ICA3-1999-10027 - HORTIMED

Deliverable 4
(draft)
CIFA & IRTA

A model to quantify the effects of climate control devices (movable shading and fogging) on water uptake.

INDEX

1.Introduction

Water is quite often a scarce natural resource in areas with warm spring and summer seasons. For this reason, there is the need to know the water consumption of greenhouse crops. A sensible use of water for irrigation requires the knowledge of crop transpiration over time intervals of a few minutes, but to determine the transpiration rate, the greenhouse microclimate has to be known (Stanghellini, 1992).

The main factors that contribute to determine the greenhouse daytime climate, the period when most transpiration takes place, are:

- Available solar radiation, which if needed may be partially reduced by shading.
- Evapotranspiration of the crop.
- Ventilation.
- Cooling by water evaporation (fogging systems, cooling system, etc.)

So, the greenhouse microclimate affects transpiration, but also transpiration has a strong effect in the internal climate. Therefore any climate control device like shading or evaporative cooling is expected to have an effect on the greenhouse climate and consequently on the transpiration rate. To study the interactions between plant response and climate, models based on the energy and mass continuity equations have been widely used.

This deliverable first presents a simplified greenhouse climate and transpiration model that is later validated by comparison with experimental measurements. The model is then incorporated in an executable Excel file that is used to make predictions of transpiration rate as a function of the external climate, leaf area index and climate control devices (shading and fogging)

2. Daytime greenhouse climate model

Since the model is aimed to study the effect of climate control devices such as shading and evaporative cooling on transpiration, and both mentioned climate control devices are used during daytime, only daytime energy and mass balances will be considered here.

For the sake of simplicity, some other assumptions have been accepted:

- The model is mono-dimensional and represents and infinitely large greenhouse.
- Air temperature and humidity are assumed to be homogeneous.
- It is a steady state model, therefore no heat capacity on any of the greenhouse elements is considered.
- Those terms of the energy and mass balances, which are less relevant for this case study, (for instance, heat transfer from the soil and water vapour condensation) are neglected. Thermal radiation heat flux is indirectly included in a global greenhouse heat transfer coefficient.
- Transpiration is the only plant physiological process that is of interest for this case, no attempt has been made to develop a complete crop model. Therefore the crop canopy is considered to be a homogeneous layer whose transpiration is calculated as explained later.

Knowing the greenhouse air and humidity as well as the available solar radiation is needed to determine transpiration rate. For this purpose, the energy balance of the greenhouse air was done. Also, the cladding properties like light transmission and reflexion determine not only the amount of light available for the plants but also the cover temperature, which also affects the greenhouse air and humidity. By doing an energy balance of the cover it is possible to incorporate in the calculations the effect of the shading screen properties (colour, percentage of shading, etc) on crop transpiration.

2.1. Energy balance for the greenhouse cover.

For the greenhouse cover it can be written,

$$G_{abs} - H_{co} - H_{ci} = 0 \ (\mathrm{W \cdot m^{-2}}) \quad (1)$$

where,

G_{abs} = Solar radiation absorbed by the cover and shading screen (if any)

$$G_{abs} = ?\, R_s \quad (2)$$

being

? = overall transmissivity of greenhouse cover to solar radiation

R_s = external solar radiation ($\mathrm{W \cdot m^{-2}}$)

H_{co}= Heat transmitted by convection from the cover to the open air

H_{ci} = Heat transmitted by convection from the cover to the greenhouse air

According to Bailey (1984),

$$H_{co} = 6.2 \cdot V_w^{0.8} \cdot (T_c - T_{out}) \ (\mathrm{W \cdot m^{-2}}) \quad (3)$$

V_w= Wind speed ($\mathrm{m \cdot s^{-1}}$)

T_c = Cover temperature (°K)

T_{out}= Outside air temperature (°K)

According to Chalabi (1989) if the greenhouse air temperature is less than that of the cover the flux is likely to be laminar. Then,

$$H_{ci} = 0.64 \cdot (T_c - T_{int})^{1.25} \ (\mathrm{W \cdot m^{-2}}) \quad (4)$$

being

T_{int} : Greenhouse air temperature (°K)

Else, if the air temperature is more than that of the cover, the flux is turbulent in most cases and,

$$H_{ci} = 1.7 \cdot (T_{int} - T_c)^{1.33} \ (\mathrm{W \cdot m^{-2}}) \quad (5)$$

2.2. Energy balance for the greenhouse air.

For the greenhouse air the energy balance states like,

$$R_{int} + H_{ci} = LE + V_{ent} + E_{vap} \quad (6)$$

Solar radiation term $\mathbf{R_{int}}$

R_{int}: Solar radiation available in the greenhouse.

$R_{int} = ?\cdot R_s\,(\mathrm{W\cdot m^{-2}})$ (7)

being:

?: greenhouse transmissivity to solar radiation.

Transpiration term, **LE**

LE: energy consumed by crop transpiration. It can be determined by using two methods:

a) The Penman-Monteith equation.

This well-known equation (Stangellini, 1987), Bakker (1991) among others, has been simplified for some greenhouse crops. For instance, for *Ficus benjamina* (Bailey *et al.*, 1993) suggested

$$LE\ ?\ \frac{R_{\mathrm{int}}\ ?\exp(0.052\ ?T_{\mathrm{int}})\ ?\ 47.5\ ?LAI\ ?3\ ?vpd\,/(d)^{1/2}}{2\cdot\exp(0.038\cdot T_{\mathrm{int}})\ ?\ 0.00262\cdot ri\,/(d)^{1/2}} \quad (8)$$

LAI : Leaf area index

vpd: greenhouse air vapour pressure deficit (kPa)

d: characteristic dimensions of the leaf (m)

$d = 2/(1/L+1/A)$ (9)

L and *A* are the length and width of the leaves (m)

r_i: crop stomatal resistance ($\mathrm{s\cdot m^{-1}}$)

for *ficus benjamina*,

$r_i = 46+54500/(55+I)$ (10)

being *I* the PAR radiation in ? E $\mathrm{m^{-2}\cdot s^{-1}}$

(Yang *et al.*, 1990) gave an expression for the stomatal resistance of a greenhouse cucumber crop,

$r_i = 142.7+953.9\ \exp(-0'0081\ R_{int})\ (\mathrm{s\cdot m^{-1}})$ (11)

Similar expressions for other greenhouse crops are available in literature

b) Empirical regressions between the transpiration rate and environmental variables

For instance, for a tomato crop Jolliet and Bailey (1992) suggested:

$Tr = 0.32\cdot R_{int} + 5.5\ vpd + 5.3\ V$ (12)

with *V* the air velocity in the greenhouse ($\mathrm{m\ s^{-1}}$)

within this Hortimed project, other empirical regressions that take into account the available solar radiation, the vapour pressure deficit and the leaf area index have been developed for several crops. These are expressions like the following one:

$LE = \mathrm{A}\ (1-\exp(-k\ LAI))\ R_{int} + \mathrm{B}\ vpd\ LAI$ (13)

where *k* is the crop extinction coefficient taken as 0.64 and A and B are coefficients of the empirical regression between the measured calculation and R_{int} and *vpd*

Ventilation term, $\mathbf{V_{ent}}$

V_{ent}: Energy exchange by ventilation or infiltration.

$$V_{ent} = ?\ \ ?\ (C_p\, T_{int} + W_{int} - Cp\, T_{out}\, W_{out}\, h_{out})\ (W\cdot m^{-2}) \tag{14}$$

? : airflow exchanged between the greenhouse and the outside air ($m^3\ s^{-1}\ m^{-2}$ of greenhouse soil surface)

?: air density (kgm^{-3})

C_p: specific heat of dry air (JKg^{-1}°K^{-1})

W_{int}, W_{out}: specific humidity of greenhouse and outside air in Kg of vapour by Kg of dry air ($kgkg^{-1}$)

h_{int}, h_{out}: enthalpy of water vapour in saturation at ambient temperature, for the internal and outside air (Jkg^{-1})

very approximately they can be calculated by:

$$h = W\,(2501+1'805\ T)\ (kJ\cdot Kg^{-1}) \tag{15}$$

where W is the specific humidity and T the air temperature (°C)

To determine the ventilation rate, the airflow exchange ? has to be modelled. For fan ventilation ? can be directly obtained from the fan curves, but for naturally ventilated greenhouses a sub model of ? is needed. For most commercial greenhouses, thermally driven ventilation can be neglected as compared to wind driven ventilation.

Most of the mathematical models that have been developed to calculate natural ventilation of greenhouse are based on both the pressure field that wind generates in the greenhouse windows as well as the resistance that the windows offers to air flow (de Jong, 1990). Research on the pressure field over the greenhouse surface has been done by several authors like (Boulard and Baille, 1995), who, for the sake of simplicity, proposed a global wind pressure coefficient that incorporated the effect of mean and turbulent pressure. Then, a simplified model of natural ventilation can be expressed by:

$$? = S/2C_d\, C_w^{\ 1/2}\, V_w \tag{16}$$

where S is the total ventilator surface of the greenhouse, C_d is the discharge coefficient of ventilators and C_w the global wind pressure coefficient.

For multi span tunnel greenhouses, Muñoz (1999) developed an expression for C_d which is a function of the ventilators aspect ratio L/H (quotient between the length and the height of the openings). He obtained a different expression for ventilators located in outer spans than for inner spans, since the vents of outer spans present less resistance to the movement of air through them.

Table 1. C_d values for different aspect ratio of the vents located in outer spans and inner spans .

L/H	13.3	16	20	26.6	40	60	80
outer	0.681	0.698	0.780	0.815	0.815	0.815	0.815
inner	0.518	0.551	0.570	0.621	0.621	0.621	0.621

For opening with flap, as ones existing in Venlo type greenhouses and in some parral type greenhouses as well, Pérez-Parra (2002) suggested to use this equation:

$$C_d = -0.206 + 0.16 \ln(?) + 0.0012\, L/H \tag{17}$$

being ? the flap opening angle.

Regarding the global wind pressure coefficient, Table 2 shows the values published by different authors for tunnel-type, Venlo-type and parral-type greenhouses. It is worthy to mention that coefficients are different according to the wind direction, either facing the openings (windward side) or in the opposite direction (leeward side).

Table 2. Global wind pressure coefficient, Cw, according to wind direction and greenhouse type .

Greenhouse type	windward	leeward
Multitunnel	0.430	0.079
Parral		
Venlo		

Evaporation term, **E_{vap}**

E_{vap}: Energy used in evaporating water given by the fog system

$$E_{vap} = M_w h_w \tag{18}$$

M_w: mass flow rate of water given by the humidifiers (kg·s^{-1}·m^{-2})

h_w: enthalpy of evaporated water (JKg^{-1}). It is determined from equation (15) for T equal to water temperature and W=1.

2.3. Mass balance for the greenhouse air

Last, the humidity in the greenhouse needs to be known to calculate some of the terms of the energy balance. For this purpose the mass balance of the greenhouse water vapour was established.

Water vapour gained by ventilation (from outside air)	-	Water vapour lost by ventilation (from inside air)	+	Water vapour added by the humidifiers	+	Water vapour added by evapo-transpiration	= ?

$$? ? \boldsymbol{(W_{out}-W_{int})+M_w+ LE/?} = \text{Ø} \tag{19}$$

? is the latent heat of evaporation for water (JKg^{-1})

If the three equations of energy balance of the cover and the greenhouse air, and the mass balance of the greenhouse air are solved simultaneously, it is possible to determine the transpiration rate as well as the greenhouse temperature and humidity as a function of the external conditions (solar radiation, open air temperature and humidity, wind speed) together with the parameters that define the greenhouse. These equations were programmed in FORTRAN language. An input needed for running the programme was the ventilation rate. For this purpose, a ventilation submodel was incorporated ina spreadsheet. It was named “AIR EXCHANGE” and will be given in the final version of this deliverable. Once ventilation was known, the programmeCLIMATE CONTROL calculated the main greenhouse climate variables, including transpiration.

3. Model Verification

A comparison of greenhouse temperature, vapour pressure deficit and transpiration rate calculated from the model and measurement taken in a real greenhouse was conducted. For this purpose, experimental data from selected days measured at CIFA (Almeria) during 2002 were used.

Data of outdoors temperature, outdoors relative humidity, solar radiation, wind speed and wind direction and greenhouse temperature and vapour pressure deficit were measured and averaged each hour. Leaf area index was measured as 2,5 for a sunny day used for comparisons.

In order to use the climate model programme, the air exchange was measured with model “air exchange”.

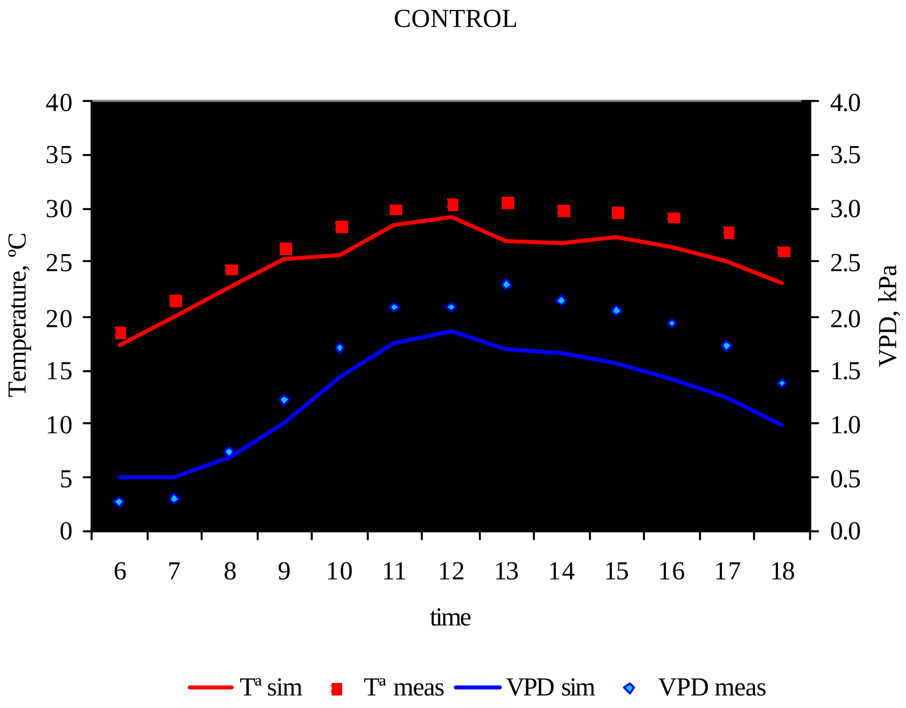


Figure 3.Simulated (line) and measured (points) temperature (red) and vapour pressure deficit (blue) in a sunnye day. Data of 1/06/2002 Almería. Spain

Figure 3 shows the measured temperatures in a sunny day of Almeria (red points) compared to the simulated temperature from the model. Estimated and measured values were closer during the morning. During the afternoon, calculated and measured values had a similar tendency, being the maximum difference of around 3°C. A possible explanation for this discrepancy is that the model does not incorporate thermal inertia effects, therefore the calculated temperature and humidity react very quickly to a change in ventilation, while the real greenhouse showed a slower response to a change in the ventilation rate. Thermal innertia effect may also be responsible for the measured increased in temperature for the afternoon hours. Also, it is worthy to mention that the model represented an infinitely large greenhouse while the experimental greenhouse had limited dimensions and may well receive an extra amount of energy from afternoon solar radiation.

Vapour pressure deficit showed better agreement during the morning. During the afternoon there was a tendency of the model to underestimate vpd. Nevertheless these differences were always below 0.5 kPa.

Figure 4 shows calculated and measured values for this day when a mobile shading screen (50% light transmission) external to the greenhouse was used. For this case, better results were achieved in predicting temperature and vapour pressure deficit than for the unshaded greenhouse.

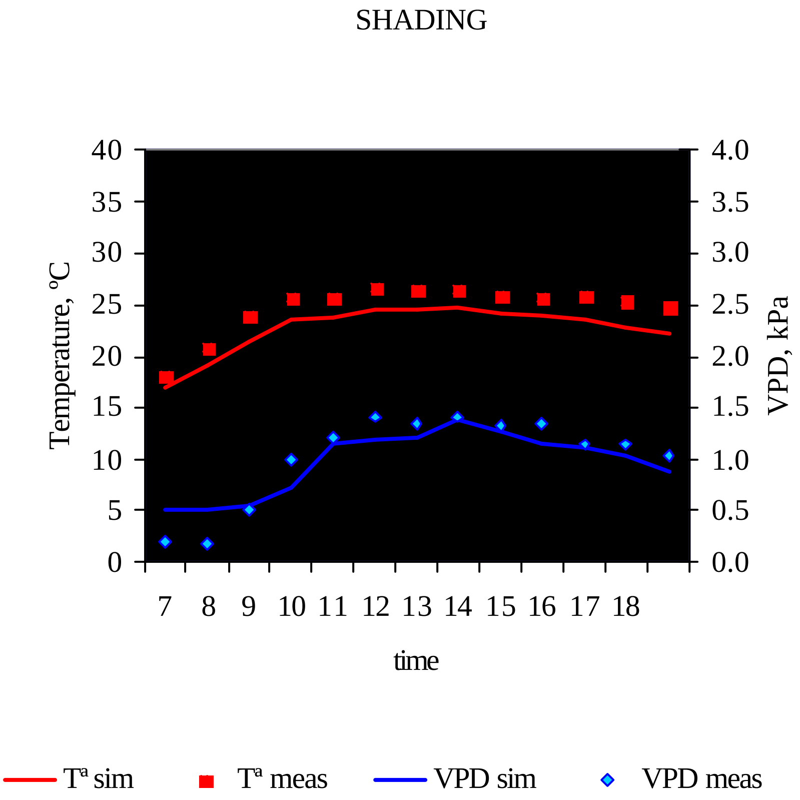


Figure 4.Estimated (line) and measured (points) temperature (red) and vapour pressure deficit (blue) in a sunny dayi a greenhouse with a mobile shade. Data of 1/06/2002 Almería. Spain.

Figures 5 a) and b) show the adjustment between measured and simulated transpiration rates for the control greenhouse with no shading (fig. 5a) and for a greenhouse with a mobile shade (fig. 5b). The slopes of the regression lines was 1.1 for both cases, but the regression coefficient was better for the control greenhouse, 0.96 versus 0.76.

A possible reason for the discrepancies found in the simulation of the greenhouse with shading could be the shading was a movable device that caused a changing percentage of light transmission, while in calculations a fixed light transmission percentage for each calculation period was assumed.

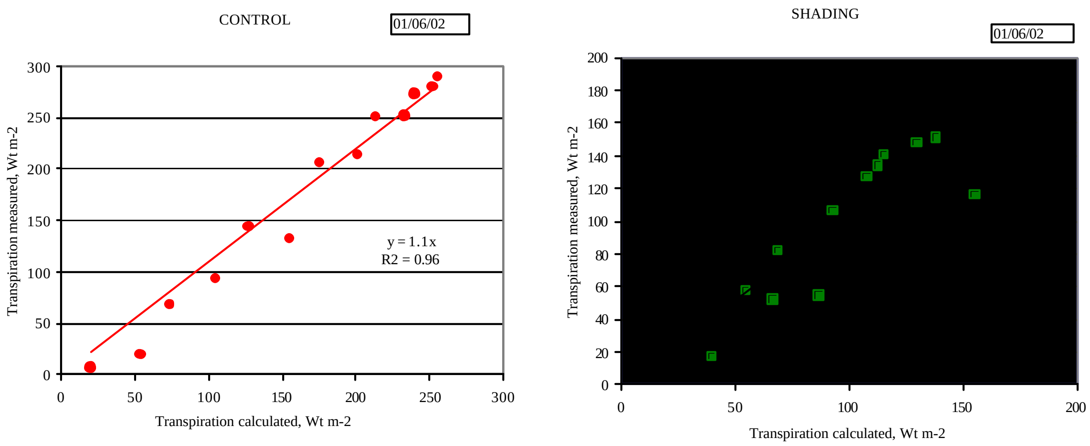


Figure 5 a) Measured and estimated transpiration for a control greenhouse and b) greenhouse with a mobile shade.

4. Model Predictions.

Once the model was validated, a series of calculations were made in order to predict greenhouse temperature and transpiration.

Figure 6 shows the temperature increase for different air exchange rates and different leaf area index. Results illustrate the importance of good ventilation, particularly when the crop canopy is not fully developed. In this case, an increase from 20 to 30 air exchanges means a decrease in temperature of 5 ºC in a sunny day. When the crop is fully developed, LAI equal to 4, the air exchange rate does not make a remarkable difference in the greenhouse temperature.

In shaded greenhouses the effect of ventilation is not so significant (figure 7). For a young crop, leaf area index equal to 1, the difference temperature between outside and inside air was 3.8 C for an air exchange rate of 16 volumes per hour. In the unshaded greenhouse these conditions lead to an increase in temperature of 17.6 ºC. It may be the case that for a fully developed crop, it could be convenient to close partially the openings in order to keep the temperature lower and the humidity higher (Fig. 7).

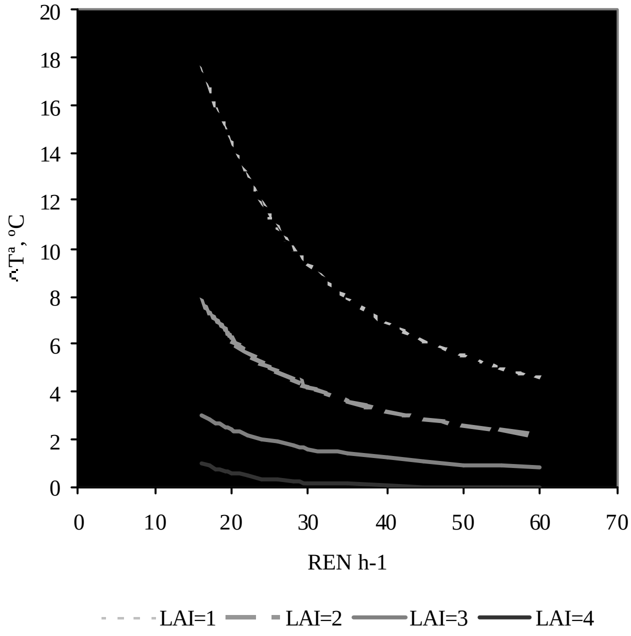


Figure 6.Temperature increase as a function of LAI and ventilation for an unshaded greenhouse.

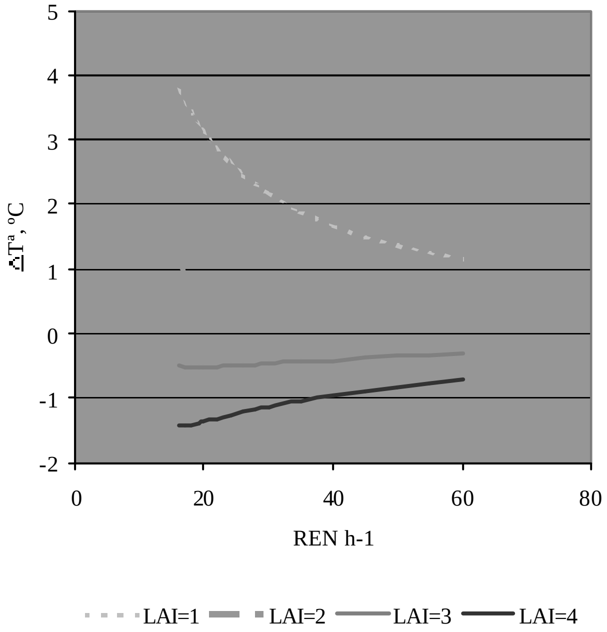


Figure 7. Temperature increase as a function of leaf area index and air exchange for a greenhouse with a mobile shade.

Transpiration was simulated to quantify the effects of tested climate control devices on water uptake. Figures 8 a) and b) represent the daily time course of transpiration for different leaf area indexes, for an unshaded greenhouse without evaporative cooling (a) and with a fog system scheduled to maintain a maximum vpd of 1.5 Kpa (b). Figure 8c) represent the greenhouse with a mobile shade and no fogging.

Shading produced a light transmission reduction that lead to a significant reduction in transpiration that can be estimated close to 50% for a sunny day (table 3). Dull days are expected to have a much lower reduction since the movable shade is expected to be folded most of the time. For the whole growing period a transpiration reduction of 33% has been previously reported in Hortimed annual reports.

Fog decreased transpiration between 11 to 50 % depending on LAI. As LAI increased the fog contribution to transpiration reduction decreased, since the humidity level in a greenhouse with fully developed crop is higher and there is less need of adding water vapour to the air. For the whole season, the ratio of T_{fog} and $T_{control}$ was measured as close to 0.85.

Table 3. Transpiration ratio of different climate devices (fogging and shading) for different LAI during sunny days.

LAI	0.5	1	2	3	4
ratio $T_{fog}/T_{control}$	0.49	0.53	0.82	0.89	0.88
ratio $T_{shade}/T_{control}$	0.50	0.49	0.47	0.48	0.49

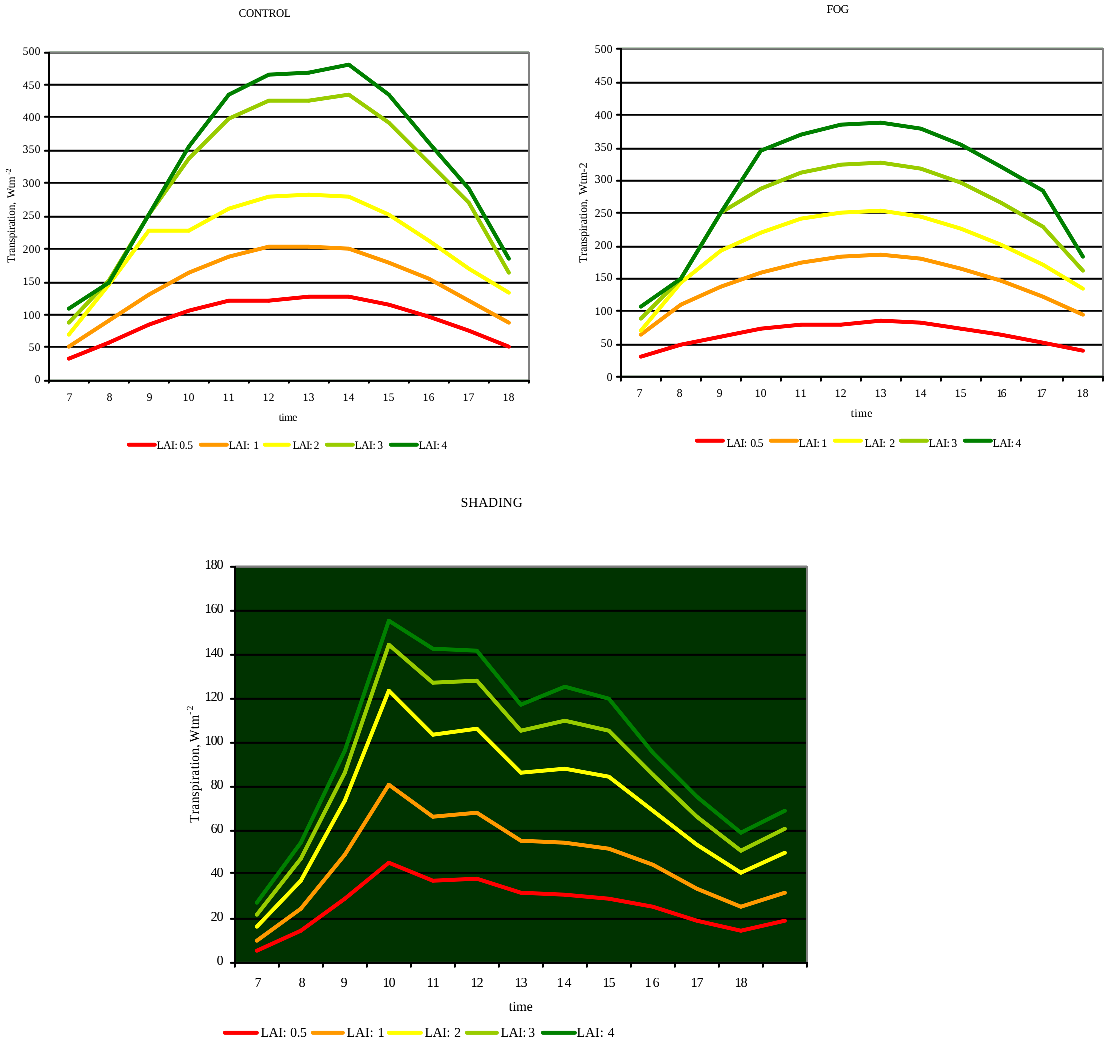
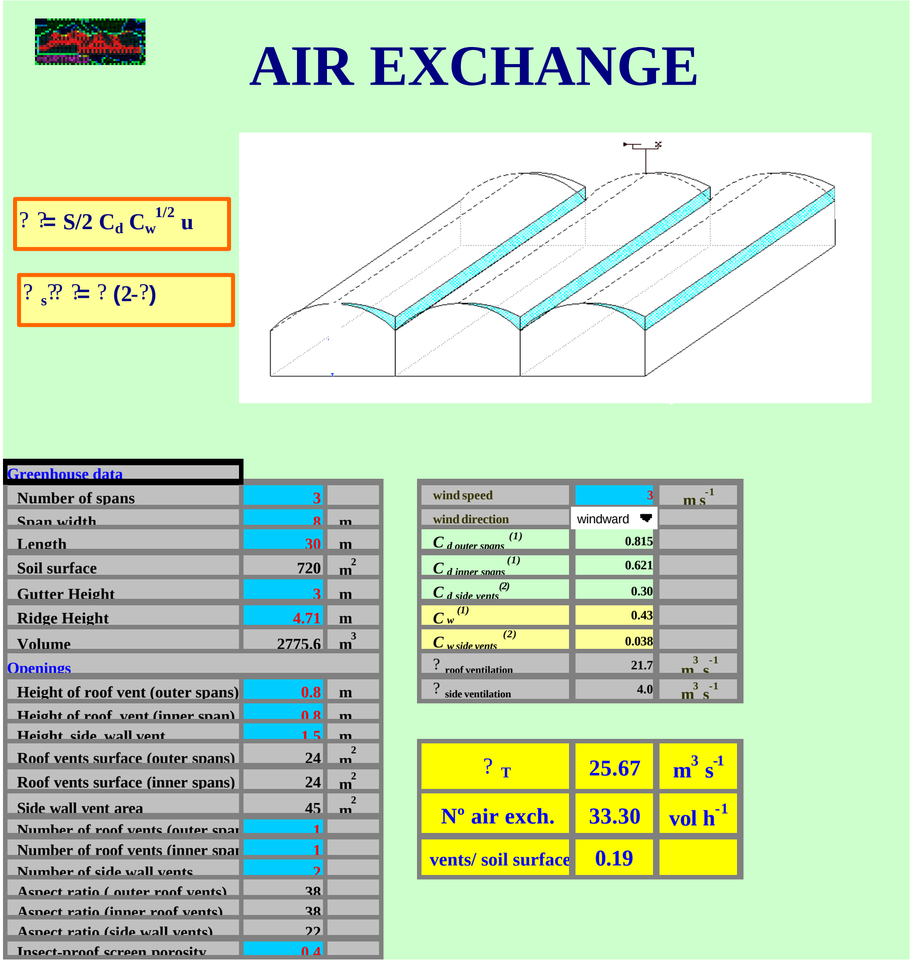


Figure 8. Hourly transpiration values for different LAI and different climate devices

1.



AIR EXCHANGE

$? \; ?= S/2 \; C_d \; C_w^{1/2} \; u$

$?_s ?? \; ?= ? \, (2-?)$

Greenhouse data

Number of spans	3	
Span width	8	m
Length	30	m
Soil surface	720	m^2
Gutter Height	3	m
Ridge Height	4.71	m
Volume	2775.6	m^3
Openings		
Height of roof vent (outer spans)	0.8	m
Height of roof vent (inner span)	0.8	m
Height side wall vent	1.5	m
Roof vents surface (outer spans)	24	m^2
Roof vents surface (inner spans)	24	m^2
Side wall vent area	45	m^2
Number of roof vents (outer spar	1	
Number of roof vents (inner spar	1	
Number of side wall vents	2	
Aspect ratio (outer roof vents)	38	
Aspect ratio (inner roof vents)	38	
Aspect ratio (side wall vents)	22	
Insect-proof screen porosity	0.4	

wind speed	3	$m\,s^{-1}$
wind direction	windward ▼	
$C_{d\ outer\ spans}$ (1)	0.815	
$C_{d\ inner\ spans}$ (1)	0.621	
$C_{d\ side\ vents}$ (2)	0.30	
C_w (1)	0.43	
$C_{w\ side\ vents}$ (2)	0.038	
$?_{roof\ ventilation}$	21.7	$m^3\,s^{-1}$
$?_{side\ ventilation}$	4.0	$m^3\,s^{-1}$

$?_T$	25.67	$m^3\,s^{-1}$
Nº air exch.	33.30	vol h^{-1}
vents/ soil surface	0.19	

Figure 9. Air exchange calculation

5. Conclusions

- Empirical regressions between the transpiration rate and environmental variables gave a good estimation of the transpiration rate. It is convenient to obtain similar regressions for different greenhouse crops.
- Air exchange differs according to the wind direction, either facing the openings (windward side) or in the opposite direction (leeward side).
- Simulations showed the importance of having good ventilation, >30 $vol{\cdot}h^{-1}$ particularly when the crop canopy is not fully developed
- In shaded greenhouse the effect of ventilation is not so significant. For a sunny day in Almeria and for a fully developed crop, it could be convenient to avoid excessive ventilation by partially closing the openings in order to keep the temperature lower and the humidity higher.
- The movable shading system achieved significant reductions in temperature, vpd and transpiration.
- Greenhouse equipped with fog systems presented better climatic conditions for similar radiation levels, but the reduction in transpiration was less than that achieved by the movable shading.

6. Recommendations for the DSS

Table 3 is a summary of the effects of fogging and 50 % shading on crop transpiration for sunny days and for different LAI. This information can be incorporated in the DSS.

A shading screen of 50% light transmission produced a transpiration reduction of 50% during sunny days. From here it can be estimated that the percentage of transpiration reduction produced by shading is similar to the percentage of shading.

Movable shades produced a seasonal light reduction lower than its percentage in light transmission. For instance, the 50% movable shading screen yielded an overall light reduction of 36% for the growing season. This gave way to an overall transpiration reduction of 33%. Therefore the DSS should consider a reduction factor of the effect of shading on transpiration when the system is mobile instead of fixed.

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