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Greenhouse Crop Transpiration Modelling

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1. Introduction

Aim of this chapter is to present the parameters affecting greenhouse crop transpiration and the existing models for greenhouse crop transpiration simulation. In the first paragraphs of the chapter, the importance of crop transpiration on greenhouse microclimate and on crop is presented and discussed. Presentation, analysis and discussion of the parameters affecting greenhouse crop transpiration and the thermal and hydrological negative feedback effects follow. Finally, the existing models for greenhouse crop transpiration simulation are presented and discussed.

Transpiration is an important component of canopy energy and water balance and thus, a major cooling mechanism of greenhouse crop canopies. Its estimation is essential for climate and irrigation control and that is why it has been given much attention in greenhouse climate research.

Air temperature and vapour pressure deficit are parameters affecting the thermal and hydrological negative feedback effects existing in a greenhouse. In addition, the main factors affecting greenhouse crop transpiration are solar radiation, vapour pressure deficit and canopy and aerodynamic conductances.

Several authors have proposed models that allow getting a more accurate estimation of the crop transpiration rate. More sophisticated transpiration models are based on leaf (canopy) transpiration and leaf energy balance models in which the transpiration is characterized by the canopy resistance, as proposed initially by Penman and modified by Monteith to account for the stomatal response of the crop (P-M formula). However, the use of the complete P-M formula requires the knowledge of several inputs or parameters that are not easily available. Particularly, the aerodynamic and stomatal leaf resistances have to be known for each crop species and possibly, for each cultivar. That is why researchers have tried to overcome the estimation of these resistances by using a simplified form of the P-M formula. Transpiration models with the greenhouse climate as a boundary condition were first developed in the northern regions of Europe and North America for horticultural crops. In these northern conditions, the glasshouse is generally poorly ventilated during a large part of the growing season. The boundary layer conductance for glasshouse crops tends to be much smaller than would be expected for similar crops growing outdoors. Thus, glasshouse crops are very strongly decoupled from the outside atmosphere by the presence of the glass, and the heat and the water released at crop surface will accumulate inside the

glasshouse. Consequently, the transpiration rate will adjust until it reaches a stable equilibrium transpiration rate dictated by the net radiation received. On the contrary, greenhouse crop transpiration in Mediterranean or similar warm conditions is much more dependent on convection. As the ventilation and the turbulent mixing are vigorous, the saturation deficit at the leaf surface is closely coupled to the deficit of ambient air, and the latter is directly influenced by the outdoor saturation deficit.

2. The importance of crop transpiration on greenhouse microclimate and on crop

Transpiration is an important component of canopy energy and water balance and thus, a major cooling mechanism of greenhouse crop canopies. Its estimation is essential for climate and irrigation control and that is why it has been given much attention in greenhouse climate research. The concentration of water in plants should be kept within a narrow range so as to provide the conditions for optimum growth. A 10% reduction could affect the functioning and development of plants or even cause their death. In plants, the water is used in a wide range of functions:
- It is the component with the highest concentration and makes up about 70% to 95% of plant fresh weight. It gives shape and rigidity in plants.
- It is used as a means of dissolution and ion source, is the means for transportation of nutrients from soil to plant and is essential in many biochemical reactions.
- Finally, due to its high specific heat, the water cools the leaves through its evaporation and prevents plant overheating.

Plant water content depends on two main factors:
- the availability of water in the substrate-soil and its absorption by the roots and
- the evaporation of water from leaves, i.e. transpiration.

Crop transpiration is affected by (Figure 1):
- intercepted radiation
- the difference between the vapour pressure of air and the saturation vapour pressure at leaf temperature (crop-air vapour pressure deficit), the conductivity of the transfer of water from the interior of the leaf surface (stomatal conductance) and the conductivity of the water transfer from the surface of the leaf to the air (aerodynamic conductance).

For short periods, when the air vapour pressure deficit increases (in response to air relative humidity reduction), stomata begin to shut down gradually to reduce water stress (Choudhury and Monteith 1986). The negative effect is significantly higher for air vapour pressure deficit values higher than 1 kPa. If plants reach higher levels of water stress, the roots can not supply the aboveground part of plants with enough water, plants lose their rigidity and turgid and irreversible damage may occur on the leaves. Under drought stress, most of the water goes to the leaves and fruit growth is reduced. In addition, damage can be caused by direct 'burning' of leaves. In this case, transpiration through the process of cooling by evaporation is playing an important role in reducing the high temperature of the crop and the appropriate actions should be taken to maintain transpiration in its maximum rate.

In greenhouse conditions it is possible to control crop transpiration rate and regulate it in desired levels. To this end, shading, ventilation and cooling systems are mainly used, regulating direct radiation R_n, air temperature T_i and vapour pressure deficit D_i (= difference between the actual vapor pressure of air to saturation vapour pressure) (Figure 2), factors affecting direct (R_n) or indirectly (T_i, D_i) crop transpiration.
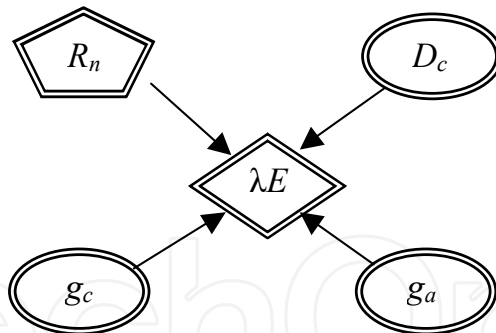
Fig. 1. Factors affecting crop transpiration. R_n = net radiation, D_c = crop-air vapour pressure deficit, g_c = crop stomatal conductance, g_a = crop aerodynamic conductance.

3. Parameters affecting greenhouse crop transpiration and the thermal and hydrological negative feedback effects

Air temperature and vapour pressure deficit are parameters affecting the thermal and hydrological negative feedback effects existing in a greenhouse. In addition, the main factors affecting greenhouse crop transpiration are solar radiation, vapour pressure deficit and canopy and aerodynamic conductances.

3.1 Natural and forced ventilation

As shown in Figure 2, ventilation directly affects the temperature and air vapour pressure deficit. At the same time affects the crop aerodynamic conductance by changes of wind velocity regime in the greenhouse. Besides crop aerodynamic conductance, ventilation affects greenhouse water vapour exchanges (greenhouse aerodynamic conductance). Experimental results on the effect of ventilation rate on greenhouse aerodynamic conductance are given in Table 1 (Fuchs et al. 1997).
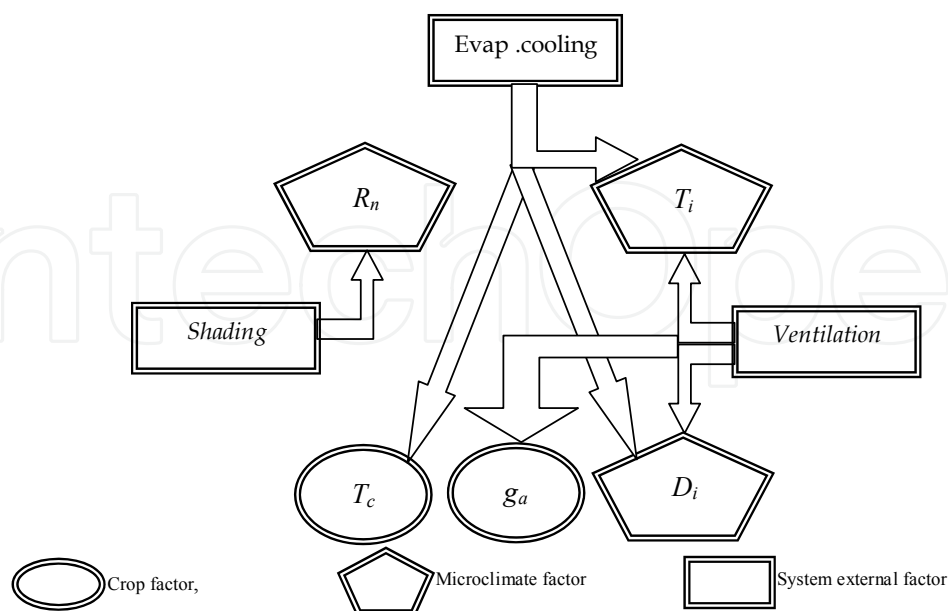

Fig. 2. Direct effects greenhouse climate control systems on greenhouse microclimate and on crop. D_i = air vapour pressure deficit, T_i = air temperature, R_n = net radiation, g_a = crop aerodynamic conductance, T_c = crop temperature.

Greenhouse ventilation effects also crop stomatal conductance through imposed effects on crop temperature and on canopy to air vapour pressure deficit crop. The last is affected by crop temperature and air vapour pressure deficit (Figure 3).

Kittas et al. (2001) observed that increasing greenhouse air exchange rate by means of forced ventilation resulted in an increase of canopy to air vapour pressure deficit and a decrease of crop stomatal conductance by 20% compared to the case of natural ventilation. Bunce (1985) observed that for the same increase in air vapour pressure deficit, total crop conductance decreased from 1.6 to 3 times more when the wind speed was 3 m s^{-1} than in the case where the wind speed was 0.5 m s^{-1}.

| N | ΔT_{i-o} | D_i | ΔD_{i-o} | g_v | β |
h-1	^{o}C	kPa	kPa	mm s-1	
3.1	20	4.69	2.43	4.0	0.55
8.1	9.65	2.98	0.97	10.8	0.66
13.3	6.55	2.55	0.55	17.7	0.79
44.1	5.05	2.83	0.23	58.8	1.44

Table 1. Effect of ventilation rate (N h^{-1}) on greenhouse to outside air temperature difference (ΔT_{i-o} ^{o}C), greenhouse air vapour pressure deficit (D_i kPa), greenhouse to outside air difference of the difference air vapour pressure deficit (ΔD_{i-o} kPa), greenhouse aerodynamic conductance (g_v mm s^{-1}) and Bowen ratio (β). (Fuchs et al. 1997).

Consequently, another variable affected by air exchange rate and ventilation regime is crop aerodynamic conductance, due to changes imposed by ventilation in greenhouse wind velocity. For the case of a leaf, the aerodynamic conductance ($g_{l,a}$) is given by (Monteith 1973):

$$g_{l,a} = 6.62 \; 10^{-3} \left(u / d\right)^{0.5} \qquad (1)$$

where u (m s^{-1}) is the mean greenhouse air velocity near the crop level and d (m) is the characteristic leaf length.

In the case of a closed greenhouse, the wind velocity inside the greenhouse is very small and a fixed value for crop aerodynamic conductance could be acceptable. This hypothesis is confirmed by experimental results (Stanghellini 1987). During periods that the greenhouse is ventilated, the wind velocity inside the greenhouse is important and its effect on crop aerodynamic conductance can not be ignored. Therefore, under these circumstances a more realistic approach should be considered which would consider crop aerodynamic conductance as a function of greenhouse ventilation rate (Seginer 1994; Kittas et al. 2001). Katsoulas (2002) states that for a rose crop with a leaf area index of 2, crop aerodynamic conductance was about 52 mm s^{-1} under natural ventilation and 123 mm s^{-1} under forced ventilation conditions.

The latent heat energy H_c (W m^{-2}) exchanged between the crop and the air is given by the following relation

$$H_c = \rho \; C_p \; g_a \; \Delta T_c \qquad (2)$$

where ρ (kg m^{-3}) indicates density and C_p (J kg^{-1} ^{o}C) specific heat of air and ΔT_c indicates crop to air temperature difference. The above function shows the effect of aerodynamic

conductance and accordingly of ventilation rate on energy partitioning into sensible and latent heat at the level of the crop.
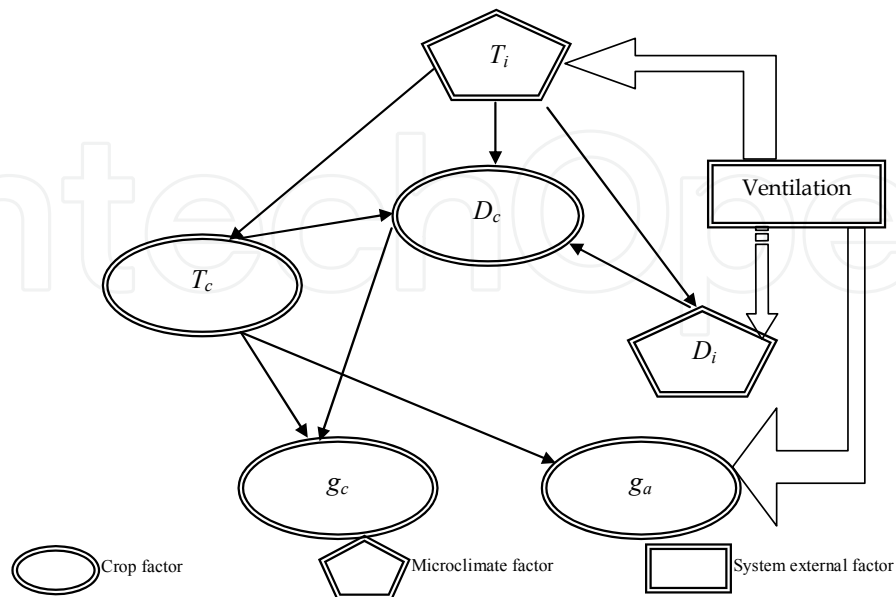

Fig. 3. Effect of greenhouse ventilation on greenhouse microclimate and on crop. T_i = air temperature, T_c = crop temperature, D_i = air vapour pressure deficit D_c = canopy to air vapour pressure deficit, g_c = crop stomatal conductance, g_a = crop aerodynamic conductance.

However, despite the significant influence of ventilation on greenhouse and crop microclimate, little is known about the effect of ventilation rate on crop energy partitioning. Boulard and Baille (1993) showed the effect of ventilation rate on greenhouse crop transpiration, indicating that transpiration is significantly affected by the air exchange rate and the air vapour pressure deficit. The above authors conclude that when vents were opened to the maximum aperture, the energy used for transpiration accounted for 45% of incoming solar radiation, while in the case of small vent openings, the transpiration accounted for 30% of incoming solar radiation.

Nevertheless, Katsoulas (2002) states that ventilation rate (with natural or forced ventilation) did not appear to significantly affect the distribution of energy into sensible and latent at the level of the crop although the average aerodynamic conductance was double under forced ventilation conditions (120 mm s^{-1}) than under natural ventilation (approximately 50 mm s^{-1}). He explains that transpiration rate remains at similar levels under the different ventilation regimes due to the interaction and feedback loops between canopy to air vapour pressure deficit and crop stomatal conductance.

Fuchs (1993) studied the transpiration rate of a tomato crop in relation to ventilation rate for different conditions of solar radiation and air relative humidity. It has to be noted that the crop aerodynamic and stomatal conductance and the greenhouse aerodynamic conductance are in series and that vapour transfer from inside the crop to outside air will be controlled by the smallest conduction. When greenhouse air exchange rate is high, transpiration will be probably controlled by crop stomatal conductance, which may not be true for low ventilation rates. Fuchs (1993), therefore, observed that for low values (10 h^{-1}) of greenhouse volume air exchange rate, transpiration was not affected by changes in crop stomatal

conductance, while for large values of greenhouse air exchange rate transpiration was directly affected by changes in crop stomatal conductance.

3.2 Greenhouse shading

In the previous section it was shown that greenhouse ventilation is important for creating the necessary conditions for crop development during summer. However, natural ventilation alone is not sufficient to remove the excess sensible energy from the greenhouse during sunny summer days (Baille 1999). For this reason, ventilation should be used in conjunction with other greenhouse cooling systems.

One of the most common methods used by the growers, due to its simplicity and low cost of implementation is white washing of greenhouse roof. By greenhouse roof white washing solar radiation entering the greenhouse is reduced something that directly affects air and crop temperature due to reduction of available energy and changes induced in crop stomatal conductance. One advantage of greenhouse shading by white washing over other techniques is that shading does not affect greenhouse ventilation while internally or externally mounted curtains adversely affect ventilation efficiency. The white washing also significantly increases the proportion of diffuse radiation in the greenhouse, which is known to increase radiation use efficiency (Alados and Alados-Arboledas 1999). Shading directly affects crop temperature and stomatal conductance due to reduction of available energy in the greenhouse and the crop. Katsoulas (2002) indicates that reduction of incoming solar radiation in the greenhouse resulted in canopy to air vapour pressure deficit. At the same time, he notes that while during the period without shading the canopy to air vapour pressure deficit was high; shading of the greenhouse led the crop to non heat and water stress conditions. Thus, the same author notes that shading of the greenhouse resulted in lower crop temperature and increase of crop stomatal conductance and transpiration rate. Finally, several researchers (Boulard et al. 1991, Abreu and Meneses 2000, Dayan et al. 2000, Fernandez-Rodriguez et al. 2000) indicate that greenhouse shading causes a decrease in crop temperature and transpiration rate.

3.3 Greenhouse evaporative cooling

The effect fog cooling on greenhouse microclimate is direct through effects on temperature and air vapour pressure deficit (Cohen et al. 1983, Arbel et al. 1999) and indirect to the crop through effects on crop temperature, stomatal and aerodynamic conductance, transpiration rate, etc.).

Fog cooling affects crop performance since reduces crop temperature and air vapour pressure deficit thus helping to reduce crop heat and water stress. In addition to reducing the temperature of the air, fog cooling directly reduces crop temperature when evaporation is done on the leaves, or indirectly through the reduction of air temperature and changes in transpiration. Moreover, by reducing the temperature and air vapour pressure deficit crop stomatal and aerodynamic conductances are modified which, together with the canopy to air vapour pressure deficit affect crop transpiration. It was found that fog cooling improved rose crop production mainly due to reduction of crop water stress index (Spoelstra 1975, Plaut and Zieslin 1977). Regarding production, several researchers (Spoelstra 1975, Plaut and Zieslin 1977, Plaut et al. 1979, Javoy et al. 1990) observed an increase in quality and quantity of production. There was no effect of fog cooling on flowers life after harvest (Urban et al. 1995). Finally, it has been observed that fog cooling increased crop leaf area

index (Plaut et al. 1979, Katsoulas et al. 2001). Many authors (eg: Kaufman 1982, el Sharkawy and Cock 1986, Schulze 1986, Munro 1989, Bakker 1991, Jolliet and Bailey 1992, Baille et al. 1994a) studied the effect of air vapour pressure deficit on crop stomatal conductance. Most work has been done in parts of northern Europe where low levels of radiation and vapour pressure deficit do exist. Bakker (1991) for example, observed reduction in stomatal conductance, about 65% caused by an increase of air vapour pressure deficit of 1 kPa. Montero et al. (2001) however, found no significant reduction of crop stomatal conduction when air vapour pressure deficit increased from 1.4 kPa to 3.4 kPa. indicate that there is no clear evidence that stomatal conductance is directly affected by air vapour pressure deficit. Nevertheless, Baille et al. (1994) and Katsoulas et al. (2001) that carried out measurements in Mediterranean greenhouses, noted that use of fog cooling increased crop stomatal conductance and indicated that maximum values of crop stomatal conductance where observed when solar radiation exceeded 300 W m-2. Regarding the effect of fog cooling on crop transpiration, several authors (eg: Plaut and Zieslin 1977, Boulard et al. 1991, Dayan et al. 2000) reported that use of fog cooling caused a reduction in crop transpiration rate. In contrast, other researchers (eg: Boulard and Baille 1993, Urban et al. 1995) report an increase of crop transpiration under fog cooling. Furthermore, Baille et al. (1994) and Katsoulas (2002), focused on the effect of fog cooling on day lag-hysteresis observed between transpiration and vapour pressure deficit on the one hand and transpiration and solar radiation on the other hand, observing a significant effect of fog cooling in the daily course of the curves of hysteresis. The hysteresis observed was reversing counterclockwise in the case of transpiration with radiation and consistent counterclockwise in the case of transpiration and air vapour pressure deficit. Moreover, Katsoulas (2002) observed a hysteresis between stomatal conduction and solar radiation and air vapour pressure deficit.

3.4 Leaf area index

Crop transpiration, through the process of cooling by evaporation, represents the main mechanism for greenhouse and crop cooling. This explains why maintaining high levels of transpiration rate in a greenhouse crop is one of the most effective and least costly ways of cooling the greenhouse environment during the warm season with high thermal loads, as happens from April to October in the Mediterranean countries Such as Greece (Baille 1999). To achieve high rates of transpiration, it is essential that certain conditions are met:

The crop should be well developed and should have a well-irrigated root system.

The leaf area of the crop must be large enough to convert the high amounts of energy in latent heat through transpiration.

Leaf stomata should remain open, but special care must be taken to avoid environmental conditions that may cause stress to plants. Stomatal closure is usually caused by inappropriate control of ventilation. The air vapour pressure deficit can be significantly increased with the introduction by high rates of dry air coming outside the greenhouse (Seginer 1994). It is known that high levels of air vapour pressure deficit lead to water stress conditions, which could lead to partial or complete stomatal closure (Baille et al. 1994a, Monteith 1995). Accordingly, adverse effects on gas exchange (transpiration, photosynthesis) and consequently on the production and product quality should be expected.

Crop aerodynamic conductance represents the main variable to controlling crop gas exchanges because it is the main factor limiting the process of sensible energy and water transfer from crop surface to the air. A large leaf area index LAI should increase crop

aerodynamic conductance ga, since, by a first approximation, can be assumed that the crop aerodynamic conductance is given by:

$$g_a = 2 \text{ LAI } g_{l,a} \tag{3}$$

where $g_{l,a}$ is the leaf aerodynamic conductance.
The same can be applied for the crop stomatal conductance g_c

$$g_c = 2 \text{ LAI } g_{l,c} \tag{4}$$

where $g_{l,c}$ is the leaf stomatal conductance.
Thus, maintaining a high crop leaf area index in the greenhouse, increases significantly gas exchanges, which in turn affect greenhouse microclimate, mainly the air temperature and vapour pressure deficit. Then the changes in the greenhouse microclimate affect stomatal conductance, leading to a control feedback (Figure 4), as has been discussed and formulated a number of papers (Aubinet et al. 1989, Nederhoff and Vegter 1994, Baille 1999).
Jolliet (1994), used HORTITRANS to show the effect of LAI on crop transpiration while González-Real and Baille (2001) showed the effect of leaf area index on canopy to air temperature difference and on crop transpiration rate.
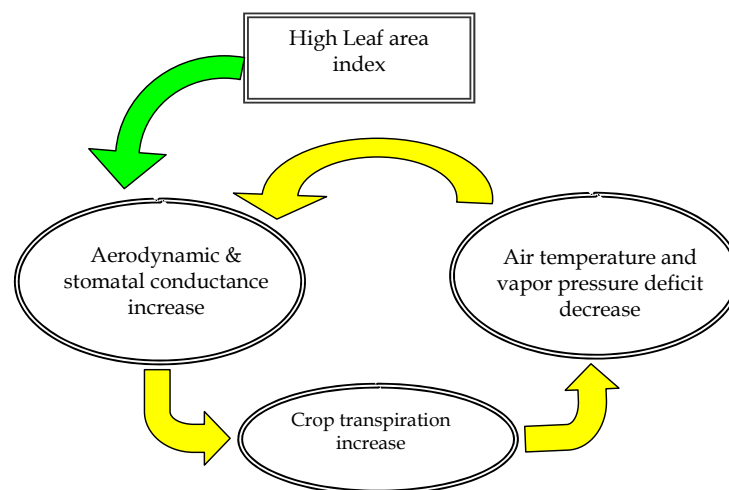

Fig. 4. Feedback control on crop transpiration.

4. Models of greenhouse crop transpiration

Transpiration is the most important part of the latent energy balance and one of the most important elements of greenhouse energy balance. As observed by many authors (eg: Morris et al. 1957, de Villèle 1972, van der Post et al. 1974 for tomato crop, Yang et al. 1990 for cucumber crop, Katsoulas et al. 2000 for rose crop) a strong correlation between crop transpiration and solar radiation exists. The air humidity inside the greenhouse is equally important but less effect on transpiration. The effect is characterized by the saturation vapour pressure deficit of air VPD (kPa), which is defined as the difference between the vapor pressure of the air at saturation e* (kPa) and the actual air vapour pressure e (kPa). The air vapour pressure deficit is variable characterising how dry the air is for a given temperature, is inversely proportional to the humidity. For constant greenhouse climate conditions VPD is correlated to solar radiation G. Therefore, in most cases, solar radiation

alone can explain most of the variability of transpiration, 'hiding' the effect of VPD. However, it is necessary to consider VPD for transpiration calculation when using any heating, ventilation, cooling and dehumidification systems.

A considerable research effort has been invested in the (evapo)transpiration of greenhouse crops (e.g. Stanghellini 1987, Jolliet & Bailey 1992, Jolliet 1994, Papadakis et al. 1994, Kittas et al. 1999). Several authors have proposed models that allow getting a more accurate estimation of the crop transpiration rate. Many of these studies are based on leaf (canopy) transpiration and leaf energy balance models in which the transpiration is characterized by the crop conductance, as proposed initially by Penman and modified by Monteith to account for the stomatal response of the crop (P-M formula), including several successful attempts to combine the P–M equation with the greenhouse energy balance (Fuchs 1993, Boulard & Baille 1993, Seginer 1994, Boulard & Wang 2000).

The calculation and simulation of mass and energy exchanges between crop and air is dominated by two trends (González-Real 1995). The first assumes that the crop is divided into discrete levels and the exchange calculations require knowledge and description of the conditions in each crop level (Yang 1995). Simple sub-models are used for calculating the exchange at each level, but sophisticated models are required for calculating the required unknown parameters for each level (temperature, humidity, radiation, wind speed, CO_2 etc) and to incorporate the individual levels (eg leaf level) in a complete model (eg crop level). The second trend to calculate the mass and energy exchanges between crop and air assumes that the crop is a large leaf ('big leaf') and that all internal layers are located in the same climatic conditions (Stanghellini 1995). The transpiration of the crop in this case is given from the Penman-Monteith formula (Monteith 1973):

$$\lambda E = \frac{\delta G}{\delta + \gamma(1 + g_a/g_c)} + \frac{\rho C_P D_i g_a}{\delta + \gamma(1 + g_a/g_c)} \tag{5}$$

where G (W m^{-2}) is the solar radiation ρ and C_p are respectively the density (kg m^{-3}) and specific heat (J kg^{-1} K^{-1}) of air, and δ is the slope of the humidity-ratio (or vapour pressure) saturation curve (kPa K^{-1}).

However, the use of the complete P-M formula requires the knowledge of several inputs or parameters that are not easily available. Particularly, the aerodynamic and stomatal leaf conductances have to be known for each crop species and possibly, for each cultivar. That is why researchers have tried to overcome the estimation of these resistances by using a simplified form of the P-M formula. Transpiration models with the greenhouse climate as a boundary condition were first developed in the northern regions of Europe and North America for horticultural crops. In these northern conditions, the glasshouse is generally poorly ventilated during a large part of the growing season. The boundary layer conductance for glasshouse crops tends to be much smaller than would be expected for similar crops growing outdoors. Thus, glasshouse crops are very strongly decoupled from the outside atmosphere by the presence of the glass, and the heat and the water released at crop surface will accumulate inside the glasshouse. Consequently, the transpiration rate will adjust until it reaches a stable equilibrium transpiration rate dictated by the net radiation received. On the contrary, greenhouse crop transpiration in Mediterranean or similar warm conditions is much more dependent on convection. As the ventilation and the turbulent mixing are vigorous, the saturation deficit at the leaf surface is closely coupled to the deficit of ambient air, and the latter is directly influenced by the outdoor saturation deficit.

4.1 Aerodynamic conductance

The aerodynamic conductance, which represents the transfer of water from the surface of the leaf or crop in ambient air can be calculated in two ways:
either as a function of crop sensible energy balance and the crop to air temperature difference (Seginer 1984),

$$g_a = \frac{H_c}{\rho C_p D T_c} \qquad (6)$$

or by the classical theory of heat transfer using dimensionless numbers (Stanghellini 1987). Following the non-dimensional heat transfer theory (Kreith, 1973; Monteith and Unsworth, 1990; Schuepp, 1993), the boundary layer conductance to heat transfer (g_b, m s^{-1}) from bodies of different shapes can be expressed as a function of the dimensionless Nusselt number, Nu:

$$g_b = \frac{\kappa\, Nu}{d} \qquad (7)$$

where κ (m^2 s^{-1}) is the thermal diffusivity of air and d (m) is the characteristic dimension of the body. Nu is generally expressed as a function of the following dimensionless numbers;
-    the Reynolds number:

$$Re = U\, d / \nu \qquad (8)$$

where U is air velocity (m^2 s^{-1}) and ν the kinematic viscosity of the air (m2 s^{-1}),
-    the Grashoff number:

$$Gr = \frac{\beta\, g\, d^3\, \Delta T}{\nu^2} \qquad (9)$$

where g is the gravitational acceleration (m s^{-2}), β the coefficient of volumetric expansion (K^{-1}), and ΔT (K) the temperature difference between the leaf and its environment, and
-    the Prandlt number:

$$Pr = \nu / \kappa = 0.705 \text{ for air}$$

Table 2 presents some functions Nu = f(Re, Gr) in laminar regime currently used for the estimation of gb of smooth flat plates or leaf replicas, distinguishing between free, mixed or forced convection mode.

Eq. nº	Mode	Formula	References
Eq.(13)	Free	$Nu = 0.50\, Gr^{0.25}$	Monteith (1980)
Eq.(14)	Free	$Nu = 0.25\, Gr^{0.30}$	Stanghellini (1987)
Eq.(15)	Mixed	$Nu = 0.37\, (Gr + 6.92\, Re^2)^{0.25}$	Stanghellini (1987)
Eq.(16)	Forced	$Nu = 0.60\, Re^{0.5}$	Schuepp (1993)

Table 2. Formulae relating Nu to Gr and Re for a flat horizontal plate parallel to the air flow, for different convection modes. Eqs (14) and (15) were derived from measurements of tomato leaf heated replicas in greenhouse (Stanghellini, 1987).

The problem that usually arises from the use of Eqn (6) is associated with the choice of the points at which the temperature difference is calculated. There are many disagreements in the literature as to what temperature difference should be taken. If the aerodynamic conductance calculated from measurements of air temperature above and not within the crop, the result is more of an indicative value (Yang 1995). Yang (1995) considered that the assumption of the big leaf is not representative, as the wind speed above the crop is up to one order of magnitude higher than that in the crop.

4.2 Stomatal conductance

The stomatal conductance plays an important role in the division of energy into sensible and latent and is affected by a number of microclimate parameters.

The stomatal conductance at the level of leaf or crop has been associated with G, VPD, air temperature and CO_2 concentration in the air, and the leaf water potential (Turner 1974, van Bavel 1974, Jarvis 1976, Takami and Uchijima 1977, Farquhar 1978, Farquhar and Sharkey 1982, Kaufmann 1982, Choudhury 1983, Zeiger 1983, Dwyer and Stewart 1984, Avissar et al. 1985, Choudhury and Idso 1985, Lindroth 1985, Simpson et al. 1985, Grantz and Zeiger 1986, Baldocchi et al. 1987, Stanghellini 1987) or physiological factors, such as photosynthesis (Ball et al. 1987, Collatz et al. 1991, Leuning 1995) and transpiration (Monteith 1973, Monteith 1995). Of these factors, as we know, the important role is played by radiation. Despite the fact that it has been found that the form of the relationship of stomatal conductance to the above factors (eg: Lange et al. 1971, Neilson and Jarvis 1975, Stanghellini 1987), a mechanistic model that could simulate stomatal conductance has not been developed and thus only empirical models are available.

The most common relationship, which reflects the influence of environmental factors on the behaviour of stomata, is that of Jarvis (1976):

$$g_c = g_M\, f_1(R_n)\, f_2(D_i)\, f_3(T_i)\, f_4(CO_2) \tag{10}$$

In this relationship, stomatal conductance is expressed as a function of maximum conductance g_M, multiplied by a number of factors. These factors are independent of each other, impose crop water stress and their result is multiplied, not added to calculate the final result. The form of mathematical functions f_1, f_2, f_3, f_4 is generally known (eg: Stanghellini 1987, Baille et al. 1994b), while the value of maximum conductance g_M, which varies from species to species, can be measured or found in the literature.

4.3 Simplified models of greenhouse crop transpiration

For greenhouse crops, the formula most currently used until now for evapotranspiration (E) prediction is based on a simple linear correlation between E and solar radiation, G (Morris et al. 1957, Stanhill and Scholte Albers 1974)

$$E = A_o\, K_c\, G + B_o \tag{11}$$

where Kc is a 'crop' coefficient depending on the crop development stage. Ao and Bo are two coefficients determined by statistical adjustment. This relation, which is mainly valid at daily or weekly time scales, presents several drawbacks, as follows:

i.   A large amount of empiricism and inaccuracy in the determination of the crop coefficient Kc.

ii. The vapour pressure deficit D is not explicitly taken into account in Eq. (11). In the case of a significant correlation between G and D, Eq. (11) can give a satisfactory estimation of E. But, under greenhouses that use heating, shading screen or fog-system, such a correlation does not stand (Bakker 1991). Moreover, for most of the species, the transpiration rate depends significantly on the saturation deficit (Okuya and Okuya 1988, Baille et al. 1994).

iii. Eq. (11) assigns a constant value (Bo) to nocturnal evapotranspiration, which can rise to a significant level in the case of heated greenhouses during cold periods (De Graaf 1985), thus contributing to a large extent to the total 24 h water loss. In fact, the coefficient Bo averages in some way the influence of nocturnal heating, but cannot predict the effect of single climate variables on nocturnal values of λE. As an example, the relation between solar radiation and crop transpiration rate of a rose crop for two different seasons, winter and summer is presented in Fig. 5. In the two cases, a linear relationship λE= aG + b was obtained with different values of the slope a for the two cases which characterises the influence of stomatal and aerodynamic conductance and of the solar radiation to vapour pressure deficit relation on evapotranspiration rate. The offset b is significant in the two cases, and reflects the contribution of the nocturnal evapotranspiration.
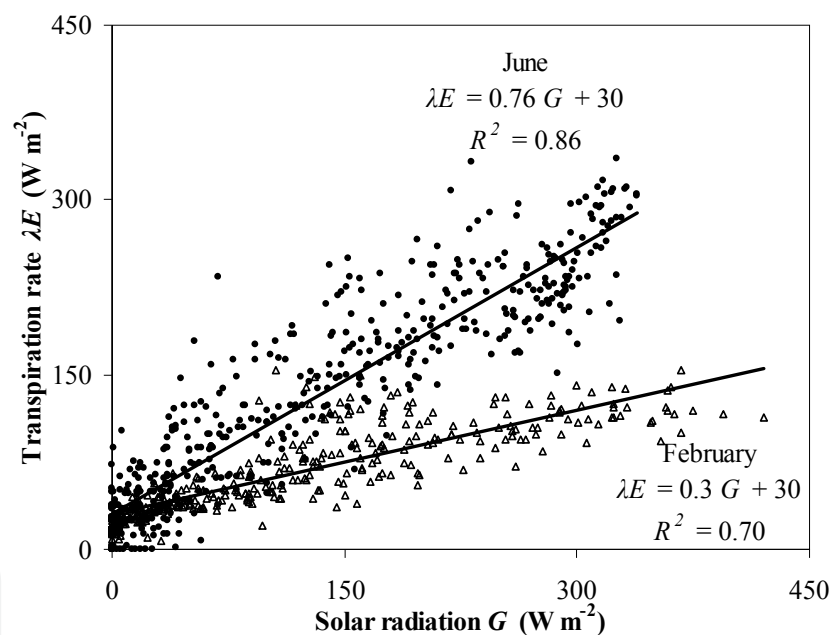

Fig. 5. Relation between solar radiation and crop transpiration rate of a rose crop for two different seasons, winter and summer.

The P–M equation (Monteith 1973) has been originally developed to calculate evapotranspiration from homogeneous vegetated surfaces. When applied to greenhouse crops it may be written as:

$$E = A\,G + B\,D_{id} \tag{12}$$

$$\text{with: } A = \frac{\delta}{\delta + \gamma(1 + g_a/g_c)} \text{ and } B = \frac{\rho C_P g_a}{\delta + \gamma(1 + g_a/g_c)}$$

A is referred to as the 'radiation term' and B as the 'aerodynamic term' (sometimes called 'advection term'). Hence A and B may be referred to as the 'radiation coefficient' and the 'aerodynamic coefficient'. Equation (12) may be regarded as empirical formulae, with A and B obtained by regressing measured evapotranspiration against measured solar radiation and VPD. From this point of view, A and B are often treated as constants for a given crop, or as simple functions of readily measurable quantities, such as the leaf area index (LAI). These coefficients may be corrected for changes in the environmental conditions and for water stress. The effect of light on A and B (via gc) may be ignored for high-radiation situations, and the expected increase with the ventilation rate, through its effect on ga, will also be ignored, based on previous precedents (Baille et al. 1994, Kittas et al. 1999), analysis (Seginer 1994), and experience (Seginer & Tarnopolsky, 2000). Baille et al., (1994a) suggested the following formulas for A and B as functions of the leaf area index, LAI :

$$A = a\, f_1(LAI) = A_0\, (1 - e^{-k\, LAI}) \qquad (13a)$$

where k is the extinction coefficient (= 0.64 for tomato, Stanghellini, 1987). The reason for the choice of Eq. (13a) is that represents the classical relationship for radiation interception by a canopy (Varlet-Grancher et al., 1989), and

$$B = b\, f_2(LAI) = B_0\, LAI \qquad (13b)$$

The choice of Eq. (13b) is straightforward as LAI can be considered as a multiplicative factor in the 'advective' term of the Penman-Monteith equation.

The constants a and b have been identified for several greenhouse species and a summary table of A and B parameters is given by Seginer (1997).

In a comparative survey of Jolliet and Bailey (1992) between the models of: (i) Penman (FAO 1977), (ii) Stanghellini (1987), (iii) Chalabi and Bailey (1989) and (iv) Aikman and Houter (1990), the model of the Stanghellini (Stanghellini, 1987) proved to be more accurate in predicting transpiration. In conclusion, they noted that solar radiation, saturation deficit and air velocity inside the greenhouse are the most important factors affecting transpiration and should be included in each simulation was calculated.

The problem is that many of the analytical models exist, such as the Stanghellini (1987), calibrated and developed in areas and periods with low values for radiation and leaf temperature. It is characteristic that during Stanghellinis' model calibration (March and April), the air temperature was almost always less than 25 $^{\circ}$ C, the temperature of the leaves slightly exceeded 24.5 $^{\circ}$ C, while the radiation was usually less from 300 W m^{-2}. Moreover, in the model of Stanghellini (1987), the effect of radiation on stomatal conductance and transpiration is taken into account more indirectly than directly, by affecting the crop to air temperature difference. Thus, an increase of radiation, according to simulation, has little influence on transpiration, but reduces leaf temperature. When the leaf temperature exceeds 24.5°C, stomatal conductance decreased sharply, leading to reduced transpiration and further increase crop temperature. Stanghellinis' (1987) model is not suitable for Mediterranean areas during the summer but it is appropriate and gives accurate predictions when used in conditions similar to those calibrated. However, other authors have developed and calibration similar to Stanghellinis' (1987) model for Mediterranean conditions (eg: Papadakis et al. 1994a, Boulard et al. 1996).

Jolliet (1994) presented a relatively simple crop transpiration model, including in the calculations cover condensation. The model was verified by experimental measurements

and the results showed that it is sufficiently accurate to be able to provide transpiration, relative humidity and air saturation deficit values. Furthermore, the model is able to predict the amount of water and energy that must be removed or added to the greenhouse to achieve a specific value of air relative humidity or crop transpiration rate.

It follows that several of the proposed simplified relationships give good estimates and could therefore be used where high precision is not required (eg monitoring of irrigation). However, the validity of simplified relationships is limited because: first, can not be used in different climatic conditions and different stages of crop development than calibrated, without a new calibration for each case and, secondly, their use is limited to applications where high precision is not required. Furthermore, it is better to use correlations derived from experimental or simulated results with constant coefficients as discussed above than to use the complex equation of Penman-Monteith with wrong stomatal conductance values.

4.4 Greenhouse crop transpiration simulation based on outside climate data

The biggest problem as far it concerns greenhouse crop transpiration prediction is the interaction of humidity and transpiration. In the case of models to be used for climate control in greenhouses it is necessary to use and included sub-models for transpiration which provide transpiration simulations as a function of external climatic conditions and greenhouse characteristics.

Until recently, only complicated dynamic models were possible to achieve this (eg: Bot 1983, Kimball 1986, Chalabi and Bailey 1989). To control the humidity and estimate crop transpiration in Mediterranean countries, other researchers (eg: Fuchs 1993, Boulard and Baille 1993, Seginer 1994) presented analytical models that allow the calculation of temperature and humidity of indoor air as well and transpiration of the crop as a function of greenhouse ventilation and cooling. Boulard and Wang (2000) gave an expression that estimates crop transpiration as a function of external climatic parameters.

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This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and student,s who intend to address these issues.

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