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Predicting reference evapotranspiration for screenhouse-grown crops

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ABSTRACT

The purpose of the study is to estimate the reference evapotranspiration of screenhouse-grown crops ($ET_{o,in}$) from routine outside weather data and main screenhouse characteristics. To this aim, all the microclimatic variables required to calculate $ET_{o,in}$ by means of the standard FAO-56 Penman–Monteith formula were measured under three cultivated (sweet-pepper, spring–summer cycle) screenhouses for a two months period observation (Aug–Sept 2012) in a Mediterranean climate (Eastern Central Greece). The screenhouses differed in transmittance to solar radiation (τ) and wind ratio (ω = ratio of inside-to-outside wind speed): (i) a pearl insect-proof screen (IP-1, $\tau \approx 0.76$, $\omega \approx 0.19$), (ii) a white insect proof screen (IP-2, $\tau \approx 0.58$, $\omega \approx 0.20$), and (iii) a green shade-screen (GS, $\tau \approx 0.56$ and $\omega \approx 0.43$). We quantified and analysed at daily scale the evolution of the radiative ($ET_{rad,in}$) and advective ($ET_{adv,in}$) components of $ET_{o,in}$. $ET_{rad,in}$ and $ET_{adv,in}$ were expressed as a function of the corresponding outside values ($ET_{rad,out}$ and $ET_{adv,out}$) through two reduction ratios ($\zeta_{rad} = ET_{rad,in}/ET_{rad,out}$ and $\zeta_{adv} = ET_{adv,in}/ET_{adv,out}$). ζ_{rad} and ζ_{adv} could be expressed as linear functions of τ and ω respectively. Based on this finding, we proposed an additive model of the form $ET_{o,in} = \zeta_{rad}\ ET_{rad,out} + \zeta_{adv}\ ET_{adv,out}$. The predictive performance of the model was fair (RMSE = 0.11 mm day^{-1}). The proposed model, based only on outside climate data and the knowledge of two screenhouse-related parameters, provides a straightforward way to estimate screenhouse ET_o, a necessary step towards the determination of screenhouse-crops water requirements.

1. Introduction

Screenhouses, also called net-houses, are becoming popular among growers in arid and semiarid regions like the Mediterranean area, due to the environmental, economic and agronomic benefits they offer (Castellano et al., 2008). Insect proof screenhouses are environmental friendly as they reduce the amount of chemical inputs in pesticides and their associated costs, health risks for workers and potential environmental pollution (Möller et al., 2004). Economically, screenhouses have lower cost compared to conventional greenhouses (Möller and Assouline, 2007). The reduction of solar radiation due to net-covering allows alleviating conditions of stress-induced limitations of the physiological fluxes (Stanhill and Cohen, 2001) which are a major constraint in the productivity and quality of greenhouse-grown crops. The positive impact of a net-covering on plant behaviour can be mostly explained by the more favourable microclimate under a screenhouse than outdoors.

In particular, the reduction in both radiation load (net radiation) and wind speed due to the presence of the cover material leads to a reduction of the climatic demand with respect to open field. This reduction of the climatic demand—generally expressed in terms of the evapotranspiration of a reference crop, ET_o, as proposed by the FAO (Allen et al., 1998), hereafter FAO-56-PM method—leads to a concomitant reduction of the actual evapotranspiration rate of screenhouse crops with respect to open field. This was demonstrated by several studies performed in the last decade (Möller et al., 2004; Tanny et al., 2006; Siqueira et al., 2012). However, whereas irrigation scheduling of open field crop by means of the calculation of the FAO-56-PM method and subsequent application of a crop coefficient (K_c) is used worldwide, it is not possible to apply this method to screenhouse crops, because the calculation of the crop net radiation, R_n, is based on formulae that are valid only for open field conditions. In particular, R_n of a screenhouse crop differs substantially from that of an open field crop, due to the presence of the cover, which changes both the net short-wave and net long-wave radiation.

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Due to this problem, intents of predicting the evapotranspiration of screenhouse crops by adapting the Penman–Monteith (PM) formula to the internal conditions specific to each screenhouse were carried out (Dicken et al., 2013; Pirkner et al., 2013). Other option is to use the PM-screen model (PM_{sc}) developed by Möller et al. (2004), which incorporates a screenhouse specific resistance that accounts for the effect of the additional boundary layer occupying the air gap between the horizontal screen and the underlying canopy. For practical applications in growers' screenhouses, such approaches present the great inconvenience to require continuous measurements of solar radiation, temperature and humidity inside the screenhouse, which does not appear feasible on a practical and economical point of view for most screenhouse growers.

To overcome this problem, we propose in this study to investigate the links between the advective and radiative components of $ET_{o,in}$ and $ET_{o,out}$ with the aim to propose a simple model of $ET_{o,in}$ based only on outside climate inputs. The specific objectives were to:

(i) Demonstrate that the radiative component of $ET_{o,in}$ is mainly driven by the screenhouse global transmittance (τ), and the advective component by the screenhouse wind ratio (ω).
(ii) Use these findings to formulate and test the performance of an ET_o-model that enables predicting $ET_{o,in}$ from the radiative and advective components of $ET_{o,out}$ and from the knowledge of τ and ω.

2. Materials and methods

2.1. Screenhouse and open field facilities

The experiments were performed in three experimental flat roof screenhouses, with the longer dimension oriented N–S, (36° declination clockwise from North), located at the University of Thessaly near Volos (Velestino: Latitude 39°22′, longitude 22°44′, altitude 85 m), on the continental area of Eastern Greece. The three screenhouses were 20 m long, 10 m wide and 3.2 m high.

Three screens were tested. Two were insect-proof (IP) screens manufactured by Meteor Ltd., Israel: (1) a pearl 50 mesh (20/10) AntiVirus™ screen, hereafter IP-1; and (2) a white 50 mesh BioNet™ (BN), hereafter IP2. The third one was a green shade screen (Thrace Plastics C S.A. Xanthi, Greece) hereafter GS. The insect proof nets have a regular mesh netting of 0.27 mm × 0.27 mm, while the green shading net, due to its different knitting, present meshes that are irregular in size and arrangement, with dimensions varying in the range 0.5 mm–3.0 mm.

The screenhouses differed by their shading factor (SF), defined as the complement to 1 of the solar radiation transmittance. Estimates of SF were obtained from measurements of the screen transmittance in laboratory by means of a spectroradiometer (Kitta et al., 2014), supplying values of 13%, 34% and 36% for IP1, IP2 and GS respectively. Note that the laboratory data represent maximum values that could substantially overestimate the *in situ* transmittance prevailing under screenhouse conditions (see section Results), where the screenhouse structure and orientation, incidence angle of the sun and dust deposition among other factors could affect the overall transmittance of the screenhouse.

2.2. Crop management

Sweet pepper plants (*Capsicum annuum L.*, cv. Dolmi) were transplanted in the three screenhouses and in open-field on May 7, 2012. Plants were laid out 0.5 m apart in the row, in five double rows with a distance between the double rows of 1.2 m, resulting in a plant density of 1.8 plants/m^2. The plants were supported vertically by cords hanging from cables attached longitudinally to the frame of the screenhouses. At the start of the observation period, the height of the crops was approximately 0.6 m with a leaf area index close to 0.8. At the end of the period, the height was approximately 1.10 m and LAI about 1.8.

Cropping techniques (fertigation, pruning and chemical treatments) were identical in all treatments. Irrigation water was supplied through drip-laterals with one drip-line per row and one dripper per plant. Irrigation scheduling was based on the concept of crop coefficient, K_c, as described in Katsoulas et al. (2006). The amount of water supplied to the crops was identical in all screenhouses and calculated as the product of K_c and a fixed integral of outside solar radiation. The value of K_c was fixed to a level that ensured that the crops were fully watered during the months with the highest water demand. It can be considered that all crops were maintained fully watered and did not suffer from soil water deficit throughout the crop cycle.

The soil in the screenhouses and open field is silty clay. Analysis of physical and chemical soil properties, made at the start of each experiment, indicated that there were no significant differences among screenhouses. During the observation period, the insect population was monitored and controlled to similar levels by colour traps and spray application of pesticides.

2.3. Climatic data

The following climatic data were continuously monitored outside (University weather station, 75 m distant of the screenhouses) and in the centre of each screenhouse:

- Air temperature (T_a) and relative humidity (RH) by means of temperature and humidity sensors (WiSensys® Wireless Sensor WS-DLTc, Wireless Value BV, NL), located at 2 m aboveground. Using the above data, the air vapour pressure deficit (VPD) was calculated.
- Global solar radiation (S), by means of pyranometers (model SP-LITE Silicon Pyranometer, Campbell Scientific, Inc., U.S.A.), placed 1.5 m aboveground, net radiation (R_n) by means of net pyradiometers (model NR-LITE 2, Kipp and Zonen, Delft, the Netherlands). The sensors were located at 1.5 m height, just above a double row, therefore viewing mainly the vegetation.
- Outside air velocity (u_{out}) at 2 m height by means of a cup anemometer (model AN1–UM–3, Delta-T devices, Cambridge, U.K.) located at the weather station.
- Air velocity inside the screenhouses by means of two sonic anemometers (model 1405-PK-040 Windsonic, Gill Instruments, Llandrindod Wells, Powys, UK) that were rotated among the screenhouses for 10 selected days of the observation period. Empirical relationships between the screenhouse and outside values (u_{out}) were obtained from this data set. The relations found were: $u_{IP1} = 0.19\ u_{out}$, $u_{IP2} = 0.21\ u_{out}$ and $u_{GS} = 0.43\ u_{out}$ for IP1, IP2 and GS screenhouses, respectively. The proportionality coefficients—hereafter, wind ratio, ω—were used to calculate the daily mean air velocity inside the screenhouse from u_{out} for all the days of the observation period.

All of the above-mentioned measurements were recorded by two data logger systems (model DL3000, Delta-T Devices, Cambridge, U.K., and WiSensys® Wireless Sensor WS-DLTc, Wireless Value BV, NL). Samplings took place every 30 s and 10-min average values were recorded.

Data processing consisted in three stages (i) removing of inconsistent data (ii) gap filling, by simple time-interpolation or from