Crop-Climate Coupling in Greenhouses. Characterization and Analysis

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Abstract
The present work analyses the degree of coupling between a greenhouse rose crop and the internal climate as a function of crop characteristics (leaf area index, LAI) and greenhouse climate functions (natural and forced ventilation, fogging) through the determination of the decoupling factor, $\Omega$. The study was conducted during summer periods, in the Eastern coast of Greece. It was found that the maximum values of $\Omega$ generally occur near midday, being about 0.30 when forced ventilation was operating and about 0.40 when natural ventilation was used. Slightly higher values were found when the fog system was operating. Increasing LAI also increased the value of $\Omega$. It was evidenced that the actual transpiration rate was closely correlated to the vapour pressure deficit. As main conclusions of this study, it should be pointed out that (i) none of the control equipment used during this study was able to reach values of $\Omega$ greater than 0.50 for LAI = 2, suggesting a relatively tight control of transpiration rate by the crop itself during most of the day and (ii) the aerodynamic term of the PM equation is by far the major component determining the intensity of vapour exchanges between the internal air and the canopy in the conditions of the experiments.

INTRODUCTION
The ability to exchange water vapour between a canopy and the atmosphere can be evaluated through the concept of coupling between the two components (McNaughton and Jarvis, 1983; Hsiao, 1990). The degree of coupling, by affecting the conditions at the canopy surface, characterizes the extent to which stomata control transpiration and CO$_2$ assimilation. The “decoupling factor” $\Omega$ was proposed by McNaughton and Jarvis (1983), for quantifying the degree of stomatal control, at the leaf scale as well as at the canopy scale. As pointed out by Jarvis (1985), this concept may be useful when comparing different types of vegetation or agricultural systems, and in particular, greenhouses vs. open fields. Concerning the latter, several studies are available that have characterized and analysed the degree of coupling for different types of vegetation (e.g. Steduto and Hsiao, 1998, for maize). However, until now, little attention was devoted to quantifying and analysing the degree of coupling between the canopy, the internal atmosphere and the outside climate in greenhouse crops. From theoretical considerations, some authors have suggested that crops growing in climate-controlled greenhouse were not, or very weakly, coupled with the external climate, due to the presence of the greenhouse covering and to the influence of the climate control system, which counteract and damp the effects of any external perturbations. In this way, it is worth mentioning the work of Aubinet et al. (1986), based on a theoretical analysis of the different feedback loops existing between the canopy and the greenhouse climate, determining an environmental gain, $C$, that can be related in some way to the decoupling factor. Their study highlighted the fact that the negative “hydraulic” feedback existing between the transpiration rate and the water content of the greenhouse air, which does not occur in the open field, giving a unique characteristic of the greenhouse ecosystem. This feedback appears to play the most
important role in determining the degree of coupling between the canopy and the internal climate.

The objectives of this paper are (i) to derive the values of $\Omega$ for a greenhouse rose crop, from experimental determinations of the aerodynamic and bulk canopy conductances and (ii) to analyze the extent to which the crop controls the gaseous exchanges under different climate conditions and canopy developments.

MATERIALS AND METHODS

Greenhouse and Climate Control Devices

The experiments were carried out in a 200 m² experimental glass-covered greenhouse, N-S oriented, located near Volos, (Lat. 39° 44') on the coastal area of Eastern Greece. The geometrical characteristics of the greenhouse were: eaves height 2.9 m, span angle 20°, total width 6.5 m, total length 31 m, ground area 200 m², volume 690 m³. The climate was controlled by either:

- natural ventilation (continuous roof vents).
- forced ventilation, with two pairs of fans, one pair in each gable. The airflow rate for each fan was 4000 m³ h⁻¹. When the fan assisted system was operating, the roof vents were opened to their maximum value.
- natural ventilation associated with evaporative cooling (high-pressure water misting system). During operation of the mist-system the roof vent was opened to about 20% of its maximum aperture.

Crop and Cultural Practices

The rose crop (cv. First Red) was planted on March 1997 in rows of containers (1 m in length and 0.3 m width) filled with perlite and the plant density was 6 plants m⁻². The distance between rows was 1 m. Water and fertilisers were supplied every hour from 6:00 to 21:00 via a drip-system, which was automatically controlled by a fertigation computer. No irrigation water was supplied to the crop during the night. The plants were grown following the “bending” technique, which consists in bending the stems that are not considered useful to flower production. During the period of measurements, the area of ground covered by the crop was about 100 m², thus giving a ratio of 0.5 for the fraction of soil covered by the crop.

Measurements

Measurements of the relevant climatic variables (air temperature with Pt-sensors, and vapour pressure deficit), average canopy temperature, transpiration rate and intercepted net radiation were continuously monitored. Accuracy of temperature, VPD and radiation measurements was ±0.2°C, ±0.04 kPa and ±5 W m⁻², respectively. Transpiration rate was measured every ten minutes by means of a weighing lysimeter located in a central row of the greenhouse compartment. The device included an electronic balance with scale capacity 12.1 kg and resolution ±0.1 g (corresponding to an error of ±5% in the lower range of transpiration rates) equipped with a tray carrying two plants, and an independent system of water supply and drainage. Data were sampled at a 1 minute interval, and averaged over 10 minutes by means of a data logger (Delta T Devices).

Determination of the Decoupling Factors

From the above measurements, and using the big leaf concept (Monteith, 1973), the aerodynamic canopy conductance, $g_a$ (mm s⁻¹) and the bulk stomatal canopy conductance, $g_c$ were derived (Katsoulas et al., 2000; Kittas et al., 2001). These conductances to water vapour transfer characterize the ability of the canopy to exchange water vapour with the air surrounding the canopy. Coupling between the canopy and the inside air was analysed using the corresponding values of the $\Omega$ factor (decoupling factor), calculated from the values of $g_a$ and $g_c$ as described in the following.
The starting point for the coupling analysis is the Penman-Monteith (PM) equation (Monteith, 1973):

\[ \lambda E = \frac{\Delta R_{n,i} + \rho C_p g_a D_i}{\Delta + \gamma (1 + g_a/g_c)} \]  

(1)

where \( \lambda E \) is the transpiration rate (W m\(^{-2}\) of covered ground), \( R_{n,i} \) the intercepted net radiation (W m\(^{-2}\)), \( D_i \) the indoor vapour pressure deficit (kPa), \( \gamma \) the psychrometric constant (kPa \(^\circ\mathrm{C}^{-1}\)) and \( \Delta \) the slope of the saturation vapour pressure curve (kPa \(^\circ\mathrm{C}^{-1}\)) at indoor temperature, \( T_i \). By taking limits of Eqn (1) for \( g_a \) tending to zero, and to infinity, one obtains, respectively:

\[ \lim_{g_a \to 0} \lambda E = \frac{\Delta R_{n,i}}{\Delta + \gamma} \]  

(2)

\[ \lim_{g_a \to \infty} \lambda E = \frac{\rho C_p g_c D_i}{\gamma} \]  

(3)

McNaughton and Jarvis (1983) defined the decoupling factor (\( \Omega \)) as:

\[ \Omega = \frac{\varepsilon}{1 + g_a/g_c} \]  

(4)

where \( \varepsilon = (\Delta + \gamma)/\gamma \). The limit for \( \lambda E \) as \( g_a \to 0 \) (\( \Omega \to 1 \)) is known as the equilibrium evaporation (\( \lambda E_{eq} \)), which depends only on the available radiative energy. The limit for \( \lambda E \) as \( g_a \to \infty \) (\( \Omega \to 0 \)) is known as imposed evaporation (\( \lambda E_{imp} \)). The PM equation becomes:

\[ \lambda E = \Omega \lambda E_{eq} + (1-\Omega) \lambda E_{imp} \]  

(5)

The value of \( \Omega \), ranging from 0 to 1, indicates the relative importance of \( \lambda E_{eq} \) versus \( \lambda E_{imp} \) in determining the actual transpiration \( \lambda E \). It also indicates the extent to which canopy conductance controls transpiration, in as much as the value of \( \Omega \) reflects the importance of \( g_a \) relative to \( g_c \).

**Data Sets**

The case studies presented below were obtained in the summer months of 1998 and 1999, during which various types of control systems were used for whole day. The selected days present similar outside conditions: sunny days with moderate wind speed (about 2 to 2.5 m s\(^{-1}\) on average, measured at 2 m above the greenhouse), maximum outside air temperature between 28-30\(^\circ\mathrm{C}\) and maximum VPD between 2.0 to 2.5 kPa. In the analysis, the following case studies are presented:

- natural ventilation (16 July 99): the greenhouse climate was controlled only by natural ventilation (with 100% roof opening most of the day)
- forced ventilation (8 August 99), during which the fan ventilation was operating the whole day;
- fogging (5 August 99), during which the fog system was operating from 9h to 19 h, with roof opening varying within 10 and 20%.

In the three cases, measurements were carried out after the greenhouse was whitened (about 40% reduction in global greenhouse transmission) and the crop LAI was 2.2. The calculation of the crop water stress index, CWSI (Jackson et al., 1986; Katsoulas et al., 2001) showed that the crop was mildly stressed during this period of August 99 (CWSI ≈ 0.5). In order to study the effect of LAI, a sunny day of summer 98 (14 July, \( LAI = 4.2 \), forced ventilation) was compared to the day 8 August 1999 (\( LAI = 2.2 \), forced ventilation).

In the following, the values of \( g_a \) were considered as constant during the whole day for a determined control system, and calculated as the slope of the relationship between the sensible heat flux \( H_s \) and the canopy to air temperature difference, \( \Delta T_c \).
(Katsoulas et al., 2001). Generally, the variation of the 30 min average were within ± 15% of the average values in the case of forced ventilation and fog system, and ± 25% in the case of natural ventilation, for which the effects of wind speed and direction are an important source of variability. Values of $g_a$ used in this study are given Table 1. It should be kept in mind that values of $g_a$ and $g_c$ include implicitly the effect of the canopy LAI.

RESULTS AND DISCUSSION

Comparison Natural – Forced Ventilation

Figure 1 presents the daytime evolution of $\Omega$ for natural ventilation and forced ventilation. The order of magnitude of $\Omega$ are similar, reaching a maximum of 0.3 for forced ventilation, and 0.4 for natural ventilation, i.e., the crop is rather well-coupled with the internal atmosphere, and more tightly in the case of forced ventilation. The values of $\Omega$ are very similar during the morning in both cases, due to the fact that the ratio $g_c/g_e$ is nearly identical. The higher $g_c$ prevailing with forced ventilation is accompanied by an equal relative increase in $g_e$ with respect to natural ventilation. In the afternoon, when VPD reaches high values, the stomatal conductance is similar in both cases, explaining the lower $\Omega$ values (i.e. higher coupling) observed under the forced ventilation regime.

The values of $\lambda E_{eq}$ and $\lambda E_{imp}$ are also relatively similar in both cases. Figure 2, presents the evolution of $\lambda E$, $\lambda E_{eq}$ and $\lambda E_{imp}$ in the case of natural ventilation. It can be seen that the imposed transpiration rate is significantly higher than the equilibrium component. As the value of $\Omega$ is relatively low, this explains why the actual transpiration rate, $\lambda E$, follows closely the imposed transpiration, $\lambda E_{imp}$.

Comparison Fogging – Natural Ventilation

Figure 3 presents the daytime evolution of $\Omega$ in the case of fogging, and its comparison with the case of natural ventilation. The maximum value of $\Omega$ occurred near midday, reaching a value near 0.50, which indicates that, with respect to natural ventilation, fogging decreases slightly the degree of coupling between the crop and the internal climate. Both $g_a$ and $g_c$ were increased when the fog system was operating, $g_c$ being more responsive than $g_a$ (Katsoulas et al., 2001). On the whole, the degree of coupling is still significant. Although fogging reduces considerably the air VPD, the imposed term is still the predominant one with respect to the equilibrium component (Figure 4). This is because fogging increases significantly the canopy stomatal conductance, therefore compensating for the decrease in VPD. As for the previous cases (Figure 2), the actual transpiration rate, $\lambda E$, follows rather closely the imposed transpiration, $\lambda E_{imp}$.

Effect of LAI on Coupling

An increase in LAI induces a decrease in the degree of coupling, as shown in Figure 5. The main cause of this behaviour is that canopy stomatal conductance increases proportionally more than the aerodynamic conductance when LAI increases, as the increase in $g_c$ could be ascribed to two additive effects: (i) a direct one through the increase in evaporation surface (LAI) and (ii) an indirect one, through the response to the lower VPD values prevailing in a greenhouse with a high LAI crop. Figure 6 confirms this statement: the imposed transpiration reached very high values ($\approx 1200 \text{ W m}^{-2}$) for $LAI = 4.2$, i.e. three times the imposed transpiration reached by the crop with $LAI = 2.2$. In other words, doubling $LAI$ from 2 to 4 induced a threefold increase in the imposed component. The abovementioned results clearly evidence the strong dependence of the actual canopy transpiration rate on the imposed transpiration, that is, the primacy of VPD and stomatal canopy conductance in determining the level of canopy transpiration rate. The reasons are (i) the relatively low values of the decoupling factor $\Omega$, giving therefore more weight to the imposed transpiration component, which is proportional to $(1 - \Omega)$, and (ii) the high values of indoor VPD, $D_i$ generally observed under Mediterranean greenhouses during summer.
Figure 7 presents the correlation obtained between the transpiration rate and the imposed transpiration for forced ventilation and fogging, and figure 8 the correlation for forced ventilation, with LAI = 4.2 and 2.2 respectively. In all cases, the correlation level was very high and quasi linear. On the opposite, correlations with the equilibrium (radiative) term are much less satisfactory, due to the hysteresis observed between actual transpiration and solar (or net) radiation (Katsoulas et al., 2001), and consequently between VPD and radiation.

From the results presented above, it appears that the hypothesis that transpiration of greenhouse crops is mainly driven by the radiative component, suggested by several authors and validated for closed or poorly ventilated greenhouses, should be revised when dealing with summer climate control or greenhouse design in warm and dry climates. The results of the present analysis clearly demonstrated that the imposed (or aerodynamic) term of the P-M equation is by far the major component of the actual transpiration rate. It should be pointed out that the results were obtained in a small glasshouse, with a relatively large portion of non-covered soil, which probably induced a strong "oasis effect", and explains the importance of the aerodynamic term.

The results of this study advocate for the use of formulas including the aerodynamic term in the estimation of the transpiration rate. In this way, it could be recommended to use preferably the dual “A-B” coefficients (Baille et al., 1994a) that allow expressing the PM equation in a simplified form:

\[ \lambda E = A R_g + B D_t \]  

(6)

where \( R_g \) is the incident global radiation on the crop. Several authors identified the values of A and B under different greenhouse operating conditions and for different species (Jolliet and Bailey, 1992; Baille et al., 1994b; Lorenzo et al., 1998), and proposed to use Eqn. 6 for estimating the crop transpiration in algorithms for climate and irrigation control. Seginer (2002) revised and analysed a large sample of A and B values given in the literature, underlining the practical interest of using standardized values of A and B for deriving the crop transpiration coefficient, \( \varepsilon \). The latter is a relevant design parameter when sizing greenhouse cooling equipment, as it allows accounting for the cooling contribution of the crop. A prerequisite to standardization would be therefore to know the order of magnitude of \( \Omega \) when using a given type of climate control device under given design climatic conditions.

Literature Cited


### Tables

Table 1. Average values of the canopy aerodynamic conductance, \( g_a \) (mm s\(^{-1}\)) corresponding to the different control systems

<table>
<thead>
<tr>
<th>LAI = 2.2</th>
<th>Natural ventilation</th>
<th>Forced ventilation</th>
<th>Fogging</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>80</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>LAI = 4.2</td>
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<td></td>
</tr>
</tbody>
</table>

### Figures

Fig. 1. Daily evolution of \( \Omega \) under natural and forced ventilation. Fitted curves are 3\(^{rd}\) order polynomials.

Fig. 2. Daily evolution of \( \lambda E \), \( \lambda E_{eq} \) and \( \lambda E_{imp} \) under natural ventilation.
Fig. 3. Daily evolution of $\Omega$ under fogging regime and comparison with natural ventilation. Fitted curves are 3rd order polynomials.

Fig. 4. Daily evolution of $\lambda E$, $\lambda E_{eq}$ and $\lambda E_{imp}$ for fogging.

Fig. 5. Daily evolution of $\Omega$ under forced ventilation regimes, for two values of LAI ($LAI = 2.2$ and $LAI = 4.2$). Fitted curves are 3rd order polynomials.

Fig. 6. Daily evolution of $\lambda E$, $\lambda E_{eq}$ and $\lambda E_{imp}$ for forced ventilation, for two values of LAI ($LAI = 2.2$ and $LAI = 4.2$).

Fig. 7. Correlation between imposed and actual transpiration under (i) forced ventilation and (ii) fogging regimes.

Fig. 8. Correlation between imposed and actual transpiration under forced ventilation, for two values of $LAI$ ($LAI = 2.2$ and $LAI = 4.2$).