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Modelling Evapotranspiration of Container Crops for Irrigation Scheduling

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1. 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 application methods that fail to measure the supply of water needed to satisfy the variable requirements of different crops. In order to achieve more profitable and sustainable cropping systems, it is essential to modernize existing irrigation systems and improve irrigation water use efficiency (WUE). 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. Accurate predictions of crop water requirements are necessary for an efficient use of irrigation water in container crops cultivated both outdoors and in greenhouse.

Irrigation scheduling (IS) has conventionally aimed to achieve an optimum water supply for productivity, with soil or container water content being maintained close to field capacity. Different approaches to IS have been developed, each having both advantages and disadvantages but despite the number of available systems and apparatus, not entirely satisfactory solutions have been found to rationalize IS, assuring optimal plant growth with minimal water use (Jones, 2004). Many growers, especially in the Mediterranean regions, use simple timers for automated irrigation control of containerized crops and scheduling is based on their own experience.

Evapotranspiration (*ET*) is the primary process affecting crop water requirements and, therefore, its knowledge is essential for efficient irrigation management. *ET* is the combined process of evaporation from soil or substrate and leaf transpiration. Evapotranspiration requires two essential components: a source of energy and a vapour transport mechanism. Energy is needed for phase change from liquid to vapour in sub-stomatal cavities whereas the leaf-to-air vapour pressure gradient ensures that water vapour crosses leaf stomata.

In container-grown plants, *ET* is affected by many factors, both environmental (e.g. air temperature, radiation, humidity, wind speed) and plant related characteristics (e.g. growth

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phase, leaf area), as well as type of growing substrate and container size. Any method used to accurately estimate plant water requirements must take these environmental and plant factors into account. The irrigation frequency of plants growing in container can be based on measured or calculated *ET* (Treder et al., 1997).

According to Baille (2001), the available advanced methods for controlling irrigation at the short-term decision level are based either on climate or on soil moisture status.

In the climate-based method, crop water use is computed by means of algorithms that estimate *ET* using meteorological data. The Penman-Monteith (PM) equation (Monteith, 1973; Stanghellini, 1987) and its simplified versions (e.g. Baille et al., 1994) have been used for predicting *ET* in many container-grown crops, where substrate evaporation losses are generally negligible and *ET* is determined almost exclusively by crop transpiration.

The soil-based method uses the measurement of soil water potential or content. A combination of climate and soil-based methods would be recommended, because this allows a check of the coherence and concordance between data regarding soil moisture and crop water demand thus making IS more reliable and accurate.

In this chapter, different approaches for *ET* modelling in container crops grown both in greenhouse and outdoor will be described and its application to IS is briefly discussed.

2. Modelling crop evapotranspiration in outdoor container-grown nursery stock

Among container crops, nursery stock ornamental plants typically exhibit a fast growth rate and require plenty of nutrients and water of high quality, due to the susceptibility to salinity that typically characterizes these crops. In these crops WUE is generally poor, especially in container crops, and the environmental impact may be remarkable due to the waste of water and the pollution of rivers and groundwater with fertilisers and other agrochemicals. Annual use of irrigation water ranges from 500 mm in soil-grown crops to 1,000-1,500 mm in container crops, which are increasingly used in many countries (e.g. United States, The Netherlands, Italy). For instance, in Pistoia (Tuscany, Italy) which currently is the most important district in Europe for the cultivation of landscaping ornamentals, approximately 1,400 ha, over approx. 4,500 ha of nurseries, are used for pot ornamentals with an estimated consumption of irrigation water (mostly groundwater) of more than 10,000,000 m³/year. Even in the most advanced nurseries, simple timers are used for irrigation control and a "water-man" is in charge for adjusting timers during the growing season, whereas the estimation of crop *ET* may provide the basis for efficient IS.

In the framework of the European project Flowaid (Balendonck, 2010), between 2007 and 2009, the research group of Pisa University conducted a series of experiments to design and test a simple *ET* model for four ornamental species (*Photinia x fraseri*; *Viburnum tinus*; *Prunus laurocerasus*; *Forsythia intermedia*) grown in container in a peat-pumice mixture (Pardossi et al., 2009a).

Pardossi et al. (2009a) used the classical "two-step" approach to calculate of *ET* [$ET = ET_0 \times K_c$ (Allen et al., 1998)], which required the knowledge of crop coefficient (K_c) and reference evapotranspiration (ET_0). The latter quantity was calculated with the California Irrigation Management Information System (CIMIS) equation (CIMIS, 2009). The CIMIS formula uses a modified PM equation with a wind function developed at the University of California, Davis, CA. Alternatively, ET_0 can be determined by evaporation pan (Brouwer & Heibloem, 1986). CIMIS equation is described in details in par. 4.2.

Main limitation to the application of “two-step” approach to calculation of ET is represented by K_C , which is crop specific and depends on leaf area, growth stage, climatic conditions and management practices. This issue is especially critical in container-grown ornamentals as the number of species/cultivars in any middle-size nursery is often in the range of hundreds and initiating time of crop production can be any time during the year for small containers. For this reason, K_C values of ornamental crops are rarely known and their behaviour and values during the growing season, as a result of cultivation in containers, are very different from those of a uniform crop canopy (Regan, 1994). Hence, it must be determined experimentally. Crop coefficient is related to the degree of soil cover by crop canopy and thus to leaf area index (LAI). Several authors attempted to model the evolution of K_C and LAI during the growing season (e.g. Orgaz et al., 2005).

In the work conducted by Pardossi et al. (2009a), the analysis of the seasonal changes of crop height (H), LAI , K_C and the ratio of K_C on LAI (C) in each species suggested the possibility to predict LAI from non-destructive measurements of H and then to compute K_C from LAI assuming a constant value for C :

$$ET = C \cdot LAI \cdot ET_0 \quad (1)$$

Linear regressions between the two variables LAI and H were computed for *Forsythia* ($r^2=0.87$), *Photinia* ($r^2=0.75$) and *Viburnum* ($r^2=0.71$), while a non-linear (exponential) regression was more adequate for *Prunus* ($r^2=0.56$). All these regressions were significant. In all species, C values oscillated during the growing season without showing any trend or possible relation with plant age and averaged 0.389, 0.352, 0.377 and 0.289 in *Forsythia*, *Photinia*, *Prunus* and *Viburnum*, respectively. The divergence of the C coefficient between *Forsythia*, *Photinia* and *Prunus*, respect to *Viburnum*, could be mainly due to the different crop habitus. The first three species have erect, ascending stems with large leaves, whereas *Viburnum* has a rounded, compact habit with small leaves. For model calibration, a mean value of 0.372 was used for *Forsythia*, *Photinia* and *Prunus*, while for *Viburnum* value was 0.289. Therefore, the following models, derived from equation 1 and implementing a crop-specific regression of LAI vs. H , were used to simulate daily ET of the four species under investigation (all values of r^2 were significant):

1. *Forsythia*: $ET = 0.372 (2.938 H - 0.276) ET_0$ ($r^2 = 0.53$)
2. *Prunus*: $ET = 0.372 (0.294^{1.957 H} - 0.276) ET_0$ ($r^2 = 0.43$)
3. *Photinia*: $ET = 0.372 (2.938 H - 0.276) ET_0$ ($r^2 = 0.42$)
4. *Viburnum*: $ET = 0.289 (6.318 H - 0.952) ET_0$ ($r^2 = 0.33$)

Grouping the data for all species, a significant ($r^2 = 0.69$) linear regression was computed between simulated and measured values, with a slope (0.96 ± 0.04) and an intercept (0.15 ± 0.09) not statistically different from 1 and 0, respectively (as assessed by using the least squares method). The mean (absolute) deviation between simulations and observations was nearly 23%; it was slightly higher for *Photinia* (27%) and *Viburnum* (25%) than for *Forsythia* (20%) and *Prunus* (18%).

In 2009, the research group of Pisa University compared two methods for IS in a nursery production scheme with four different crop species (the same used for modeling) grown in the same irrigation plot, according to the standard practice of nurserymen in Pistoia. In particular, timer-based control was compared with an irrigation control system based on ET modeling. In this system, irrigation was automatically activated whenever cumulated ET (estimated on hourly time step) of the reference crop exceeded a predetermined value

corresponding to the maximum allowed substrate moisture deficit. Every week, H was measured on ten representative plants of each species and K_C was calculated accordingly. The species with the highest K_C regulated the irrigation frequency during the following week. As a matter of fact, the calculated K_C is the input value in the software integrated in the irrigation controller, which also computed ET_0 using the CIMIS PM equation. The two methods for IS did not affect crop ET and growth. However, compared to timer, the application of ET model reduced by approximately 40% the seasonal water use as a result of lower irrigation frequency.

3. Modelling evapotranspiration in greenhouse crops

Protected crops are often over-irrigated and this result in water loss and pollution due to fertilisers leaching (Vox et al., 2010). Thompson et al. (2007) reported that inappropriate IS was responsible for nitrate leaching from greenhouse tomato crops in Almeria.

Annual use of irrigation water in protected cropping system ranges from 150-200 mm (kg m^{-2}) in short-cycle, soil-grown crops, such as leafy vegetables, to 1,000-1,500 mm in soilless-grown row crops such as solanaceas and cucurbits.

ET model may be a relevant component of a decision support system (DSS) for greenhouse growing system. It could be employed for both on-line (daily management of irrigation) and off-line (simulation study to define best strategies for managing irrigation or fertigation) decisions. In addition, simulation model for ET can provide a soft-sensor for an early warning system for the grower (Elings & Voogt, 2006). A reduction of actual ET (as measured, for instance, with weighing gutter) with respect to predicted ET suggests alterations of plant water status resulting from technical failure of irrigation system, mistakes in fertigation management or the occurrence of root diseases.

Models of different complexity have been developed for predicting ET in greenhouse crops. Among the different approaches used to calculate ET , the FAO Penman-Monteith (PM) equation is currently considered a standard reference (Stanghellini, 1987; Allen et al., 1998; Walter et al., 2002):

$$\lambda \cdot ET = \frac{\Delta \cdot R_n + \left(\frac{\rho \cdot c_p}{r_a} \right) \cdot (e_s - e_a)}{\Delta + \gamma \cdot \left(1 + \frac{r_c}{r_a} \right)} \quad (2)$$

where R_n is the net radiation ($\text{kJ m}^{-2} \text{s}^{-1}$), $(e_s - e_a)$ is the vapour pressure deficit of the air (kPa), ρ is the mean air density at constant pressure (kg m^{-3}), λ is the latent heat of vaporization (J kg^{-1}), c_p is the specific heat of the air (kJ kg^{-1}), Δ is the slope of the saturation vapour pressure temperature relationship ($\text{kPa } ^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), and r_c and r_a are the canopy and aerodynamic resistances (s m^{-1}). These parameters are directly measured or calculated from weather data.

Nearly isothermal conditions generally occur under greenhouse and thus long-wave exchange can be neglected in first approximation (Bontsema et al., 2007). Some authors (Baille et al., 1994; Bailey et al., 1993) reported that in most conditions the contribution of radiation to crop transpiration depended only from the short-wave component (e.g. incident

R). Moreover, under unheated greenhouse conditions R_n generally matches R during the light period (Bailey et al., 1993). Indeed, in a study conducted with gerbera in a unheated glasshouse at the University of Pisa, R_n was closely related to R (A. Pardossi and P. Battista, unpublished):

$$R_n = 0.981 \cdot R \quad (r^2 = 0.923; n = 590)$$

As crop canopy is not homogenous, the radiation term in equation 2 corresponds to the radiation intercepted by the crop, which is estimated from LAI and the light interception coefficient (k) of the crop, as follows:

$$R_{int} = 1 - \exp^{-k \cdot LAI} \quad (3)$$

Along with environmental variables (net radiation intercepted by the canopy, air and leaf temperature, and vapour pressure), the r_s (stomatal resistance, $s \cdot m^{-1}$) and r_a have to be accurately assessed. The r_s value can be directly measured with a porometer, and the measured values can be related to the main environmental variables. For a hypostomatous crop, the exchange area for latent heat is the leaf area index (LAI). Accordingly, a mean canopy resistance, r_c , can be defined as (Bailey et al., 1993; Montero et al., 2001):

$$r_c = \frac{r_s}{LAI} \quad (4)$$

The aerodynamic resistance of the canopy to the transfer of vapour (r_a) can be obtained from the convective heat transfer coefficient, as the eddy diffusion process transports both air and water vapour. The relationship between the canopy resistance and the heat transfer coefficient for individual leaves can be assumed to be (Bailey et al., 1993):

$$r_a = \frac{\rho \cdot c_p}{2 \cdot LAI \cdot h} \quad (5)$$

where ρ is the mean air density at constant pressure ($kg \cdot m^{-3}$), c_p is the specific heat of the air ($kJ \cdot kg^{-1}$), LAI is the leaf area index and h is the heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$).

Convective heat transfer is generally analyzed using the Grashof or Reynolds numbers. The numbers of Grashof and Reynolds correspond to the air flow occurring in free and forced convection, respectively. The Grashof number is a function of the temperature difference between the leaf (T_l) and the air (T_a):

$$Gr = \frac{\beta \cdot g \cdot d^3 \cdot |T_l - T_a|}{\nu} \quad (6)$$

where β is the thermal expansion coefficient of air ($1/K$), g is the acceleration due to gravity ($m \cdot s^{-2}$), d is the characteristic dimension of the leaf (m) and ν is the kinematic viscosity of air ($m^2 \cdot s^{-1}$).

The Reynolds number can be expressed as a function of air velocity (u , $m \cdot s^{-1}$):

$$Re = \frac{u \cdot d}{\nu} \quad (7)$$

Leaves are generally thin, so the temperatures of the upper and lower surfaces may be assumed to be equal. Therefore, the formula proposed by McAdams (1954) could be used to calculate the average heat transfer coefficient for free convection:

$$h = 0.37 \left(\frac{k_c}{d} \right) Gr^{1/4} \quad (8)$$

where k_c is the thermal conductivity of air ($W m^{-1} K^{-1}$).

When moving air comes into contact with a warm body, heat is lost by forced convection. The average value of the heat transfer coefficient for forced convection is given by Grober & Erk (1961) as:

$$h = 0.60 \left(\frac{k_c}{d} \right) Re^{1/2} \quad (9)$$

Under greenhouse, the air is rarely stationary. Stanghellini (1987) found that the convective heat transfer is due to forced as well as free convection (mixed convection) and proposed the following expression:

$$h = 0.37 \left(\frac{k_c}{d} \right) (Gr + 6.92 Re^2)^{1/4} \quad (10)$$

In all cases the characteristic dimension of the leaf (d , m), is defined by:

$$d = \frac{2}{(1/l) + (1/w)} \quad (11)$$

where l and w are, respectively, average length and width of the leaves.

Obviously, accuracy of ET predictions with the PM equation depends on the accuracy of the measurements or estimates of both LAI and r_s . Leaf area could be determined either by destructive sampling or by non-destructive measurements of leaf dimensions (e.g. Carmassi et al., 2007b; Roupael & Colla, 2004) or whole leaf area (with hand-held ceptometer).

Generally, two sub-models for LAI and r_s are aggregated to the PM equation. The evolution of LAI is often modeled through computation of growing degree days (GDD). Accumulated thermal time was used widely to describe crop growth both in open field and in greenhouse crops (e.g. Incrocci et al., 2006; Pasion & Lieth, 1996; Xu et al., 2010).

However, since under greenhouse conditions the leaf area components (e.g. leaf appearance rate, leaf number) are not only affected by temperature, but also by photosynthetically active radiation (Heuvelink & Marcelis, 1996), the use of product of daily thermal time and daily photosynthetically active radiation instead of GDD gave a better estimation of leaf area components for greenhouse crops (Roupael et al., 2008).

Leaf stomatal resistance could be modeled as a function of environmental variables, in particular irradiance and vapour pressure deficit (VPD). For instance, Roupael & Colla (2004) reported that in pot-grown zucchini (*Cucurbita pepo* L.) the response of r_s to R (expressed in $W m^{-2}$) was explained by an exponential regression (Fig. 1).

The PM equation aggregated to sub-model for both LAI and r_s has been successfully applied at all scales, from single leaves to whole canopies (Stanghellini, 1987; Bailey, 1993), and for a

wide range of horticultural crops (e.g. Yang et al., 1990; Pollet et al., 1999; Montero et al., 2001; Roupael & Colla, 2004).

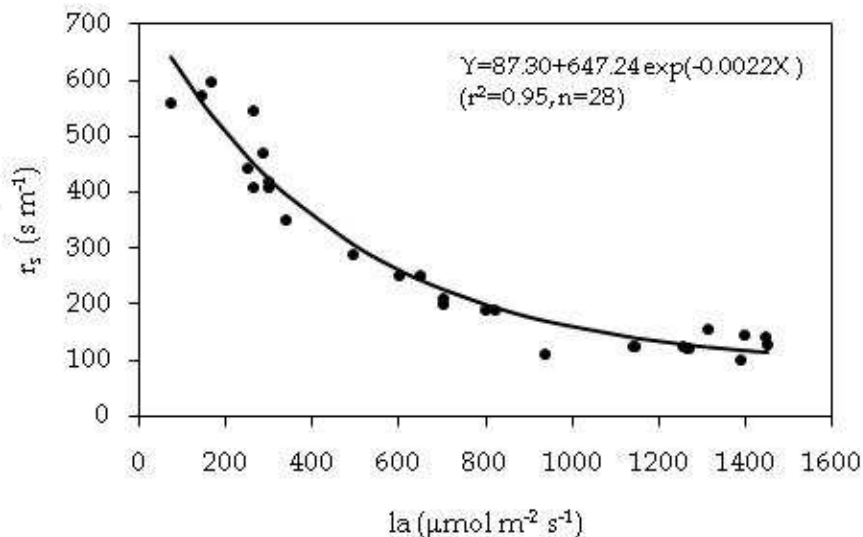


Fig. 1. Instantaneous values of leaf stomatal resistance (r_s) measured on potted zucchini squash with a porometer as a function of photosynthetically active radiation at the top of the canopy (I_a) measured during the entire growing cycle carried out at Tuscia University during spring-summer season.

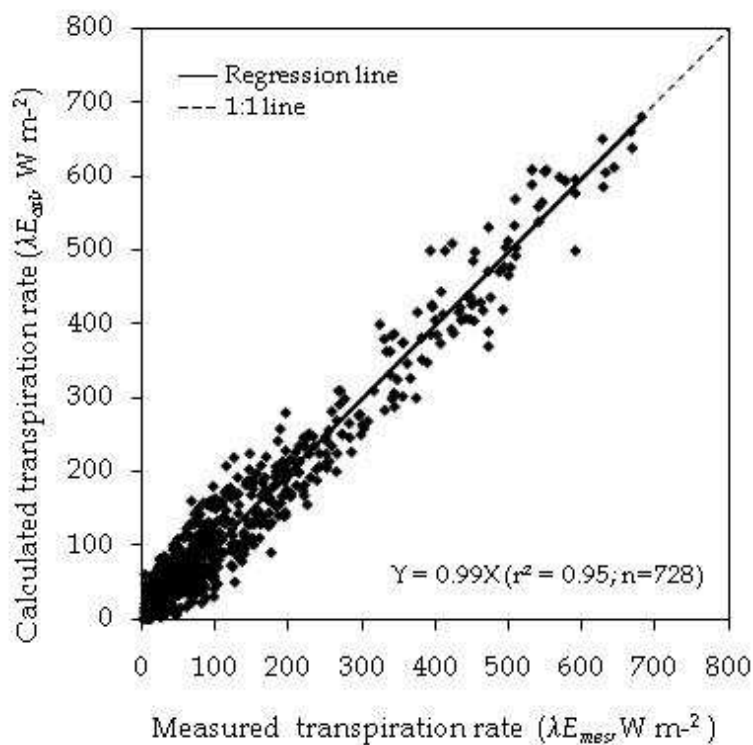


Fig. 2. Calculated daytime transpiration rates (30-min average) by the Penman-Monteith equation assuming forced convection (λE_{cal}) versus measured transpiration rates (λE_{mes} , electronic weighing balance) of potted greenhouse zucchini squash carried out at Tuscia University during spring-summer season.

Figure 2 shows the comparison of simulations and measurements of ET in greenhouse zucchini (Rouphael & Colla, 2004). Simulations were obtained using the PM equation where r_s and LAI were estimate as a function of irradiance (see Fig. 1) and growing degree days, respectively.

However, the application of the PM equation is not straightforward as it requires the knowledge of several inputs or parameters that are not easily available. Therefore, several authors proposed simplified equations for predicting ET as a function of LAI , R_{int} ($\text{MJ m}^{-2} \text{h}^{-1}$) and VPD (kPa) as explanatory variables:

$$ET = A \cdot \frac{R_{int}}{\lambda} + B \cdot LAI \cdot VPD \quad (12)$$

where A (dimensionless) and B ($\text{kg m}^{-2} \text{h}^{-1} \text{kPa}^{-1}$) are empirical coefficients.

After appropriate calibration, equation 12 predicted accurately ET in a variety of greenhouse crops, such as geranium (Montero et al., 2001; Colla et al., 2009), cucumber (Yang et al., 1990; de Graaf & Esmeijer, 1998; Medrano et al., 2005), rose (Baas & Rijssel, 2006; Baille et al., 1994; Kittas et al., 1999), tomato (e.g. Bailey et al., 1993; Baille et al., 1994; Carmassi et al., 2007a; Jolliet & Bailey, 1992; Okuya & Okuya, 1988; Stanghellini 1987), zucchini squash (Rouphael & Colla, 2004), and several pot ornamentals (Baille et al., 1994).

Figure 3 reports the comparison of simulations and measurements of hourly ET in greenhouse gerbera (*Gerbera jamesonii* Bolus ex Hook.) (A. Pardossi and G. Carmassi, unpublished); simulations were obtained using the equation 13.

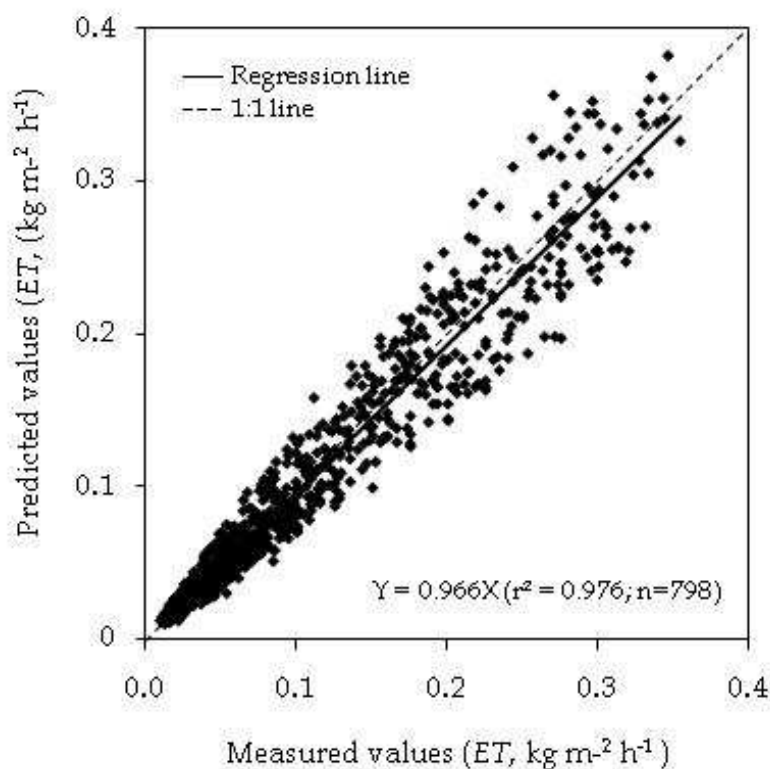


Fig. 3. Comparison between predicted and measured values of hourly ET in the daytime of greenhouse gerbera grown in rockwool. Measurements were taken with a weighing gutter while simulations were obtained by multiple regression equation (Eq. 13 in the text).

$$ET = 0.550 R_{int} + 0.019 LAI \cdot VPD \quad (13)$$

This equation is valid for LAI ranging from 0.9 to 2.5, approximately. R_{int} was calculated using a k value of 0.60. The regression coefficients (0.550, dimensionless; $0.019 \text{ kg m}^{-2} \text{ h}^{-1} \text{ kPa}^{-1}$) used for gerbera in the calibration procedure are similar to those reported by Baille et al. (1994) or by Montero et al. (2001) for several ornamental crops as *Gardenia*, *Impatiens* and *Pelargonium*.

A simple model for estimating daily ET of row crops in heated greenhouse was proposed by De Graaf (1988):

$$ET = \frac{h}{m} \cdot \left[a \cdot R + b \cdot \sum_{1440}^1 \min_i (T_i - T_a) \right] \quad (14)$$

where h and m are actual and maximum height of the crop, respectively; R is the inside global radiation; a and b are crop-specific coefficients, the latter being attributable to heating; \min_i is the successive minute during the day that the temperature of heating pipeline (T_i) is different from air temperature (T_a). The value of b is $0.22 \cdot 10^{-4}$ for tomato and cucumber grown in Dutch growing conditions.

As solar radiation is the main climate variable influencing ET in protected crops, especially under unheated greenhouse conditions (Baille et al., 1994; van Kooten et al., 2008), simple linear regression of ET against outside or inside solar radiation has been also proposed for practical management of irrigation in greenhouse crops (Morris et al., 1957; de Villèle, 1974). In the first case, the light transmission coefficient of the covering material must be known; this coefficient typically ranges from 0.60 to 0.70.

Table 1 reports the ratio of ET on R determined in a few greenhouse crops as determined in a series of experiments conducted with soilless-grown greenhouse crops under unheated greenhouse in Central Italy. The ratio ranged from 0.65 to 0.80 and, as expected, was higher for crops with larger LAI .

Crop	Growing system	Season	LAI	ET/R
Tomato	Pumice; NFT*	Autumn - spring	3.0 - 3.5	0.75 - 0.80
Melon	NFT*	Autumn - spring	3.0 - 3.5	0.70 - 0.75
Strawberry	substrate	Spring	2.0 - 2.5	0.65 - 0.70
Gerbera	substrate	Year-round	2.4 - 2.8	0.65 - 0.70
Rose	substrate	Year-round	2.4 - 2.8	0.70 - 0.75

Table 1. Measured values of LAI and the ratio between evapotranspiration (ET) and incident radiation R (converted in $\text{kg m}^{-2} \text{ day}^{-1}$) in different greenhouse crops grown in soilless culture. * NFT: nutrient film technique.

An aggregated model for ET in greenhouse tomato was designed and tested by Carmassi et al., (2007a). The model consists of two sub-models to predict the evolution of LAI and then daily ET as function of intercepted R . In particular, LAI was modeled using the Boltzmann sigmoid equation (Motulsky & Christopoulos, 2003):

$$LAI = -0.335 + \frac{(4.803 + 0.335)}{1 + \exp\left(\frac{755.3 - GDD}{134.7}\right)} \quad (15)$$

where a , b , c and d are numerical coefficients.

The second model consisted of a simple linear regression between daily ET and R :

$$ET = 0.946 \cdot [1 - \exp(-0.69 \cdot LAI)] \cdot \frac{R}{\lambda} + 0.188 \quad (16)$$

Model's capability to predict LAI evolution resulted in accurate prediction of daily ET in both spring and autumn tomato crops.

The model proposed by Carmassi et al. (2007a) considered an appreciable night-time water consumption (the intercept of Eq. 16), which indeed reached values up to 10% of daily-cumulated ET . The equation did not include VPD as it was significantly correlated to R ($r = 0.59$). In the development of empirical regression model, the number of variables is generally limited by omitting those that are closely correlated to others.

Similarly, Colla et al., 2009 proposed a simplified model:

$$ET = 0.34 [1 - \exp(-0.6 \cdot LAI)] R + 30.27 \cdot LAI \cdot VPD \quad (17)$$

for predicting short-term ET rate in greenhouse geranium (*Pelargonium x hortorum*) grown in winter and spring. There was good agreement between predictions and measurements (Fig. 4).

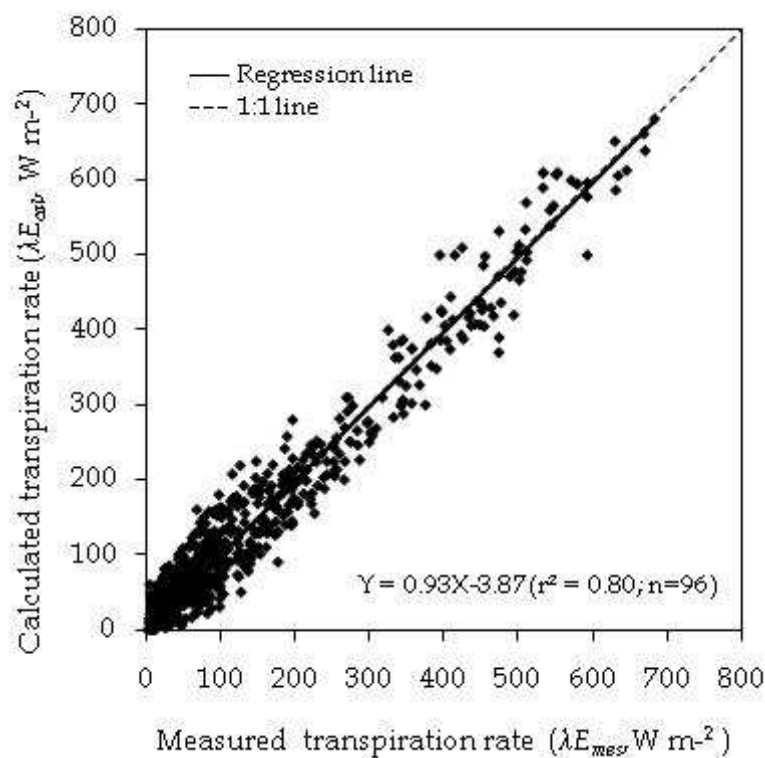


Fig. 4. Calculated daytime transpiration rates (60-min average) by the simplified Penman-Monteith equation (ET_{cal}) versus measured transpiration rates (ET_{mes} – electronic balance) of geranium plants grown in the winter and spring growing seasons.

4. Modelling evapotranspiration by integrating measurements of substrate water status and climatic parameters

According to different authors (Zazueta et al., 2002; Baille, 2001), the combined use of available advanced methods (e.g. climate and soil-based methods) for irrigation control is strongly recommended as it allows the control of data coherence and results in higher reliability of irrigation scheduling (IS). In fact, these systems are expressly designed to manage operations unattended, with only periodic human interventions, since “feed-back” and “fall-back” controls are included (Norrie et al., 1994a; Norrie et al., 1994b; Bowden et al., 2005).

Soil-based method for IS uses the measurement of soil or substrate water potential (tensiometers) or volumetric water content (e.g., dielectric sensors). Unfortunately, a series of technical problems can affect these apparatus like a wrong placement of the sensors, or a progressive decreasing of the measurement representativeness, requiring frequent and accurate controls with heavy indirect cost (Gillet, 2000, Lea-Cox et al., 2009; Pardossi et al., 2009b).

In the climate-based method, instead, ET is computed applying the simple equation $ET = ET_o * K_c$, where ET_o is the reference evapotranspiration and K_c is the crop coefficient. The K_c is defined as the ratio of actual evapotranspiration (ET) of a specific crop on a given condition, to the reference condition (ET_o). The methods used to estimate actual water use include direct measurement of soil moisture, by weighting or drainage lysimeters, gravimetric method, soil moisture balance.

As already stated in par. 2 the main challenge for an effective application of the climate-method for the irrigation management, is the determination of crop coefficient (K_c). In containers, K_c typically are higher than in agronomic crops or orchard trees (Niu et al., 2006), which rarely exceed 1.3 (Doorenbos & Pruitt, 1975). They are also higher than those obtained in lysimeter experiments (García-Navarro et al., 2004).

In recent research projects, supported by Italian Ministry of Agriculture, an integrated method able to combine climate and soil-based methods, was proposed by the research group of IBIMET - Firenze (Bacci et al., 2008). In this procedure ET_o was obtained by applying the CIMIS equation while ET was estimated first by tensiometers readings to calculate K_c values, and then by the equation $ET_o * K_c$. ET estimated values were compared with measured values taken with an electronic balance. Data were collected on three different container grown species, cultivated in greenhouse: *Pelargonium x hortorum*, *Callistemon viminalis* and *Petunia x hybrida*. The container volume was 1.5 L.

4.1 Estimation of ET by means of tensiometric readings (ETt)

The estimation of ET by means of tensiometer readings is valid into the range of the Available Water Content (AWC), corresponding to the amount of water retained in the substrate reservoir that can be readily used by plants. Available water is the difference between water content at matricial potential of -1 kPa (by definition, container water capacity) and that at -10 kPa (de Boodt & Verdonck, 1972).

The first step to estimate ET from tensiometer readings is the definition of a soil-specific tensiometric curve in the laboratory for the conversion of soil water potential in soil water content. One of the most simple procedure to obtain soil water retention curve was suggested by Retzlaff & South (1985). According to this methodology, laboratory soil water potential and related water content are measured by tensiometer and by gravimetric method, respectively. The relationship between water content and water potential has the following form:

$$WC = a \cdot (b - \exp(c \cdot MT)) \quad (18)$$

where WC = soil water content (g cm^{-3}); MT = absolute value of soil potential value measured by tensiometer (hPa); a, b, c = coefficient.

In table 2 a, b, c values of some substrates used in container crops are shown. Tensiometric curves of other growing media are reported by Bibbiani (1996) and Milk et al. (1989).

Substrate	a	b	c
Peat (60%) - Sand(10%) - Pumice (30%)	-0.1491	-3.7981	0.0196
Peat -Perlite (1:1)	-0.1825	-1.5201	0.0193
Peat -Pumice (1:1)	-0.2278	-2.0817	0.0044

Table 2. a, b, c values for equation 18 of some substrates.

Due to relatively low AWC in container crops, at least hourly measurements of soil water potential are advisable to adequately follow the changes in substrate water content by means of equation 18. The difference between two consecutive WC measurements represents the actual evapotranspiration (ETt_h):

$$ETt_h = [WC_h - WC_{h-1}] \cdot V_{pot} \cdot T^{-1} \quad (19)$$

where ETt_h = actual evapotranspiration ($\text{g pot}^{-1} \text{h}^{-1}$); WC_h = soil water content at hour h (g cm^{-3}); WC_{h-1} = soil water content at hour $h-1$ (g cm^{-3}); V_{pot} = volume of pot (cm^3); T = time between two consecutive measurements (one hour).

Values of ETt_h are converted to ET per ground area based on the number of pots per m^2 . Figure 5 shows the comparison between predicted (ETt) and measured (ET_b) hourly values of ET for selected days.

4.2 Estimation of reference evapotranspiration (ET_o)

ET_o can be computed at different temporal scale, but the needs to manage information at hourly step reduce the choice among a limited number of methods. The CIMIS equation (CIMIS, 2009) was chosen to calculate ET_o as appears more suitable for plants with high LAI and high density, like those grown in a greenhouse or nursery. Besides it gives a higher weight to the wind factor that has a relevant effect when container ornamentals are grown outdoor. There were no important differences between the values of ET_o determined with CIMIS formula or the Penman-Monteith (PM) equation (Allen et al., 1998).

The CIMIS equation takes into account four meteorological parameters (net radiation, air temperature, relative humidity and wind speed) as follows:

$$ET_{O_h} = W \cdot R_n + (1-W) \cdot VPD \cdot f(u_2) \quad (20)$$

where ET_{O_h} = hourly reference evapotranspiration (mm h^{-1}); W = dimensionless partitioning factor; R_n = net radiation (mm h^{-1} of equivalent evaporation); VPD = vapour pressure deficit (kPa); $f(u_2)$ = empirical wind function ($\text{mm h}^{-1} \text{kPa}^{-1}$).

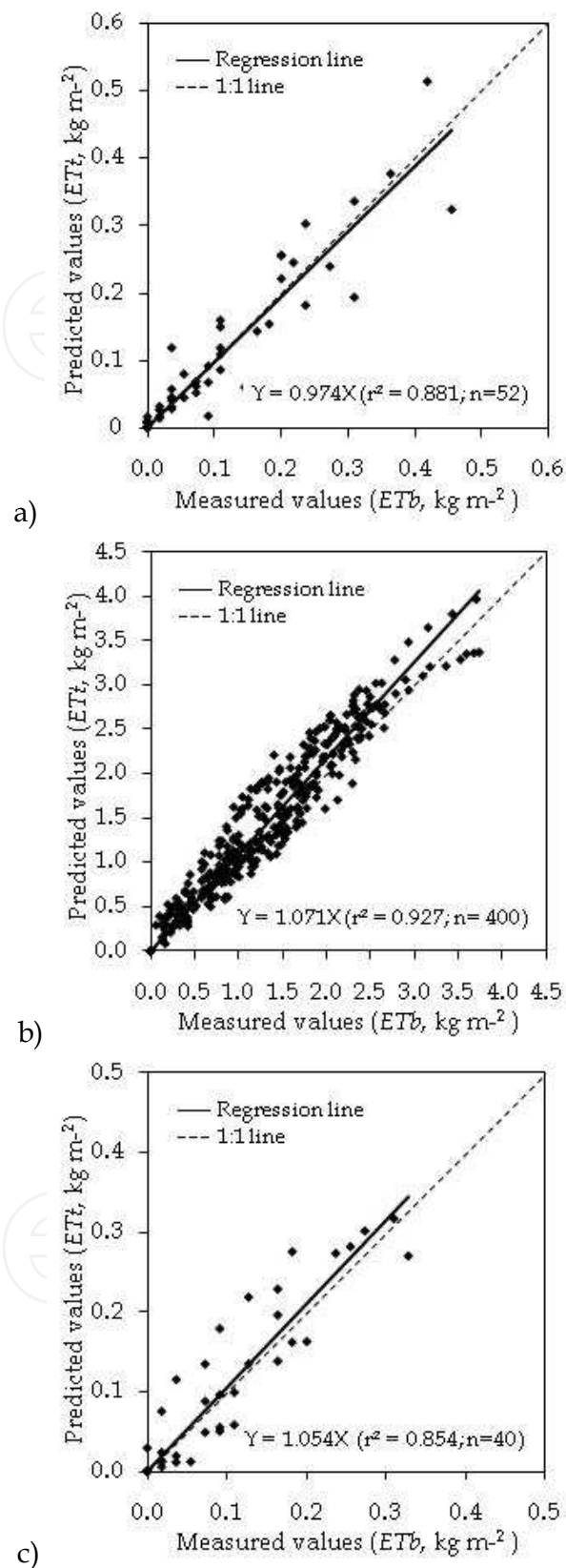


Fig. 5. Relationship between cumulated ET measured values (ET_b) and cumulated predicted values by tensiometric readings (ET_t) of *Pelargonium x hortorum* (a), *Callistemon viminalis* (b) and *Petunia x hybrida hort.* (c). Values were cumulated between two successive irrigations.

The partitioning factor, W , was computed as follows:

$$W = s / (s + \gamma) \quad (21)$$

where s represents the slope of the saturation vapour pressure curve at T_a (air temperature, °C) and γ is the psychrometer constant (kPa °C⁻¹):

$$s = e_s \cdot (597.4 - 0.571 T_a) / [0.1103 (T_a + 273.16)^2] \quad (22)$$

$$\gamma = 0.000646 P \cdot (1 + 0.000949 T_a) \quad (23)$$

where e_s = saturation vapour pressure at T_a (kPa); P = atmospheric station pressure (kPa).
The wind function, $f(u_2)$, is:

$$f(u_2) = 0.03 + 0.0576 u_2 \quad (24)$$

where u_2 = mean hourly wind speed at a height of 2 m (m s⁻¹).

Since a meteorological station only seldom is equipped with a net radiometer, while it is usually available a solarimeter to measure global radiation, net radiation can be estimated from global radiation data by applying simple linear relations. An example of linear relation between hourly global radiation measurements and hourly net radiation measurements is shown in equation 25. It refers to an experiment on *Hypericum hidcote* grown in container outdoor.

$$R_n = 0.7101 \cdot R - 0.3828 \quad (r^2=0.9113^{***}) \quad (25)$$

where R_n = hourly net radiation (MJ m⁻² h⁻¹); R = hourly global radiation (MJ m⁻² h⁻¹).

As already stated in par.3 in a greenhouse global radiation measurements can be used in CIMIS equation in place of net radiation data.

Solar radiation data below the threshold of 0.21 MJ m⁻² should be excluded by the computation, assuming these values corresponding to night time period (Brown, 1998).

4.3 Estimation of ET by climate-method application (ET_{cm})

The values of hourly K_{ch} , can be calculated by applying the following equation:

$$K_{ch} = ET_{th} / ET_{oh} \quad (26)$$

During daytime, the K_c usually follows solar radiation, describing theoretically a bell-shaped curve with a significant difference between early morning and half day values. For this reason, considering that plants grown in pots can transpire all available water in few hours, demanding more irrigation events during a single day, the significance of a reliable hourly K_c is evident.

The high variability of the hourly behavior of K_c , depending on meteorological and plant physiological conditions, suggested the use of an average hourly values to improve the ET_{cm} estimation. In the frame of the experiments of IBIMET research group, a minimum of seven hourly values (7-day average) was used according to the following equation:

$$\overline{K_{chj}} = \frac{\sum_{j=1}^{J-8} K_{chj}}{7} \quad (27)$$

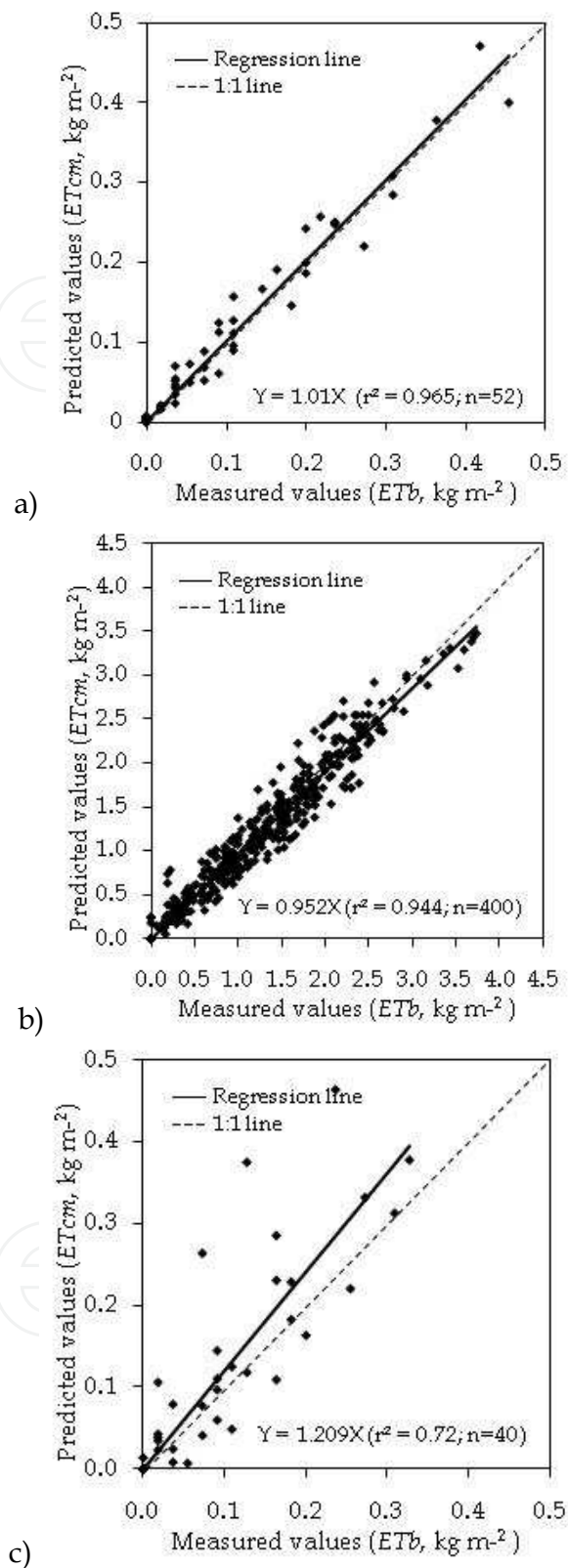


Fig. 6. Relationship between cumulated ET measured values (ET_b) and cumulated predicted values by climate-method application (ET_{cm}) of *Pelargonium x hortorum* (a), *Callistemon viminalis* (b) and *Petunia x hybrida hort.* (c). Values were cumulated between two successive irrigations.

where $\overline{K_{C_{hj}}}$ = average value of K_{C_h} on day j at hour h .

Obviously as new K_{C_h} are calculated for the successive days, new $\overline{K_{C_{hj}}}$ are obtained according to mobile average method. Starting from the previous data, hourly $ET_{cm_{hj}}$ can be calculated by applying the following equation:

$$ET_{cm_{hj}} = ET_{o_{hj}} \cdot \overline{K_{C_{hj}}} \quad (28)$$

A comparison between ET measured and estimated values is shown in figure 6.

4.4 Data integration and irrigation management

According to the previously described method, every hour two values of ET are available: ET_t , estimated by tensiometric measurements, and ET_{cm} , estimated by climate-method application. The comparison between the two values allows a direct cross-control of the representativeness of the data provided by the sensors, improving the reliability of the automatic irrigation system in which this integrated method should be implemented (Fig. 7). In case of a representativeness loss of the sensor, for example, the use of average values (eq. 27) strongly reduces possible errors, while to maintain a high security level in plant watering, unrealistic differences between ET_t and ET_{cm} values can be easily detected and alternative solutions can be adopted.

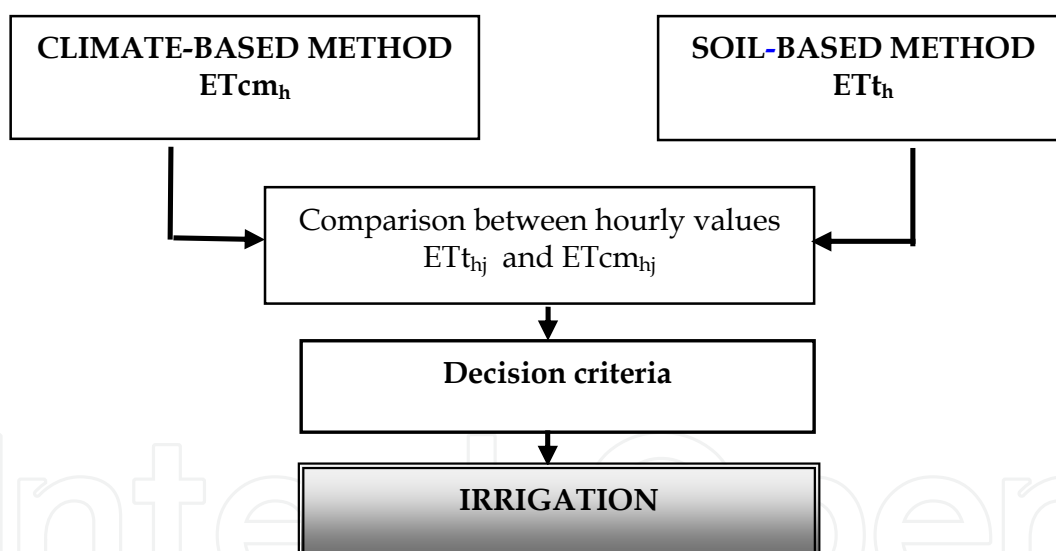


Fig. 7. Operating diagram of the integrated method.

5. Conclusions

Improved irrigation use efficiency requires appropriate irrigation methods, such trickle irrigation and subirrigation, and precise scheduling. Effective operation of irrigation systems requires a sensing system that determines crop needs in real time; this rules out manual control as an automated monitoring system is necessary.

Once implemented in a dedicated hardware/software system, ET models described in the previous paragraphs can be employed for daily or hourly management of irrigation or fertirrigation as they stand or integrated with the measurements of substrate moisture.

Besides *ET* model may be a relevant component for simulation studies to define best strategies for managing irrigation or fertigation.

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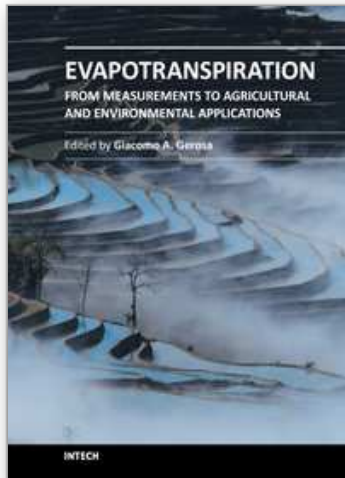
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This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (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 students who intend to address these issues.

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