Effects of Different Cooling Strategies on the Transpiration Rate and Conductance of Greenhouse Sweet Pepper Crops

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Abstract

This paper presents some experimental results concerning the effects of three greenhouse cooling devices (fan-ventilation, fog-system and whitening) on the crop transpiration rate and on the conductance of sweet pepper plants growing in summer (planted in July) under a semi-arid climate (Almería, South-Eastern Spain). The influence of the climatic conditions created by the cooling devices, and of the crop leaf area index (LAI), was studied and analysed. It was found that young sweet pepper plants have their own pattern of adaptation to a given cooling strategy, showing quite differentiated responses in transpiration rate and canopy conductance with respect to the prevailing greenhouse climate. The results indicated that, at the beginning of the growth cycle (LAI <1), the transpiration rate was likely to be limited by the plant root capacity to take up water. The large differences in transpiration rate per unit of leaf area can probably be ascribed to differences in the root development and partitioning of assimilates between the root system and the aerial part of the plants. The differences in transpiration rate and conductance between treatments progressively decreased as the crop developed, indicating that the crop was taking more control over the climate with increasing LAI. For LAI >2, the cooling devices appeared to have a rather limited influence on greenhouse climate and on crop gas exchanges.

INTRODUCTION

The main objectives of greenhouses are to maintain adequate environmental conditions for plant growth and development. This requires the simultaneous control of several environmental variables, including air temperature, humidity and CO_2 concentration, as well as solar radiation and soil-related factors. The need of a multivariable control strategy leads to a high level of complexity in the search and design for a *bio-climatic* greenhouse and its associated climate control system, which can satisfy all year-round the physiological requirements of a given species. Researchers and growers are now aware that greenhouse structures and equipment must be specifically designed, by taking into account local climatic conditions and plant requirements (Seginer, 2002). In Mediterranean countries, the great challenge concerns climate control during the warm season (Baille et al., 2001; Katsoulas et al., 2001). Cooling the greenhouse air is an important issue for greenhouse operators during the warmest months, because the climatic conditions potentially limit crop yield and quality and constrain benefits. The challenge consists in adapting and improving the greenhouse structure and equipment, and in skilfully managing the different components of the production system (climate, crop, irrigation...).

The present paper describes with the evaluation of three different cooling systems as a means of alleviating the harsh climate conditions prevailing during summer in Mediterranean greenhouses. Special focus was devoted to the characterisation and analysis of the effects of the cooling systems on transpiration rate and plant temperature during the period corresponding to the establishment of the crop, when the leaf area index is low and the contribution of the crop transpiration to greenhouse cooling is small.

MATERIALS AND METHODS

Greenhouse and climate control devices

The experiments were carried out in three multi-span experimental plastic-covered greenhouse, 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 eave, 4.5 m height at the ridge, total width 22.5 m, total length 28 m, ground area 630 m^2, volume 2,923 m^3. The three cooling systems were:

- Forced ventilation, greenhouse C1, with three fans located at the eastern gable, at 3 m height, and the entrance in the opposite gable. 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 its maximum aperture and the side vents were closed.
- Natural ventilation with evaporative cooling, greenhouse C2, (high-pressure water misting system). The set point of the air vapour pressure deficit, VPD, was fixed at 1.5 kPa.
- Natural ventilation plus whitening, greenhouse C3, (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 17.

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

Crop and cultural practices

The rows of sweet peppers (cv. Melchor) were planted on 21 July 2004 in containers (40 L volume) filled with perlite. Plant density was 2.97 plants m^{-2}. The distance between rows was 1.60 m, and the distance between plants was 0.21 m. Water and fertilisers were supplied by means of a drip system which was automatically controlled by a fertirrigation computer. The plants were managed following the “trellis” technique, which consists of keeping two main stems per plant and pruning all axillary shoots.

Measurements

The relevant climatic variables were continuously monitored outside and inside the three greenhouses. Air temperature, T_a (ºC), and VPD, Da (kPa), were measured by aspirated psychrometers, located 1.5 m above ground, and solar radiation, R_s (W m^{-2}) by a solarimeter. The accuracy of the temperature, DPV, Da and radiation measurements was ± 0.2ºC, ± 0.04 kPa and ± 5 W m^{-2}, respectively. The transpiration rate (E, g m_{ground}^{-2}) was obtained using of a weighing lysimeter located in a central row of each greenhouse. The device included an electronic balance (KCC150, Mettler Toledo GmbH, Germany) with scale capacity 150 kg and resolution of ±1 g. The balance was equipped with a tray carrying six plants, and an independent system of water supply and drainage. Leaf temperature was measured in different leaf layers on two plants in each compartment by means of fine wire Pt-100 inserted in the abaxial side of the leaves (8 per plant, 4 located in the basal leaves and 4 in the top leaves). The average value of the 8 leaf temperatures was considered representative of the canopy temperature, T_c. The data were sampled at 1 minute intervals, and averaged over 5 minutes by a data logger (HP3497 A, Hewlett Packard, USA).

Data treatment

The following variables were calculated at an hourly and daily (24 h) scale:

- The canopy-to-air temperature difference, $\Delta T_c = T_c - T_a$:
- The canopy-to-air vapour pressure deficit, D_c (kPa)
- The latent heat flux of transpiration per unit ground, λE (W m_{ground}^{-2}) and per unit of leaf area, $\lambda E^* = \lambda E/LAI$, W m_{leaf}^{-2}, LAI being the leaf area index ($m_{leaf}^{2}\ m_{ground}^{-2}$)
- The total canopy resistance, g_t (mm s^{-1}), was calculated directly from the transpiration data from:

$$\lambda E^* = \frac{\rho C_p}{\gamma} g_t\, D_c \qquad (1)$$

and the canopy stomatal conductance per unit of leaf area, g_s, was estimated from:

$$1/g_s = 1/g_t - 1/g_a \qquad (2)$$

where g_a (mm s^{-1}) is the canopy aerodynamic conductance. In the fan-ventilated compartment (C1), g_a was assumed to be constant and equal to 30 mm s^{-1}, and in the compartments with natural ventilation (C2 with fog-system, and C3 with roof whitening) g_a was taken equal to 20 and 16 mm s^{-1}, respectively (Kittas et al., 2001). During the period without ventilation (night), g_a was taken equal to 8 mm s^{-1} in the three compartments.

RESULTS AND DISCUSSION

Transpiration Rate

The values of the crop LAI under the three compartments were very different at the beginning of the crop cycle. On August 16 (corresponding to 30 days after transplant, (30 DAT)), the LAI was 0.18, 0.31 and 0.54 in the compartments C1, C2 and C3, respectively. The differences in LAI were still substantial until DAT = 50 (0.84, 1.16 and 1.37, respectively), but decreased progressively until 80 DAT, when all the crops reached a LAI value close to 2.2.

These differences in LAI were not reflected in the transpiration rate. The three crops presented a rather similar evolution of the transpiration flux referred to unit ground area, λE, throughout the day (Fig. 1a), with peak values at noon of about 80 W m_{ground}^{-2} on 30 DAT. This means that the evaporative cooling effect of the crop on the greenhouse atmosphere was similar in absolute magnitude under the three treatments. This explains why the compartment with the lowest radiation load (C3) and that provided with the evaporative cooling system (C2) presented lower air temperature and VPD than the compartment equipped with fan-ventilation, C1 (data not shown). On the other hand, the transpiration rate per unit of leaf area, λE^*, was much higher under the fan-ventilated greenhouse than under the other two greenhouses (Fig.1 b). The amount of latent energy released by the crop in C1 at 30 DAT was about 400 W m_{leaf}^{-2} near noon (i.e., similar to the radiation load, R_s). This amount was much higher than the corresponding values observed for the crops growing in C2 and C3 (250 W m_{leaf}^{-2} and 200 W m_{leaf}^{-2}, respectively). This behaviour can be ascribed to a substantial increase of the evaporative demand experienced by the crop in C1, mainly induced by the aerodynamic component which was enhanced by air velocity and higher VPD than in the greenhouses C2 and C3.

Figure 2 presents the evolution of the ratio of the daily integrated values of λE and R_s (both expressed in MJ m^{-2} d^{-1}) during the period 1-70 DAT. It can be seen that under C3 the ratio $\lambda E/R_s$ is significantly higher than under C1 and C2. The sharp decrease observed for C3 on 30 DAT was due to a strong rainfall which washed away part of the roof whitening. At 70 DAT, the three greenhouses presented similar values of $\lambda E/R_s$ close to 0.60, and therefore, had the same transpirational cooling effect at that time. The evolution of the daily transpiration rate *vs* DAT for the three crops is given in Fig. 3. It can be seen that the increase of λE with time is sustained throughout the considered period (1-70 DAT) and did not seem to have reached a clear plateau by 70 DAT. At that time, the maximum rate of transpiration was near 8 to 9 MJ m^{-2} d^{-1}, i.e. 3 to 3.5 mm d^{-1} in the three greenhouses.

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}, which was approximated by the simple relationship:

$$\lambda E_{max} = 0.12\ \mathrm{DAT} \qquad (3)$$

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 analysis of the time pattern of the daily integrated transpiration per unit leaf area, λE^* (Fig. 4) revealed some interesting traits of the crops 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 crops, with a rapid increase from planting until 20 DAT, 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 greenhouse C1, 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 C2 and C3, respectively. These values can be considered as indicative of the maximum daily transpiration rate per unit leaf area, λE^*_M.

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 20 DAT, thus leading to a strong decrease in the transpiration rate per unit leaf area.

The explanation for the large difference found in the maximum values of λE^* at 20 DAT is probably due to a different capacity of the roots system to uptake water. The recently transplanted plants have to develop a root system allowing the plant to match the climatic demand. The latter was much higher in the fan-ventilated greenhouse, C1, than in greenhouses C2 and C3. Therefore, the sweet pepper plants growing in C1 might have given a priority to the development of a strong and efficient root system, to the detriment of the aerial part. On the other hand, under conditions of the lower climatic demand in C2 and C3, the development of the root and aerial parts appeared to be more balanced, leading to LAI values which were twice or more than that observed in C1. This explanation is supported by the data given in Fig. 3, which indicate that the plants were transpiring a similar amount of water per unit ground area, i.e., *per plant*, whatever the cooling device. At 20 DAT, the crop in C1 had a LAI (=0.1) and a transpiration rate (λE^*_M = 28 MJ m_{leaf}^{-2} d^{-1}) which were, respectively, three times lower and three times higher that the corresponding values measured for the crop in C3. It should be stressed that λE^*_M in C1 was of the same order of magnitude as the outside solar radiation, and 50% higher than the incident solar radiation in C1.

Canopy-to-air Temperature Difference

The canopy-to-air temperature difference ΔT_c, considered as an indicator of the stress conditions experienced by the crop (e.g. Idso and Jackson, 1981), exhibited marked differences between the three greenhouses. The results obtained during the most critical period (1-30 DAT, corresponding to the initial development stage with low LAI, Fig. 5a) indicated that the plants under a dry atmosphere (fan-ventilated and whitening) maintain more negative values of ΔT_c than those subjected to a moist atmosphere (fog-system). In the latter greenhouse, periods with positive values of ΔT_c were rather frequent, especially during the morning. As observed for the transpiration rate, the differences in ΔT_c between treatments diminished progressively with increasing LAI, leading to rather comparable values and time-patterns after 60 DAT (Fig. 4b).

Canopy Conductance

During the first month after planting, the values of the stomatal conductance were higher in greenhouse C2 (fog system) than in greenhouses C1 and C3 (Fig. 6a), indicating that the stomata responded mainly to VPD when the LAI was small. The maximum values of g_c and $g_{c,M}$, were about 25 mm s^{-1} in C2 and about 15 mm s^{-1} in C1 and in C3. These maximum values decreased with time, as illustrated in Fig. 6b (62 DAT). The decrease was substantial for the crops growing in C1 ($g_{c,M} \approx$ 8 mm s^{-1}) and in C2 ($g_{c,M} \approx$ 10 mm s^{-1}), but was less marked for the crop in C3; the latter reaching the highest value of $g_{c,M}$ ($g_{c,M} \approx$ 12 mm s^{-1}). The general decreasing trend of $g_{c,M}$ with time can be due to leaves ageing and to the fact that the surface of sunlit leaves (with higher $g_{c,M}$) decreased with increasing LAI.

A general feature that can be drawn from the above results is that the differences between treatments were very marked when LAI was small, and progressively vanished with time and increasing LAI. When LAI was about 2 (≈ 70 DAT), all the climate and plant variables were similar under the three treatments, indicating that the crop was taking more control over the climate. For LAI >2, the cooling devices appeared to have a rather limited influence on greenhouse climate and on crop gas exchanges.

CONCLUSIONS

The general conclusions from this comparative study are:

1– The results suggest that young sweet pepper plants growing under three contrasting climate conditions probably differed in their maximum capacity for water uptake by the root system, compensating a lower LAI (fan-ventilated compartment) by a higher potential water uptake by the root system.

2– Sweet pepper appears to be a species capable of maintaining high transpiration rates under conditions of high radiation loads associated with high VPD and temperature.

3– Forced ventilation is the cooling system which creates the least favourable conditions for a young sweet pepper crop growing in South-Eastern Spain during the warmest month.

4– Evaporative cooling is the most efficient system for decreasing air temperature and VPD, but the least efficient reducing canopy temperature.

5– Shading appears to be the most suitable method for alleviating the stress conditions of young sweet pepper crops in Mediterranean greenhouses.

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Figures

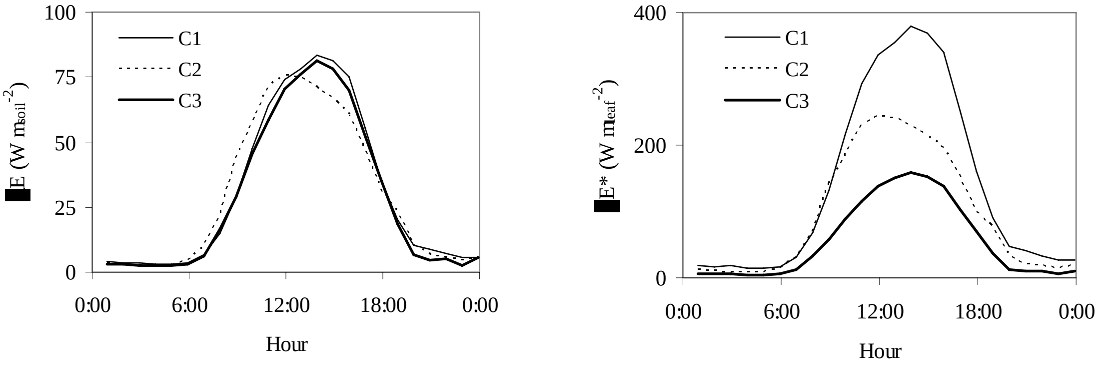

Fig. 1. Daily evolution of the hourly transpiration flux (left) per unit of ground area, λE, and (right) per unit of leaf area, λE*. Data of 16 August 2004 (26 DAT). C1, fan-ventilation; C2, fog-system; C3, whitening.

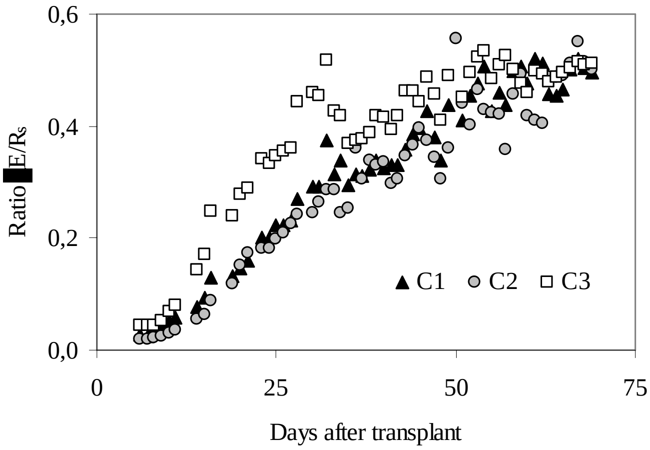

Fig. 2. Evolution of the ratio λE/R_s during the period 1-70 DAT. C1, fan-ventilation; C2, fog-system; C3, whitening.

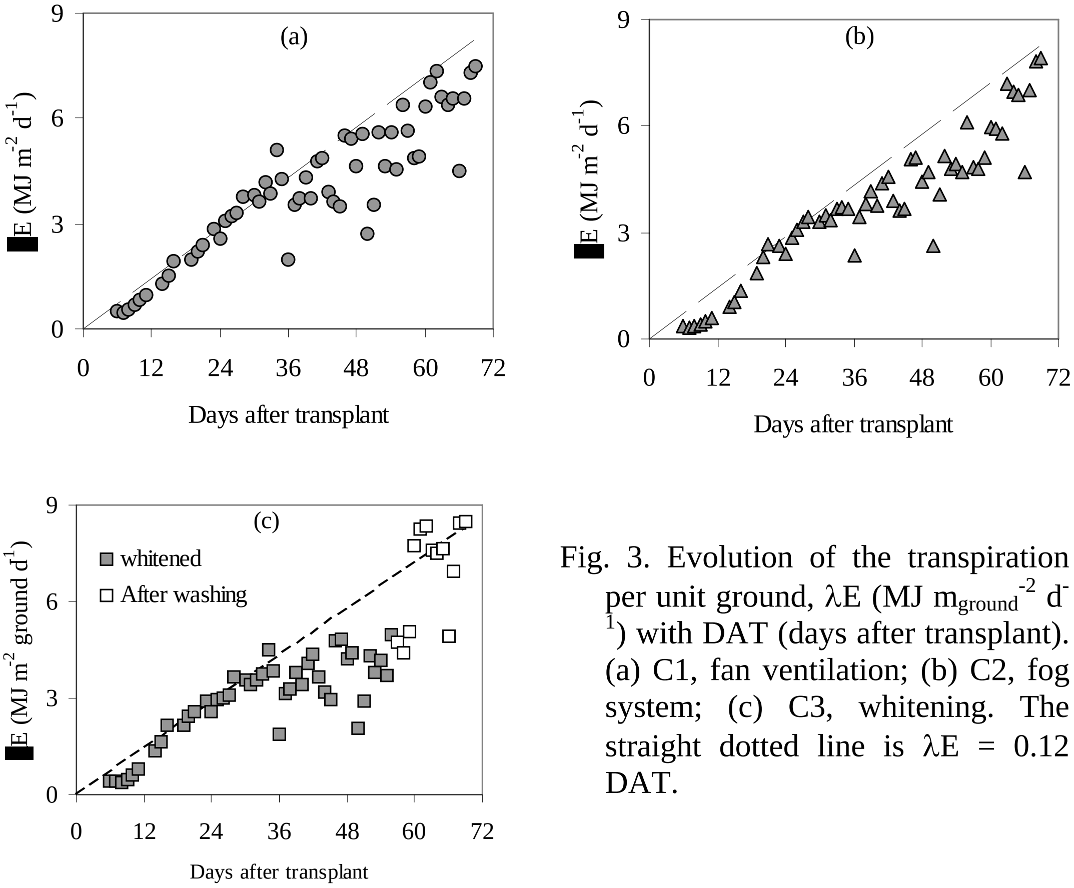

Fig. 3. Evolution of the transpiration per unit ground, λE (MJ m_{ground}^{-2} d^{-1}) with DAT (days after transplant). (a) C1, fan ventilation; (b) C2, fog system; (c) C3, whitening. The straight dotted line is λE = 0.12 DAT.

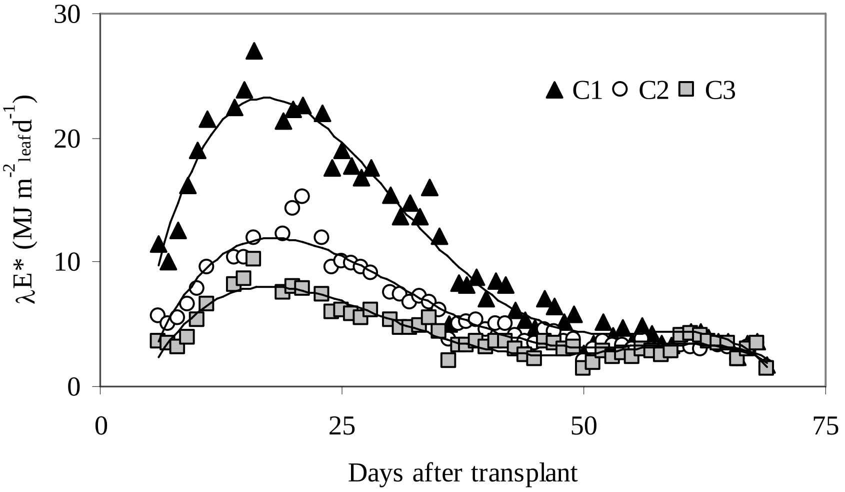

Fig. 4. Evolution of the transpiration flux, λE*, per unit of leaf area with DAT. C1, fan-ventilation; C2, fog-system; C3, whitening. Curves are 4th order polynomials fitted to the data.

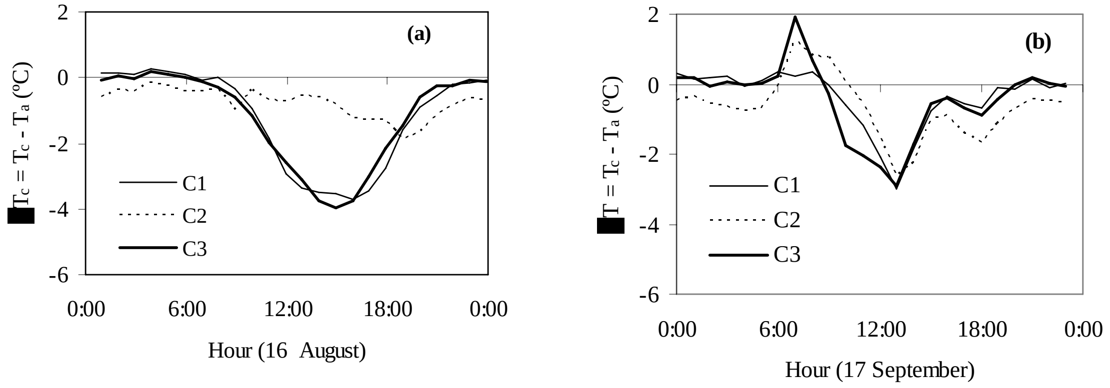

Fig. 5. Hourly evolution of the canopy-to-air temperature difference (a) at 26 DAT, and (b) at 58 DAT. C1, fan-ventilation; C2, fogging-system; C3, whitening.

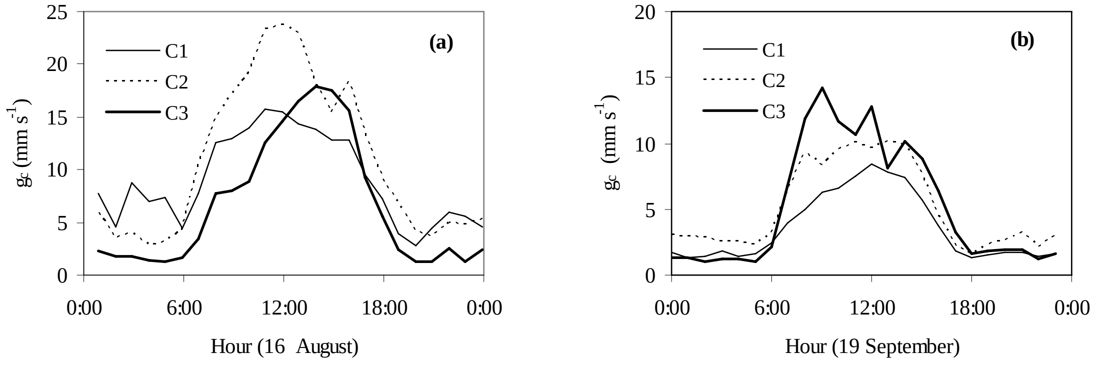

Fig. 6. Hourly evolution of the canopy stomatal conductance, g_c, (a) at 26 DAT, and (b) at 60 DAT. C1, fan-ventilation; C2, fogging-system; C3, whitening.