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OVERVIEW OF GREENHOUSE CLIMATE CONTROL IN THE MEDITERRANEAN REGIONS

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Abstract : Research on greenhouse climate control in Mediterranean regions has received much attention during the last years. The main reasons for this increasing interest are related to the following agronomic objectives:(i) to extend the growing season and the potential yield; (ii) to manage the climate in order to reach higher standards of quality; (iii) to develop low-cost production systems, compatible with the scarcity of resources and the low investment capacity of Mediterranean growers. This paper presents an overview of the scientific and technical issues that have to be solved in order to reach suitable climate control and management in the low-cost plastic greenhouses commonly used in the Mediterranean regions. Emphasis will be mainly directed towards the following topics: -the respective roles of external climate, greenhouse structure, climate control equipment and crop behavior in the establishment of the internal climate. The concept of "coupling" factor will be addressed, in order to evidence the interactions between the different components of the system; -the importance of evaporative processes (evapotranspiration of the crop, cooling pads, fog-systems...) in the heat and mass balance of the greenhouse, and the way to control temperature and humidity by controlling the evaporative processes; - the key role of ventilation rates in controlling the internal climate, with particular attention to the characterization and modeling of air exchange rates. Following these general aspects, some techniques (ventilation, fog-system, shading...) for controlling greenhouse climate will be presented and discussed. In the conclusion, we deal with the prospective and needs for future research and developments in greenhouse climate control are. We shall stress on the necessity to combine both physical and ecophysiological studies, because of the crucial role played by the crop in determining the microclimate in greenhouses.

INTRODUCTION

Greenhouse cultivation has extended significantly in the Mediterranean Regions (South of Europe, Maghreb countries, Egypt...) during the last two decades. The energy crisis and the introduction of plastic film (Tognoni and Serra, 1988) have been the main factors contributing to the displacement of protected cultivation from Northern Europe to Mediterranean countries. The availability of low-cost plastic shelters, together with some skillful adaptation of Northern technology and know-how, enabled the emergence of this out-of-season Mediterranean production system (Monteiro, 1990). Presently, the total growing areas in these regions is about 60.000 ha (Baille, 1995), with a large majority of plastic shelters.

The Mediterranean protected cultivation system is characterized by a low level of energy input (Stanhill, 1980), comparable to open-field systems. The reason is that growers use only a small amount of energy for controlling the greenhouse environment. Most of the shelters are provided with hand-operated systems of ventilation and are not heated (or, in the best case, have some rudimentary heating system). The insufficient ventilation (during summer) and the lack of heating (during winter) lead to inappropriate extreme air temperature and humidity. Furthermore, the structure and the shape of these shelters (low height and volume, flat roof) are often unadapted to the climatic conditions of the regions (Castilla and Lopez Galvez, 1994), aggravating instead of alleviating the problems.

The consequence of this situation is that the resulting microclimate is far from being satisfactory for the crop during a large part of the year. Several works described the microclimatic conditions prevailing in these low-cost shelters (Montero et al., 1985, Lagier, 1990), where the lack of environmental control facilities results in poorly adequate environment and difficult or prevent the use of the shelters for crop production during both winter and summer periods (Castilla, 1994).

The effects of this inadequate microclimate on the components of the production (yield, quality) are very negative. It is not possible for the grower to take advantage of the high radiation levels in late spring and summer, because of the high temperature and vapor pressure deficit under shelters. The potential production of a tomato crop in South of Spain during the summer months is 50 % higher than in the Netherlands (Baille, 1995). However, it is not possible to obtain satisfactory levels of yield and quality in the shelters of the Mediterranean countries during summer, while high yields of good quality are obtained in the North of Europe during the same period. The reasons of the high productivity of the Northern greenhouses are twofold:

- first, the outside climate is much more temperate in the North of Europe in summer, and no special problems are encountered in order to maintain an adequate greenhouse environment;

- secondly, growers of Northern Europe have acquired a high level of expertise in optimizing climate management, with the help of sophisticated glasshouses, climate control equipment and computers (Challa et al., 1988).

As stated by Castilla (1994), there is a tendency in the Northern countries to **optimize** the greenhouse environment, in order to attain the **potential crop production**. In contrast, in the Mediterranean area, the prevailing trend is rather to **adapt the plant to an "non-optimal" environment**. However, there is a limit to this strategy of adaptation, and it should be judicious to look for technological solutions that can alleviate the extreme conditions prevailing in Mediterranean shelters, mainly during summer periods. Researchers and growers are now aware that greenhouse structures must be designed specifically for the locality (Hanan, 1990), and that the environment can be significantly improved by using some basic and simple rules in the management of the greenhouse (Baille, 1989).

Therefore, for Mediterranean growers, one of the great challenge is, by adapting and improving their shelter structure and equipment and managing skillfully the different components of the production system (climate, crop, fertirrigation...), to achieve the following objectives:

- to extend the growing season and the period of use of the shelter;
- to reach satisfactory levels of marketable yield and quality;
- to increase the net income of their farming systems.

However, many obstacles and constraints remain to be solved. The existing technology and know-how developed in Northern Europe countries are generally not directly transferable to the Mediterranean growers: high-level technology is out of reach for most of the Mediterranean growers because their cost is too high compared to the modest investment capacity of these growers. Know-how from Northern Europe growers is often inappropriate to the problems encountered in the Mediterranean shelters. In the case they could be used, an important effort in training and educating Mediterranean growers will be necessary.

Taking into account this context, specific research and development tasks were initiated by the research institutes and extension services of the Mediterranean countries. The issues that are addressed in this paper concern the means and practices. by which Mediterranean growers can alleviate the climate-generated stress conditions that inhibit the growth and the development of the crops during the long extending warm season. Before, we recall some basic elements of the greenhouse climate, its energy and water balance and the interactions between processes and factors that determine the greenhouse environment.

THE GREENHOUSE CLIMATE: CHARACTERISTICS AND DETERMINISM

A global view

The greenhouse can be considered as a system. The environment of the system is composed by (i) the outside climate and (ii) the grower, who acts on the greenhouse equipments in order to control the internal environment (external control). The greenhouse system can be divided into three main components that interact in a more or less strong way : the internal atmosphere, the crop and the soil. The latter is often considered as the main thermal mass of the system. The behavior of the whole system depend on these interactions, but also on the outside climate (driving forces) and on the actions that are exerted on the components of the system via the climate-control equipment (heating, cooling, CO_2 enrichment,...). The presence of the crop, with its own internal control processes (i.e. stomatal regulation), is fundamental in the determinism of the system behavior. When the set-points can be maintained whatever the outside climate and the plant response, the control of the system is perfect, and the growth and development of the crop is optimal in the sense that it will correspond to the objectives and planning of the grower. This is the case in the sophisticated computer- controlled glasshouses of Northern Europe.

When only a partial control is possible, the inside environment will depend both on the changes of outside weather and on the response of the plant to its immediate environment. In turn, the immediate environment, unperfectly controlled, will depend at some extent of the response of the crop. This type of "feedback" loop between the crop and the environment is the predominant trait that determines the behavior of the greenhouse system (Fuchs, 1990; Baille, 1993). This is why the knowledge and modeling of the crop physiological responses (and particularly, transpiration and photosynthesis) to environmental factors are fundamental for understanding why and how the greenhouse system evolves under a given external action (ventilation, shading,...), and for predicting and controlling the system behavior.

The greenhouse climate

Some general characteristics of the greenhouse thermal behavior have to be kept in mind :

The first one is that the greenhouse has a limited thermal mass (the soil is the most important) which implies that the climatic external perturbations will be not significantly damped or lagged by the greenhouse itself, at the difference of buildings. So, very rapid changes in the greenhouse environment will result from external changes, unless they are corrected by an efficient climate-control system.

The second one is that the diurnal "greenhouse" effect is mainly due to the confining of the air in the greenhouse enclosure (and less to the radiative properties of the cover), and that ventilation is one effective way to decrease the so-called "greenhouse effect", by increasing the overall heat loss coefficient of the greenhouse.

The third one is the predominant role of the canopy transpiration in the determinism of the greenhouse environment, and more precisely, on temperature and vapor pressure deficit. That is why the control of evaporative processes is so primordial in greenhouse cropping.
Other important aspects to point out are:

- Air velocity inside a greenhouse is close to zero. This fact implies that, in many situations, the heat and mass transfer between the atmosphere and the canopy or the soil will be limited by the aerodynamic canopy resistance, and not by the biological resistance;

- There is a significant reduction in solar radiation, inherent to the presence of the cover.

All these specifities of the greenhouse system result either in advantages, either in some drawbacks, depending upon the characteristics of the outside environment. In fact, the presence of a more or less tight enclosure above a crop gives rise to positive changes in the environment only when the outside climate is relatively temperate, so that it is possible, without sophisticated means, to maintain the variables of the greenhouse environment within suitable ranges. This is mainly the case in late winter or spring in Mediterranean climates. But, during the other periods of the year, the presence of the cover is source of some major deficiencies and problems that have to be corrected.

THE GREENHOUSE ENERGY BALANCE

The components of energy balance

To analyze the greenhouse energy balance, it is worthwhile to use greenhouse models. Simplified models are available (Seginer and Kantz, 1986, Boulard and Baille, 1987, 1993) that allow to investigate the effects of the numerous factors and processes involved in the determinism of the inside microclimate. These models based on the energy and mass (H_2O, CO_2) balances of the greenhouse, explicit the different processes of energy and mass transfer in terms of "source" and "sinks".

From a physical point of view, greenhouses can be considered as solar collectors and their performance described in an analogous way. The main difference with the solar collector's equations (Duffie and Beckman, 1974) is the presence of a transpiring surface, which will give a special importance to the latent heat transfer processes. Using this analogy with the solar collector, we can consider that the solar energy gain of the greenhouse, R_n, is splitted into two components (Figure 1):

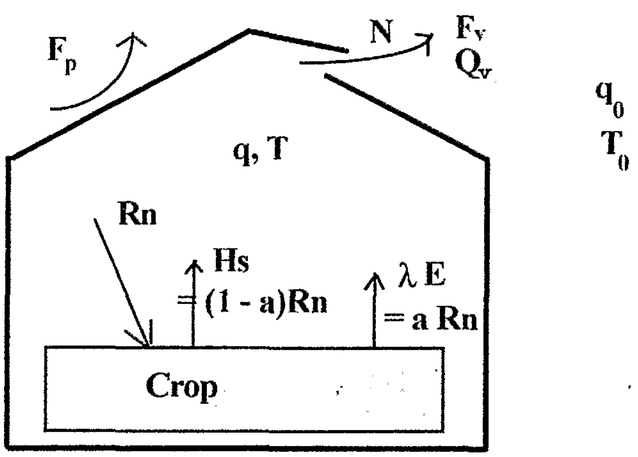

Figure 1. Simplified energy balance of an unheated greenhouse (Symbols : see text)

- A sensible energy component, H_S, that serves to heat the greenhouse air (and represents the main part of the "useful" energy that can be extracted from an air solar collector);

- A latent energy component, lE, that represents the evapotranspiration rate of the crop.

The partition of net energy between sensible and latent heat gains is often expressed by a parameter called the Bowen ratio, b = H_S/ lE, that depends upon the intensity of the evapotranspiration processes (Landsberg et al., 1979). In this section, we adopt the following simplified formulations :

$$H_S = (1\text{-}a)\, R_n \qquad (1)$$
$$l\,E = a\, R_n \qquad (2)$$

Eqn. 2 is an approximative estimate of the evapotranspiration rate, whose complete formulation is more complex.

The sensible heat losses are mainly composed by :

(i) the losses by convection and radiation from the walls, $\Phi_{P.}$, that can be globally expressed as :

$$\Phi_{P.} = K_G\,(T - T_0) = K_G\, DT \qquad (3)$$

where K_G is the global heat loss coefficient (W m^{-2} °C^{-1}), and DT is the difference between the greenhouse air temperature T and the outside temperatures T_0.

(ii) the convective losses due to leakages and ventilation, Φ_V;

$$\Phi_V = K_V\, DT \qquad (4)$$

where K_V (W m^{-2} °C^{-1}) is the coefficient of heat transfer by ventilation, that can be expressed as a function of the air renewal rate, N (s^{-1}):

$$K_V = r\, C_P\, N\, (V/S) \qquad (5)$$

with r = air density (kg m^{-3}), C_P = heat capacity of air (J kg^{-1} °C^{-1}) and V/S = ratio of greenhouse volume to ground area.
Then, from the sensible heat balance:

$$(1\text{-}a)\, R_n = \Phi_P + \Phi_V \qquad (6)$$

we can deduce the air temperature of the greenhouse, assuming steady state conditions (dT/dt=0):

$$T = T_0 + \frac{(1-a)R_n}{K_G + \rho C_P N(V/S)} \qquad (7)$$

It can be seen from eqn. 7 that, if we want to decrease the greenhouse air temperature, it is possible to act on the following factors :

- decreasing Rn (shading screen, whitewashing,...);
- promoting the evaporative exchanges (by increasing the transpiration rate, by misting...);
- increasing K_G (water sprinkling on the roof);
- increasing the air renewal, N;

- decreasing T_0 (cooling pads);
- increasing the volume of the greenhouse, V.

The water vapor balance

In the same way than for sensible heat, we can establish the water vapor balance of the greenhouse (Figure 2) with the different terms relative to water production and water loss.

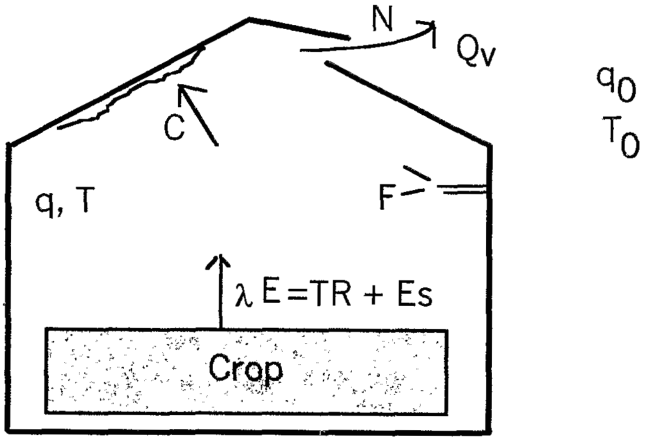

Figure 2. Water vapor balance of a greenhouse (Symbols : see text)

The general form of the water vapor balance of the greenhouse air volume can be written as follows:

$$\frac{V}{S}\frac{dq}{dt} = TR + E_s + F - Q_v - C \qquad (8)$$

where :

dq/dt = rate of change of internal humidity ($kg_{water}\ m^{-3}\ s^{-1}$);
q = water vapor concentration ($kg_{water}\ m^{-3}$) of the greenhouse air;
V, S = greenhouse volume (m^3) and area (m^2) respectively;
TR = transpiration rate of the crop ($kg_{water}\ m^{-2}\ s^{-1}$);
E_s = soil evaporation ($kg_{water}\ m^{-2}\ s^{-1}$);
F = water supply into the greenhouse air from misting, cooling pad... ($kg_{water}\ m^{-2}\ s^{-1}$);
Q_v = loss of water vapor from leakage and ventilation ($kg_{water}\ m^{-2}\ s^{-1}$);
C = condensation rate on ground or vegetation ($kg_{water}\ m^{-2}\ s^{-1}$);

During daytime, the greenhouse water balance depends mainly on the evapotranspiration, $E = TR + E_S$, and on the loss from ventilation, Q_v. Condensation seldom occurs during the day (however, the condensation term cannot be neglected during nighttime). Soil evaporation is generally negligible if localized irrigation is practiced in soilless cultures or if the soil or substrate is covered by a white reflective cover. Then, in the majority of cases (no water supply from a mist system), we have :

$$\frac{V}{S}\frac{dq}{dt} = TR - Q_v \qquad (8.a)$$

For steady state conditions, we get :

$$TR \approx Q_v \qquad (8.b)$$

As a first approximation, TR can be assumed equal to Q_V. If estimates of the air renewal rate N are available, it is possible the transpiration rate of the whole greenhouse crop by measuring the air exchange rate of the greenhouse (Bakker, 1986).

Using eqn. 2 for E, and expressing Q_v by :

$$Q_V = N(V/S)(q - q_0) \qquad (9)$$

where q_0 is the outside humidity, we get :

$$q = q_0 + \frac{aR_n/\lambda}{N(V/S)} \qquad (10)$$

Eqn. 10 indicates that the greenhouse humidity can be modified by acting on :the following factors :

- a, promoting the evapotranspiration rate will increase greenhouse air humidity;
- R_n: shading screen or white washing will decrease crop transpiration hence humidity;
- N : increasing the air renewal rate will decrease the humidity.

However, eq. 10 is an oversimplification of the evaporative processes in greenhouses because it is assumed that E is proportional to radiation only. In fact, the evapotranspiration depends in a rather complex way on humidity and there are several feedback loops between E and q. A realistic prediction of humidity in greenhouses requires to take into account these interactions

FEEDBACK AND COUPLING IN THE GREENHOUSE

The importance of evaporative processes in the greenhouse system

The importance of evaporative processes in greenhouses has been evidenced in the previous sections (eqns. 7 and 10). A greenhouse without crop or with a stressed crop will present the characteristics of a desertic climate. A closed greenhouse with a highly transpiring crop will create a tropical climate. Between these two extremes, there is a wide range of sub-optimal to optimal temperature and humidity where crops can be grown.

Many growers give special care to the control of air and soil temperatures in their greenhouses, but surprisingly do not devote much attention on humidity and tend to underestimate its possible effects on the crop behavior, except when extreme humidity conditions are prevailing. This is an attitude that could result in impaired management of the greenhouse The important role of atmospheric humidity on the biological processes (it would be better to use the term "vapor pressure deficit", D, as it allows to deal directly with plant processes such as transpiration) is now recognized by the physiologists. In the recent years, the concept of "transpiration" set point was introduced (Stanghellini, 1986), which is the basis for calculating the couple of temperature and humidity set points that permits to maintain a given transpiration rate. The physicists know that the latent heat of evaporation in a greenhouse is the main mechanism for cooling and humidifying the atmosphere, and that it is essential to couple the energy and water balances in order to get reliable predictions of the greenhouse environment (Boulard and Baille, 1993).

The order of magnitude of the partition of radiative energy between sensible and latent heat in a greenhouse is 30/70, i.e. about 2/3 of the net radiative energy received by the canopy is dissipated through the process of transpiration. If compared to the case of open field crops, it can be seen that the main difference lies in the possibility for the greenhouse grower to adjust the potential climatic demand, Ep, by acting on the climate control facilities. This means that he can play both on the demand (or output) Ep and the offer (or input), i.e. the water supply, W, through its irrigation system.

The concept of "transpiration" set point is a clear illustration of this specificity of the greenhouse system : the water flux, and consequently, the water status through the soil-plant-atmosphere system can be controlled by the grower when adequate equipment for climate control is available (Stanghellini and van Meurs, 1992). However, if an accurate control of canopy transpiration can be reached in sophisticated glasshouses with al the necessary facilities, it is quite more difficult in the rudimentary shelters of the Mediterranean areas.

Greenhouse crop transpiration

The transpiration rate depends on the amount of radiative energy absorbed by the canopy, Ra, and on the vapor pressure deficit, $D = e_s(T) - e$, $e_s(T)$ being the saturated humidity at temperature T. TR is generally expressed by means of the Penman-Monteith formula (Monteith, 1973) extended to the whole canopy considered as a "big leaf":

$$\lambda TR = \frac{\Delta R_n}{\Delta + \gamma^*} + \rho C_P \frac{g_a \Delta}{\Delta + \gamma^*} \qquad (11)$$

where :

R_n = net radiation absorbed by the canopy (W m^{-2});

l = latent heat of vaporization (J kg^{-1});

$g^* = g\ (1 + g_a/g_s)$, g being the psychometric constant, g_a and g_s (m s^{-1}) respectively the aerodynamic and stomatal resistances of the canopy to water vapor transfer;

D = slope of the water vapor saturation curve at T;

The stomatal conductance, g_s, depends upon the environmental conditions Many authors (Jarvis, 1976; Avissar et al., 1985; Stanghellini, 1987, Baille et al., 1995) found a dependence of TR on radiation and vapor pressure deficit and express g_s as :

$$g_s = g_{smax}\, f_1(R_n)\, f_2\,(D) \qquad (12)$$

We can see from equations (11) and (12) that it exists a complex feedback loop between the air humidity and the transpiration of the crop. If D increases, then TR increases, but the stomatal conductance g_s decreases, counteracting the increase in TR. However, as the limiting factor in transpiration under greenhouse is the aerodynamic conductance ($g_a << g_s$), the decrease in g_s does not influence significantly the total conductance and the transpiration rate (Hsiao, 1993), until there is a very strong stress due to high saturation deficit. Only in this last case, stomatal regulation is sufficiently important to affect significantly the canopy transpiration rate of greenhouse crops.

The key role of ventilation in the greenhouse system

An useful concept for analyzing the interactions between the atmosphere and the crop is the concept of "decoupling factor", Ω, introduced by Jarvis and McNaughton for field crops (1986). This concept was applied recently to greenhouse crops by Boulard (1996), who shows that the degree of coupling between the crop and the outside atmosphere is governed mainly by the ventilation rate, and to a lesser extent, by the leaf area of the crop. This analysis indicates that another important limiting factor to transpiration of greenhouse crop is the conductance related to the air renewal rate, g_N.(Figure 3). For a closed greenhouse, g_N can be lower than g_a and will constitute the main limitation to crop transpiration. A minimum ventilation rate is therefore needed to maintain g_N higher than g_a, allowing the transpiration rate to reach its maximum value imposed by g_a.

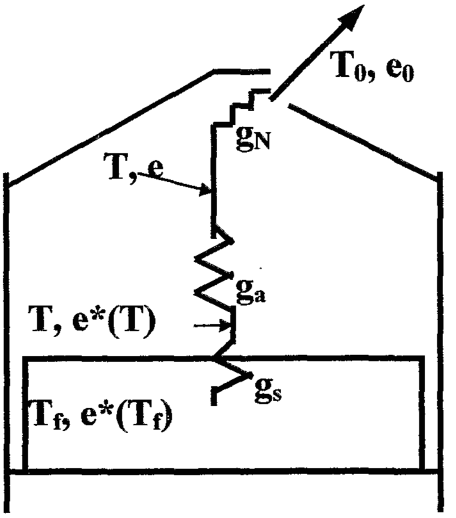

Figure 3. The conductances governing the water exchanges in a greenhouse (Symbols : see text)

Figure 4 summarizes the different interactions between the crop and the greenhouse atmosphere. It can be seen that there is several negative feedback loops (thermal and hydraulic) that tend to stabilize the transpiration rate. On the contrary, stomatal regulation is a positive feedback loop that tends to enhance the trend towards either higher or lower transpiration rate. Due to the low physically related conductances (g_a and g_N) in greenhouses, the physiological control does not seem to play a predominant role on the level of transpiration, except when strong stress conditions are prevailing. But this may precisely occur in the Mediterranean shelters, and one of the problems is to avoid the occurrence of these conditions. Experiments on several greenhouse crops seem to indicate that saturation deficit higher than 15 mb for tomato (Boulard et al., 1991) or 20 mb for roses (Baille et al., 1995) can induce the start of a decrease in transpiration, which will in turn increase the saturation deficit, and so on..., until a complete stomatal closure and a very dry atmosphere.

From all these considerations, it can be stressed that ventilation rate plays a key role in establishing the inside microclimate and then, the response of the crop to these conditions. The simultaneous control of humidity and temperature is without doubt one of the more difficult, because these two variables are strongly influenced not only by outside humidity and temperature, but by radiation and the physiological response of the crop. In unheated greenhouses, the only mean to control these two variables is ventilation. Ventilation also remains about the only way to avoid condensation on plants at night, and this is now a common practice in many locations.

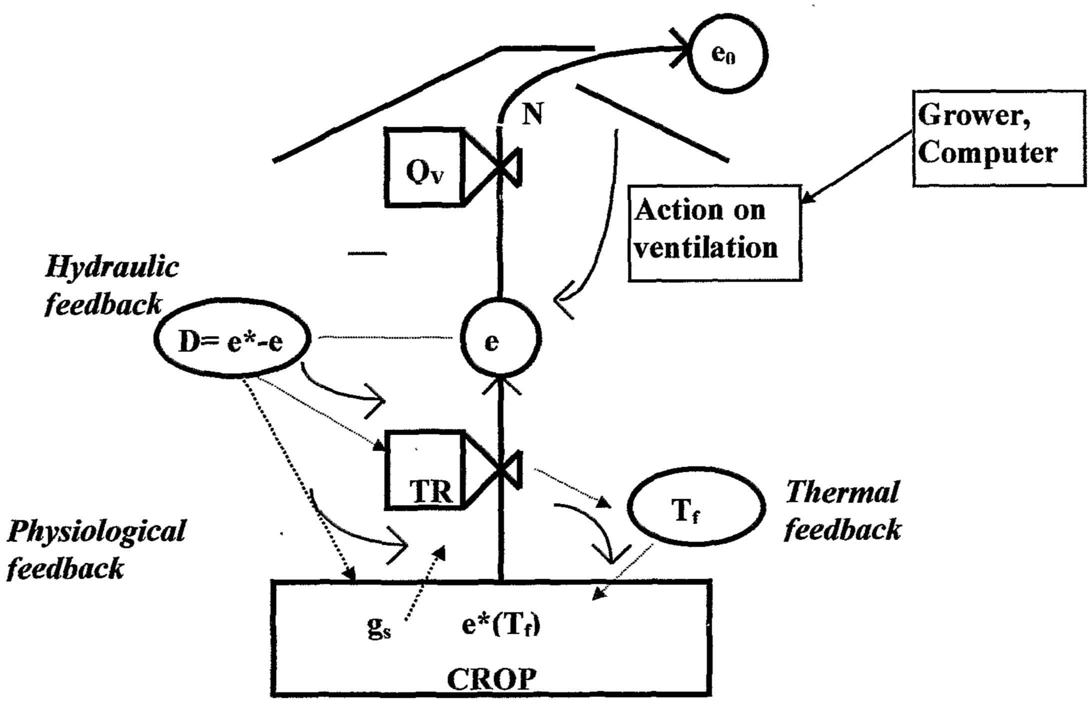

Figure 4. The different feedback loops in the control of transpiration in greenhouse (T_f = leaf temperature, e* = saturated vapor pressure deficit. Others symbols : see text)

THE MAIN PROBLEMS TO BE SOLVED IN MEDITERRANEAN CLIMATES

Radiation

During the winter period, the high number of clear days and the latitude (longer daylength) of the Mediterranean countries allow the crop to receive enough solar radiation for its growth and development, without the need to add CO_2 or artificial light. This is one of the clear (and claimed) advantages of these countries compared to Northern Europe. However, the structure and the shape of the Mediterranean plastic shelters have generally lower light transmission than glasshouses. This poor transmissivity induces loss of production during the winter and spring months, which are generally the most important in economic returns.

Temperature

Because limited means of control are available, large diurnal amplitudes of air and soil temperature are frequent under Mediterranean shelters, with too low temperature during winter nights and too high temperatures during summer days.

The problem of too low temperatures during winter can be solved by some heat supply to the greenhouse during the critical periods. The problem is not technical, as it is easy to heat an enclosure, but economical, as the investment and the running costs are relatively high.

The problem of too high temperature high radiative load during late spring and summer period is one of the most important aspect to deal with (shading screen, blanking...)

Humidity

The low efficiency of the ventilation systems in Mediterranean shelters give rise to impaired humidity conditions. High humidity are observed during overcast and humid periods (shelters are often located in the seashore) and during the night. During summer, very low humidity conditions are induced because of inadequate management of the openings, when growers give priority to temperature control by ventilation.

CO_2 concentration

During winter, CO_2 concentration could be a limiting factor when the shelter is closed in order to rise temperature. Due to crop photosynthesis, CO_2 depletion (until 200 ppm) occurs, with the consequent decrease in canopy net assimilation. Here also, ventilation management is crucial, because CO_2 enrichment is not a current practice in Mediterranean greenhouses. There are several reasons that explain why this technique, usual in Northern Europe, is not practiced in the Mediterranean countries : (i) it is expensive, (ii) the potential period of CO_2 enrichment is limited due to the necessity of aeration early in the season (Enoch et al., 1988) and (iii) it is not really necessary as the amount of radiation in winter is generally enough for plant growth.

GREENHOUSE TECHNOLOGY IMPROVEMENT

Structure and shape

The low-cost structures used in Mediterranean countries have limited roof slopes, giving a good resistance to wind, but reducing significantly the light transmission in winter. It would be advisable to build greenhouse with convenient roof slopes (symmetrical or asymmetrical, gothic arch...) in order to improve greenhouse transmission and evacuation of the condensed water (von Zabeltitz, 1988). Many Mediterranean shelters have low height and volume. Higher height would improve transmission, ventilation and offer a higher inertia to changes in temperature and humidity.

Equipment for climate control

The basic device for environmental control in Mediterranean greenhouse is ventilation, for its strong influence on all the climatic variables (except radiation). Blanking is also a current practice. Sometimes, some additional equipment as shading screen, misting, cooling pads, passive heat storage systems , low temperature heating systems... are also available. The use of unconventional energy (waste water, geothermal energy...) is often the opportunity for supplying some heating during cold periods.

Temperature control.

Heating. Use of conventional or alternative heating systems is not widespread in Mediterranean countries. The economical benefit of greenhouse heating in the Mediterranean area is not clear. Heating have to increase productivity, quality and earliness sufficiently to account for the investment and the running costs (Abou-Hadid et al., 1995). The use of alternative energy is facing with economical rather than technical problems. Some simple passive solar systems as water tubes for heat storage (Grafiadellis, 1986) can be recommended, but are of limited efficiency when the vegetation is increasing in volume.

Heating is not a technical problem : we know how to heat a greenhouse, with conventional or alternative energy. The problem is to take the decision or not to use a heating system, and this must be done from an economical point of view.

Cooling. It represents the most important and strategical aspect to address with. Several methods are available:

- Static or forced ventilation;
- Evaporative cooling (pads, misting, sprinkling...)
- Shading (screens, white washing,...)

Other technological solutions are available (heat pump, heat exchangers,...), but are very expensive and are not used in the greenhouse industry, even in the developed countries.

In the last years, significant progress has been obtained on the knowledge of these cooling mechanisms. The impact of different ventilation system on the internal environment has been investigated (Verlodt et al., 1984; Verlodt et al., 1990; Fernandez and Bailey, 1994). Experimental data on greenhouse exchange rate through ventilation are now available and provide a better insight on the mechanisms and factors that drive the energy transfer between the greenhouse and its near outside environment (Fernandez and Bailey,1992; Kittas et al., 1995, Boulard and Draoui, 1995, Papadakis et al., 1996). These data allowed to develop and calibrate models for estimating the ventilation rate; ventilation, and for a better design of the vents (Boulard and Baille, 1995). Roof ventilation can be very efficient in limiting excessive greenhouse air temperature during high radiation period (Brun and Lagier, 1985), and the increase in height of the shelters have brought some improvement in the ventilation efficiency. But installation of roof ventilators, located at the higher part of the greenhouse, is not easy in unsophisticated structures. Some original devices for roof aeration were recently proposed (Montero and Sevilla, 1992).

Evaporation cooling is without doubt the most efficient way to cool the environment (Cohen et al., 1983; Giacomelli et al., 1985; Montero et al., 1990), especially if the outside atmosphere is dry. The technology is now available, but these techniques require water of good quality. This is the main restriction to the use of fog-systems (figure5).

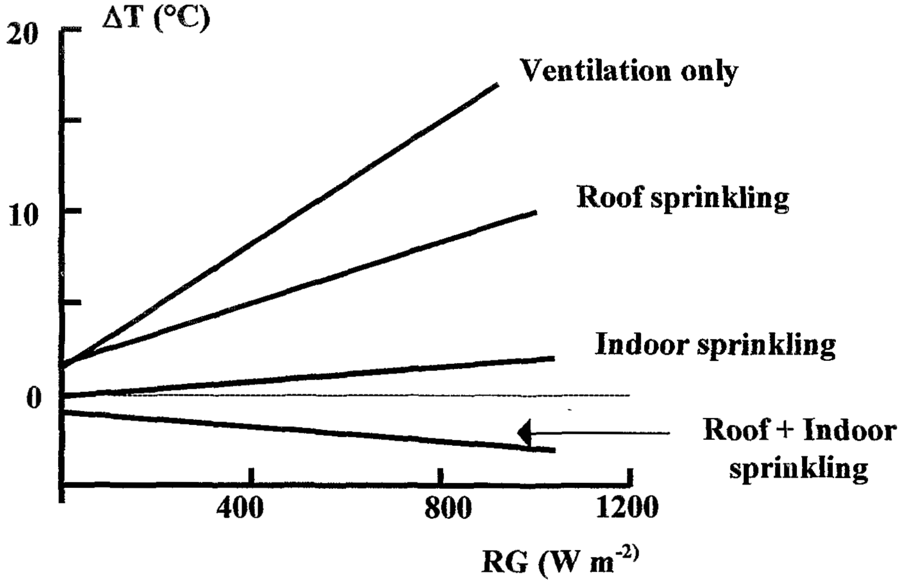

Figure 5: Influence of different cooling techniques on greenhouse temperature (DT = T_{INT} - T_0). From Cohen et al., 1983

Shading is the ultimate solution to be used for cooling greenhouses, because it affects the productivity. However, in some cases, a better quality can be obtained from shading. More knowledge about the effect of shading on fruit or flower yield and quality must be obtained in order to determine the optimal intensity of shading (Cockshull et al., 1992)

Dehumidification. The common solution adopted for dehumidification by European growers is the simultaneous use of heating and ventilation, which is an energy consuming and expensive solution. In Mediterranean greenhouses, the only available solution for dehumidification is ventilation. Attention has been focused recently on hygroscopic control of greenhouse humidity (Peiper et al., 1987; Assaf et al., 1988,), which makes interesting use of the low-grade latent heat in transpired water.

CO_2 enrichment: This technique is not really necessary in Mediterranean areas. The periods of enrichment are very limited, due to ventilation requirements (Enoch, 1984; Bellamy and Kimball, 1986.). This is not a technical problem, but an economical one.

GREENHOUSE MANAGEMENT

In this section, two important point will be addressed : the first one concerns the crucial role of irrigation and ventilation on the water status of the greenhouse and of the plant. The second one addresses the importance of the information available for control and decision making.

Control of greenhouse and plant water status

In Mediterranean countries, because of the lack of external (grower) control, the crop is the component that plays the predominant role in the evolution of the greenhouse environment, especially through the evapo-transpiration rate, which is the main cooling process. With the little available equipment in a Mediterranean greenhouse, it is a big challenge to keep the crop transpiring at his maximum rate. But this is the necessary objective of the climate control, if one does not want that the Mediterranean greenhouse ecosystem tends towards a desertic ecosystem....

That is why irrigation and ventilation have to be controlled and managed with a very special care. These two functions are vital because they control and affect the water supply and thus the water balance of the crop and its transpiration rate (Baille, 1993). It has to be noted the cropping techniques (plant density, defoliation....) also may have a significant influence on the internal microclimate. Another important point is to have, when the warm season begins, a crop enough vigorous and provided with a large root system in order that it can hold the non-optimal greenhouse conditions. A weak crop will not last long if repetitive thermal or water stresses are occurring.

The need of information for control and decision making

1.Information for short-term control

Even with the most sophisticated air-conditioning equipment, it would not be possible to control the greenhouse environment without the availability and the treatment of the pertinent information and knowledge on the behavior of the system. It should be stressed that the availability of real-time data and informations (sensors, grower observations) is essential for managing the greenhouse climate. Unfortunately, only little information on the climatic and physiological variables is available in Mediterranean shelters, because of the lack of sensors and related electronics and microprocessors. So, observations of the crop, intuition and the own expertise of the grower remain until now the key for the control of the climate and crop behavior.

However, taking into account the constantly decreasing cost of microprocessors, computers and electronics, I think that the natural evolution of the technology for environmental control in Mediterranean countries will follow the one observed in Northern Europe. There is no reason to consider that real-time control of ventilation or automated irrigation scheduling on the basis of radiation and saturation deficit are useful and beneficial only to North European growers. They are without doubt still more useful to the Mediterranean growers.... The problem is more linked to the education and training of the farmers than on the actual cost of these technologies.

2.Decision-making : the need for a systemic approach

The problem is to find a compromise between the cost of maintaining a given environment in the greenhouse and the benefits expected from this control. So, before deciding on the type of greenhouse and equipments ("strategical" decision), or before establishing the planning of the cultivation ("tactical" decision), we have to evaluate the costs and benefits derived from each type of decision. This is a difficult task, even if the pertinent knowledge and information are available. The high number of complex interactions between variables and processes, the various constraints and objectives to take into account is too high to allow an intuitive solution. A "systemic" approach, based on the modeling and simulation of the greenhouse system, seem to be better adapted to this problem of decision making. This approach is now possible because of the emergence of greenhouse and growth simulators that can predict the outputs necessary to the agronomic and economical assessment of the production system.

These simulators would be very useful in order to give valuable recommendations about the configuration of the greenhouse cropping system. They are the only way to achieve the optimization of the production system under given environmental and economical constraints. And we know how these constraints are strong in the Mediterranean countries...

This systemic approach was used for the design of greenhouse cooling facilities by Fang (1995), who raises the following questions:

(i) what is the affordable cooling facility (economical constraint due to the available budget)?

(ii) what are the limits of the cooling facility when working in a given climate, and its efficiency (technical constraint)?

(iii) what crops can be grown in such a controlled environment (biological constraints)?

(iv) what is the potential benefit that the cooling facility will return (performance criteria)?

The last question is probably the most difficult to answer, as the response of the crop to a given environment (with more or less prolonged stress periods) is not straightforward to predict.

CONCLUSION

As stated by Castilla (1990), the research and production strategies in Mediterranean countries were until recent years more directed towards biological aspects than to solve the problems related to the control of greenhouse environment. But the limitations and shortcomings due to this poor environmental control have been evidenced, and it is now time to try to "help" the plant to produce best (in quality) in a more adequate environment, but keeping in mind that the technological solutions must be adapted to the socio-economical constraints of the Mediterranean countries. Improving the greenhouse environment requires the use of more expensive structure, therefore the economics may limit the investment threshold of the structure to assure their economic viability.

There is still large room for improvement of Mediterranean shelters. I think that the most important problems are not linked to the development of specific technology, because the technical solutions are known and available. The problems are more linked to the following aspects :

- adaptation and optimization of these technologies for the Mediterranean conditions;

- assessment of the agronomic and economical consequences of the use of such technologies;

- training and education of the growers, mainly in the "know-how" necessary to manage adequately the greenhouse environment.

Concerning the first point, and after this broad overview on greenhouse environmental control in the Mediterranean regions, the main conclusions about the research priorities seem to be the following:

- improving the ventilation devices and management
- improving light transmission
- focus not only on temperature control, but also in humidity control and management

For the second point, which is undoubtedly one of the higher priority in greenhouse research, it would be advisable to concentrate our efforts :

- in assessing the biological response of greenhouse crops when submitted to the specific conditions of Mediterranean shelters. For example, we need more knowledge on the effects of shading on fruit quality. In this way, ecophysiological and agronomic studies must be coupled to environment studies.

- in the development of a systemic approach of the different greenhouse agrosystems, using and integrating models (physical, biological and economical) that will allow to evaluate the inputs and outputs of a given greenhouse agrosystem. This is the most promising way for strategic decision making in matter of greenhouse configuration.

The third point is more related to the priorities in matter of knowledge and know-how transfer to the Mediterranean growers. The expertise relative to greenhouse management has increased significantly in the last years, and must be disseminated as rapidly and efficiently as possible. We all know that the overall efficiency in managing an agricultural system depends first on the capacity of the growers to understand and to control the behavior of the whole system of production.

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