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Improving Greenhouse Microclimate Control with the Help of Plant Temperature Measurements

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IMPROVING GREENHOUSE MICROCLIMATE CONTROL WITH THE HELP OF
PLANT TEMPERATURE MEASUREMENTS

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Using plant temperature measurements to increase the efficiency of greenhouse cooling

ABSTRACT

A model of the energy balance of a transpiring crop in a greenhouse was developed in a format suitable for use in climate control algorithms aimed at dissipating excess heat during the warm periods. The model's parameters use external climatic variables as input. It incorporates radiation and convective transfer functions related to the operation of control devices like shading screens, vents, fans and enhanced evaporative cooling devices. The model identified the leaf boundary-layer resistance and the leaf stomatal and cuticular resistance as critical parameters regulating the temperature of the foliage. Special experiments evaluated these variables and established their relation to environmental factors. The research established that for heat load conditions in Mediterranean and arid climates transpiring crops maintained their foliage temperature within the range allowing high productivity. Results specify that a water supply ensuring minimum leaf resistance to remain below 100 s m^{-1} , and a ventilation rate of 30 air exchanges per hour, are the conditions needed to achieve self cooling. Two vegetable crops, tomato and sweet pepper fulfilled maintained their leaf resistance within the prescribed range at maturity, i.e., during the critical warm season. The research evaluates the effects of additional cooling obtained from wet pad systems and spray wetting of foliage.

OBJECTIVES OF THE ORIGINAL PROPOSAL

The problem of extending the greenhouse growing into the warm summer period guided the conception of the proposal. The reason for the difficulty was improper management of the climate control operations. As the research program developed, it appeared rapidly that often a few changes in the management could maintain proper growing conditions in greenhouses. Part of the experience derived from the present research, but initiatives of individual growers and extension agents were also instrumental in showing possible solutions.

The original objective was to use measurements of foliage temperature for controlling the cooling. It appeared (Chapter III) that leaf temperature has a very large spatial variability. As the model (Chapter II) showed the factors modifying leaf temperature, the study of these factors became the primary objective of the research.

The analysis deriving from the model (Chapter II) prompted the experiment on the energy balance of the empty greenhouse reported in Chapter I. This experiment did not figure in the original research plan. Yet, it revealed that the accepted understanding of the heat dissipation processes had to be revised. It suggested that surface dryness did not prevent latent heat flux since liquid water remained underneath the surface, but increased temperatures. Therefore, the study of the leaf resistance became a crucial issue in the research program. Chapter IV reports the results showing that the current practice of drip fertigation of tomato and sweet pepper is adequate for allowing self cooling of the foliage. The second objective of the proposal for improving water supply had already received an adequate solution and therefore, needed no further consideration.

The model (Chapter II) and the experiment in the empty greenhouse (Chapter I) showed the importance of the internal boundary-layer resistance in all energy exchange processes in the

greenhouse. Although the investigation of this system variable did not figure in the original research plan, its major impact on the internal microclimate induced us to devote a considerable effort to this subject. Results relevant to the report are summarized in Chapter V. Technical information regarding the theory and development of the study of leaf boundary-layer is the theme of a research thesis not yet completed.

Supplemental cooling was evaluated, though not exactly according to the original plan of the proposal. Breakdowns of the recording systems during critical experimental periods impaired the precision of the data and prevented completion of the original program. Chapter VI reports the achievements on this objective.

The original proposal assumed that the study would develop more than three years with a tomato as a model crop. A severe virus infection forced replanting the greenhouse with sweet pepper. The change delayed the program. Yet, it enhanced the practical scope of the program by showing that the results can easily extrapolate from one species or variety to another.

OTHER BENEFITS

The work on leaf temperature distribution showed the interest of thermal imaging for the study of plant water relations in open field conditions. This subject may generate new research ideas on efficient water use, and on deficit irrigation management.

The program on boundary-layer resistance and heat transfer will find applications in the study of greenhouse heating systems. It can provide objective evaluation of heating efficiency and separate between convective and radiative heat losses.

CHAPTER I

Effects of ventilation on the energy balance of a greenhouse with bare soil

Marcel Fuchs, Ehud Dayan, David Shmuel and Ytzhak Zipori

Abstract

Measurements of the radiation and the energy balances in a polyethylene greenhouse covering a bare, dry sandy soil, were used to define the heat dissipation efficiency of four ventilation methods. The 62% of downward solar radiation transmitted by the roof provided the heat load on the system. The four ventilation treatments consisted of passive ventilation obtained by rolling up opposite side walls, activating two fans mounted in one gable and opening the opposite wall, the same configuration but with a single fan, and closing completely the greenhouse. Opening opposite walls generated sufficient draft to exchange air at a rate of 44 volumes per hour. Operating one and two fans produced exchanges of 8 and 13 volumes per hour, respectively, much below the specified rating of the equipment, because of pressure losses across insect proof nets on the vents. Closing the greenhouse limited air exchange to 3 volumes per hour. External wind speed and internal buoyancy forces affected passive ventilation, but had no significant effects on active ventilation. Despite the dryness of the top layer of soil, latent heat flux remained a large term of the energy balance. High ventilation rates diminished soil heat flux, increased sensible heat flux and slightly decreased latent heat flux.

1. Introduction

The greenhouse is a growing environment that is partly separated from the surrounding climate. Its dependance on solar radiation for photosynthesis establishes a link between its internal microclimate and the outdoor atmospheric conditions. To quantify the physical modifications introduced by the structure, the cladding material and the climate control equipment, identifying parameters associated with their properties is necessary. In the energy balance equations, these parameters appear as radiometric, conductive and convective transport coefficients regulating heat absorption and dissipation. Ventilation, by modifying the heat exchange between the radiation absorbing surfaces, the internal air space and the free atmosphere, provides a means for regulating the internal microclimate. The objective of the experiment reported here is to measure the parameters affected by ventilation and to establish the efficacy of different ventilation methods.

2. Theory

a. Energy balance

Consider a greenhouse a few days after the plants have removed. The soil surface is dry and therefore evaporation or latent heat flux density E of residual moisture in the soil is slow. This condition allows for a large proportion of the solar radiation absorbed by the soil to warm the soil and the air. For steady state, the energy balance of the greenhouse reduces to:

$$R_n = E + H + G \quad (1)$$

where R_n is net radiation absorbed by the soil surface, H is the sensible heat flux density to the air and G is the heat flux density into the soil. Assuming that air exchange removes sensible and latent heat, measurements of the air temperature T_i , the water vapor pressure e_i inside the greenhouse, the air temperature T_o , and e_o the water vapor pressure outside the greenhouse, allow the air exchange resistance r_x to be derived from Eq.(2):

$$r_x = \frac{\rho c_p (T_i - T_o)}{H} = \frac{\rho c_p (e_i - e_o)}{\gamma E} \quad (2)$$

where ρ is the density of air, c_p is the specific heat of air and γ is the psychrometric constant. Eq.(2) neglects sensible heat transport through the greenhouse clad, restricting its validity to ventilated greenhouses. This approximation implies that convective and radiative transport to the free atmosphere surrounding the greenhouse dissipates completely the solar radiation absorbed by the roof. The solution of Eq.(2) involves the additional step:

$$\begin{aligned} \beta &= \frac{H}{E} = \gamma \frac{T_i - T_o}{e_i - e_o} \\ H &= \frac{\beta (R_n - G)}{1 + \beta} \\ E &= \frac{R_n - G}{1 + \beta} \end{aligned} \quad (3)$$

where β is the Bowen ratio of the energy exchange through the vents of the greenhouse. For engineering applications, expressing the ventilation rate is convenient as the number of air volumes exchanges per hour, X :

$$X = \frac{3600}{r_x Z} \quad (4)$$

where Z is the average height of the greenhouse.

With measurements of the surface temperature of the soil T_s , the internal boundary-layer resistance r_i of the bare soil can be calculated:

$$r_i = \frac{\rho c_p (T_s - T_i)}{H} \quad (5)$$

The values of these resistances for a greenhouse with a fully developed canopy will differ from those determined for an empty greenhouse because the large internal surface of the foliage exerts additional drag on the motion of air. The size of the greenhouse is another factor modifying the internal air flow because losses of pressure across fans and vents have fixed values, whereas pressure gradients depend on greenhouse dimensions. Still, experimentation in a scaled down, empty greenhouse can compare the relative efficacy of ventilation methods.

b. Transmission of radiation through the roof

Weathering of the cladding material and interception by the structure affect the transmission of solar radiation through the roof of the greenhouse. As documented information on effective transmission of standing greenhouses is lacking, developing *in situ* measurement methods is necessary. The solar radiation balance of the greenhouse's floor has a downward component, S_{id} :

$$S_{id} = \tau_r S_{od} + \delta_r S_{iu} \quad (6)$$

$$S_{iu} = \delta_s S_{id} \quad (7)$$

In these expressions the subscript i refers to inside the greenhouse, the subscript o to outside, d to downward and u to upward, r to the roof and s to the soil. The radiometric properties, transmissivity τ , reflectivity δ , and absorptivity α must satisfy the constraints:

$$\alpha + \delta + \tau = 1 \quad ; \quad \alpha \geq 0 \quad ; \quad \delta \geq 0 \quad ; \quad \tau \geq 0 \quad (8)$$

Measurements of the downward solar radiation inside S_{id} and outside S_{od} , give the value of the apparent transmissivity, τ_{app} a quantity that depends on the reflectivity of the ground. Substituting S_{iu} in Eq.(6) by its value from Eq.(7) yields:

$$\tau_{app} = \frac{S_{id}}{S_{od}} = \frac{\tau_r}{1 - \delta_r \delta_s} \quad (9)$$

Measuring S_{iu} with an inverted pyranometer gives directly δ_s from Eq.(7). This value becomes a fixed parameter in Eq.(9).

Without independent measurements of δ_r , we can only obtain the values that bracket τ_r . For $\delta_r=0$, τ_r reaches its upper bound:

$$Upper \ bound(\tau_r) = \tau_{app} \quad (10)$$

The lower bound, for $\alpha_r=0$, is:

$$Lower \ bound(\tau_r) = \frac{(1 - \delta_s) \tau_{app}}{1 + \delta_s \tau_{app}} \quad (11)$$

Eq.(11) is an implicit function because τ_{app} changes with δ_s . At $\delta_s=1$, i.e., the soil is a perfect mirror, $\tau_{app}=1$, meaning that downward radiation inside the greenhouse equals that outside. Thus, for a roof with low solar absorptivity, a reflective ground increases the radiation in the greenhouse (Stanhill et al., 1975).

3. Experimental Procedure

We isolated a span, 7.5 m wide and 23 m long, of a multi-span greenhouse by erecting lateral polyethylene side walls. The structure had a height of 5.6 m at the ridge and 4.0 m at the gutter. The ridge was oriented north-south. The roof cladding material was a polyethylene film with infrared absorbing additives. The north and south sides had roll-up walls from 0.8 m above the floor to a height of 2.0 m and 2.8 m on the south and north walls, respectively. Plastic nets with a maximum free passage of 0.35 mm covered the openings. Two exhaust window fans, with a rated out flow of $16,000 \text{ m}^3\text{h}^{-1}$ at zero static pressure, were mounted on the south gable. The soil of the greenhouse is an imported fine sand with clay and silt contents less than 5%.

The experiment started on 28 June 1992, two weeks after cultivation and disinfection of the soil. At the time of the experiment the polyethylene glazing had weathered for a full year. The upper 0.05 m soil layer was air dry.

The following four ventilation treatments were applied in sequence for 24 hours on four consecutive days:

1. open; passive ventilation by rolling up the north and south walls
2. closed; closure of all vents
3. one-fan; forced ventilation with one fan in operation, south wall closed, north wall open
4. two-fans; forced ventilation with two fans in operation, south wall closed, north wall open

All the measurements were taken from 1100 to 1300 hour when solar radiation varies the least during the day. All the variables were sampled at 30 s intervals and averaged every 600 s. The solar radiation balance was measured with three pyranometers (model CM-5, thermopile with no temperature compensation, Kipp and Zonen, Delft, The Netherlands). One instrument, installed above the greenhouse, measured outdoors downward solar radiation. A second instrument, mounted underneath the ridge at 3 m above the ground, measured inside downward radiation. From the same location, an inverted pyranometer measured reflected radiation. Using only one pyranometer to sense inside downward radiation does not account for the variability of transmitted radiation resulting from sun ray interception by the structure (Stanhill et al., 1973; Heuvelink et al., 1995). Averaging the radiation reading over the noon period, when the change of the sun zenith angle is the slowest but the sun's azimuth motion is the fastest, diminished the effect of spatial variability. Figure 1 shows that downward solar radiation inside the greenhouse remained fairly constant during the period of measurement, except for a slight dip around 12:30 when an element of the structure intercepted direct radiation.

Figure 1. Components of the radiation balance of a polyethylene covered greenhouse with a bare dry sandy soil.

A polyethylene dome shielded net pyrradiometer (Siemen Ersking, Frederikssund, Denmark), positioned below the ridge 3 m above the soil, measured the net short and long wave radiation. Figure 1 indicates that the representativeness of the single fixed location of this measurement is acceptable as variation caused by the structure was small.

Air temperatures and the humidities were measured with aspirated shielded psychrometers. The wet and dry sensing elements were copper-constantan thermocouples. Inside the greenhouse, psychrometers were mounted at 1 and 2 m above the soil. Outside, the psychrometer was in an open area at 2 m above the ground. A cup anemometer (Met One, model 014A, Campbell Scientific, Logan, USA) at 2 m above the ground measured wind speed.

Copper-constantan thermocouples inserted at 3 and 30 mm below the soil surface in four locations, measured soil temperature. Four heat flux plates (Fuchs and Hadas, 1973) buried 30 mm in the soil measured the soil heat flux. To obtain heat flux at the surface of the soil, the change of heat content in the top 30 mm of soil was evaluated from the average temperature change of the soil layer during the 600 s interval between two successive recordings of the data. The heat capacity for the dry sand is $1.13 \text{ MJ m}^{-3} \text{ }^{\circ}\text{K}^{-1}$ (de Vries, 1963).

All the signals were processed and stored in a CR-10 data logger through an AM416 multiplexer (Campbell Scientific, Logan, USA).

4. Results and discussion

a. Radiation transmission

Using the data in Figure 1, we found that the average soil reflectivity δ_s is 0.164. The measured 0.63 for τ_{app} is an upper bound for the true value of the roof transmissivity. The lower bound for transmissivity according to Eq.(11) is 0.59. The small range between the maximum and minimum indicates that the measurement of τ_{app} yields a reasonable estimate of the roof transmissivity. Yet, this result is a consequence of the low value found for the reflectivity of the soil. Covering the soil with a plastic mulch, which raised ground reflectivity δ_s to 0.303, increases only slightly τ_{app} to 0.64, but dropped the lower bound to 0.373. This result shows that in contrast with the finding by Stanhill et al., (1975) in a glass-covered greenhouse, a reflective coating of the floor would not increase appreciably light penetration in a greenhouse of the type considered here. Combining the data collected over the bare with those over the plastic mulch allows to solve Eq.(9) simultaneously for τ_r and δ_r to yield values of 0.62 and 0.11, respectively. The absorptivity of the roof α_r is thus 0.27, a surprisingly high value. The precision of the calculation is low because τ_{app} in the two sets of measurements differed only by 0.01. Yet, the very fact that the two values were so close suggests that α_r is high. This result merits further investigation.

b. Ventilation

Wind speed outside the greenhouse during the experiment was approximately 2 m s^{-1} (Table II). Opening the north and south walls of the greenhouse allowed this moderate wind to produce a sufficient dynamic pressure drop to obtain the lowest resistance to heat transport and the highest air exchange rate of all treatments (Table I.). Even in the presence of an insect proof net that impedes air movement through the vents, this method of ventilation ensures a high exchange rate.

Operating two fans displacing a nominal $32,000 \text{ m}^3 \text{ h}^{-1}$ should have produced an exchange rate of 38.6 h^{-1} . The measured value of only 13.3 h^{-1} suggests that the fans could not overcome the drag caused by the nets. Whereas in the two-fans treatment exchange resistance increased threefold over that of the open passive treatment, the internal heat transport resistance from soil to air grew only 46%. Forced ventilation with a single fan lowered the air exchange rate by another factor of two. This proportionality shows that aerodynamic resistances, probably generated by the insect proof net, prevented proper operation of the fans. Better ventilation would require fans capable of working against steep pressure drops. The decrease of ventilation increased only very slightly the internal soil surface to air resistance to heat transfer. Closing the greenhouse considerably diminished the air exchange rate. Yet, recalling that this result derives from the assumption that convective exchange is much larger than conductive exchange is necessary. For the closed greenhouse this assumption is weak and leads to an overestimation of the true value of the air exchange rate.

Table I. Effect of the ventilation method on the resistances to heat transport and air exchange rate in a polyethylene greenhouse with a bare sandy soil topped by a 50 mm air dry layer.

Treatment	Internal Resistance	Exchange Resistance	Volume Exchange
	s m^{-1}	s m^{-1}	h^{-1}
Open	113	17.0	44.1
Two-fans	165	56.4	13.3
One-fan	170	92.6	8.1
Closed	157	245.5	3.1

Similar outdoor temperature, humidity and wind, provided a good experimental basis for a comparison between treatment (Table I). In the closed greenhouse, average internal air temperature was 20°C higher than outside. Ventilation lowered the air temperature rise to 5°C (Table II). Yet, soil surface cooling was only 7°C .

The air temperature at 2 m above the ground was systematically higher than at 1 m (Table II). As the soil absorbed 52% of the outdoor solar radiation, the elevated soil temperature heated the air by convection. Normally this transport mechanism cannot account for the observed temperature inversion. With a solar radiation absorptivity of 27%, claiming that the roof served as a second source of internal sensible heat justifying the inversion is possible. The existence of an additional heat exchange would invalidate the energy balance approach used in the present analysis. A roof warmer than internal air implies the absurd conclusion that transport by conduction across the thermally stable internal air layer below the roof would be more efficient than the convective heat exchange with the free and unstable air above the roof. The vapor pressure profile in the greenhouse provides compelling evidence against a link between energy transfer from the roof and the inversion. The vapor pressure has the same inversion, as the temperature (Table II). As the roof is in no way a water vapor source, it could not have generated the inversion. We attempt to explain this observation later in the paper.

The closed treatment has a lower net radiation than the others (Table III). Yet this difference does not indicate that radiative load was less on that day. Between the open and closed treatments, the surface temperature rose from 54.1 to 61.5°C , increasing thermal emission by

55 W m^{-2} , calculated with an emissivity of 0.90 for this soil type (Fuchs and Tanner, 1968). The additional emission exceeds the 41 W m^{-2} difference in net radiation.

Table II. Effect of the ventilation regime on the average midday temperature and humidity in a polyethylene greenhouse with a bare sandy soil topped by a dry layer 50 mm thick.

Treatment	Greenhouse					Outdoor		
	Surface Temperature	Air Temperature		Water Vapor Pressure		Air Temperature	Water Vapor Pressure	Wind Speed
		1 m	2 m	1 m	2 m			
	°C	°C	°C	K Pa	K Pa	°C	K Pa	m s ⁻¹
Open	54.1	34.4	36.5	2.67	3.00	30.4	2.60	2.20
Two fans	54.4	35.0	36.1	2.29	2.81	29.0	2.00	2.40
One fan	56.2	38.5	38.8	2.75	3.21	29.0	2.01	2.30
Closed	61.5	49.4	50.0	4.40	4.99	29.7	2.26	2.20

Increasing the ventilation rate lowered very rapidly the temperature elevation in the greenhouse. The weak air exchange of the one-fan treatment reduced the temperature excess to 10°C . Yet a further increase of ventilation rates produces only slight additional cooling (Figure 2). This result supports the prediction of a cooling model (Fuchs, 1993) showing that internal temperatures change rapidly at the low end of the ventilation range, but that any increase of ventilation beyond 20 h^{-1} has practically no effect. Closing the greenhouse lead to a considerable increase of the internal humidity. Although the relative humidity in the greenhouse did not rise above 80%, the vapor pressure was 2 KPa higher than the condensation vapor pressure at outdoor air temperature. A sudden drop of the load heat would induce condensation. Conditions propitious for condensation persist until ventilation exceeds 15 h^{-1} . As with temperature, the humidity elevation dependence on ventilation rates beyond 20 h^{-1} becomes insignificant.

Temperature and vapor pressure elevations are linearly related to exchange resistance (Figure 3).

The humidity elevation extrapolates to 0.045 KPa (not significantly different from zero at $p = 0.05$) for zero resistance. According to Eq.(2), this result shows, that the latent heat flux densities were about the same at the time of the measurement on the four days (Table III). The same extrapolation for the temperature elevation yields a positive offset of 3.4°C . This offset has not a specific physical meaning, because the energy balance demands that T_i equal T_o at zero exchange

Figure 2. Effect of air exchange rate on temperature and humidity elevation in a greenhouse with a dry bare sandy soil.

resistance. It does however indicate that sensible heat flux density increases with decreasing air exchange resistance. The Bowen ratios in Table III show the same effect. As the radiative heat load during the four measurement periods were nearly identical, the contrast between the responses of sensible and latent heat flux to ventilation suggests that the physical factors controlling their transport differ.

Ventilation induces very large changes in the energy balance of the greenhouse with bare soil (Table III). Exposure of the dry soil surface to solar radiation elevates its temperature and consequently diminishes the net radiation as already discussed in the presentation of the results in Table II.

Ventilation modifies the soil heat flux. The participation of soil heat flux in the midday energy dissipation increases from 25% of the net radiation in the well ventilated open treatment to 44% in the closed treatment (Table III). The effect of atmospheric convective transport on the partition of heat between bare soil and air is well known in meteorology (Lettau, 1951), but to our knowledge, it has not been previously reported for greenhouses.

Figure 3. Temperature and humidity elevation in a greenhouse with a bare sandy soil as a function of the exchange resistance.

Table III. Effect of the ventilation regime on the average midday energy balance of a polyethylene greenhouse over a bare sandy soil with a top dry layer 50 mm thick.

Treatment	Net Radiation	Soil Heat Flux	Evaporation		Sensible Heat Flux	Bowen Ratio
	W m ⁻²	W m ⁻²	W m ⁻²	(mm h ⁻¹)	W m ⁻²	
Open	456	118	132	(0.20)	204	1.55
Two fans	453	145	170	(0.25)	136	0.80
One fan	457	155	180	(0.27)	92	0.66
Closed	415	182	144	(0.22)	86	0.60

Whereas ventilation increases sensible heat transport, the effect on evaporation, shown in Table III, is unexpected. Evaporation decreases with ventilation except in the closed greenhouse, for which the computation of the Bowen ratio is inaccurate. The reason for this surprising result is the exponential dependance of saturation vapor pressure on temperature. Because of its low thermal conductivity, the temperature of the dry soil layer is high. Ventilation lowers slightly soil

temperature which causes a large decrease of the vapor pressure gradient across the dry layer. This mechanism reduces the evaporative driving potential. To meet the law of energy conservation, the sum of sensible and latent heat must balance net radiation minus soil heat flux. If ventilation increases sensible heat flux more than it decreases soil heat flux (Table III), then latent heat must decrease. A theoretical transpirational cooling model, when applied to a crop with high stomatal resistance also predicts a lowering of transpiration when ventilation increases (Fuchs, 1993). For a stomatal resistance below a critical value, the model predicts that transpiration increases with ventilation, as normally expected.

Ventilation in the open treatment relies on the dynamic pressure generated by the natural wind and buoyancy resulting from temperature and humidity gradients. Figure 4 illustrates the negative correlation between the wind speed and the exchange resistance for the open treatment. Each data point represents a 600 s average of the measurements. Despite the narrow range of wind speed recorded during the midday measurement period, the data show a strong link between exchange resistance and wind ($r = -0.496$ at $p = 0.06$). Over the 0.6 m s^{-1} wind speed range, the change of the air exchange resistance is threefold, corresponding to air exchange rates from 20 to 60 h^{-1} .

Movement of air should affect the value of the internal boundary layer resistance above the soil surface. This linkage appears as a correlation between the exchange resistance and the internal boundary layer resistance of the air above the bare soil (Figure 5). Except for one point, the data show an apparently high correlation. Yet, the correlation coefficient is not applicable because the two variables share the same value of H , the sensible heat flux density. For this reason, the statistics of the correlation are not shown. The range of variation of the internal boundary-layer resistance is only 35% as compared with the 200% range for air exchange resistance, suggesting a dependence on other factors. Further direct investigation of the relation between internal resistance and air flow would require independent measurements of ventilation rates such as those obtained with tracers.

The data contain additional information on the factors affecting the internal resistance. Because of the steady value of H during the midday period, as quantified by a low coefficient of variation of 10.3 %, the temperature elevation in the greenhouse increases linearly with air exchange

Figure 4. Correlation between wind speed and air exchange resistance

Figure 5. Apparent correlation between air exchange resistance and internal boundary-layer resistance above the soil

resistance. The correlation coefficient is 0.872, significant at $p = 0.00005$, with a zero offset of $1.7\text{ }^{\circ}\text{C}$ (Figure not shown). According to Eq.(5) a similar relation should hold between the internal boundary-layer resistance and the soil-air temperature gradient. Yet, the correlation between these two variables is not significant (Figure 6, solid squares). A possible explanation of this result is that the very steep temperature gradient generates intermittent localized heat convection cells. Aubinet's (1991) experimental evidence for the existence of convective cells above heating pipes provides credibility to this hypothesis. Convective cells could also explain why the temperature and the vapor pressure measured at 2 m were systematically higher than at 1 m above the ground (Table II). Businger (1963) also postulates large convective cells induced by the external wind to explain the air temperature and humidity inversion, and the spatial distribution of air temperature he recorded in a large multi-span greenhouse. As in our experiment, the ground was the major surface with the highest temperature and was the only source of water vapor in the greenhouse, another mechanism for counter-gradient flow across the inversion layer is difficult to conceive. Unfortunately, neither the thermometers' time constants nor the sampling procedures were adequate to provide direct evidence in support of the hypothesis of coherent convective cells.

The data show a strong correlation between the soil-to-air temperature difference and the resistance to air exchange (Figure 6, hollow circles and regression line). This result suggests that buoyancy forces drive the air exchange through the vents of the greenhouse. Yet, despite the highly significant correlation ($r = -0.772$, $p = 0.00074$), it is unlikely that buoyancy alone could account for the entire variation of air exchange resistance because the large temperature differences are confined within a narrow range. Air exchange resistance and soil-to-air temperature difference are both implied variables influenced by the outdoor wind, which is an independent variable. The confounding effect of the wind appears through the correlation coefficient of -0.496 with rejection probability of 0.060 , between wind speed and exchange resistance shown in Figure 4. The correlation coefficient between soil-to-air temperature difference and wind speed is -0.534 with a rejection probability of 0.04 . As both correlations are weaker than that found in Figure 6 (left-hand y-axis), the data provide statistical evidence of heat transport enhancement by buoyancy in the greenhouse with passive ventilation. Forced ventilation should weaken the effect of buoyancy. The two-fans treatment supports this presumption. The correlation coefficient between soil-to-air temperature difference and air exchange resistance drops to a non significant value of -0.282 with a rejection probability of 0.350 .

5. Conclusions

The conclusion emerging from the comparison of four ventilation methods is that rolling up opposite side walls to generate a natural draft of air is the most effective. Yet, its sensitivity to

Figure 6. Relation between the soil-to-air temperature difference in a greenhouse and the resistances to heat transport.

wind speed restricts dependable application to regions with regular winds. Forced ventilation with exhaust fans operated with low efficiency and the air exchange rates of the fans were below those specified, suggesting that pressure loss across the insect proof nets was large.

The buoyancy is most noticeable in a greenhouse with dry bare soil such as that used in this study, because temperature gradients over an evaporating surface or vegetation would be weaker. Therefore, the results found here may not be directly applicable to a greenhouse with a large transpiring biomass. Still, the experiment represents the conditions of a newly planted greenhouse with sparse vegetation (Seginer, 1994).

The small size of the experimental greenhouse is another factor that restricts applicability of the results to situations encountered in commercial operations. The ratio of vent areas over greenhouse volume and the action of fans decrease with the length of the ridge axis. Extrapolation of the results on ventilation efficacy to a greenhouse with longer ridges would require careful scaling of the drag forces.

High ground surface temperature enhances radiation emission. Crops with sparse canopy intercept part of this radiation and therefore, bear an additional heat load. Increased ventilation and shading would lessen this stress. The large contribution of soil heat flux to energy dissipation is another major characteristic of the empty greenhouse. Ventilation decreased the relative soil heat flux density. The resulting change of heat partition between soil and air, may ease or worsen the heat load on sparse vegetation depending on ventilation and stomatal resistance (Seginer, 1994).

In spite of the soil dryness, evaporation remained a significant part of the energy balance. The high temperature of the soil elevates its vapor pressure to overcome the large vapor diffusion resistance of the dry layer of soil. Interestingly, increasing the ventilation rate, because it lowers soil temperature and increases sensible heat flux, slightly diminished evaporation.

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CHAPTER II

Transpiration and foliage temperature in a greenhouse

Marcel Fuchs

Abstract

A simplified energy balance model of a ventilated greenhouse evaluates latent heat dissipation by transpiration from a fully developed canopy. The model parameters were fitted to simulate a mature tomato crop, in a 4.5-m-high greenhouse covered with polyethylene. Transpiration is strongly dependent on solar radiation. This link is almost linear, but the linear fit has a positive offset, which grows if the ventilation rate increases. At low and moderate ventilation, high outdoors relative humidity and high leaf resistance to gas diffusion hardly affect transpiration, but elevate considerably the temperature of the foliage. Raising the ventilation rate increases transpiration, but also enhances the cooling efficiency of latent heat. The model suggests that a volume exchange rate of approx. 30 h^{-1} achieve most of the potential transpirational cooling.

1. Introduction

Micrometeorologists and plant physiologists have traditionally considered transpiration as the most important energy dissipating mechanism determining the thermal environment of vegetation. Engineers have recognized that it causes high humidity in greenhouses, increasing the heating requirements because of either latent heat dissipation (Deltour et al., 1987) or ventilation to evacuate disease-promoting water vapor (Seginer, 1984). However, the contribution of transpiration to the cooling of greenhouses in the sunny and warm Mediterranean climate has largely been ignored (Elsner, 1980; Hashimoto, 1980). Under these conditions greenhouses must be ventilated to dissipate excess heat and to resupply the internal volume with atmospheric CO_2 .

Early studies showing the effect of plants on greenhouse microclimate (Takami and Uchijima, 1977; Van Bavel et al., 1985) have received limited attention. The first serious attempt to quantify the role of transpiration in the temperature control inside greenhouses was made by Stanghellini (1987), who concentrated on heated greenhouses operated at low ventilation to conserve energy. In the present paper, a model of the energy balance of a transpiring crop inside an unheated ventilated greenhouse explores how controllable factors such as the ventilation rate and the plant water supply, or external climatic factors, i.e., radiation, air temperature and humidity, affect the transpiration of the plants. The energy balance equations are also solved to compute the average canopy temperature and the internal air temperature.

2. Energy balance equations

Several models describing in detail the energy balance of the greenhouse are available to predict the microclimate of the internal volume (Bailey, 1985; Kimball, 1986; Takakura et al., 1971). However, their application involves many transport processes for which quantitative information is not available. The treatment of the crop canopy energy balance used here is simplified, restricting its scope to a well ventilated unheated greenhouse. Its purpose is exploratory and therefore assumptions introducing errors about 10% of the largest term entering the balance are deemed acceptable.

The first step considers the transfer of solar radiation through the envelope of the greenhouse and the resulting radiant flux density S_α , absorbed by the foliage:

$$S_\alpha = \frac{(1 - \delta_c) \tau_r S_o}{1 - \delta_r \delta_c} \quad (1)$$

where S_o is the solar flux density incident on the greenhouse, τ designates transmissivity, δ represents reflectivity, and the subscripts r and c refer to roof and canopy, respectively. Eq. (1) accounts for the full multiple reflection between roof and canopy.

Thermal radiation balance is simplified to its first order approximation by setting canopy and roof at outdoors air temperature. The net long wave radiation L_α :

$$L_\alpha = (\epsilon_{sky} - 1) \tau_R \sigma T_o^4 \quad (2)$$

where ϵ_{sky} is the emissivity of the atmosphere, τ_R is the long wave transmissivity of the roof (differs from τ_r the transmissivity in the solar wave band), and T is the outdoors air temperature. At first sight it seems illogical to assume that outdoors air and internal canopy temperatures are equal because the latter is a final output of the model, but the resulting error is small. Emitted radiation changes at a rate of $5 \text{ W m}^{-2} \text{ K}^{-1}$, introducing a widely recognized negative feedback in the radiation balance (e.g., Paw U, 1984). Assuming that roof long wave transmissivity is 0.3, a typical value for polyethylene incorporating a weak infrared opaque additive, and that both roof and canopy temperature equal the 25°C outdoors air temperature, yields a long wave radiation balance above the foliage of -16 W m^{-2} . This balance would be -38 W m^{-2} for roof at 28°C and foliage at 31°C . The 22 W m^{-2} error is less than 10% of the 300 W m^{-2} of net solar radiation absorption needed to elevate the canopy temperature by 6°C above outdoors air. This error is also negligible in comparison with the large uncertainty of the convective heat transfer.

The net radiation R_n :

$$R_n = S_\alpha + L_\alpha \quad (3)$$

is intercepted according to foliage angular distribution. As this datum is usually unavailable to calculate the exact distribution of radiation interception, leaf temperature, internal vapor pressure and vapor conductance are assumed to change linearly with radiation. This assumption allows R_n to be averaged over the total leaf area index, LAI, and to treat the active surface for the energy and mass exchange as if the canopy had uniform temperature and vapor conductance.

Convection through the leaves' boundary layer transports most of the latent and sensible heat generated in the foliage into the internal space of the greenhouse. From there, ventilation expels the energy to the outdoors. The model assumes that air exchange is sufficiently rapid to override all other transport processes. Consequently, heat conduction through the cladding material and its insulating internal boundary layer, the construction and the soil underneath the canopy is neglected. Latent, E, and sensible, H, heat flux densities are simply:

between canopy and air

$$E = \left(\frac{\rho c_p}{\gamma} \right) \frac{e(T_c) - e_i}{r_a + r_c} \quad (4)$$

$$H = \rho c_p \frac{T_c - T_i}{r_a} \quad (5)$$

between in and outside

$$E = \left(\frac{\rho c_p}{\gamma} \right) \frac{e_i - e_o}{r_x} \quad (6)$$

$$H = \rho c_p \frac{T_i - T_o}{r_x} \quad (7)$$

where ρ is the density of the air, c_p is the specific heat of air at constant pressure, γ is the psychrometric constant, T is the temperature and e is the water vapor pressure. The subscripts o, i and c refer to outdoors, internal greenhouse space and canopy, respectively. The transport properties are expressed as resistances, r , subscripted by c for canopy, a for the internal boundary layer of the foliage, and x for the convective mass flow exchange caused by greenhouse ventilation.

Values for these resistances derive from empirically fitted relations to experimental data. For the boundary layer resistance r_a , in sm^{-1} , (i.e., Campbell, 1977):

$$r_a = \frac{305 \sqrt{\left(\frac{D}{u} \right)}}{LAI} \quad (8)$$

where D is the diameter of the leaf (m), and u , the mean speed of the air flow (m s^{-1}) in the greenhouse, is:

$$u = X \sqrt{A} \quad (9)$$

with X as the volume exchange rate (s^{-1}), and A , the ground area of the greenhouse (m^2).

Leaf resistance introduces the physiological response of the plant to environmental inputs. For many plants, stomatal aperture is related to intercepted photosynthetic photon flux density and water availability in the root zone (Petersen et al., 1991). Daytime leaf resistance

of greenhouse tomato, without water stress, obeys a hyperbolic reciprocal response to light (Stanghellini, 1987; Boulard et al., 1991):

$$\frac{1}{r_c} = \frac{1.8 \times 10^{-2} LAI}{1 + \frac{250}{S_a}} \quad (10)$$

where r_c (sm^{-1}) is the resistance of the canopy. Eq. (10) assumes that the photosynthetic photon flux density is a constant fraction of solar radiation (W m^{-2}).

The volume exchange rate by ventilation, X (s^{-1}), can be expressed as a resistance:

$$r_x = \frac{1}{XZ} \quad (11)$$

where Z is the mean height of the greenhouse (m).

The energy balance of the canopy:

$$R_n = E + H \quad (12)$$

can be solved explicitly for E , using Penman's (1948) first-order approximation as:

$$E = \frac{s(1 + \frac{r_a}{r_x})R_n + \frac{\rho c_p}{r_x}(e(T_o) - e_o)}{\gamma + s(1 + \frac{r_a}{r_x}) + \gamma(1 + \frac{r_c}{r_a})\frac{r_a}{r_x}} \quad (13)$$

for a given outside incoming solar radiation, air temperature, humidity and ventilation rate. Here, s represents the slope of the saturated water vapor pressure curve at T_o . Subsequently internal temperature and humidity, and foliage temperature, can be calculated from Eqs. [7], [6] and [5].

3. Results

All forthcoming results were calculated with the numeric values given in table I. Leaf resistance was determined by Eq. [10] in all examples for which solar radiation is the independent variable; otherwise it was treated as an independent parameter.

a. Solar radiation

Transpiration expressed as latent heat flux density is the first output of the computations. Its response to outdoors solar radiation when all other independent parameters are kept constant, is shown in Figure 1. Transpiration is proportional to radiation when humidity is high or at a low ventilation rate, in full agreement with experimental findings (Morris et al., 1957; Stanhill and Scholte Albers, 1974). It appears that under these conditions, solar radiation data can serve to control the irrigation scheduling of greenhouses. The proportionality

coefficient between solar radiation and transpiration increases slightly with outdoors temperature, because s , the slope of the saturated vapor function is a multiplier of the radiation term in Eq. 13. At a ventilation of 10 h^{-1} and an outdoors relative humidity of 75%, a temperature rise from 25 to 35°C increases the coefficient from 0.35 to 0.39. Outdoors air temperature measurements would improve the accuracy of irrigation control.

Table I. Numerical value of physical properties used in the computation of the energy balance of a tomato crop in a greenhouse.

	Symbol	Property	Value
Solar Radiation	δ_c	canopy reflectivity	0.25
	δ_r	roof reflectivity	0.20
	τ_r	roof transmissivity	0.60
Terrestrial Radiation	δ_R	roof reflectivity	0.15
	τ_R	roof transmissivity	0.30
	ϵ_{sky}	sky emissivity	0.86
Air	γ	psychrometric constant	0.066 KPa K^{-1}
	ρ	density at 273 K	1.293 Kg m^{-3}
	c_p	specific heat	$1005 \text{ J Kg}^{-1} \text{ K}^{-1}$
Greenhouse	Z	mean height	4.5 m
	A	ground area	1000 m^2
Crop (tomato)	LAI	leaf area index	3
	D	leaf diameter	0.03 m

At low humidity, transpiration has two domains of dependence on radiation. For incoming solar radiation below 200 W m^{-2} , the relation is curvilinear; above this value it is practically linear, with an offset dependent on humidity, temperature and ventilation rate. Passing from relative humidity of 75% and ventilation of 10 h^{-1} , to 15% and 30 h^{-1} , respectively, sets off the transpiration by 150 W m^{-2} . Yang et al. (1990) found that the linear relation between greenhouse cucumber transpiration and internal solar radiation had a significant offset. The reported measurements were not stratified according to air temperature and rate of ventilation, and therefore the scatter of data is large. These additional input data are needed for accurate greenhouse irrigation control in dry climates.

The incoming solar radiation increases the temperature of the foliage inside the greenhouse. The example in Figure 2 is for a moderately ventilated greenhouse. At low humidity, outdoors solar radiation must exceed 650 W m^{-2} before foliage temperature in the greenhouse rises above that of the air outside. Yang et al. (1990) show that transpirational

latent heat dissipation may exceed net radiation. When this occurred, the leaf temperatures were cooler than those of the air.

Israeli tomato growers consider 28°C as a critically high temperature. This temperature is reached for 900 W m^{-2} , 650 W m^{-2} , and 450 W m^{-2} at relative humidities of 15, 50 and 75%, respectively. Increasing the ventilation rate to 30 h^{-1} will maintain the foliage temperature below the 28°C limit for all conditions specified in Figure 2. The minimum foliage temperature occurs at solar radiation above zero, because light is required to open stomata and initiate transpirational cooling.

Solar radiation, by powering transpiration, increases the humidity, expressed as water vapor pressure, inside the greenhouse (Fig. 3). The rate of humidity rise is nearly constant and independent of that outdoors, shown in Fig. 3 as the vapor pressure at zero solar radiation.

b. Ventilation

Ventilation is the most commonly used method for adjusting greenhouse temperature. The air exchange rate affects both sensible and latent heat flux. Its effect on transpiration for leaves having a fixed resistance of 100 s m^{-1} , i.e., corresponding to conditions of good water supply, is shown in Figure 4, in which outside solar radiation, air temperature and humidity are the other fixed parameters. Air exchange is varied between 5 (very low) and 100 h^{-1} (very high). Eq. 8 does not consider possible effects of leaf flutter on the transport coefficients. Therefore the model may underestimate turbulent exchange at high ventilation. At high outdoors temperature and low humidity, air exchange increases transpiration, but when humidity is high, it produces practically no effect. The transpiration converges to a value of 230 W m^{-2} by extrapolation to zero volume exchange rate. This result is physically impossible, because temperature must increase indefinitely to maintain evaporation. At this limit the model breaks down because it violates the assumptions implied in Eqs. 7 and 2.

Increasing the ventilation rate lowers the temperature of the transpiring canopy inside the greenhouse, as indicated in Figure 5, where parameters represent meteorological conditions of Mediterranean early autumn or late spring. The cooling follows the model of an imperfect wet bulb thermometer in diabatic conditions, with very steep temperature change in the low range of ventilation. Above the exchange rate of 30 h^{-1} , no significant additional cooling of the foliage is obtained. At low humidity the temperature of the foliage drops rapidly below that of the outside air; the transpiring canopy acts like a cooling pad which lowers air temperature. At high humidity, the foliage temperature remains above that outdoors. Most of the additional cooling produced by ventilation is through sensible heat convection as shown in Figure 4 where latent heat dissipation at 75% outdoors relative humidity increases only very slightly with the ventilation rate. For the entire range of conditions defined in Figure 5, the critical temperature limit of 28°C is not exceeded if the exchange rate is at least 30 h^{-1} .

The pattern of internal air temperature response to ventilation is less obvious, being coupled partly to the temperature of the foliage and partly to that of outdoors. Ventilation decreases temperature if the air within the greenhouse is warmer than outside, but increases it if the inside is cooler. An exchange rate of 30 h^{-1} is sufficient to obtain most of the attainable air cooling.

Proper ventilation of a greenhouse in a dry desert (Fig. 5, low humidity) can maintain the temperature of the foliage below the critical 28°C . The cooling is achieved by the enhancement of latent heat dissipation (Fig. 4). The air inside is cooler than outside. Yet the condition of non-transpiring organs is not known, but Figure 6 shows that if the air exchange rate is above 20 h^{-1} , internal humidity remains low. Consequently additional latent heat dissipation is possible in theory, by easing the transport of vapor from a liquid interface. Spraying water on the foliage produces this condition. A zero leaf resistance in Figure 7 simulates the several $^{\circ}\text{C}$ foliage temperature drop of wetted leaves below tomato leaves with their normal resistance around 150 sm^{-1} . However, internal air temperature is hardly affected by the treatment, in sharp contrast with the air cooling that would be produced by a wet pad and fan system.

c. Leaf resistance

Increasing leaf resistance to water vapor diffusion, between 150 and 400 sm^{-1} elevates foliage temperature (Fig. 7). At low and moderate ventilation rates, the temperature rises linearly with resistance. Temperatures become excessively high when the humidity is high. By contrast, transpiration at low and moderate ventilation rates is almost insensitive to changes in the leaf resistance (Fig. 8). This confirms the finding of Aubinet et al. (1989) on the decoupling between transpiration and leaf resistance in greenhouses. However, when the ventilation rate is high, transpiration is strongly dependent on leaf resistance. Figure 8 also shows that at 75% relative humidity, the lines for high and moderate ventilation rate cross over at a leaf resistance of 200 sm^{-1} , indicating that for larger resistances increasing the ventilation rate causes transpiration to decrease. The theory of evaporation from unsaturated surfaces (Monteith, 1964) predicts this peculiar response of transpiration to convective transport. At high ventilation rates, the increase of resistance from 0 to 100 sm^{-1} causes a rapid temperature rise (Fig. 7), which remains below the critical value provided outdoors temperature and humidity do not exceed 25°C and 50%, respectively.

4. Discussion and conclusions

It is important to keep in mind the exploratory nature of the results presented here. Many transport coefficients used to operate the model are approximate. Before including the model results in a climate control algorithm it is necessary to assess experimentally the validity of the invoked parameters. The errors induced by the linearized solution of the energy balance equations should also be investigated.

The overall transmissivity of the greenhouse roof used in the model is approximately 0.6. The resulting solar energy input is sufficiently attenuated not to require additional shading for maintaining the tomato foliage below the critical 28°C , provided the air exchange rate normally achievable by opening side and roof vents is allowed. However, the temperature of non-transpiring organs like fruit, flower and buds, if exposed to full solar radiation, may exceed the critical value. Another limitation to the applicability of the results is the variability of foliage exposure to incident solar radiation, which can cause leaf temperatures to range over several degrees in full sunlight (Fuchs, 1991). However, the high proportion of diffuse radiation in greenhouses may diminish the range of leaf temperature variability.

It would thus appear that ventilation can maintain a favorable thermal environment for the tomato crop with a fully developed transpiring canopy, even during the warmest periods of the year in Mediterranean and arid climates. The hot, dry climate of the desert provides a good background for greenhouse cultivation. For this conclusion to stand, the water transport system from the root medium, through the stem and the leaves, must maintain the transpirational drive. This condition is not always achieved. For instance, artificial substrates and high frequency irrigation treatments may create a very small root volume in which water uptake is impeded. If the water transport mechanism is disturbed, leaf resistance to water vapor diffusion takes on values considerably larger than those predicted by Eq. [10]. Although changes in leaf resistance have a small effect on transpiration in a moderately ventilated greenhouse, foliage temperature rises significantly with increasing resistance (Fig. 7).

The analysis shows that transpiration enhanced by proper ventilation is an effective mechanism for cooling the foliage inside a greenhouse. Ventilation producing a volume exchange rate of ca 30 h⁻¹, provides the optimum cooling effect. Low outdoors humidity increases the efficacy of the cooling.

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Figure 8. Effect of leaf diffusive resistance on transpiration inside a greenhouse.

CHAPTER III

Predicting Canopy Temperatures by Dynamic Simulation

K. Jordan, T. Takakura, E. Dayan

Introduction

The success of utilizing plants in hot arid environments depends upon the ability of the plant to cool through transpiration. The cooling effect was predicted in several models where the effects of a range of parameters were established. Experimental measurements in a well instrumented greenhouse in Besor, Israel are used to establish what actually occurred. Plants were developed with an extended root system in order that maximum cooling potential could be realized.

The predictive model showed that plant cooling was possible if certain environmental conditions existed. However when looking at the range of parameters that existed in May 1993 during experiments conducted at the greenhouse the range of conditions that existed naturally was much restricted. A simple direct model was developed capable of following the dynamic relationships that actually occurred.

The dynamic model based upon an energy balance at the center of the greenhouse where sensors were installed. The model utilized measured solar radiation, a calculation of long wave radiation and sensible and latent heat equations. The prediction of canopy temperature in the center of the greenhouse simplified the interrelationships of the equations and provided a buffer area to account for edge effects. This model however involves the output variable in several governing equations which must be solved implicitly. Fortunately simulation languages exist (e.g. ASCL, CSMP, FST) which have functions to accomplish this task.

Model Development

Solar radiation, SI , inside the greenhouse was measured. It is the primary input variable to the model. In order to input the daily variation a piece-wise linearization was prepared and introduced using a function generator, AFGEN. This linearization shows abrupt changes in the simulated data which is absent in the recorded data.

The long wave radiation exchange between the canopy and the surroundings has three components $Q_{sky} + Q_{glazing} - Q_{canopy}$. These are calculated using the Stephan-Boltzman equation, where the symbols have the usual meaning ϵ is the emissivity, σ is the Stephan Boltzman constant (5.67×10^{-8}) and T must be in degrees Kelvin for Q to have the units of W/m^2 .

$$Q = \epsilon \sigma T^4$$

The radiation from the cold sky can be developed from the outside temperature using an emissivity, $\epsilon_{sky}=0.75$. This is transmitted through the cover, $\tau_{glazing}=0.3$, and adds heat to the canopy, $\epsilon=0.98$.

Also since the glazing can radiate to the canopy the emissivity, $\epsilon_{glazing}=0.65$, of the glazing

$$L = \alpha_{canopy} \tau_{glazing} \epsilon_{sky} \sigma T_o^4$$

is

$$L = \alpha_{canopy} \epsilon_{glazing} \sigma \left(\frac{T_o + T_i}{2} \right)^4$$

involved. The temperature of the glazing, T_g , was not measured but it was assumed to be between the inside and outside temperature, thus an average value was used. The canopy radiates heat and is a negative quantity in the long wave heat balance. The canopy emissivity, $\epsilon=.98$ was used and multiple reflections were considered small enough to neglect.

$$L = \epsilon_{canopy} \sigma T_c^4$$

The expression for the long wave radiation on the canopy is developed as the evaluation of

$$\Sigma L = 0.98 * \sigma * (0.75 * 0.3 * T_o^4 + 0.65 * 0.3 * T_g^4 - T_c^4)$$

the long wave radiation terms requires the input of outside air temperature.

Thus the net radiation absorbed by the canopy is the sum of the absorbed short wave solar energy with an absorptivity, $\alpha=0.75$, and the absorbed long wave energy.

This radiant energy absorbed by the canopy is transferred into the greenhouse by sensible and latent heat. These two components can be evaluated using the relationships typically used by plant scientists involve the conductance or its reciprocal, the resistance.

These equations are of the form where C_a is the volumetric heat capacity of the air

$$Q_s = \frac{C_a * (T_i - T_c)}{R_a}$$

$$Q_l = \frac{C_a * (e_{T_c} - e_i)}{\gamma * (R_a + R_c)}$$

[Jm-3C-1], T is the leaf, c, or air, i, temperature [C], e is the water vapor pressure evaluated

at leaf temperature, T_c , or air T_i [kPa], R is the resistance to the transfer of heat in the leaf, R_c , or to the air R_a [s m⁻¹], and γ is the psychrometric constant (.066), the slope of the wet bulb line [kPa/C]. With these units the calculation of sensible heat and latent heat has the units W/m².

The input data required for evaluation of the sensible and latent heat is the inside air temperature. The inside vapor pressure was established by converting the recorded wet and dry bulb temperatures using psychrometric relationships. No pattern was discernible from the determinations as can be seen in Figure 1 from 19 May 1993 data. This pattern is typical of inside vapor pressure. Thus the vapor pressure inside was averaged daily and used for the simulations.

The two resistances had to be established, R_c & R_a . The leaf resistance was determined experimentally as shown in Figure 2. Relationships used in the earlier prediction models were not as satisfactory as the experimental determinations. The equation from these tests is in the simulation, PAR was estimated from the Solar radiation measured and dividing by 2.5 $\mu\text{Mol PAR} = 1\text{J Solar Radiation}$. (The range given in Principles of Environmental Physics are 2.1 to 2.9 but appears to be rather insensitive to variation over this range.) The aerodynamic resistance is often related to the leaf size and the air velocity. This was the only parameter that was adjusted in order to bring the measured and simulated readings into agreement.

If explicit functions were required other assumptions or relationships would have to be developed. Using one of the analog computer simulation program these equations are sufficient to describe the system and obtain a unique solution. The input variables are measured values of inside radiation in a plane parallel to the canopy surface (eliminating the need for complex angle calculations), inside air temperature, inside water vapor content, and for the long wave radiation calculations the outside temperature is needed.

Simulated Output

The output is the canopy temperature, described implicitly in the above equations. Canopy temperature was measured using an IR radiometer, an IR scanner and by an instrumented leaf. Measured and simulated canopy temperature in the center of the greenhouse were compared. A plot of the air temperature and the simulated canopy temperature is shown in Figure 3 for six days in May 1993. In reviewing both the simulated and the measured canopy temperature it appears that in the experimental period that transpiration cooling was insufficient to provide depression of leaf temperature below the inside air temperature. Measured data had greater variability and on a number of occasions the canopy was below the air temperature but it was not possible to say that this was not caused by random variation in the measured data. The heat absorbed by the canopy must be less than the heat to vaporize the transpired moisture. The rapid rise of the Solar heat was greater than the increase in transpiration rate, so that conditions necessary for a lowered canopy temperature appear rather unlikely. The transpiration energy was less than 250 w/m² whereas the net

absorbed energy was often greater than 400 w/m². Figure 4 gives the balance of net absorbed radiation that is transferred to the air by sensible and latent heat.

Lowering the vapor pressure of the air below what was observed did not simulate a latent heat exchange sufficient to lower the canopy temperature below the air temperature. From IR scanning of the canopy a temperature variation of 2-3 C was observed. The effect of this spread upon the transpiration could not be evaluated with either model.

Vapor Pressure, Leaf and Air

Figure 1.

Figure 2.

Temperatures, Inside and Canopy

Temperatures, Inside and Canopy

Temperatures, Inside and Canopy

Temperatures, Inside and Canopy

Temperatures, Inside and Canopy

Temperatures, Inside and Canopy

Figure 4.

Captions and comments on figures from IR Scanner

Fig.1 The distribution of temperatures in a canopy are not normally distributed. The mean is established where an equal area above and below exists. One deviation contains 69.3% of the area under the curve. Nadir viewing shows soil temperatures below the leaf temperatures in the early morning and is used as a mask to remove the soil temperatures from the distribution.

Fig.2 The shape of the temperature distribution is quite variable and was not considered a normal distribution.

Fig.3 The cumulative distribution or area of leaves above the temperature of the other leaves is shown at various times of the day. Note the tail in both directions approaches the axis asymptotically.

Fig.4 Fig 3 in the afternoon

Fig.5 Mean and std. dev of May 19th IR scans with times converted to zenith angle. These should fit the simulations in Infrared Measurement of Canopy Temperature and Detection of Plant Water Stress. M. Fuchs

Fig 6 Mean and std.dev. of May 20th IR scans

Fig.7 Mean and std.dev. of May 21st IR scans

Fig.8 Mean and std.dev. of May 23rd IR scans

Figures 5-8 would best be fit to a simulation of Nadir view with zenith angles as the x axis.

Tomato Leaf Temperature Distribution May 19 1993 Habsor Exp. Sta. 8 AM

Figure 1

Leaf Temperature Distribution Habsor Exp. Station May 19 1993

Figure 2.

Fraction of Leaves above Temperature Habsor Exp. Station May 19 1993

Figure 3.

Fraction of Leaves above Temperature

Habsor Exp. Station May 19 1993

Figure 4.

Habsor Experiment Station, May 19 1993

Infrared Scan of Tomato Canopy

Figure 5.

Habsor Experiment Station, May 20 1993

Infrared Scan of Tomato Canopy

Figure 6

Habsor Experiment Station, May 21 1993

Infrared Scan of Tomato Canopy

Figure 7.

Habsor Experiment Station, May 23 1993

Infrared Scan of Tomato Canopy

Figure 8.

```

* Appendix: Model code
* Find canopy temperature Tc
* Data was taken in Israel
*
* Inside Net Radiation RCAN
* = Si + Rfrom the glazing + Rcoming in from sky
*   - Rfrom the canopy
* Canopy received radiation QCAN
* = aSi + e(Rfilm + Rsky) - Rcanopy
* = aSi + SIG*(EGLA*TG4 + TGLA*EPSA*TO4 - TC4)
*   where TG = (Ti + To)/2
* Qs = CA/RA*(Ti - Tc)  Tc is canopy temperature
* Ql = CA/PSCH/(RA + RC)*(Ei - Ec)
* Ec is a function of Tc
*
MACRO TT4 = TABS(TT)
  PROCEDURAL
  TAA = (TT+273.16)/100.0
  TT4 = TAA*TAA*TAA*TAA
ENDMAC
*
MACRO VAPRES = PSYCR(TEMP)
  VAPRES = 0.611*EXP(17.4*TEMP/(239. + TEMP))
* VAPRES in kPa
ENDMAC
*
INITIAL
CONSTANT ABSO = 0.75, CA = 1164, PSCH = 0.066
  SIG = 5.67
  EPSA = 0.75
PARAM RA = 10.0, EGLA = 0.65, TGLA = 0.3
*
* ABSO is absorptivity of the canopy for solar radiation (ND)
* CA is heat capacity of the air (J/m3/C)
* PSCH is psychrometric constant (kPa/C)
* SIG is the Stephan-Boltzman constant
*   in consistent units (W/m2/K4)
* EPSA is the sky radiation
* RA is resistance of air boundary layer (sec/m)
* RC is resistance of the canopy (sec/m)
* Egl is the glazing long wave emissivity
* Tgl is the glazing long wave transmissivity
DYNAMIC
  SI = AFGEN(SITAB, TIME)
*   (W/m2)
  TO = AFGEN(TOTAB, TIME)
*   (C)
  TI = AFGEN(TITAB, TIME)
*   (C)
  EI = AFGEN(EITAB, TIME)
*   (kPa)
FUNCTION SITAB = 0.0,0.0, 5.0,0.0, 7.7,300.0, ...
  9.4,530.0, 10.2,550.0, 10.8,720.0, ...

```



```

12.3,730.0, 12.8,710.0, 16.2,305.0, ...
17.1,100.0, 17.5,50.0, 18.6,0.0, 24.0,0.0
*
FUNCTION TOTAB = 0.0,15.7, 1.5,14.0, 2.0,14.5, ...
                2.8,13.5, 4.5,13.6, 5.0,14.1, 6.5,18.0, ...
                10.1,24.5, 14.1,25.6, 17.0,23.0, ...
                17.8,20.6, 21.1,15.9, 21.6,16.2, ...
                22.7,15.3, 24.0,16.0
*
FUNCTION TITAB = 0.0,15.9, 1.1,14.9, 4.0,13.4, ...
                5.0,13.6, 7.8,26.6, 9.1,29.9, 10.5,27.7,...
                11.9,27.6, 12.2,30.8, 14.6,27.2, ...
                16.7,24.5, 18.2,20.0, 24.0,16.8
*
FUNCTION EITAB = 0.0,2.06, 24.0,2.06
*
PROCED  RC= RCIF(SI)
*
      IF (SI .LT. 100.0) GO TO 10
      RC= 93*(1+243/(SI/2.5))
***    RC=1/(3.2E-05*3.0*SI/2.5)
*
*    2.1 - 2.9 uMol of PAR = 1J of total solar radiation
*    From Principles of Environmental Physics by
*    Monteith and Unsworth
*
      IF (RC .GE. 1000.0) THEN  RC=1000.0
      GO TO 20
10      RC=1000
20      CONTINUE
*        [RC in s/m]
ENDPRO
*
      TC = IMPL(20.0, 0.1, TCEND)
*
      TG  = (TI+TO)/2
      TG4 = TABS(TG)
      TO4 = TABS(TO)
      TC4 = TABS(TC)
      EC = PSYCR(TC)
      RCAN = ABSO*SI ...
            + SIG*(EGLA*TG4+TGLA*EPSA*TO4-TC4)
*        [RCAN, QS & QL are in W/m2]
      QS = RCAN-QL
      QL = CA/PSCH/(RA+RC)*(EC-EI)
      TCEND=TI+QS*RA/CA
*
TERMINAL
      TIMER FINTIM=24.0, DELT= 0.2, PRDEL=0.2, OUTDEL=0.2
      PRINT TC, TI, EC, RC, QL
      PRTPLT TC, TI, EC, RC, QL
END
STOP

```

Transpiration from Canopy

CHAPTER IV

Resistance to water vapor diffusion of greenhouse tomato and pepper leaves

Marcel Fuchs, Shabtai Cohen, Jean Christophe Simon and Suguru Sato

1. Introduction

Stomatal aperture and cuticle permeability regulate the exchange of water vapor between the leaf and the surrounding air. Transport depends also upon the vapor pressure gradient established between the inner gas phase in the leaf and the free air. A major property of the greenhouse environment is the diminished convective flow, which increases considerably the boundary-layer resistance of the air in contact with the leaf. This resistance is in series with the leaf resistance. Therefore, the ability of stomata to regulate transpiration is much lower than that obtained outdoors. Solar radiation absorbed by the leaves generates heat which is dissipated inefficiently through the large boundary-layer resistance. If latent flux density is slowed by high leaf resistance, leaf temperature will rise. The increased temperature gradient accelerates sensible heat transfer, but also increases latent heat flux because of the exponential elevation of the saturation vapor pressure in the leaf. These relationships between leaf temperature, transpiration and leaf conductance are illustrated in a study of transpirational cooling in a greenhouse (Fuchs, 1993).

Cooling methods to prevent excessive temperatures in a greenhouse must take into account the variable component of leaf resistance which depends on stomatal aperture. The purpose of the following study is to determine the leaf conductance and to examine the influence of environmental factors prevailing in greenhouses on its value.

2. Methods

All the leaf resistance measurements were carried out in a climate controlled greenhouse with a polyethylene roof covered with a 30% shading screen at the Besor Experiment Station. The combined effect of the shade and the polyethylene film resulted in a 40% transmission of global radiation. The instrument was a LICOR 1600 steady porometer (Lincoln, Nebraska, U.S.A.). It measured diffusion of water vapor and incident photosynthetically active radiation (PAR) with a sensor fitted with a filter tailored for quantum response. Leaves were selected randomly, in two categories either in full direct sunlight or completely shaded. The porometer chamber was clamped to the leaf without changing its inclination and orientation. The PAR reading thus represented the incident light on the leaf. Measurements were taken on both sides of the leaves, but the reference PAR was always taken for an upward facing sensor. Measurements started in the morning when the sun was sufficiently high in the sky for direct radiation to pass exclusively through the roof. They stopped in the afternoon for the symmetric condition.

The tomato crop was taken at its mature stage of development in May. The crop had been planted in October the year before. Because most of the older leaves were necrotic, the studied sample consisted of middle aged taken from the middle one-third layer of foliage, and

young leaves from upper one-third layer. The crop received water and soluble fertilizers daily by drip application.

Leaf resistance of sweet pepper was measured in May and June, in a mature crop planted in September of the previous year. Measurements were also carried out in young plantation dating from January. The mature crop canopy was divided in three layers to stratify the data according to leaf age. There was no segregation of the young plantation.

3. Results

Leaf inclination and orientation exposed the leaves to a wide range of direct incident PAR. Position of the leaf inside the canopy and the time of the day affected the intensity of the diffuse radiation. Other environmental conditions like temperature and humidity remained within a narrow range of variation, because temperature set points controlled the ventilation of the greenhouse. As soil moisture supply was always high, PAR remained the only environmental variable affecting directly leaf resistance.

Figure 1 shows all the data collected for the tomato plant. The mathematical model selected to fit the data is a rectangular hyperbola parameterized by a minimum resistance and a PAR sensitivity factor indicating the photon flux density for which the actual leaf resistance is twice the minimum value. These two parameters have been shown to respond to soil moisture stress.

The stomatal resistance of the tomato leaf varies rapidly with light intensity reaching a value twice its minimum for a photon flux density of $280 \mu\text{mol m}^{-2} \text{s}^{-1}$. The minimum leaf resistance is not a very low value. Yet, according to the model (Fuchs, 1993) it is sufficiently low to allow efficient self cooling by transpiration. Stanghellini (1987) has compiled leaf resistance data of tomato for use in a transpiration model in greenhouses, but uses different mathematical formulations. For the few points with comparable data, the values of leaf resistance are similar to those reported here. Another study by Boulard et al., (1991) was analyzed according to the mathematical model proposed here. This analysis is shown in Figure 2. The results are remarkably similar to those measured at Besor, suggesting that the functional relation reported here can serve adequately climate control models.

A similar study for sweet pepper yielded the same general functional dependence of leaf resistance on light. The segregation of leaves of a mature crop in three classes according to height, showed not difference between leaves of the upper one-third layer and the mid layer. Leaves from the bottom had higher minimum leaf resistance, but a greater sensitivity to light, reaching minimum resistance at low light intensity. These results are illustrated in Figures 3, 4, and 5. The leaves in the upper two thirds of the canopy had very low minimum resistance, but the change of resistance with incident light was slower than that of the tomato leaves. A second set of measurements carried out on a much larger sample that includes only leaves of the upper two thirds of the canopy confirmed the low value of minimum leaf resistance, but showed faster change with incident light (Figure 6). The sweet pepper can cool itself much more efficiently than tomato.

Figure 1. Tomato leaf response to incident photosynthetically active radiation.

Figure 2. Tomato leaf resistance response to incident photosynthetically active radiation, replotted from Boulard et al., (1991).

Figure 3. Diffusion resistance response to photosynthetically active radiation of old sweet pepper leaves.

Figure 4. Diffusion resistance response to incident photosynthetically active radiation of sweet pepper leaves in the middle of the canopy.

Figure 5. Sweet pepper leaf resistance response to incident photosynthetically active radiation in the one third upper layer of the canopy in a mature crop.

Figure 6. Sweet pepper leaf resistance response to incident photosynthetically active radiation. Combined data for upper two third canopy layer of mature crop, and all layers of a young plantation.

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CHAPTER V

Using artificial leaves to characterize the boundary-layer resistance in greenhouses

Marcel Fuchs and Ziva Barel

1. Introduction

The high value of the boundary-layer resistance of items in a greenhouse is the main factor differentiating the aerial environment of plants from outdoors conditions. The importance of this boundary-layer emerges from the previous sections. Yet, very few studies have addressed this issue in greenhouses. A frequent method of investigation in the free atmosphere uses artificial leaves. The principle is to follow the dissipation of a known amount of heat while measuring the temperature difference between the leaf and the bulk air. To compensate for the uncontrolled environmental heat load, the differential response of two artificial leaves is measured: one leaf received a controlled amount of heat, the other submitted only to environmental heat sources (Pearman, et al., 1972; Brenner and Jarvis, 1995). The technique implies that the two replicas are identical and submitted to the same environmental heat sources. Stanghellini used a similar approach to study boundary-layer resistances of tomato leaves in a greenhouse. Two separate devices in an obstruction free environment, have similar exposure to the environmental energy load, but in a vegetation canopy uneven distribution of sun and shade, and uneven hindrance of air movement creates heterogeneity.

We considered an approach based on a single artificial leaf submitted to cyclic heating. By making the period of the cycle sufficiently short and repeating the cycling for a long period, variability caused by the movement of the sun and of the air become negligible. Relating the amplitude of the heating with the amplitude of the temperature difference between leaf and air yields heat transfer coefficient directly related to the boundary-layer resistance.

2. Methods

The analytical solution of the heat transfer problem and the technical details about the construction of the artificial leaves constitute the M.Sc. thesis of Ziva Barel. For an understanding of the results relevant to the present report, the following information is relevant.

The artificial leaves were constructed of thin (10 μm) aluminum foil. This material has high reflectivities in the solar (0.87) and thermal (0.95) wave length bands. Therefore, it minimizes radiative exchanges. Most of the heat dissipation of the artificial leaves was through convective exchange to improve the accuracy of the determination. Aluminum foil has also a small thermal mass lowering the time constant of the artificial leaf to allow a cycling periodicity of 300 s.

Table I. Geometrical and electrical characteristics, and heat transport calibration factors of artificial leaves. The calibrated heat transfer coefficient is $h = A^*(U/L_p)^{1/2} + B^*(\Delta T/L_p)^{1/4}$, where U is the bulk air wind speed in $m\ s^{-1}$ and ΔT is the temperature difference between the leaf and the bulk air in K .

leaf no.	shape	A $J\ m^{-2}\ s^{-1/2}\ K^{-1}$	B $W\ m^{-7/4}\ K^{-5/4}$	Standard deviation		R^2	Resistance Ω	area cm^2	Dimension L in m		
				A	B				L_n natural	L_f forced wind tunnel	L_f forced greenhouse
1	ellipse	4.49	2.27	0.35	0.25	0.877	29.46	40	0.0167	0.0694	
2	ellipse	4.59	1.94	0.53	0.35	0.761	30.48	40	0.0167	0.0694	
3	ellipse	5.12	2.18	0.44	0.28	0.857	28.00	40	0.0167	0.0694	
4	ellipse	4.96	2.35	0.20	0.15	0.964	29.51	40	0.0167	0.0694	
18	ellipse	5.59	1.84	0.22	0.16	0.921	29.16	40	0.0167	0.0694	
17	rectangle	4.86	1.96	0.17	0.10	0.934	28.94	40	0.0146	0.095	0.0767
13	rectangle	4.14	2.24	0.40	0.23	0.849	29.05	40	0.0146	0.095	0.0767
10	rectangle	5.47	2.27	0.46	0.27	0.845	29.86	40	0.0146	0.095	0.0767
11	rectangle	5.12	2.51	0.55	0.30	0.809	30.33	40	0.0146	0.095	0.0767
12	rectangle	5.74	2.38	0.29	0.17	0.943	29.44	40	0.0146	0.095	0.0767
8	tomato	4.22	1.96	0.50	0.31	0.770	29.58	40	0.0142	0.0638	
14	tomato	3.96	2.15	0.04	0.03	0.989	69.14	100	0.0185	0.098	
15	tomato	4.40	2.25	0.05	0.02	0.996	70.29	100	0.0185	0.098	
16	tomato	3.40	2.38	0.44	0.26	0.688	28.66	40	0.0142	0.0638	
7	tomato	4.04	2.26	0.22	0.17	0.866	29.55	40	0.0142	0.0638	
5	tomato	4.07	2.36	0.24	0.18	0.931	29.42	40	0.0142	0.0638	

The heater was a boustrophedon patterned winding of a resin coated copper wire 0.08 mm in diameter and a resistance per unit length of $3.44 \Omega \text{ m}^{-1}$. The pace of the winding is 1 mm. Five copper constantan thermocouple wires 0.127 mm in diameter were inserted in the heater winding. The heater and the thermocouples were glued between two layers of foil. Artificial leaves were installed in a separated span 7.5 m wide and 23 m long of a multi-span greenhouse. Height at the ridge was 5.6 m and 4.0 m at the gutter. The ridge was oriented north-south. The roof cladding material was a polyethylene film with infrared absorbing additives. The north and south sides had roll-up walls from 0.8 m above the floor to a height of 2.0 m and 2.8 m on the south and north walls, respectively. Plastic nets with a maximum free passage of 0.35 mm covered the openings. Two exhaust window fans, with a rated out flow of $16,000 \text{ m}^3 \text{ h}^{-1}$ at zero static pressure, were mounted on the south gable. The crop was tomato in 1993 and sweet pepper in 1994. Both species were grown in twin rows on a 0.8 m wide bed separated by a path 1 m wide trellised to identical row geometry. The artificial leaves were mounted among the leaves in the outer layer of the foliage at various heights and locations to characterize vertical and horizontal profiles.

To vary ventilation we opened end walls or operated one or two fans mounted on the north gable of the greenhouse. We measured the internal air flow with a hot-bulb anemometer (Testoterm model 490, Lenzkirch, Germany).

3. Results

A total of 19 artificial leaves was made. Their characteristics are summarized in Table I. Some leaves were given defined geometrical shapes to establish a comparison with results of heat transport theory. All the leaves were calibrated in a wind tunnel. The calibration factors for free and forced convection are summarized in Table I.

The wind tunnel calibration showed that heat transport measured by the cycling heating procedure followed reproduced the classical heat transfer coefficients. This agreement is illustrated in Figure 1. Figure 2 shows the same data after conversion to a boundary-layer resistance compatible with the formulation of the mode:

Figure 1. Heat transfer coefficient of an artificial leaf simulating a tomato leaflet.

Figure 2. Boundary-layer resistance derived from Figure 1.

$$r_a = \frac{\rho c_p}{h} = 203 \left(\frac{U}{L} \right)^{1/2}$$

where ρ is the density of air and c_p its specific heat. A linearized multi-variate analysis extracted the calibration factors in Table I from the data collected in the wind tunnel.

Because wind varied during the experiments, the data were analyzed according to wind speed and leaf area density to establish patterns of heat transfer distribution within the greenhouse.

A first result is that the wind speed in the greenhouse is extremely low and varies under the influence of ventilation treatments. Leaf area distribution affected the development of air flow profiles (Figure 3). Where the leaf area density is high, we find a marked decrease of wind speed. Interestingly, the data show evidence of air flow acceleration near the ground, probably associated with convective cells.

Measured transfer coefficient also had a narrow range of variations within the tested experimental conditions. This finding confirms the results of slowly varying boundary layer resistances over bare soil in earlier section of the report. Analysis of the data according to wind speed and leaf area density showed the direct effect of wind speed was sufficiently dominant to mask other factors (Figure 4).

4. Conclusions.

The experiment showed that the boundary-layer of the leaves has a large value associated with the reduced air movement in the greenhouse. Yet, its variability is low and accountable by variations of the air movement in the greenhouse.

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Figure 3. Air velocity and leaf area profile in a greenhouse.

Figure 5. Heat transfer coefficients of leaves in a greenhouse.

CHAPTER VI

Enhancing latent heat dissipation

Marcel Fuchs

1. Introduction

The theoretical model in Chapter II of this report has shown that the leaf resistance to water vapor diffusion played a dominant role in the control of foliage and air temperature in greenhouses. The study of leaf resistance of two major vegetable crops, tomato and sweet pepper, in Chapter IV showed that with proper irrigation, the leaf resistance is sufficiently low to allow adequate cooling in most warm weather and high solar radiation conditions. Still some crops may have higher leaf resistances and extremely warm weather may cause excessive heating. Enhancing latent heat dissipation by putting the air of the greenhouse in contact with free liquid water surfaces is a possible way to improve the growing environment. Several techniques are available to achieve this result. We investigated two of the simplest and most commonly used: the wet pad system, and plant canopy wetting by overhead spray sprinklers. Although the research plan included theoretical and experimental treatment of the cooling operation in greenhouses, we discovered a severe malfunction of the temperature recording system, that impairs the reliability of the data in the research greenhouse at Besor. Therefore, the following results refer only to the theoretical analysis.

2. Theory

The model developed in Chapter II allows evaluating the effect of a wet pad and fan. Replacing the temperature T_o , and the water vapor pressure e_o , of the air entering the greenhouse by the wet bulb temperature T_w , and saturation vapor pressure $e(T_w)$ simulates a 100% efficient system. The computation of these two variables derives from the solution of the following equations:

$$T_w = T_o + \frac{e_o - e(T_w)}{\gamma}$$

$$e(T_w) = 610.8 \exp\left(\frac{17.27T_w}{237.3 + T_w}\right)$$

where γ is the psychrometric constant. The expression for saturation vapor pressure is an empirical integration of the Clausius-Clapeyron equation. (Tetens, 1930). A Newton-Raphson iteration was used to solve the nonlinear equations:

$$T_{w[n+1]} = T_{w[n]} - \frac{F(T_{w[n]})}{F'(T_{w[n]})}$$

$$F(T_{w[n]}) = T_{w[n]} - T_o - \frac{e_o - e(T_{w[n]})}{\gamma}$$

$$F'(T_{w[n]}) = 1 + \frac{\frac{4,098}{(237.3 + T_{w[n]})^2} e(T_{w[n]})}{\gamma}$$

where n is the iteration step. Latent dissipation by the wet pad is:

$$E_{pad} = \frac{\rho c_p}{\gamma} \frac{(e(T_w) - e_o)}{r_x}$$

where ρ is the density of air, c_p is its specific heat and r_x is the air exchange resistance. In the result section latent heat dissipation is converted into evaporation in mm h^{-1} and the exchange resistance in air volume exchanges h^{-1} .

The procedure for simulating the cooling of spray wetting on the internal microclimate derived from the transpiration model developed in Chapter II. Wetting the foliage surface sets the value of leaf resistance in Eq. 13 in Chapter II to zero.

3. Results

a. Wet pad and fan

Cooling produced by wet pad operations depends on the humidity of the outdoor air and the rate air renewal in the greenhouse. The other inputs of the greenhouse microclimate model are treated at fixed parameters representing typical growing conditions of a warm summer day.

A common engineering specification for fan selection is to provide 20 air exchanges per hour in the greenhouse. Using this datum as an input, we evaluated the effect of external humidity on the cooling in a greenhouse submitted to 1000 W m^{-2} of global radiation and an outdoor air temperature of 32°C . The calculations were made for a tomato crop with a leaf area index of 3 and a leaf resistance of 100 s m^{-1} . Comparing between foliage temperature with ventilation only and wet pad in operation shows practically no differences over the entire range of outdoors humidity (Figure 1). The conclusion is that at the prescribed ventilation rate, wet pad and fan does not improve the thermal environment of transpiring foliage. By contrast, it cools the internal air by several degrees, decreasing the heat load on non-transpiring organs. It increases internal humidity. For an outdoors relative humidity of 40%,

Figure 1. Cooling effects of wet pad and fan at an air exchange rate of 20 volumes per hour.

internal water vapor pressure rose from 2,947 Pa without the pad to 3,225 Pa with the pad. Corresponding relative humidities changed from 62 to 66%.

Water consumption by the evaporating pad, for these conditions, is of the same order of magnitude as the transpiration of the crop (Figure 2). Evaporation and transpiration are compensating processes, because they depend on the same supply of radiant energy and the enthalpy of the fresh air from outdoors.

Keeping the same input conditions, but doubling the air exchange rate to 40 per hour improves substantially the cooling of foliage. Still, the relative humidity must be below 40% (Figure 3).

In regions with dry air, the wet pad is an effective cooling device. Yet, ventilation rates should be higher than those currently recommended. The price of this cooling is a considerable increase of the water consumption by the pad (Figure 4).

As ventilation rate appears is a critical design feature of the wet pad and fan, its effect on cooling is simulated in Figure 5. The results show that the efficacy of the system increases up to 40 air exchanges per hour. Above this rate, the marginal return is insignificant. Yet, water consumption of the evaporating increases linearly with ventilation rate (Figure 6). Therefore, exceeding 40 air exchanges per hour is not recommended.

Figure 2. Water use of crop and wet pad with a ventilation rate of 20 volume exchanges per hour.

Figure 3. Cooling effect of a wet pad and fan at a ventilation rate of 40 volume exchanges per hour.

Figure 4. Water use by crop and wet pad at 40 volumes of air exchange per hour.

Figure 5. Effect of ventilation rate on the cooling produced by a wet pad.

Figure 6. Effect of ventilation rate on the water use of crop and wet pad.

Figure 7. Cooling produced by wetting foliage when ventilation rate is 20 air exchanges per hour.

Figure 8. Cooling produced by wetting the foliage when ventilation rate is 40 air exchanges per hour.

b. Foliage wetting

The cooling effect of wetting the foliage was tested for the same environmental conditions as those used for the wet pad and fan. At a ventilation rate of 20 h^{-1} , wetting the foliage cooled it 2 to 4°C below the control over the entire range of outdoors relative humidity (Figure 7). Yet for outdoors humidities above 60%, the cooling was not sufficient to cool the tomato foliage to values ensuring a high quality production. Cooling of the internal air temperature was only between 1 and 2°C . Increasing the ventilation rate to 40 h^{-1} did not change the difference between wetted foliage and dry control (Figure 8). Yet, it extended the range of effective treatment to outdoors relative humidities of 70%. Therefore, the wetting of the foliage may be applied effectively in areas with high humidities provided ventilation is adequate.

Wetting the foliage is considered a hazardous practice because it favors the development of fungal disease.

Avoiding excess water application can minimize the risks. Figure 9 gives the water consumption of the wetted foliage. These data are essential for proper timing and operation of the overhead sprinklers. Evaporation from the wet foliage is only higher than the transpiration of the crop alone. Wetting completely the foliage would suppress transpiration. Yet, because of superficial tension, water forms droplets on the leaf. Therefore, the effective water use and cooling ability may fluctuate between the boundaries set by the curves in Figures 7, 8 and 9.

References

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Figure 9. Water consumption of a wetted and a normal crop at 40 air exchanges per hour..

COOPERATION

The major cooperative effort was the research carried out at Besor during the stay of Dr. Jordan in Israel. Dr. Jordan organized the rental of a thermal camera that allowed to map and evaluate the temperature heterogeneity in the greenhouse. The data obtained by the camera received preliminary review during the visit of Dr. Jordan, using a special electronic image grabber. A special software made by the manufacturer of the thermal camera decoded, calibrated and screened the data. Because of high cost of the image grabber and associated software the use of the equipment was shared by partners. Analysis of the data produced a model described in Chapter III. The data collected during the experiment are compiled as graphs in the Appendix. We planned a visit of Dr. Fuchs to the University of Arizona for additional work on image analysis had to be canceled for health reasons.

CONCLUSIONS

The main practical finding of the research is that two of the major vegetable crops, tomato and sweet pepper can withstand the high heat load at the end of their growing season. Irrigation according to the current recommendation ensures that leaf resistance to water vapor diffusion is sufficiently to maintain the foliage and the air in the greenhouse below harmful temperatures. Ventilation must be at least 30 air exchanges per hour.

Passive ventilation obtained by rolling up opposite side walls, though highly dependent on outside wind, proved superior to electrical fans. The efficiency of wet pad cooling depended very much on outdoors relative humidity, but cooling required ventilation rates twice those recommended currently.

The cooling efficiency of latent heat depended largely on the resistance of the evaporating surface to water vapor diffusion. Any decrease of this resistance reduces considerably the temperature of the evaporating surface. Yet, the corresponding increase of water consumption remained low. Spray wetting the foliage enhanced cooling by approximately 2 °C for most conditions encountered in greenhouses.