Effects of Vapour Pressure Deficit and Radiation on the Transpiration Rate of a Greenhouse Sweet Pepper Crop

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Abstract

The effects of air vapour pressure deficit (VPD) and radiation reduction by whitening on the transpiration rates of a greenhouse sweet pepper crop (transplanted in July) under a semi-arid climate (Almería, South-Eastern Spain) were studied. Measurements were carried out during ontogeny in three analogue multi-span curved greenhouses: (i) without air VPD control and no whitening ii) with a fog-system operating when air VPD was higher than 1.5 kPa and iii) without air VPD control and with whitening (about 30% reduction in greenhouse solar radiation transmission). Leaf transpiration *vs.* inside solar radiation, air VPD and leaf area index were studied and analysed. A model has been developed (multiple regression analysis), based on the simplified Penman-Monteith formula, between the measured transpiration rate and the radiative and advective components, equation: $?E = A\ f_1(LAI)R_g + B\ f_2(LAI)VPD$, **which for different conditions of air VPD and inside radiation, gave a good prediction of the hourly water consumption. This simplified transpiration model can be used to manage irrigation with different conditions of VPD and incoming radiation.**

INTRODUCTION

During the last decades a great expansion of protected horticulture has occurred all around the Mediterranean basin, which has caused an overexploitation of water resources in many areas, as is the case of Almería, resulting in a deterioration of the quality of water used for irrigation, due to sea intrusion and to the leakage of fertilizers into the aquifers. In view of this situation, it is necessary to have a good knowledge of the crop water demand, aiming at using water and fertilizers more rationally avoiding unnecessary losses (Montero *et al*., 1998). A proper management of the greenhouse climate would allow an increase of the yield and a decrease of the crop evaporative demand, improving therefore the water use efficiency of the different crops.

There are several research works showing the effects of fogging systems on the transpiration rates of the canopy (Boulard *et al*., 1991; Katsoulas *et al*., 2001; Medrano *et al*., 2003; Baille *et al*., 2006) and on the fruits quality (Leonardi *et al*., 2000). Determination of transpiration rates and of their relation with climate variables (air VPD and solar radiation) has generated important information about some crops grown in protected environments (Medrano *et al*., 2005; Baille *et al*., 2006). The most widely accepted method to calculate transpiration rates in protected environments is that proposed by Penman-Monteith (Monteith, 1990). In the present work, a simplification of the Penman-Monteith equation (Baille *et al*., 1994) for a sweet pepper summer crop has been used to estimate the canopy transpiration per unit soil area.

The aim of this study was to evaluate the effect of controlling greenhouse air humidity by means of a fogging system and of the reduction of inside radiation (obtained by whitening), on the transpiration rate of a sweet pepper crop and to evaluate a simplified model to predict plant transpiration rates during the warmest months of the Mediterranean area.

MATERIAL AND METHODS

The experiments were carried out in three analogue multi-span greenhouses, E-W oriented, located near Almería (36º 47´ N, 2º 43´ W) on the coastal area of South-Eastern Spain. The geometrical characteristics of the greenhouses were: 3 m height at the eaves, 4.5 m height at the ridge, total width 22.5 m, total length 28 m and ground area 630 m^2. The greenhouse cooling strategies were:

T1- Fan ventilation, the maximum airflow rate was 40,000 m^3 h^{-1}, and temperature set points were modulated in the range 22-25 ºC depending on the humidity level. During the operation of the fans, the roof vents were opened to about 30% of their maximum aperture and the side vents were closed.

T2- Natural ventilation plus evaporative cooling (high-pressure water fogging system). The set point of the air vapour pressure deficit, VPD, was fixed at 1.5 kPa.

T3- Natural ventilation plus whitening (about 30% reduction in greenhouse solar radiation transmission) during the first 2 months of the crop cycle, and only natural ventilation after washing off the whitening on September 17th.

All actuators were connected to a commercial climate controller which maintained the desired set-points.

Crop and Cultural Practices

The sweet pepper plants (cv. Melchor) were transplanted on 21st July 2004 in plastic bags (40 L volume) filled with perlite. Plant density was 3 plants m^{-2} (6 plants per bag). The plants were managed following the “trellis” technique (two main stems per plant and pruning all auxiliary shoots).

Measurements

The most relevant climatic variables were continuously monitored outside and inside the three greenhouses. Air temperature, Ta (ºC), and VPD (kPa), were measured by aspirated psychrometers located 1.5 m above ground, and solar radiation, Rg (W m^{-2}), was measured by a solarimeter. The accuracy of the Ta, VPD, and Rg measurements was ± 0.2ºC, ± 0.04 kPa and ± 5 W m^{-2}, respectively.

The transpiration (λE, MJ m^{-2} d^{-1}) was measured every 5 minutes by means of a weighting lysimeter (Van Meurs and Stanghellini, 1992) located in a central row of each greenhouse. A metal structure with a drain collector held one perlite bag. The device included an electronic balance (KCC150, Mettler Toledo GmbH, Germany), scale capacity=150 kg, resolution ± 1 g) which was equipped with a tray carrying a perlite bag with six plants, and an independent system of water supply and drainage. Considering that the evaporation loss from the perlite substrate was negligible, the weight loss measured by the electronic balance was assumed equal to the crop transpiration.

The transpiration per unit leaf area was also calculated (dividing by leaf area instead of soil area).

In each greenhouse the transmissivity of the covering material for PAR radiation was measured with a linear sensor (LICOR Inc, Lincoln, Nebraska, USA), on clear days (7 measurements through the cycle) at 12:00 (GMT time), measuring the radiation outside the greenhouse before and after the measurements (10 measurement points per greenhouse) performed inside the greenhouse. Intercepted radiation by the canopy was also measured with the same sensor described previously, and the light extinction coefficient through the canopy (K) estimated using the equation described by Russell *et al*. (1989): $I = I_0 e^{-K\ LAI}$, where I = radiation at the base of the crop, I_0 = incident radiation just above the canopy, K = light extinction coefficient through the canopy and LAI = Leaf area index. Seven determinations of LAI were carried out during the experiment, each one on six plants randomly distributed in each greenhouse. Besides, once a month two plants were selected in each treatment, in which length, width and area of each one of their leaves were measured, in order to obtain a relation between leaf area with the width and with the length of the leaf, and therefore, establishing a non destructive leaf area measurement method.

Every ten days a field monitoring of the six plants located in the weighting lysimeters was performed for each treatment. The monitoring included the measurement of the width of all the leaves, to obtain the leaf area, applying the relation previously obtained from the destructive measurements previously commented. These values were compared with those obtained from the biomass plants.

Transpiration model

The model used to estimate the transpiration rate of the canopy per unit soil area ?E, has been derived from the Penman-Monteith equation simplified by Baille *et al*. (1994). Therefore, the adjustment of ?E during the day and during the night responded to the following equation: ?E = A (1-exp(-k LAI) Rg + B LAI VPD, where: Rg= incident solar radiation (W m^{-2}), k=light extinction coefficient, A and B= values of equation parameters (A dimensionless, B (J m^{-2} s^{-1} kPa^{-1}), ? = vaporisation heat of water (MJ kg^{-1}). Day transpiration rates (Rg>0) were determined independently from night transpiration rates (Rg=0), so coefficient B had two values assigned, day B_d and night B_n. Model parameters (A and B_d) were estimated by means of multiple regression analysis with 1,773 (Fan ventilated), 1,543 (Fog-system) and 1,680 (Whitening) sets of measured diurnal transpiration, solar radiation, VPD and LAI data, during the whole growing cycle.

The model has been adjusted for the whole cycle (1-229 days after transplanting, d.a.t.), and also dividing the whole cycle in two periods: the period previous to the cleaning of the whitening (period 1, 1-58 d.a.t.), when LAI ranged from 0.5 to 2 and the cooling systems were more active (more cooling requirements) and another period (period 2) which went from the cleaning of the whitening to the end of the growing cycle (59-229 d.a.t.) whit a final LAI of 3.5. The comparison between calculated rates of ?E from the simplified model and the measured values was carried out using data sets different from those used for the estimation of the A, B_d and B_n coefficients.

RESULTS AND DISCUSSION

The transpiration rate per unit soil area was very similar in the three greenhouses (Figure 1) despite the differences in the inside radiation and VPD (data not shown). As an example, in the whitened greenhouse the solar radiation was on average 33% lower than in the greenhouse with mechanical ventilation during this period and the VPD was up to 1.5 kPa lower). Therefore, the transpiration demand in the forced ventilation greenhouse was clearly higher than in the whitened greenhouse, whereas the transpiration values were similar due to the differences in LAI between treatments at the beginning of the crop cycle, i.e. on day 30 after transplant (16^{th} August) LAI was 0.18, 0.31 and 0.54 for the compartments with fan ventilation, fog-system and whitening, respectively (with significant differences). The differences in LAI were still substantial until d.a.t. = 50 (0.84, 1.16 and 1.37, respectively), but decreased progressively until d.a.t. = 80, when all the crops reached a LAI value close to 2.2.

Considering the values of λE obtained during clear days (maximum values of λE, λE_{max}), a linear relationship can be inferred from the trend of λE_{max} (Figure 1), which was approximated by the simple relationship: λE_{max} = 0.12 d.a.t., that is, the maximum transpiration rate per unit ground area increased steadily, at about 0.12 MJ m^{-2} per day in the three greenhouses. Therefore, the rate of increase in the evaporative cooling power of the crops appears to be independent of the cooling system, the climatic conditions imposed by the outside climate and the climate control system.

The transpiration per unit leaf area, λE^* (Figure 2) revealed some interesting traits of crop transpiration responses during the two months after planting, when the plants had a low LAI and faced harsh climatic conditions. The first characteristic is that the time evolution of λE^* followed a similar pattern in all treatments with a rapid increase from planting until d.a.t. = 20, corresponding to the date when the peak of λE^* was simultaneously reached by the crops in the three greenhouses. The second noticeable trait is that the amplitude of the peak was very high in the fan ventilation, treatment with values reaching 25-28 MJ m_{leaf}^{-2} d^{-1}, whereas it only reached 12 and 9 MJ m_{leaf}^{-2} d^{-1} in fog-system and whitening, respectively. These values can be considered as indicative of the maximum daily transpiration rate per unit leaf area, The observed time-pattern of λE^* can be explained by: (i) a possible post-transplant shock that followed planting, which could have altered temporarily the activity of the young transpiring leaves. The curves indicate that the leaves needed a period of acclimation of about 2 weeks to recover from the stress and to reach their full potential of transpiration, and (ii) the rapid increase in LAI once the maximum λE^* was reached at d.a.t. 20, thus leading to a strong decrease in the transpiration rate per unit leaf area.

Figure 3 shows the comparison between transpiration rate per unit soil area (W m^{-2}), and the incident global radiation (W m^{-2}), for the 31st of August (42 d.a.t.), for the three cooling treatments. It can be observed that the crops under whitening and under forced ventilation increase their transpiration rate almost linearly with the increases in radiation, whereas for the crop under fogging there is almost no response in transpiration as the radiation increases above 350 W m^{-2}. Figure 4 shows the correlation between transpiration and VPD at 42 d.a.t. It can be deduced that the fog system VPD set point (system activated when VPD >1.5 kPa), was probably not the best, because it caused a limitation on the transpiration of the plants. This hypothesis has been confirmed in view of the temperature difference data between leaf and air (data not shown). A very pronounced hysteresis between ?E and VPD is also observed. This result can be partly explained, as an imbalance between the transpiration rate and the root re-absorption, which is not compensated during the afternoon, with frequently higher VPD values. These results are coincident with those of Boulard *et al. (*1991), Jolliet and Bailey (1991), Kittas *et al.* (2001) and Medrano *et al*. (2003). This effect may be due to the fog system set point, which might have induced a less developed root system in this treatment, which is not able to compensate the water loss through the leaves during the afternoon. The hysteresis phenomena becomes less marked as the leaf development of the crop becomes higher, coincident with Kittas *et al*., 2000; Katsoulas *et al.,* 2001; Medrano *et al.,* 2003. The gap of leaf transpiration *vs* radiation, confirms that the equations to estimate the transpiration rate based only on radiation, do not provide the required precision at a small time scale of hours or minutes (González, 1995).

Table 1 shows the A, B_d and B_n values obtained in three different periods, as well as the interval of leaf development for each one of them, distinguishing between day and night. For the whole crop cycle, values for A were 0.36, 0.35 and 0.29, for B_d 29.44, 27.92 and 38.59 and for B_n 13, 18.9 and 16.1, for the mechanical ventilation, fogging and whitening treatments respectively. The multiple regression coefficients were similar for the three cooling treatments and ranged from 90.6 % for the forced ventilation and fogging, and 91% for whitening. The values of the A, B_d and B_n coefficients for the whole growing cycle were similar to those obtained for period 2 and lower to those of period 1.

The model explains 92, 85 and 94% of the transpiration rate per soil area and underestimates the transpiration rates by 18, 10 and 6 %, for the mechanical ventilation, fogging and whitening treatments, respectively, and this represents the error the model over a long term (the whole growing cycle). The average absolute error (AAE) and the standard error of the estimations (SEE) are a measure of the dispersion and quantify the errors in short term estimations (hourly periods). The AAE was 11 J $m^{-2}s^{-1}$ for the mechanical ventilation treatment, 9 J $m^{-2}s^{-1}$ for the whitening treatment and 21 J $m^{-2}s^{-1}$ for the fog system treatment. The SEE values were 18, 33 and 14 J $m^{-2}s^{-1}$ for the mechanical ventilation, fogging and whitening treatments, respectively.

The application of a unique value of the A (0.36), B_d (29.44) and B_n (13.0) coefficients to the whole crop cycle of the mechanically ventilated greenhouse provided an important underestimation of the model, being also less precise to estimate the transpiration in short time intervals in the fogged greenhouse (A=0.34, B_d=26.92 and B_n=16.9). Therefore, it seems more appropriate to use different values of these coefficients for each period. This type of relationship s will have to be validated for the specific climate conditions of each area in order to achieve an acceptable precision. From the practical point of view this model could be useful to estimate the irrigation requirements of a sweet pepper crop, under the climate conditions of the Mediterranean area.

CONCLUSIONS

Although the three greenhouses were under different cooling strategies (different climate conditions) the transpiration rates per unit ground area were similar in the three greenhouses during period 1, mainly due to differences in LAI. However, the plants under the mechanical ventilation treatments experienced the higher leaf transpiration rate values (per unit leaf area), mainly due to the higher air renewal rate which propitiates the entrance of dry outside air which causes a sudden increase of VPD values. The leaf transpiration rate (per unit leaf area) decreases as the crop develops, due to the decrease of the incident radiation and VPD, to the increase of the shaded leaf area and the age of the crop. VPD set points of 1.5 kPa or lower are not advisable during the first stage of the pepper crop because they may limit transpiration.

The multiple regression model proposed explains more than 90% of the transpiration rate of the leaves in the three analyzed treatments. The use of a unique value of the model coefficients for the whole growing cycle underestimated transpiration by 18%, 10% and 6% for the greenhouses with mechanical ventilation, fogging and whitening, respectively. When different coefficients are used for the period in which the cooling systems are active and for the rest of the cycle, a higher precision is achieved. The validation has shown that the model estimates with precision the transpiration in greenhouse with the studied cooling systems. However, it would be advisable to verify this model in other crop cycles, so that its use to control irrigation in a substrate grown pepper crop can be done with maximum guarantees.

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Figures:

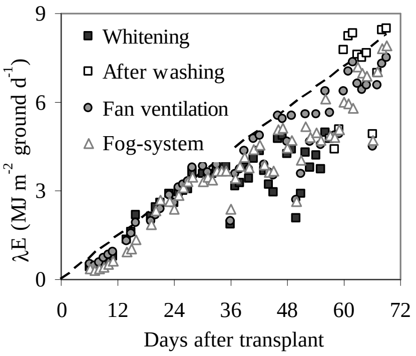

Figure 1. Evolution of the transpiration per unit soil area λE (MJ m^{-2} d^{-1}). Two different sets of data for the whitening, before and after cleaning. The straight dotted line is λE = 0.12 d.a.t.

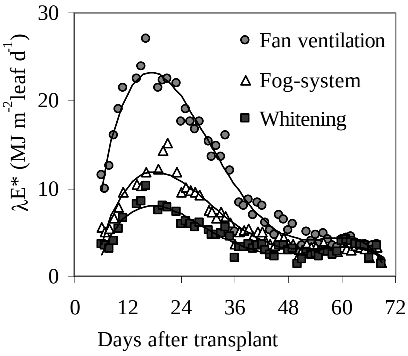

Figure 2. Evolution of the transpiration per unit leaf area, λE*. Curves are 4th order polynomials fitted to the data.

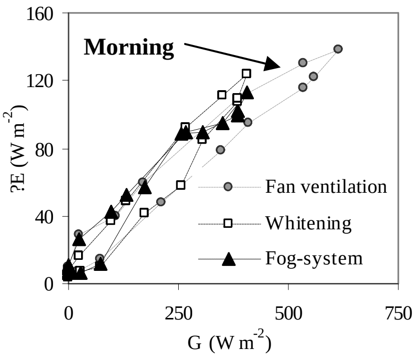

Figure 3. Comparison between transpiration rate per unit soil area (W m^{-2}) *vs* incident global radiation (W m^{-2}) 42 d.a.t., for the fan ventilation, whitening and fog–system treatments.

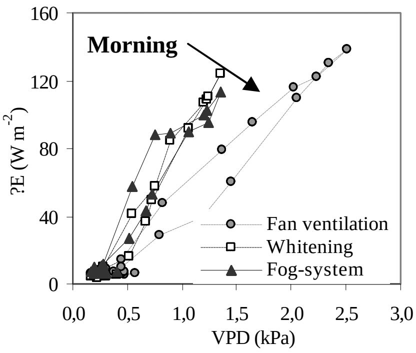

Figure 4. Comparison between transpiration rate per unit soil area (W m^{-2}) *vs* VPD (kPa) 42 d.a.t., the fan ventilation, whitening and fog–system treatments.

Table 1. Estimation of coefficients A, B_d and B_n from observations performed on different periods (the whole crop cycle and periods 1 and 2), distinguishing between day and night, for a sweet pepper crop under three different cooling strategies. R^2= determination coefficient of the coefficients (A, B_d and B_n) and of the model and n= number of observations.

			DAY				NIGHT		
Treatment	**Period**	**LAI**	**A**	**B_d** (J m^{-2} s^{-1})	**R^2**	**n**	**B_n** (J m^{-2} s^{-1})	**R^2**	**n**
Forced ventilation			0.36	29.44	90.6	1606	13.0	84.9	1733
Fog system	Crop cycle	0.5-3.5	0.35	27.92	90.6	1557	18.9	83.4	1543
Whitening	(1-229 d.a.t.)		0.29	38.56	91.1	1599	16.1	81.2	1680
Forced ventilation			0.45	47.02	93.4	850	19.9	85.2	639
Fog system	Period 1	0.5-2	0.49	27.37	92.5	806	21.2	83.0	613
Whitening	(1-58 d.a.t.)		0.53	33.55	95.0	851	16.0	76.4	609
Forced ventilation			0.35	21.89	94.6	756	12.0	78.9	1094
Fog system	Period 2	2-3.5	0.32	24.26	92.6	751	18.2	83.9	934
Whitening	(59-229 d.a.t.)		0.35	23.08	92.6	748	16.1	81.0	1071