buffer can offset moderate water deficits. It also could compensate for the inherent minor inaccuracies of irrigation scheduling programs based on historical climatic data, which have been developed in this region for use by local farmers (Fernández *et al.*, 2001). In previous studies in greenhouses in Almeria, with zucchini and melon, mild water shortage did not affect production (Gallego *et al.*, 1992). These observations support the suggestion from the present studies, that these soils can provide a certain percentage of ETc before water use, growth and production of horticultural crops are affected. The magnitude of the allowable depletion may vary with species; factors such as rooting depth, and relative sensitivity to water stress may influence threshold values.

Production functions and WUE

Production functions that relate crop productivity to ETc are useful for determining crop water requirements on both farm and regional scales (Steward and Hagan, 1973). In the present studies, there were linear relationships between both (i) shoot biomass and (ii) marketable fresh fruit production with ETc. Linear production functions, for both shoot dry matter and fresh fruit production, have been reported for pepper crops grown in open fields (Beese *et al.*, 1982; Dalla-Costa and Gianquinto, 2002).

Water use efficiency values for shoot dry matter production (WUE_b) and for total fresh fruit production (WUE_t) in these greenhouse studies were considerably higher than those reported for field-grown pepper crops (e.g. Besse *et al.*, 1982, Pellitero *et al.*, 1993). WUE_b was 4-times higher, and WUE_t 10-times higher than reported by Besse *et al.* (1982). The much higher water use efficiency for shoot dry matter and fruit production reported here for peppers grown in the greenhouse compared to open fields is consistent with the appreciably reduced evaporative demand inside greenhouses (Montero *et al.*, 1985; Castilla *et al.*, 1990; Fernandez *et al.*, 1994). Additionally, within the greenhouse system of the south-eastern Mediterranean coast of Spain, the sand mulch used to cover the soil is likely to appreciably reduce evaporation from the soil surface.

A survey of water use for pepper crops grown in commercial greenhouses in Almeria indicated that the average WUE_m was 13.5 g m^{-2} mm^{-1} (Caja Rural de Almería, 1997) compared to 25.2 g m^{-2} mm^{-1} (average for two growing seasons) for the well-watered treatment in the present studies. These data suggest that the adoption by farmers of scientific irrigation scheduling methods, using either computer programs to calculate crop water requirements, which are now available for Almeria (Fernandez *et al.*, 2001; http://laspalmerillas.cajamar.es), or measurements of soil water status using tensiometers or capacitance sensors (Thompson *et al.*, 2002b) could substantially improve farm WUE resulting in large savings in regional water use.

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REFERENCES

BEESE, F., HORTON, R. and WIERENGA, P. J. (1982). Growth and yield response of chile pepper to trickle irrigation. *Agronomy Journal,* **74,** 556-61.

CAJA RURAL DE ALMERÍA. (1997). *Gestión del regadío en el campo de Dalías: las comunidades de regantes Sol y Arena y Sol-Poniente.* Caja Rural de Almería, Almería, España.

CASTILLA, N. (1994). Greenhouses in the Mediterranean areas: Technological level and strategic management. *Acta Horticulturae,* **361,** 44-56.

CASTILLA, N., ELIAS, F. and FERERES, E. (1990). Evapotranspiración de cultivos hortícolas en invernadero en Almería. *Investigación Agraria: Producción Vegetal,* **5,** 117-25.

CHARTZOULAKIS, K. and DROSOS, N. (1997). Water requirements of greenhouse grown pepper under drip irrigation. *Acta Horticulturae*, **449,** 175-80.

DALLA-COSTA, L. and GIANQUINTO, G. (2002). Water stress and watertable depth influence yield, water use efficiency, and nitrogen recovery in bell pepper: lysimeter studies. *Australian Journal of Agricultural Research*, **53,** 201-10.

DOORENBOS, J. and KASSAM, A. H. (1986). Yield response to water. *Irrigation and Drainage Paper* **33,** FAO, Rome, Italy.

FAO. (1991). Protected cultivation in the Mediterranean climate. *Plant Protection Paper* **90**. FAO Rome, Italy.

FERNÁNDEZ, M. D., ORGAZ, F., VILLALOBOS, F. and LÓPEZ-GÁLVEZ, J. (1994). Evaluación de métodos de cálculo de la evapotranspiración de referencia bajo condiciones de invernadero en Almería. *Comunicaciones XII Congreso Nacional de Riegos, Pamplona, Spain*, 63-9.

FERNÁNDEZ, M. D., GALLARDO, M., BONACHELA, S., ORGAZ, F. and FERERES, E. (2000). Crop coefficients of a pepper crop grown in plastic greenhouses in Almería, Spain. *Acta Horticulturae,* **537**, 461-9.

FERNÁNDEZ M. D. (2000). *Necesidades hídricas y programación de riegos en los cultivos hortícolas en invernadero y suelo enarenado de Almería*. PhD Thesis, Universidad de Almería, España.

FERNÁNDEZ, M. D., ORGAZ, F., FERERES, E., LÓPEZ, J. C., CÉSPEDES, A., PÉREZ, J., BONACHELA, S. and GALLARDO, M. (2001). *Programación del riego de cultivos hortícolas bajo invernadero en el sudeste español.* Cajamar, Almería, España.

GALLEGO, A., LÓPEZ, J. C., LÓPEZ-GÁLVEZ, J. and CASTILLA, N. (1992). Effects of drip water levels on leached nitrogen and water use of greenhouse squash. *Acta Horticulturae,* **335,** 109-14.

ITGME. (1991). Control de la explotación del Campo de Dalías (Almería) 1989-1990. Ministerio de Industria y Energía.

MONTERO, J.I., CASTILLA, N., GUTIÉRREZ-RAVE, E. and BRETONES, F. (1985). Climate under plastic in the Almeria area.. *Acta Horticulturae,* **170,** 227-34.

PÉREZ, C. and CARREÑO, J. (1996). Productividad del agua de riego en cultivos protegidos de pimiento en Almería. *Comunicaciones XIV Congreso Nacional de Riegos, Almería, Spain*, 642-9.

PELLITERO, M., PARDO, A., SIMÓN, A., SUSO, M. L. and CERROLAZA, A. (1993). Effect of irrigation regimes on yield and fruit composition of processing pepper (Capsicum annuum L.). *Acta Horticulturae,* **335,** 257-63.

RUBINO, P., MASTRO, M. A. and MONTEMURRO, N. (1993). Studio di diversi livelli di stress idrico su coltura di peperone (*Capsicum annuum* L.). *Rivista di Agronomia,* **27,** 220-5.

THOMPSON, R. B., GALLARDO, M. and GIMENEZ, C. (2002a). Risk of nitrate leaching from the horticultural industry of Almería, Spain. *Proceedings of the VII Congress of the European Society for Agronomy,* 755-6.

THOMPSON, R. B., GALLARDO, M. and FERNANDEZ, M.D. (2002b). Continuous soil moisture monitoring for irrigation scheduling of drip-irrigated vegetables grown in greenhouses. *Proceedings of the VII Congress of the European Society for Agronomy,* 415-6.

VANDERWERKEN, J. E. and WILCOX-LEE, D. (1988). Influence of plastic mulch and type and frequency of irrigation on growth and yield of bell pepper. *Hortscience,* **23,** 985-988.

WITTWER, S. H. and CASTILLA, N. (1995). Protected cultivation of horticultural crops worldwide. *HortTechnology*, **3,** 6-19.

TABLE I

Physical properties of the sand, the imported soil (10–30 cm depth) and the original soil (30-60 cm depth) for the experimental greenhouse

Depth (cm)	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Upper limit [a] (cm^3 cm^{-3})	Lower limit [a] (cm^3 cm^{-3})
0-10	1.80	100	0	0	0.031	0.014
10–30	1.51	21.6	57.4	21.0	0.37	0.14
30–45	1.60	42.3	39.0	18.7	0.26	0.12

a) Upper and lower limits of soil moisture correspond, respectively, to tensions of 0.01 and 1.5 MPa

TABLE II

Total volumes of applied irrigation water and total crop evapo-transpiration (ETc) for the three irrigation treatments in 1996/97 and 1997/98

Irrigation treatment	Season 1996/97 Water applied (mm)	Season 1996/97 ETc (mm)	Season 1997/98 Water applied (mm)	Season 1997/98 ETc (mm)
T1	385 (100)[a]	362 a* (100)	393 (100)	346 a (100)
T2	191 (50)	239 b (66)	197 (50)	246 b (71)
T3	78 (20)	137 c (38)	80 (20)	160 c (46)

(*) Values followed with the different letters are significantly different at* P *≤ 0.05

a) In parentheses, are values expressed relative to T1
b) Data are means of two (T1) or four replications (T2 and T3)
c) Drainage of 38 mm and 58 mm was collected from the lysimeters of treatment T1 in the 1996/97 and 1997/98 growing seasons, respectively

TABLE III

Seasonal soil water extraction (mm) at each soil depth, and total for the 10 to 70 cm depth of soil, for the three irrigation treatments in each growing season

	Irrigation treatment		
	T1	T2	T3
Soil depth (cm)	mean ± SE	mean ± SE	mean ± SE
Season 1996/97			
10–30 [a]	5.4 ± 1.5	24.4 ± 2.4	27.4 ± 0.96
30–50	5.9 ± 2.3	14.9 ± 2.0	16.3 ± 0.85
50–70	3.0 ± 4.3	7.5 ± 4.0	15.7 ± 1.6
TOTAL	14.3	46.8	59.4
Season 1997/98			
10–30	4.6 ± 4.0	23.8 ± 5.8	33.0 ± 1.7
30–50	4.2 ± 4.6	19.3 ± 4.0	24.7 ± 0.62
50–70	2.1 ± 2.7	13.0 ± 1.6	17.8 ± 0.22
TOTAL	10.9±	56.2	75.5

a) Soil water extraction from the top 10 cm, a layer of course sand, was not included
b) Data are means of four replications ± 1 SE

TABLE IV

Total shoot dry matter, total and marketable fruit production, yield components, percentage of unmarketable fruits, and harvest index for the three irrigation treatments during each cropping season

		Total fruit production			Marketable fruit production				
Irrigation treatment	Shoot dry matter (g m^{-2})	Fresh fruit production (kg m^{-2})	Number of fruits (fruits m^{-2})	Individual fresh fruit weight (g fruit^{-1}) mean ± SE	Fresh fruit production (kg m^{-2})	Number of fruits (fruits m^{-2})	Individual fresh fruit weight (g fruit^{-1}) mean ± SE	Unmarketable fruit (%)	Harvest index
Season 1996/97									
T1	1612 a*	11.1 a	48.3 a	229.4 a ± 5.4	9.3 a	33.4 a	278.0 a ± 3.0	16	0.55 a
T2	1329 b	7.8 b	46.1 a	168.9 b ± 13.7	5.3 b	20.0 b	265.0 a ± 2.6	32	0.53 a
T3	925 c	4.7 c	37.8 a	124.6 c ± 9.2	3.4 c	13.1 c	256.5 a ± 6.3	29	0.54 a
Season 1997/98									
T1	1636 a	11.8 a	62.2 a	190.1 a ± 4.9	9.1 a	33.1 a	275.2 a ± 6.2	23	0.51 a
T2	1285 b	7.5 b	60.6 a	123.1 b ± 2.3	4.4 b	15.5 b	286.8 ± a 6.1	40	0.53 a
T3	878 c	3.9 c	36.5 b	105.6 c ± 3.9	2.7 c	11.2 c	240.3 b ± 11.4	30	0.49 a

(*) Values in each column followed by different letters are significantly different at **P** ***≤ 0.05***

a) Data are means of four replications

TABLE V

Water use efficiency for total shoot dry matter (WUE_b), for total fresh (WUE_t) and marketable (WUE_m) fruit production for the three irrigation treatments in each growing season

Irrigation treatment	WUE_b (g m^{-2} mm^{-1})		WUE_t (g m^{-2} mm^{-1})		WUE_m (g m^{-2} mm^{-1})	
	1996/97	1997/98	1996/97	1997/98	1996/97	1997/98
T1	4.45 c*	4.71 b	30.6 a	32.5 a	25.8 a	24.7 a
T2	5.48 b	5.24 ab	32.1 a	30.4 a	21.9 a	18.1 bc
T3	6.43 a	5.51 a	32.9 a	24.2 b	23.3 a	16.9 c

(*) Values in each column followed by different letters are significantly different at **$P \leq 0.05$.**

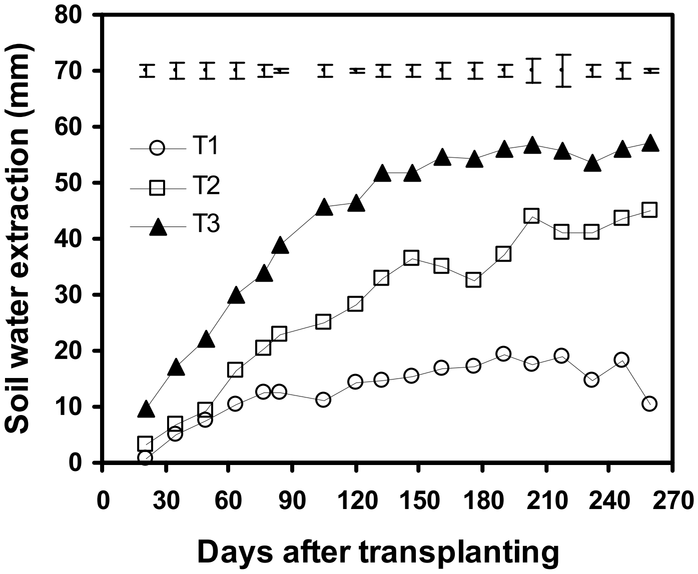

Fig. 1. Time-course of cumulative soil water extraction for 0–45 cm soil for the three irrigation treatments during the 1996/97 growing season. Bars indicate ± 1 SE error of the mean, averaged for the three treatments.

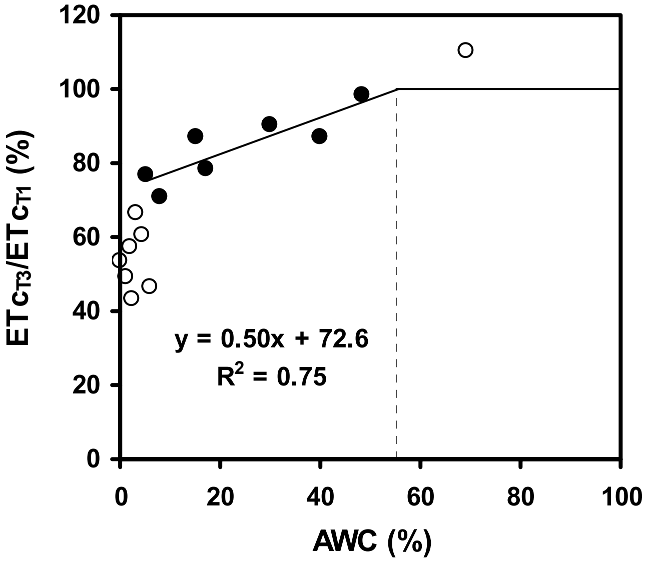

Fig. 2. Relationship between crop evapo-transpiration, for 2 week periods, of treatment T3 relative to that of treatment T1 (ETc_{T3}/ETc_{T1}) and available water content (AWC) determined for the upper 45 cm of soil. Open circle data points were not included in the linear regression.

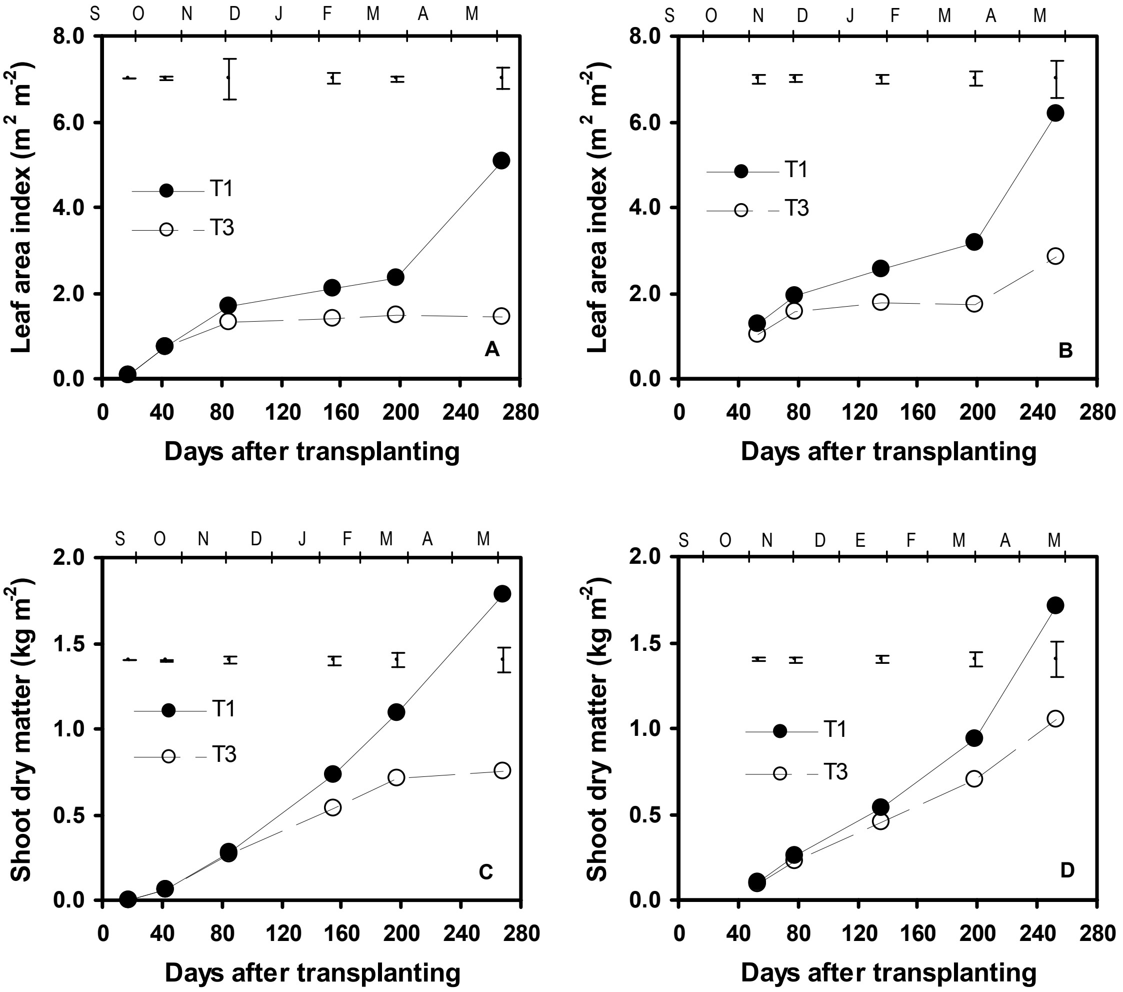

Fig. 3. Time course of leaf area index (A, B) and shoot dry matter (C, D) during the 1996/97 (A, C) and 1997/98 (B, D) growing seasons for irrigation treatments T1 and T3. Data are means of 4 replications. Vertical bars indicate ± 1 SE of the mean, averaged for the two treatment. Months of the year are given on the upper x-axis.

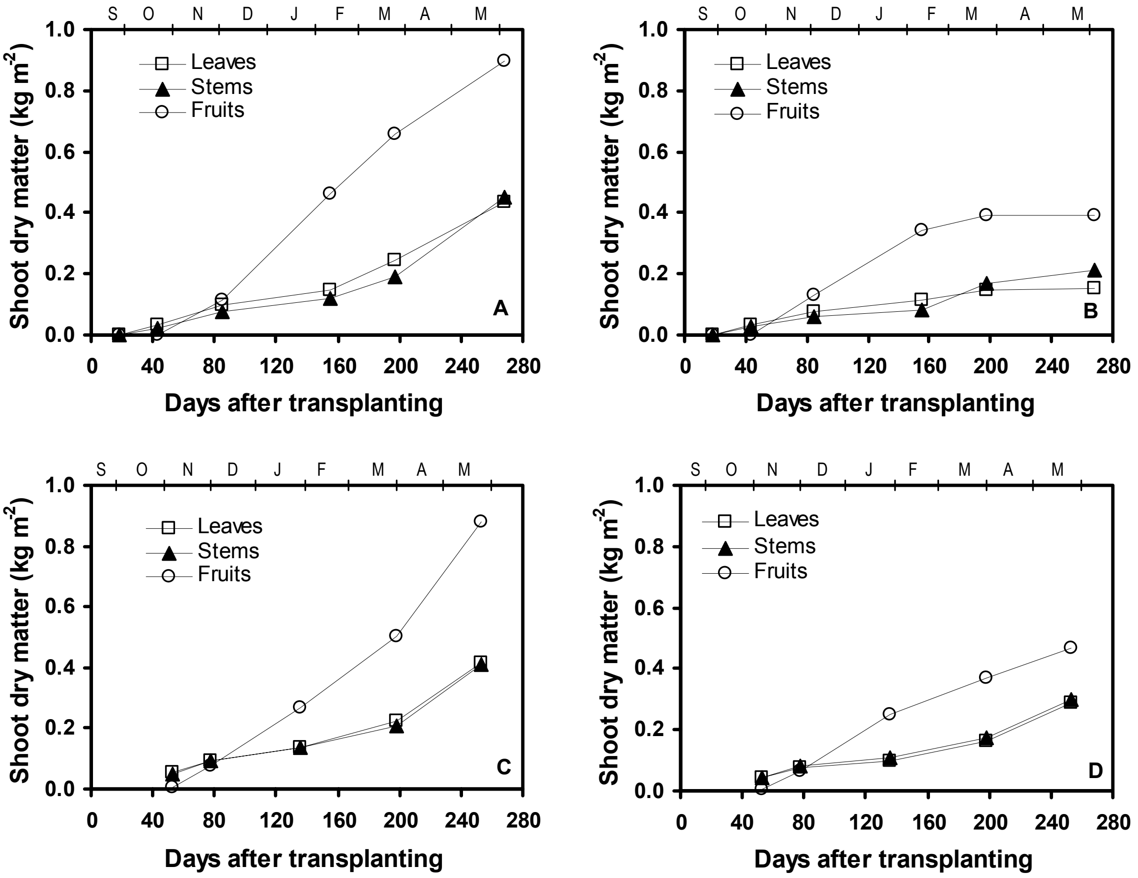

Fig. 4. Time-course of dry matter accumulation in leaves, stems and fruits during (A) 1996/97 growing season for treatment T1, (B) 1996/97 for T3, (C) 1997/8 for T1, and (D) 1997/98 for T3. Data are means of 4 replications. Months of the year are given on the upper x-axis.

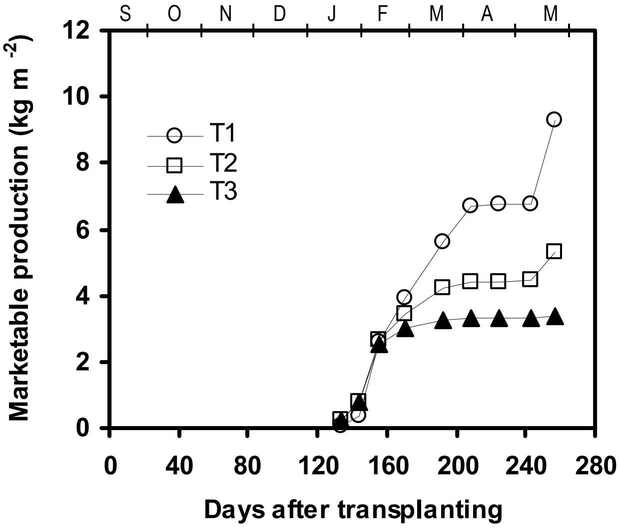

Fig. 5. Time-course of cumulative marketable fresh fruit production m^{-2} for the three treatments during the 1996/97 growing season.

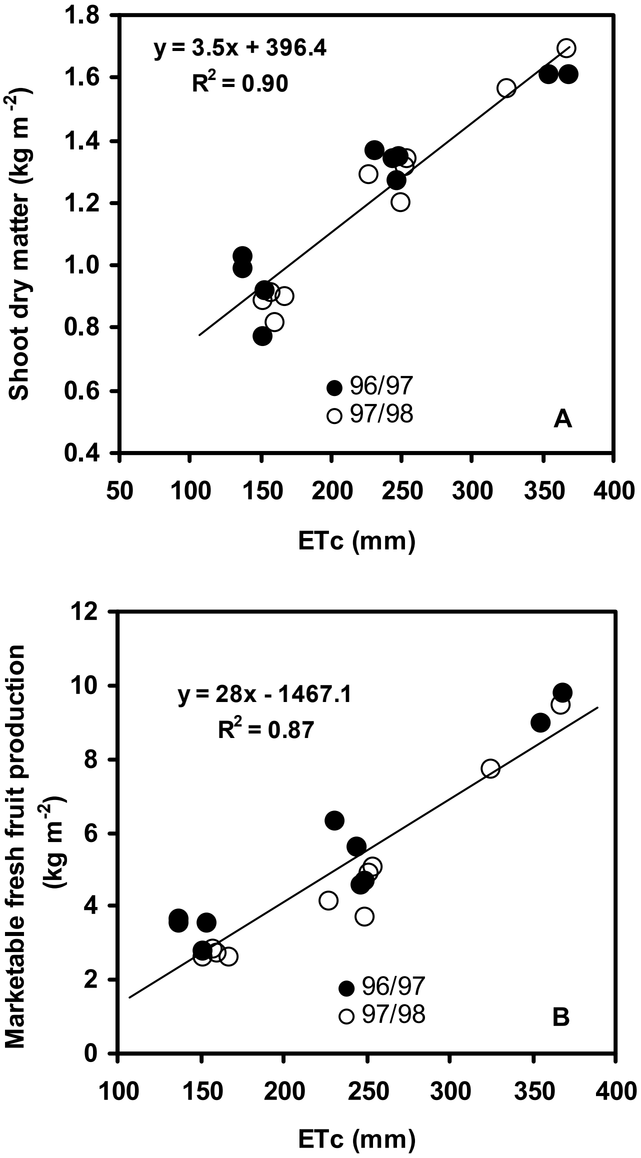

Fig. 6. Seasonal evapotranspiration in relation to (A) total shoot dry matter and (B) marketable fresh fruit production. Individual data points are from the three irrigation treatments (T1, T2, T3) and the two growing seasons (1996/97 closed circles; 1997/98 open circles).