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PRINCIPLES AND METHODS FOR PREDICTING CROP WATER REQUIREMENT IN GREENHOUSE ENVIRONMENTS

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Abstract : Accurate short-term estimates of crop water requirements in protected cultivation are a prerequisite for a good and efficient management of irrigation and greenhouse microclimate. The availability of adequate and pertinent information is needed to improve water management methods and to reduce environmental impacts resulting from leaching of agricultural chemicals. The aim of this paper is to present an overview of the basis and hypothesis that sustend the methods presently used for predicting crop water requirements in protected cultivation.

INTRODUCTION

Irrigation is now recognized as an important component in the agriculture economy of Mediterranean regions. As practiced by many growers, it is often based on traditional methods of distribution and application which fail to measure and optimize the supply of water needed to satisfy the variable requirements of different crops. Inadequate irrigation tends to waste water, nutrients and energy, and may cause soil degradation by water-logging and salinisation.

In order to achieve higher levels of profitable and sustainable production, it is essential to modernize existing irrigation systems improve water management. Up-to-date methods of irrigation should likewise be based on sound principles and techniques for attaining greater control over the soil-crop-water regime and for optimizing irrigation in relation to all other essential agricultural inputs and operations.

As in open field, accurate predictions of crop water requirements are necessary for an efficient use of irrigation water in greenhouse crop production. Furthermore, under closed spaces as greenhouses, the predominant role of crop transpiration in decreasing the heat load during warm periods is a supplementary reason to develop irrigation scheduling that allow the maximization of the transpirational fluxes.

For reliable estimates of water requirements, information is needed on the crop environment (climate, soil) and physiological behavior of the crops. This information has to be stored and processed adequately in order to extract the useful parameters and data that will serve to irrigation scheduling and management. Practical irrigation scheduling algorithms for greenhouse crops have been developed during the last twenty years, many of them based on estimates or measurements of the crop transpiration.. The aim of this paper is to present an overview of the basis and hypothesis that sustend these algorithms.

THE GREENHOUSE WATER CYCLE

The main process involving the fate of water in the greenhouse, and hence the water requirements of crops, is evapotranspiration, a process that is driven by a constant inflow of energy. In fact, the water balance is intimately and reciprocally related to the cycle and balance of energy (Boulard and Baille, 1993), since the state and content of water in the soil and its vegetative cover is affected by, and in turn, affects, the way the energy fluxes reaching the soil is partitioned and utilized. Control of the soil-plant-atmosphere system must therefore be based on simultaneous consideration of both the water and the energy balance.

Two components of the greenhouse water cycle are important to measure and to control. The first one is the soil component (or artificial substrate), where the water balance is an account of all quantities of water added to, subtracted from and stored within the root zone during a given period of time.

[Storage] = [Gains] - [Losses]

For greenhouses, this general statement can be written as follows:

$$\mathbf{DS = W - (DR + Es + TR)} \qquad (1)$$

where DS is the quantity of water stored in the substrate, DR is the drainage, Es is the soil evaporation and TR the actual transpiration of the crop. The last two variables are difficult to separate, and are generally lumped together and termed **"evapotranspiration"** (ET = Es + TR).

It is still rather difficult to measure in practice the soil water balance. Often, the larger component of the "losses" side, and the most difficult to measure directly, is the evapotranspiration, ET.

To obtain the irrigation requirement, W, from the water balance (eq. 1), we must have accurate measurements of the other terms of the equation. For a long period, the change in water content of the root zone is likely to be small in relation to the total water balance. Soil evaporation is negligible if localized irrigation is practiced in soilless cultures or if the soil or substrate is covered by a mulch or plastic cover. If we neglect Es, W is approximately equal to the sum of TR plus the drainage, DR. TR is equal to the water uptake by the plant, A, minus the water stored in the plant organs, DW_P. Then :

$$\mathbf{W = TR + D = A - DW_P - DR} \qquad (2)$$

Some important aspects have to be underlined in the water balance :

1.-.W is generally discontinuous (except in closed-loop or hydroponics NFT cultures), whereas TR is continuous. Even during nighttime, transpiration is effective and can reach important levels in heated greenhouses. Then, the role played by the several water reservoirs has to be taken into account, as these reservoirs will act as buffers (the substrate, the plant) between the demand and the offer. In soilless cultures, due to the limited water capacity of the substrates, high frequency irrigation is necessary, which implies short-term estimation of transpiration rate.

2 - The actual *transpiration rate of the* crop, TR_A, occurs at its maximal rate, TR_M, when stomata are fully open. In greenhouses, under inadequate water supply or by lack of climate control, plant water stress may occur and then stomata close, resulting in decreasing photosynthesis and transpiration. This situation is more likely to occur in Mediterranean greenhouses during spring and summer, and can persist during several hours or several days.

3 - The water uptake rate, A, depends on many factors : length and age of plant roots, soil water potential at the vicinity of the root, the previous stress history of the plant....A precise determination of A is very difficult and not yet available in spite of many attempts and efforts from crop researchers in the last decade (Keppler and Rickman, 1990).

That is why the estimation of TR_M (i.e. of crop water requirements, CWR) is of prime importance in the determination of irrigation needs, and that many methods of irrigation scheduling are based on the estimation of either TR_M, (or ET_M, if soil evaporation is included), estimation that is generally deduced from a calculated reference evapotranspiration and a crop coefficient.

The second important component to consider in a greenhouse is the air volume, where the water vapor balance in its more general form can be written as follows :

$$\rho \frac{V}{S}\frac{dq}{dt} = TR + E_s + F - Q_v - C \qquad (3)$$

where :

dq/dt = rate of change of internal humidity ($kg_{H2O}\ m^{-3}\ s^{-1}$);
q = water vapor concentration ($kg_{H2O}\ m^{-3}$) of the greenhouse air;
V, S = greenhouse volume (m^3) and area (m^2) respectively;
TR = actual transpiration rate of the crop ($kg_{H2O}\ m^{-2}\ s^{-1}$);
E_s = soil evaporation ($kg_{H2O}\ m^{-2}\ s^{-1}$);
F = water supply into the greenhouse air from misting, cooling pad ($kg_{H2O}\ m^{-2}\ s^{-1}$);
Qv = loss of water vapor from leakage and ventilation ($kg_{H2O}\ m^{-2}\ s^{-1}$);
C = condensation rate on ground or vegetation ($kg_{H2O}\ m^{-2}\ s^{-1}$);

During daytime, the greenhouse water balance depends mainly on the crop transpiration, TR, and on the loss from ventilation, Q_v. The others terms are generally negligible (However, F can be significant if evaporative cooling is acting, and the condensation term cannot be neglected during nighttime).

Thus, in steady-state conditions (dq_i/dt =0), we have :

$$TR = Q_v + F \qquad (4)$$

The transpiration rate depends on the amount of radiative energy absorbed by the canopy, R_A, and on the vapor pressure deficit, D = $e_s(T)$ - e, $e_s(T)$ being the saturated pressure vapor deficit (mb) 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":

$$TR = \frac{D}{D+\gamma^*}\frac{R_A}{\lambda} + \frac{\rho C_P}{\lambda}\frac{g_a D}{D+\gamma^*} \qquad (5)$$

where :

TR = transpiration rate ($kg\ m^{-2}\ s^{-1}$)
R_A = radiation absorbed by the canopy ($W\ m^{-2}$);
l = latent heat of vaporization ($J\ kg^{-1}$);
rC_p = volumetric heat capacity of air ($J\ m^{-3}\ °C^{-1}$);
g* = g (1 + g_a/g_s), g being the psychrometric constant, g_a and g_s ($m\ s^{-1}$) respectively the aerodynamic and stomatal resistance of the canopy to water vapor transfer;
D = slope of the water vapor saturation curve at T;

From eq. 5, it can be seen that an alternative to measure the transpiration rate is to evaluate the term Q_v, i.e. if we know (from measurements or from model predictions) the ventilation rate of the greenhouse and if measurements of the outside and inside humidity are available. This points out the importance of predicting accurately the ventilation rate (Boulard and Baille, 1995) when ones intends to estimate TR from the water vapor balance of the greenhouse (Bakker, 1986).

DEFINITIONS

Definitions are extremely important in making evapotranspiration estimates because consistency is essential with respect to different reference crops (Burman et al., 1983).

A Potential ET and reference ET

The process of evapotranspiration obviously depends on both the outside weather regime (G, T°, HR, Wind) and the internal state of the crop/soil system itself. Conceptually, therefore, one might suppose that there ought to be a definable ET rate for the special case in which the crop is maintained perpetually wet, and that this rate should depend only on the outside weather. The concept of potential evapotranspiration (PET) is an attempt to characterize the climatic environment in terms of its evaporative power, i.e. the maximal evaporation rate that the atmosphere is capable of extracting from a well-watered field under given conditions. The PET is thus said to represent the climatically imposed "evaporative demand". Penman (1956) defined PET more restrictively as the "amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water".

As such, PET is a useful standard of reference for the comparison of different climatic regions (or seasons) and of different crops within a given climatic region. PET is conditioned, first of all, by the flux of energy reaching the surface via solar radiation. Despite the field specific nature of several of the variables affecting the energy balance, PET is often assumed to depend predominantly on the climatic inputs and to be practically independent of crop properties. Various empirical approaches have been proposed for the estimation of PET. The simplest methods are based on air T°, since this climatic variable is readily available. The formulation of Blaney-Criddle is still used, but the uncertainty involved in this type of formula is high (Hillel, 1990)..

The method proposed by Penman (1948), and modified by Monteith (1973) is physically based, hence more meaningful than the strictly empirical methods. In derivations of the different forms of the Penman Monteith equation (for example, eq. 5) for estimating ET, PET is the ET that occurs when the vapor pressure at the evaporating surface is at the saturation point. This definition is not restricted to a standard surface and has lead to different interpretation of PET. Many irrigation scientists have used ET from a well watered crop such as alfalfa or grass to represent PET. It is essential that any reference to PET be explicit in its definition so that the reader can properly interpret the results. The use of PET is replaced in many areas by the term reference evapotranspiration, ET_0.

Two main definitions of ET_0 are commonly used (Burman et al., 1983):

(i) ET_0 is "the rate of ET from an extensive surface of 8 to 15 cm, green grass cover of uniform height, actively growing, shading the ground, and not short of water" (Doorenbos and Pruitt, 1977).

(ii) ET_0 is "the upper limit or maximum ET that occurs under given climatic conditions with a field of alfalfa, well watered, with 30 to 50 cms of top growth (Jensen et al., 1971).

If the method selected for estimating ET for open field crops is based upon ET_0, then the decision must be made whether to use grass - or alfalfa - related procedures.

B. Pan evaporation

In view of the complexity of the physically based estimations of potential ET, it is not surprising that many practitioners continue to prefer the simplified empirical methods which depend on correlation with past records rather than on explicit formulation of ongoing process or mechanisms.

Various evaporation measuring devices, called evaporimeters, have been proposed and tried for the purpose of obtaining an estimate of the climatically driven potential evapotranspiration. Of these, the most frequently used are evaporation pans. They provide an effect of the integrated effect of radiation, wind, temperature and humidity on evaporation from an open water surface. The most widely adopted is the "Class A" pan standardized by the U.S. Weather Bureau. Pans are relatively inexpensive and are easy to install, maintain and monitor. They do, however, have several important shortcomings.

(i) The process of evaporation from a water filled tank is not a true portrayal of ET from plants and soils. the daytime storage of heat within the tank can cause considerable evaporation at night (10 to 40% of the diurnal total, while night-time transpiration from crops is generally around 5 % (with the exception of heated greenhouse crops). Also, turbidity of the water and possible shadings from nearby plants affect the measurement.

(ii) Pan evaporation depends greatly on the exact placement of the pan relative to wind exposure and advection from outside the field. The use of a correction factor is necessary..

All these shortcomings notwithstanding, pan evaporimeters, if properly sited and maintained, can indeed be used to assess PET.

C. Crop Evapotranspiration and Water Requirements

The daily rate of actual evapotranspiration (ET_a) from a crop will seldom equal the potential rate (PET) or the reference rate (ET_0). Canopy characteristics, stand density, stage of growth and degree of surface cover, and, especially the moisture regime, all affect actual ET. The maximal seasonal ET from a well watered crop stand of optimal density, ET_M, is likely to range between 0.6 and 0.9 of total seasonal PET. Knowledge of ET_M for the major crops in a given region can therefore serve as a basis for planning the irrigation regime. In fact, ET_M is often taken to represent the crop's water requirements. Because ET_M is affected by both the climate and the characteristics of the crop, it should be measured in the field for each region and major crop.

Using ET_0 (whether calculated from a Penman type formula or measured in the field by using a well watered stand of alfalfa or grass), it is possible to account for the effect of specific crops characteristics on crop water requirements (CWR) using an empirical "crop coefficient", Kc

$$\mathbf{CWR = ET_M = Kc\ ET_0} \qquad (6)$$

Values of Kc are generally derived from soil water balance experiments, using lysimeters and well watered crops. For most crops, Kc generally lies between 0.6 to 0.9. Research determining crop coefficients is costly and time consuming. They change with location, season, crop development stage, even method of irrigation. The fluctuations of crop coefficient to weather, crop height and stomatal conductance, analyzed theoretically by Annandale and Stockle (1994), can be significant. Overall, the accuracy of predictions is low, and Kc values are frequently updated locally on the basis of soil moisture measurements and crop response to water application. This explains why so much effort was directed to extrapolate these empirical factors to different climatic zones and management conditions (Doorenboos and Pruitt, 1977).

Notwithstanding, the concept of crop coefficient, simple and affordable, has been a successful means for transferring best available practical knowledge of irrigation needs, and has been widely accepted by irrigation practitioners in the last twenty years.

COMMON METHODS OF ESTIMATING GREENHOUSE CROP EVAPOTRANSPIRATION

A. Specific problems related to ET estimations of greenhouse crops

The problem encountered in greenhouse crop ET_M estimation is that the inside microclimate is affected by the outside climate, the type of greenhouse, the climate control strategy and the feedback between the crop and the inside microclimate. So, the concept of PET for greenhouse crop can often lead to misleading interpretations. Many authors have intended to propose calculation methods based on outside weather variables, eluding the fact that the outside climate is often poorly coupled to the internal microclimate. The concept of reference evapotranspiration is also somewhat difficult and delicate to be applied to greenhouse crops water requirements, because the two "reference" crops (grass, alfalfa) are not commonly grown in greenhouse production. The data from pan evaporimeters are affected by the spatial heterogeneity of greenhouse climate and the proximity and continuous evolution of the vegetation.

Another problem is inherent to the crop coefficient, Kc. Stanghellini et al. (1990) developed an analytical formulation of Kc, expressed as the ratio of the theoretical crop transpiration (calculated from eq. 5 assuming maximal crop conductance, g_s) to a given reference evapotranspiration. They showed for greenhouse tomato crops that this coefficient is a function of crop parameters, leaf area and prevailing weather, and that it is a coincidence that the crop coefficient in greenhouse crops was "almost" constant in its seasonal trend, due to the lucky combination of two opposite effects.

All these considerations suggest that the use of physically-based formulations of ET_M that take into account both crop parameters (such as maximal conductance) and the prevailing climatic regime in the greenhouse seem to be preferable to other empirical methods. However, these specific crop parameters are not available for all the main species grown under greenhouses. That is why the classical methods based on a given reference ET and crop coefficient are still largely used for estimating water requirements of greenhouse crop, although their shortcomings are now well recognized.

B. The pan evaporation method

The use of the pan evaporation method, adapted to greenhouse conditions, is described in several reports (Abou-Hadid and El-Beltagy, 1988, Abou-Hadid and Eissa, 1992, Sirjacobs, 1987) relative to the estimation of PET under plastic greenhouses of the Mediterranean countries.

Results of reference evapotranspiration obtained with this method are only of local use, as they depend on many local factors. As mentioned previously, the pan method is hazardous to use in greenhouse, because of the strong heterogeneity of inside solar radiation and the shading of the nearby vegetation. The effect of pan location inside the greenhouse may affect significantly the PET or ET_0 estimations, and hence ET_M. However, when no other methods are applicable because of the lack of climatic data, this can be a first step for rough estimation of water requirements by means of an inexpensive and simple system.

C. Solar radiation based methods

The main role of solar radiation in determining the evapotranspiration in a greenhouse has been evidenced in numerous works in the 60' and 70' (Morris et al., 1957, Lake et al., 1966, Stanhill and Alberts, 1974, De Villele, 1974), showing a strong correlation between daily evapotranspiration and solar irradiance. This constatation has given raise to the so called "solar radiation" method, or "solarimeter" method, based on a simple relationship giving the reference evapotranspiration under greenhouse if the outside global radiation, RG_0 and the greenhouse transmission, t, are known:

$$ET_0 = K\,t\,RG_0 / 2.5 \qquad (7)$$

(ET_0 in mm day^{-1}, RG_0 in MJ m^{-2} day^{-1})

where K is an empirical coefficient, whose value is about 0.6 to 0.7.

Crop coefficients based on this reference ET have been proposed for the main greenhouse species (Laberche et al., 1977?, De Graaf and van der Ende, 1981, Benzarti et al., 1982).

This method is still of common use among greenhouse farmers in Europe .Many commercial automated irrigation systems are based on this simple algorithm, where the only needed on line measurement is solar radiation. Simple and cheap radiation sensors are now available, and solar radiation measurements are often a routine part of greenhouse irrigation scheduling operation. In cases where solar radiation measurements are not available or are distant from the site in question, procedures for the estimation of solar radiation are available. An extensive table of constants for use in empirical expressions for predicting RG_0 from extraterrestrial radiation is given by Doorenbos and Pruitt (1977).

This method gives generally good results when irrigation is operated at a daily or weekly intervals. However, for soilless crops, the high frequency of water applications implies short term estimates of ET. In this case, transpiration can be significantly influenced by the saturation deficit inside the greenhouse. Inadequate irrigation scheduling can derive from the solar radiation based method during hot and dry periods of weather, frequent in the Mediterranean countries.

D. The Penman Monteith method

The Penman equation has been extensively studied and its application is presently worldwide (Doorenbos and Pruitt, 1977). Although the Penman method was introduced in 1950 (Penman, 1948), it may be more vital today than when it was first published. The rapid changes in electronic technology, combined with the world-wide research into the Penman equation, has enabled the accurate calculation of reference ET from real-time weather data. In modern greenhouses, the availability of climate sensors is now the rule (Baille, 1992). This allows the use of the Penman Monteith equation (eq. 5), with the introduction of crop physiological parameters such as the stomatal conductance. Models that predict stomatal conductance against solar radiation, vapor pressure deficit, temperature and CO_2 concentration have been developed and validated for greenhouse crops (Avissar et al., 1985, Boulard et al., 1991, Baille et al., 1994a). They permit to calculate the maximum crop transpiration rate, TR_M, as well as the actual transpiration, TR_A . With such models, it is now possible to get a very accurate control of the climatic demand and of the response of the plant to environmental factors. Simplified versions of the P-M equation are now proposed, of the form :

$$TR_M = a\,RG + b\,D \qquad (8)$$

where a and b are coefficients that depend on the species (Jolliet and Bailey, 1992, Baille et al., 1994b). These coefficients can also be identified in-situ if measurements of water supply and drainage are available (Jemaa, 1995).

This method is the best adapted to estimate crop water requirements, but requires sensors for the measurement of RG and D, as well as specific crop parameters such as the aerodynamic and stomatal conductance. It also requires an estimation of the leaf area index. This last point is the main shortcoming of the method, but it is possible to tackle this problem by using correlation between LAI and the height or the age of the crop, for example. Unfortunately, such a method is not possible to apply in most of the Mediterranean greenhouses, by lack of climate sensors.

CONCLUSION

The process of irrigation consists of introducing water into the part of the soil profile that serves as the root zone, for the subsequent use of the crop. A well-managed irrigation system is one that optimizes the spatial and temporal distribution of water, so as to promote crop growth and yield, and to enhance the economic efficiency of crop production.

The practice of irrigation has evolved gradually in the direction of increasing the farmer's control over crop, soil and even weather variables (greenhouses). Modern irrigation is now a highly sophisticated operation, involving the simultaneous monitoring and manipulation of numerous factors of production. And yet, progress continues.

At present, the irrigation of greenhouse crops is mainly controlled on the basis of solar radiation. Some advanced algorithms introduced saturation deficit as supplementary variable. Automatic measurements of drainage rate, used as a feedback information improves the control of water supply. The grower's experience is still present, allowing adjustment of the model parameters if necessary. While the grower might not be fully confident in a control system based on these algorithms, the provision of information will support the grower in making decisions and will in the long term increase acceptance of fully automatic, on line control of irrigation.

The concept of "transpiration" set point is a clear illustration of the specificity of the greenhouse system : the water flux, and consequently, the wetter status through the soil-plant-atmosphere system can be controlled by the grower when adequate equipment for climate control is available. However, if an accurate control of canopy transpiration can be reached in sophisticated glasshouses with all the required equipment and facilities, it is quite impossible in the rudimentary shelters of the Mediterranean areas, for two main reasons :

(i) the lack of information. The availability of real-time data, measurements and information (sensors, grower's observations) is essential for managing greenhouse irrigation. Unfortunately, only little information on the climatic and physiological variables is available in Mediterranean shelters, because of the lack of sensors and related electronics. So, observations of the crop, intuition and the own expertise of the grower remain until now the key for irrigation scheduling, as for climate control and fertilization. However, taking into account the constantly decreasing cost of microprocessors, computers and electronics, It is probable that the natural evolution of the technology for environmental control in Mediterranean greenhouses will follow the one experienced in Northern Europe. It is of course too soon to think about complete computerized greenhouse operation for most of the Mediterranean countries, but a progressive introduction and adaptation of the technology available in Northern countries must be encouraged. There is no reason to consider that real-time control of ventilation, or automated irrigation and fertilization are useful and beneficial only to North European growers. They are without doubt still more useful to

Mediterranean growers. The problem is more linked to the education and training of the farmers than on the actual cost of these technologies.

(ii) the lack of an efficient climate control. Parallel to the improvement and automation of irrigation scheduling, it will be necessary to get a better control of temperature and humidity, in order to avoid a too high climatic demand in summer and its negative consequences on the crop water status, even when adequate soil or substrate moisture is ensured by adequate irrigation management. This is one of the most important problem to be solved in the Mediterranean greenhouses for a more profitable greenhouse production.

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