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Water and Radiation Use Efficiencies in Drip-irrigated Pepper (*Capsicum annuum* L.): Response to Full and Deficit Irrigation Regimes

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Summary

Bell pepper (*Capsicum annuum* L., cv. 'Mercury') response to full and deficit irrigation was studied during the 2005 growing season at Tal Amara research station in the Central Bekaa valley of Lebanon. Treatments were (C) well-watered treatment receiving 100 % of crop evapotranspiration (ET_{crop}), and three water-stressed treatments receiving irrigation at 80 (WS_1), 60 (WS_2) and 40 % (WS_3) of ET_{crop}. Pepper seasonal evapotranspiration varied from a low of 275 mm in the more stressed treatment (WS_3) to a high of 478 mm in the well irrigated control, while in WS_1 and WS_2 seasonal ET accounted for totals of 427 and 360 mm, respectively. Relative to plants grown in WS_1 treatment (31.9 t ha^{-1}), marketable fruit yields of C, WS_2, and WS_3 were reduced by 11.3, 12.2, and 38.2 %, respectively. WS_1 and WS_2 treatments enhanced fruit quality (dry matter and total soluble solids contents) compared with C. Water use efficiency at dry yield basis (WUE_y) of the control was 0.35 kg m^{-3} while WS_1, WS_2 and WS_3 treatments had WUE_y higher by 22, 35 and 39 %, respectively. Radiation use efficiency (RUE) observed in the C and WS_1 treatments (avg. 2.20 g MJ^{-1}) was higher by 13 % in comparison to WS_2 and WS_3 treatments (avg. 1.96 g MJ^{-1}), with no significant differences between C–WS_1 and WS_2–WS_3. We concluded that WS_1 treatment is recommended for drip irrigated bell pepper under field conditions in order to obtain higher yield and optimized WUE under the Mediterranean dry climate of the Central Bekaa Valley.

Key words. *Capsicum annuum* L. – deficit irrigation – evapotranspiration – radiation use efficiency – water use efficiency

Introduction

Agricultural development in the semi-arid central Bekaa Valley of Lebanon is limited by the scarcity of available surface water resources. Rainfall in this region is relatively low with comparison to the rest of the country and the groundwater table has fallen continuously in some areas as a result of irrigation (Karam and Karaa 2000). Add to this the low water use efficiency of the cultivated crops as a result of inappropriate irrigation systems and management practices that often lead to water stress periods and yield reduction.

The reduction in plant growth and yield caused by water stress has been well documented (Kirnak et al. 2002; Şimşek et al. 2004). Limited water availability reduces the efficiency with which absorbed photosynthetically active radiation (PAR) is used by the crop to produce new dry matter (radiation use efficiency, RUE). This can be detected as a decrease in the amount of crop dry matter accumulated per unit of PAR absorbed over a given period of time (e.g., Stone et al. 2001), or as a reduction in the instantaneous whole-canopy net CO_2 exchange rate per unit of absorbed PAR (Jones et al. 1986).

The advent of precision irrigation methods such as drip irrigation has played a major role in reducing the water required in agricultural and horticultural crops, but has highlighted the need for new methods of accurate irrigation scheduling and control. In recent years it has become clear that the maintenance of a slight water deficit can improve the partitioning of carbohydrate to reproductive structures such as fruit and also control excessive vegetative growth (Chalmers et al. 1981), carrying out what was called "regulated deficit irrigation" (RDI) by Chalmers et al. (1986). This technique is widely used in the horticultural industry, as it results in more efficient use of irrigation water and often improves product quality (Turner 2001).

Bell pepper (*Capsicum annuum* L.), widely grown under greenhouse and open field conditions in Lebanon, is a valuable crop and high-quality yield is an essential prerequisite for its economic success. This crop has been classified as susceptible to very susceptible to water stress, with blossom stage being the most sensitive period (Doorenbos and Kassam 1986). Bell pepper has been subject of comprehensive studies especially under protected cultivation, on the effect of irrigation frequency and regimes on growth, yield and water use efficiency (Dorji et al. 2005; Fernandez et al. 2005; Agele et al. 2006). However, in comparison with other vegetable crops grown under open-field conditions there is a few information (Sezen et al. 2006) on the influence of regulated deficit irrigation on yield, growth, fruit quality, physiological responses water use efficiency (WUE) and especially radiation use efficiency (RUE) of pepper.

The first objective of this study was to determine daily and seasonal water use of bell pepper using precise weighing lysimeter and to account for seasonal irrigation requirements of this crop under semi-arid conditions. The second objective was to study the effects of deficit irrigation on growth parameters (leaf area index and dry matter production), yield, fruit quality, water and radiation use efficiencies of pepper.

Materials and Methods

Experimental site and climatic data

The experiment was conducted during the 2005 growing season at Tal Amara Research Station in the Central Bekaa Valley of Lebanon (33 °51 '44 " N lat., 35 °59 '32 " N long., 905 m asl). The details of the experimental site have been described elsewhere (Karam et al. 2005; 2006). Tal Amara has a well-defined hot and dry season from May to October and a very cold one for the remainder of the year. Average seasonal rain is 592 mm, with 95 % of the rain occurring between November and March.

Crop management, irrigation treatments and experimental design

Seeds of Bell Pepper (*Capsicum annuum* L. cv. 'Mercury' F_1) were germinated in peat on 12 April 2005 in a controlled nursery. The seedlings were then transplanted in the field on 31 May. An NPK-fertilizer (20-20-20) was applied by fertigation in two splits of 80 kg ha^{-1} each at crop establishment (7 days after transplanting, DAT) and first flower bud (45 DAT). In addition, potassium nitrate (12-46-0) was applied by fertigation in two splits of 45 kg ha^{-1} each at early fruiting (70 DAT) and late fruiting set (80 DAT).

Table 1 summarizes irrigation treatments used in this experiment. Treatments were arranged in a randomized complete-block design with four replicates. Each experimental unit consisted of 6 rows, 9 m in length, with 0.7 m row spacing and 0.3 m in-row spacing, giving a plant density of 35000 plants ha^{-1}. The middle of two rows of each plot were used for harvesting.

Reference evapotranspiration ($ET_{rye\text{-}grass}$) was measured at weekly basis using two drainage no-suction type lysimeters of 4 m^2 area (2 m × 2 m) and 1 m depth each, cultivated with rye grass (*Lolium prerenne*). Soil water content in the lysimeters was estimated using digital tensiometers (Watermark, Soil Moisture Meter, Irrometer Company, Inc.) installed in two replicates in each lysimeter at 30 cm of the soil depth. Drainage water was collected and measured in a central reservoir situated at half distance between the lysimeters. $ET_{rye\text{-}grass}$ was then calculated for a given interval as the difference between irrigation (I) and drainage (D_r), assuming the variation of the soil water storage (ΔS) is 0 (all terms are expressed in mm):

$$ET_{rye\text{-}grass} = I - D_r \pm \Delta S \qquad (1)$$

Crop evapotranspiration (ET_{crop}) was measured by an electronic weighing lysimeter of 16 m^2 surface area (4 m × 4 m) and 1.2 m deep, containing the clay soil type of the experimental site. Watering of the lysimeter was made upon 30 % soil water depletion in the 0–100 cm soil layer. The weight loss of the lysimeter due to evapotranspiration was measured with load cells and recorded at a 15-min interval on a computer located in a control unit near the lysimeter. ET_{crop} was determined as the difference between lysimeter weight gain (irrigation and/or rain or dew) and weight loss (from evapotranspiration) divided by the lysimeter surface area, so that day/night ET from midnight to midnight was computed as the average of 96 readings per day (Karam et al. 2005).

Water was distributed to the plots uniformly and simultaneously using a drip irrigation system. Drip lines, with in-line emitters located 0.30 m apart and an emitter flow rate of 4 L h^{-1}, were placed 10 cm away from the plants and were spaced with a 0.7 m distance between each lateral. Applied irrigation amounts were calculated as:

$$V = ET_{crop} \times A \qquad (2)$$

where V is volume of irrigation water (in liters), ET_{crop} is weighing lysimeter measured crop evapotranspiration (in mm) and A is plot area, (m^2).

Soil water content in the 0–90 cm of soil profile was measured during the growing season using a Time Domain Reflectometry (Sentry 200- AP, 1994). For that purpose, 16 access tubes, 90 cm in length and 5 cm in diameter, were installed in the central row of each plot. TDR readings were used to estimate seasonal evapotranspiration (ET) in the treatments using the soil water balance

Table 1. Irrigation treatments used in the current experiment.

Treatments	Description
C	Control irrigated at 100 % of crop evapotranspiration (ET_{crop}) during the growing period
WS_1	Treatment irrigated at 80 % of ET_{crop} during the growing period
WS_2	Treatment irrigated at 60 % of ET_{crop} during the growing period
WS_3	Treatment irrigated at 40 % of ET_{crop} during the growing period

approach as the difference between inputs and outputs within the soil profile:

$$P + I - D_r - R_o - ET \pm (S_e - S_b) = 0 \quad (3)$$

where P is precipitation, I irrigation, D_r drainage, R_o run-off, S_e the soil water content at the end of a time interval and S_b is the water content at the beginning of the same time interval. All terms in equation (3) are expressed in mm.

For bell pepper, we consider four growth periods; the first from transplanting to the end of vegetative growth (0–38 DAT), the second from the end of vegetative growth to the end of flowering set (38–66 DAT), the third from the end of flowering set to the end of fruiting period (66–87 DAT) and the fourth from fruiting to the third harvest (87–112 DAT). Obtained values were then summed to account for seasonal evapotranspiration in the different treatments.

Plant biomass, yield, and fruit quality

Four randomly selected plants per treatment were sampled at weekly-basis to determine leaf area, and dry matter accumulation. Leaf area was measured by an electronic leaf area meter (LI 202, LI-COR, Inc., Lincolin NE). Leaf area index (LAI) was then computed as the ratio of green leaf area to ground area. Aboveground organs (leaves + stems + fruits) were dried in a forced draft oven at 80 °C until constant dry weight (this was attained in 72 h) for recording plant dry weight (g $plant^{-1}$). Fully mature green fruits were harvested weekly starting from 2 September (94 DAT) to 18 September (110 DAT). Fruit number, fruit mean weight and marketable yield were determined from the two rows in the middle of each plot. Five representative marketable fruits per plot were analyzed for fruit quality parameters. Immediately after harvest, fruit volume was calculated using the following equation reported by MARCELIS and HOFMAN-EIJER (1995) on bell pepper:

$$V = 1/4\ \pi\ LD^2 \quad (4)$$

where V is the volume (cm^3) and L and D are the longitudinal and equatorial length.

Fruit shape index (SI) was defined by the ratio of equatorial and longitudinal lengths. Fruit firmness was determined by removing three discs of the skin surface in the equatorial area and using a penetrometer (Bertuzzi FT 011; Brugherio, Milan, Italy), fitted with an 8 mm-diameter round-head probe. The pericarp thickness was also measured using a vernier caliper at the equatorial region of the fruit. From the liquid extract obtained from liquefying and filtering the mesocarp of each fruit, total soluble solids (TSS) contents in juice was determined by an Atago N1 refractometer (Atago Co. Ltd., Japan) and expressed as Brix at 20 °C.

Water use efficiency at biomass basis (WUE_b) was calculated as the ratio of aboveground dry matter (t ha^{-1}) and crop evapotranspiration (ET) (mm), while at yield basis (WUE_y) it was calculated as the ratio of fruit yield (at fresh and dry basis; t ha^{-1}) and ET (mm).

Calculation of radiation use efficiency

Radiation use efficiency (g MJ^{-1}) was computed as the slope of the linear regression (y = a + bx) of cumulative above dry matter (g m^{-2}) versus cumulative intercepted photosynthetically active radiation (MJ m^{-2}) (CEOTTO and CASTELLI 2002; GOMES et al. 2005). The amount of instantaneously incoming solar radiation (0.4–3 μm) was measured with a Degreane pyranometer (Auria 12E, Degreane, France) at the weather station, 50 m apart from the experimental site. The photosynthetically active radiation (PAR) in the incoming solar radiation is assumed to be 50 % (MONTEITH 1972). The intercepted photosynthetically active radiation (IPAR) was calculated using the formula of Lambert-Beer (SHIBLES and WEBER 1965):

$$IPAR = PAR/PPD \times (1 - e^{-k\ LAI}) \quad (5)$$

where PPD is the plant population density (plants m^{-2}), k is the extinction coefficient and LAI is the leaf area index ($m^2\ m^{-2}$); k-value representative for the crop could be calculated as the slope of the regression line between the fraction of PAR reaching the soil underneath the canopy and LAI (CEOTTO and CASTELLI 2002). In this study, k-value for bell pepper was assumed to be 0.35 (JOVANOVICH 2000). IPAR was calculated during the growing season by a simple dynamic model using an Excel sheet, which accounts for daily values of LAI and PAR.

Statistical analysis

All data were statistically analyzed by ANOVA using the SPSS software package (SPSS 10 for Windows, 2001). The differences among treatments were determined by calculating the least significant difference LSD ($P<0.05$) values.

Results and Discussion

Evapotranspiration and crop coefficients

Seasonal evapotranspiration of bell pepper as measured on the weighing lysimeter amounted 506 mm for a total growing cycle of 112 days. During the vegetative growth (0–38 DAT), ET_{crop} totalled 137 mm, while during the flowering period (38–66 DAT) it was 130 mm. Then, ET_{crop} accumulated during the fruiting period (66–87 DAT) a total of 113 mm. Lysimetric data showed a consistent increase in ET_{crop} from 5.0 to 6.5 mm d^{-1}during the fruiting to values slightly >7 mm d^{-1} during mature fruits stage (91 DAT) and during the period from the first to the second harvest. Throughout the harvesting time (87–112 DAT) cumulative ET_{crop} was 126 mm, or 25 % of seasonal evapotranspiration.

After full cover was reached, which roughly occurred at the first harvest (98 DAT) pepper used water almost at the same daily rate of grass reference evapotranspiration ($ET_{rye\text{-}grass}$). At this growth period, crop coefficient (K_c= $ET_{crop}/ET_{rye\text{-}grass}$) was at its highest value (0.94), thus corresponding to the maximum water use of the crop (Fig. 1). After that, ET_{crop} and $ET_{rye\text{-}grass}$ decreased slightly so that K_c decreased to 0.82 by the end of the growing period.

Seasonal water use (ET) of drip-irrigated bell pepper treatments, calculated from equation (3), varied from a

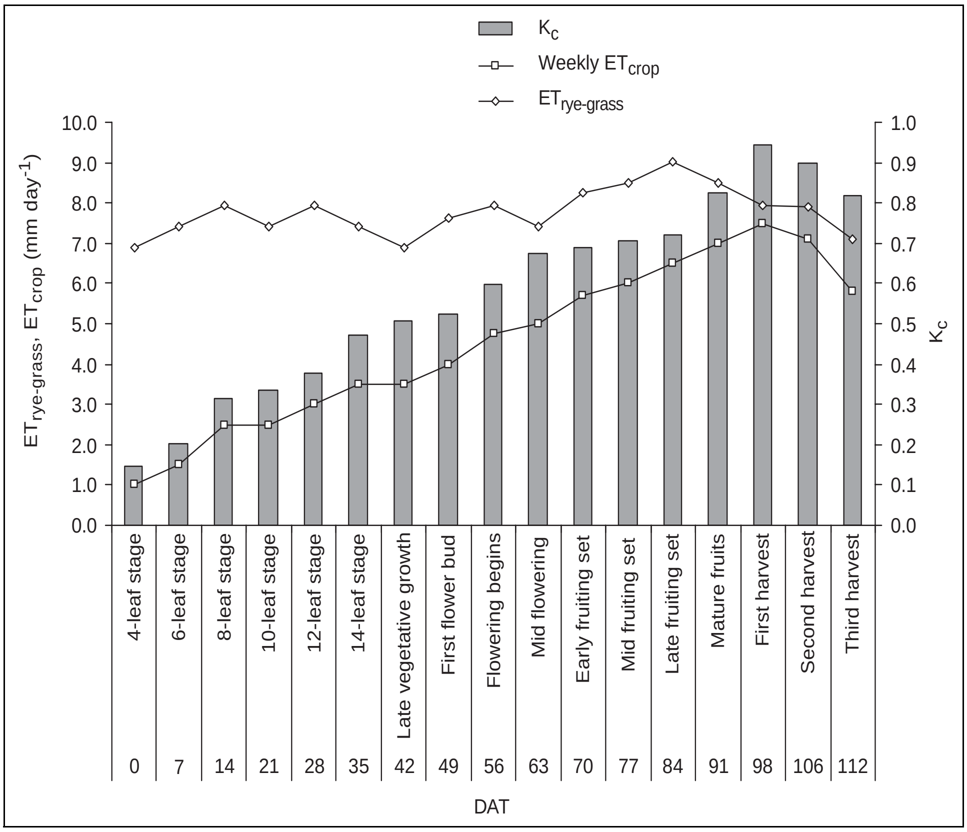

Fig. 1. Time course evolution of weekly reference evapotranspiration ($ET_{rye-grass}$), crop evapotranspiration (ET_{crop}) and crop coefficients (K_c) of pepper, in days after transplanting (DAT).

low of 275 mm in the more stressed treatment (WS_3) to a high of 478 mm in the well irrigated control, while in WS_1 and WS_2 seasonal ET accounted for totals of 427 and 360 mm (Table 2). The water conservation with WS_1, WS_2 and WS_3 treatments was lower by 10.7, 26.6 and 42.4 %, respectively, with comparison to the control.

Growth analyses

Leaf area index (LAI) pattern of pepper has been shown to vary with deficit irrigation (Fig. 2). After the plant has achieved complete flowering (66 DAT), significant differences ($P<0.05$) appeared between the control and the more deficit irrigation treatments WS_2 and WS_3, while no significant differences were found between the control (C) and the less deficit-irrigated treatment (WS_1). The maximum value (LAI_{max}) recorded in the fully irrigated treatment towards the end of the growing season (94 DAT) was about 2.5 $m^2\ m^{-2}$, while deficit irrigation at 80 % of ET_{crop} (WS_1) resulted in a slight increase of LAI_{max} (3.0 $m^2\ m^{-2}$). The delay in reaching maximum leaf area index in bell pepper arises from the indeterminate growth nature of this crop, as long as favourable growing conditions under watering regimes, which allow new leaves, continue to develop (Gomes et al. 2005). Moreover, Fernandez et al. (2005) found higher LAI values in bell pepper plants exposed to mild water stress conditions than in well irrigated plants. On the other hand, deficit irrigation at 60 (WS_2) and 40 % (WS_3) of ET_{crop} resulted in a significant decrease ($P<0.05$) of LAI_{max} (2.0 and 1.8 $m^2\ m^{-2}$, respectively). Fig. 2A shows that the date of LAI_{max} in the more deficit treatments (WS_2 and WS_3) was observed one week earlier (87 DAT) than that of the control and WS_1 treatment, probably because of accelerated crop phenology and leaf senescence (Delfine et al. (2002).

Table 2. Effect of deficit irrigation on yield, fruit number and mean weight of pepper plants. Data are means of four replicates.

Treatments	Fresh fruit yield (t ha^{-1})	Fruit number (no. ha^{-1})	Mean fruit weight (g)
C	28.3	250.0	112.5
WS_1	31.9	252.0	127.1
WS_2	28.0	241.5	114.7
WS_3	19.7	212.5	92.5
$LSD_{0.05}$[a]	3.5	27.1	11.3

[a]Least significant difference at $P\leq0.05$

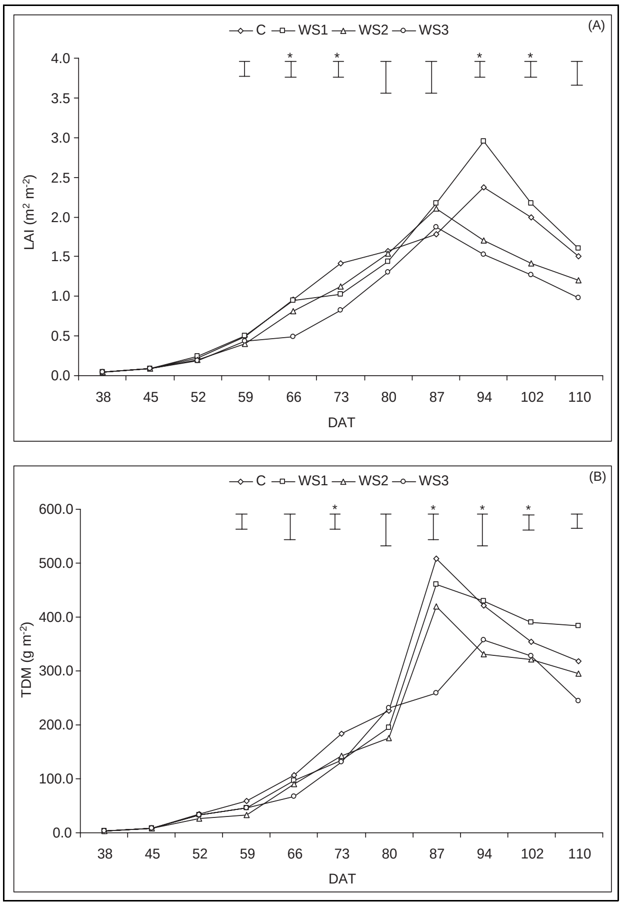

Fig. 2. Time course evolution of (A) leaf area index and (B) aboveground dry matter production of pepper plants, in days after transplanting (DAT). Data points are means (n = 5). LSD_5 ($P \leq 0.05$) are presented as vertical bars. The asterisks denote significance at $P \leq 0.05$.

There were significant differences in dry matter production (DM) between the control and deficit irrigation treatments. These differences became more evident at mature fruit stage (87 DAT), where plants of the control produced 508 g m^{-2}, while deficit-irrigated treatments WS_1, WS_2 and WS_3 produced 460, 420 and 260 g m^{-2} (Fig. 2B). However, the differences between the control (C) and WS_1 were not significant at $P<0.05$. After mature fruit stage, DM production was reduced in all treatments probably because of leaf senescence. A remarkable decrease in DM production in pepper plants after mature fruits was observed in several studies, namely DELFINE et al. (2002), DALLA COSTA and GIANQUINTO (2002) and DORJI et al. (2005). By the end of the growing season, total dry matter production from the well irrigated treatment had reached 3.18 t ha^{-1}, of which 52 % in fruits, while WS_1 treatment produced 3.83 t ha^{-1} of which 50 % in fruits, while WS_2 and WS_3 produced 2.95 and 2.45 t ha^{-1}, respectively, of which 69 % and 62 %, respectively, in fruits.

Fruit yield and quality

In the current study, marketable fruit yield, fruit number and the mean fruit weight were significantly ($P<0.05$) affected by deficit irrigation (Table 2). Relative to plants grown in WS_1 treatment, marketable fruit yields of C, WS_2, and WS_3 were reduced by 11.3, 12.2, and 38.2 %, respectively. The higher pepper marketable yield recorded under mild stress conditions (WS_1), has been previously reported by several authors (CHARTZOULAKIS et al. 1997; DALLA COSTA and GIANQUINTO 2002). The decrease in marketable yield in C and WS_2 in comparison to WS_1 was attributed to a reduction in the fruit mean weight rather than a change in the number of fruits per plant, whereas the greatest yield reduction recorded in WS_3 was mainly attributed to a reduction in both fruit weight and fruit number (Table 2). The better performance of the crop in WS_1 treatment is probably due to the better maintenance of internal water balance by plants and an improved utilization of water and nutrients (MITCHELL et al. 1991; RAMALAN and NWOKEOCHA 2000).

In this study, fruit volume, fruit firmness, epicarp thickness, total soluble solids (TSS) contents and fruit dry matter (DM) were significantly ($P<0.05$) affected by water deficit, whereas no significant difference among treatments was observed for the shape index (Table 3). However, fruits from control treatment exhibited higher values of epicarp thickness and firmness than did fruits from the water stress treatments. Moreover, the fruit quality aspects most affected by deficit irrigation were also those which are particularly important for consumer satisfaction (i.e. TSS and DM). Increasing water stress improved fruit quality by increasing fruit DM and TSS contents (Table 3). A similar positive effect of water stress on TSS contents was also found in tomato (MITCHELL et al. 1991), eggplant (KIRNAK et al. 2002) and watermelon (ŞIMŞEK et al. 2004). The increase in total sugars of pepper fruits due to deficit irrigation may reflect an osmotic adjustment obtained by enhanced synthesis of sugars in the plant tissue (GREENWAY and MUNNS 1980). Nevertheless, MITCHELL et al. (1991) indicated that the water stress influenced osmotic potential and solute content of tomato fruit by reducing water accumulation.

Water use efficiency

Water use efficiency at dry yield basis (WUE_y) of the control was 0.35 kg m^{-3} while those of WS_1, WS_2 and WS_3 were 22, 35 and 39 %, respectively, higher than the control. The range of WUE at dry yield basis obtained in this experiment was within the values obtained by KANG et al. (2001) for hot pepper. When WUE_y is calculated at fresh yield basis, the values become 5.9 kg m^{-3} in the control, 7.5 kg m^{-3} in WS_1, 7.8 kg m^{-3} in WS_2 and 7.2 kg m^{-3} in WS_3. In general, Water use efficiency at both dry and fresh yield basis increased with decreasing irrigation application. Finally, biomass related water use efficiency (WUE_b) was 0.66 kg m^{-3} in the control, while in the deficit irrigation treatments it was 20–27 % higher.

Radiation use efficiency

Daily cumulative above dry matter production, showed a strong linear relationship (R^2 between 0.92 and 0.96) with accumulated intercepted photosynthetically active radiation (PAR) (Fig. 3). Linear relationship between crop growth and cumulative intercepted PAR has also been reported by MONTEITH (1994). The RUE value observed in the current study under well watering condi-

Table 3. Effect of deficit irrigation on fruit shape index (SI), fruit volume, firmness, pericarp thickness (PT), fruit dry matter (DM), and total soluble solids (TSS) contents of pepper plants. Data are means of four replicates.

Treatments	SI	Volume (cm^3)	Firmness ($N\ mm^{-1}$)	PT (mm)	DM (%)	TSS (Brix)
C	0.88	565.5	5.3	6.2	4.8	3.5
WS_1	0.90	560.8	4.4	6.0	4.5	3.6
WS_2	0.90	478.5	4.6	5.4	5.8	4.2
WS_3	0.93	388.5	2.8	4.8	7.0	4.7
$LSD_{0.05}$[a]	0.07	102.4	0.4	0.5	1.0	0.3

[a]Least significant difference at $P \leq 0.05$

tions (2.22 g MJ^{-1}) is similar to the one reported earlier on bell pepper (2.10 g MJ^{-1}) by Dorais et al. (1995). Data analysis showed significant differences between the four slopes of the regression equations ($P<0.05$). The RUE observed in the C and WS_1 treatments (avg. 2.20 g MJ^{-1}) was higher by 13 % in comparison with the RUE recorded in the WS_2 and WS_3 treatments (avg. 1.96 g MJ^{-1}), with no significant differences between C–WS_1 and WS_2–WS_3.

It is well established that the whole canopy absorption of incident PAR may be reduced, either by drought-induced limitation of leaf area expansion as observed in this study, and by temporary leaf wilting or rolling during periods of severe stress, or by early leaf senescence (Jones et al. 1986). Moreover, the water stress reduces the efficiency with which intercepted PAR is used by the crop to produce dry matter (RUE). This can be detected as a decrease in the amount of crop dry matter accumulated per unit of intercepted PAR over a given period of time (Stone et al. 2001), or as a reduction in the instantaneous whole-canopy net CO_2 exchange rate per unit of intercepted PAR (Jones et al. 1986).

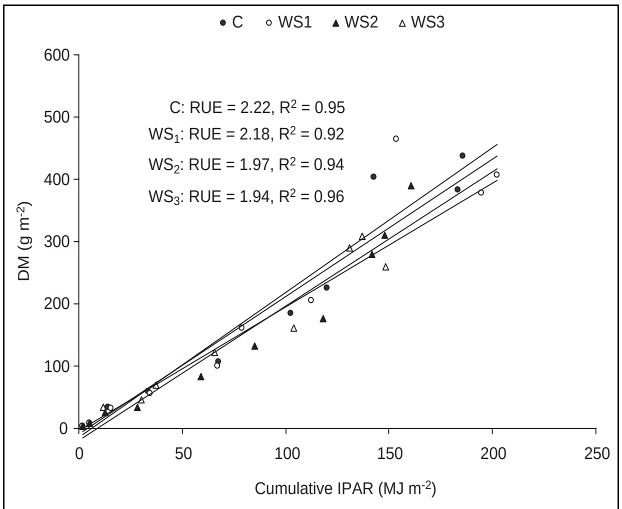

Fig. 3. Relationship between cumulative dry matter production and cumulative intercepted photosynthetically absorbed radiation (IPAR) for pepper plants grown under control (C) and water stress (WS_1, WS_2, WS_3) conditions. Data points are means (n =5).

Conclusions

Mild water stress treatment (WS_1) in semi-arid regions can be a good choice for pepper since it could save 20 % of water with an increase of 10 % in yield in comparison to the control. Moreover, deficit irrigation at 60 % of ET_{crop} (WS_2) could save 40 % of water without a significant decrease in fruit yield. This phenomenon could be explained by the reduction in water losses from the plant when applying deficit irrigation because drying partially the root system can indeed inhibit stomata opening to some degree but keep the shoot turgid at he same time, so that no trade-off of biomass production occurs at the same water consumption (Blackman and Davies 1985). In that sense, Kang et al. (2001) suggested that partial irrigation can restrict water losses from the plant without however affecting the rate of production of dry matter, which yet in deficit-irrigation treatments is comparable to that in well irrigated treatments.

Water deficit can significantly improve fruit quality of field-grown pepper, but this advantage is accompanied by reduction in marketable yield. The results also indicate that water deficit reduced the ability of the crop to accumulate biomass by reducing the capacity to convert intercepted energy to biomass and leading to lower RUE values In conclusion, WS_1 treatment is recommended for drip irrigated bell pepper grown under field conditions in order to obtain higher yield and WUE under the Mediterranean climate.

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