Scientia Horticulturae 134 (2012) 210–221

Contents lists available at SciVerse ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Comparison of three evapotranspiration models for a greenhouse cooling strategy with natural ventilation and variable high pressure fogging

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ARTICLE INFO

Article history:
Received 20 June 2011
Received in revised form
29 September 2011
Accepted 16 October 2011

Keywords:
Control strategy
Evapotranspiration
Fogging
Greenhouse
Ventilation

ABSTRACT

Even though several models to predict evapotranspiration (ET) of greenhouse crops have been developed, previous studies have evaluated them under fixed greenhouse conditions. It is still not clear which model is more appropriate, accurate, and best suited for applications such as inclusion in greenhouse cooling strategies for different crops, climatic conditions and greenhouse cooling settings. This study evaluated three theoretical models (Stanghellini, Penman–Monteith and Takakura) to simulate the ET of two crops (bell pepper and tomato), under two greenhouse cooling settings (natural ventilation with fog cooling and mechanical ventilation with pad and fan), and for three growing seasons (spring, summer, fall). Predictions of ET from the models were compared to measured values obtained from sap flow gauges. Inputs of internal and external crop resistances for Stanghellini and Penman–Monteith models were calibrated separately by crop and by model. Even though Stanghellini model produced the smallest deviations of the predicted ET from the measured ET, having the best overall performance under all conditions evaluated, an analysis of variance of the daily mean square errors did not show significant differences ($\alpha = 0.05$) between the three models. This suggested that any of the three models could be used for inclusion in a greenhouse cooling climate control strategy. However, parameter adjustments such as stomatal and aerodynamic resistances, and the need of leaf area index (LAI) in the models of Penman–Monteith and Stanghellini represent a limitation for this application. The Takakura model was found to be easier to implement; however as the crop grows, careful adjustments on the height of the solarimeter used for this approach are required. Such adjustments determine the field of view of the solarimeter and play a significant role on the determination of radiation balances and the average apparent temperature of the evaporative surface.

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1. Introduction

The high capital investment for greenhouse production systems must be justified by the ability of the greenhouse system to provide year-round high quality produce with predictable yields. In the global and highly competitive marketplace, the growers must secure long term markets with the ability to deliver high quality produce year-round. Thus, improvements and adaptations on greenhouse structures, equipments and skillful management of greenhouse and crop systems are needed to extend crop production period with acceptable levels of marketable produce quality, and to maintain high net income for greenhouse businesses (Katsoulas et al., 2009). In particular, in greenhouses located in hot climates, the high air temperature and humidity in the greenhouse can severely limit greenhouse production with reduced yield and low produce quality during a significant part of the year. During these months, greenhouses are either not in use or generate non-marketable produce. Greenhouse crop production during warm periods can be maintained by proper use of greenhouse climate control and various cooling methods. Natural ventilation is usually the simplest and preferred greenhouse cooling method due to its low cost and simplicity. However, natural ventilation alone is generally not adequate for efficiency removing the surplus energy during hot periods. Furthermore, increased ventilation rates may not be the best solution for minimizing the stress on the crop (Kittas et al., 2001; Katsoulas et al., 2009). Evaporative cooling, which relies on conversion of sensible heat into latent heat through the evaporation of mechanically supplied water, along with

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0304-4238/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.scienta.2011.10.016

Nomenclature

C_p	specific heat capacity of air, J kg^{-1} °C^{-1}
E	evapotranspiration, kg m^{-2} h^{-1}
h	coefficient of the convective heat transfer, kJ m^{-2} h^{-1} K^{-1}
I_s	incoming shortwave radiation, W m^{-2}
l	leaf characteristic dimension, m
Re	Reynolds number, dimensionless
r_i	internal crop resistance, s m^{-1}
T	temperature of the air, °C
u	wind speed, s m^{-1}
z	wind speed measurement height above the ground, m
$E\lambda$	evapotranspiration flux, W m^{-2}
λ	latent heat due to water vaporization, kJ kg^{-1}
ρ_a	density of air, kg m^{-3}
c_i	constants used for parameterization of r_i
d	zero-plane displacement height, m
Gr	Grashof number, dimensionless
k	von Karman constant, dimensionless
LAI	leaf area Index, dimensionless
Nu	Nusselt number, dimensionless
r_e	external crop resistance, s m^{-1}
R_n	net shortwave radiation, W m^{-2}
T_w	evaporative surface temperature, °C
VPD	vapor pressure deficit at the air, Pa
z_0	reference crop momentum aerodynamic surface roughness length, m
γ	psychrometric constant, Pa °C^{-1}
λ_a	thermal conductivity of air, W m^{-1} K^{-1}
δ	slope of the saturation curve of the psychrometric chart, Pa °C^{-1}

natural ventilation can help avoiding exceedingly high temperatures in the greenhouse. Evaporative cooling systems are particularly required in semiarid greenhouses most of the year due to harsh climatic conditions. Nevertheless, large amount of water is needed to accommodate the desired climate inside the greenhouse for crop production. Sabeh et al. (2011) reported water usage as high as 11 L m^{-2} day^{-1} for a pad and fan cooled greenhouse located in semiarid region. Water is a scarce resource especially in arid and semi-arid regions, thus potential savings by optimal climate control is of high importance. Crops have significant role in contributing to greenhouse cooling through transpiration, which is the main evaporative cooling process for the crop. And, as the energy dissipation component from the crop is larger, the required ventilation and cooling is smaller (Seginer, 2002). Therefore, accurate predictions of contributions of cooling and humidification from the plant canopy (transpiration) in the greenhouse energy balance are desired to achieve an efficient climate control strategy.

Methods to quantify greenhouse crop transpiration should provide information timely, be non-destructive and practical for implementing them in effective real-time greenhouse cooling strategy. By comparison, current technology to monitor greenhouse crop transpiration is either expensive (i.e. weighting lysimeters) or abrasive (i.e. stem gauges) and may not be practical to implement in commercial greenhouse settings. Thus, modeling of crop transpiration represents an alternative method to quantify crop water use. Transpiration modeling has been proven to be a reliable and effective tool for use in greenhouse ventilation design (Seginer, 2002), irrigation scheduling (Boulard and Jemaa, 1993; Lorenzo et al., 1998), on-line climate control (Baille et al., 2006; Bontsema et al., 2007; Li et al., 2001) or for irrigation and climate control (Kittas et al., 1999; López-Cruz et al., 2008).

The first evapotranspiration (ET) model developed by Penman (1948) simulated the crop canopy as a single big leaf. This model was mainly applicable for field crops. Monteith (1965) included parameters for the resistance of water vapor transfer between the canopy and air, which improved the accuracy of the model. This model is well-known as the Penman–Monteith model. Stanghellini (1987) revised the previous model and included a new term (i.e. LAI). The Penman–Monteith was primarily developed for predicting ET of crops grown in open field conditions while Stanghellini model was mainly used for greenhouse settings. Takakura et al. (2005) developed an ET model based on the heat balance equation of the crop canopy, which is the basis of the Penman–Monteith (P–M) equation. This model is simpler than the P–M model and it was shown to provide accurate crop ET predictions for tomato crop by using a crop solarimeter (Takakura, 2008; Takakura et al., 2009).

Even though several models to predict ET of greenhouse crops have been developed, to our knowledge, no work has focused specifically on determining which model is more suitable and accurate for different crops, climatic conditions and greenhouse cooling settings. Previous studies comparing ET models with green pepper (Jolliet and Bailey, 1992), tomato (López-Cruz et al., 2008), and acer rubrum tree (Prenger et al., 2002) have shown higher accuracies with the Stanghellini model. However, these studies also pointed out that these models required the calibration of several hard-to-measure parameters (i.e. resistances). Based on an extensive literature review study, Fazlil-Ilahil (2009) pointed out that most of the previous studies have been conducted under fixed greenhouse conditions, for a specific crop and for particular outside climates. There is a lack of information regarding the performance of ET models when conditions such as cooling settings, growing seasons and different crops change. The objective of the present work was to evaluate three theoretical ET models (Stanghellini, Penman–Monteith and Takakura) under two evaporative greenhouse-cooling settings (fan-pad, natural ventilation with high pressure fogging) for two crops (bell pepper, tomato) with three growing seasons (spring, summer, fall). The overall ET prediction capabilities of the three models under these settings were studied, their advantages and limitations in a control strategy for a naturally ventilated greenhouse with fog cooling were discussed.

2. Materials and methods

The experiments were conducted from June to August of 2009 with bell pepper (*cv.* Triple Star) and from November 2009 to May 2010 with the tomato (*cv.* Rhapsody). The two crops were grown in a single span research greenhouse (PolyTex, USA) located at University of Arizona Controlled Environment Agriculture Center, Tucson, Arizona.

The greenhouse has 270 m^2 of ground area. The end walls are covered with polycarbonate and a double air-inflated layer of polyethylene covers its arched roof. The greenhouse has continuous roof and side vents and is equipped with a pad and fan cooling system as well as a variable high pressure fogging system. The fog system is capable of producing fogging rates continuously from 0.31 to 0.50 g m^{-2} s^{-1}, operating at pressures from 4.83 to 10.34 MPa, respectively. The fog lines are evenly spaced on the east and west sides of the greenhouse at 0.5 m above the canopy. During the experiments, both the bell pepper (6.14 plants m^{-2}) and the tomato crop (2.89 plants m^{-2}) were grown hydroponically in a rockwool growing media. The greenhouse climate was controlled by an automatic climate control system (Argus Control Systems Ltd., Canada).

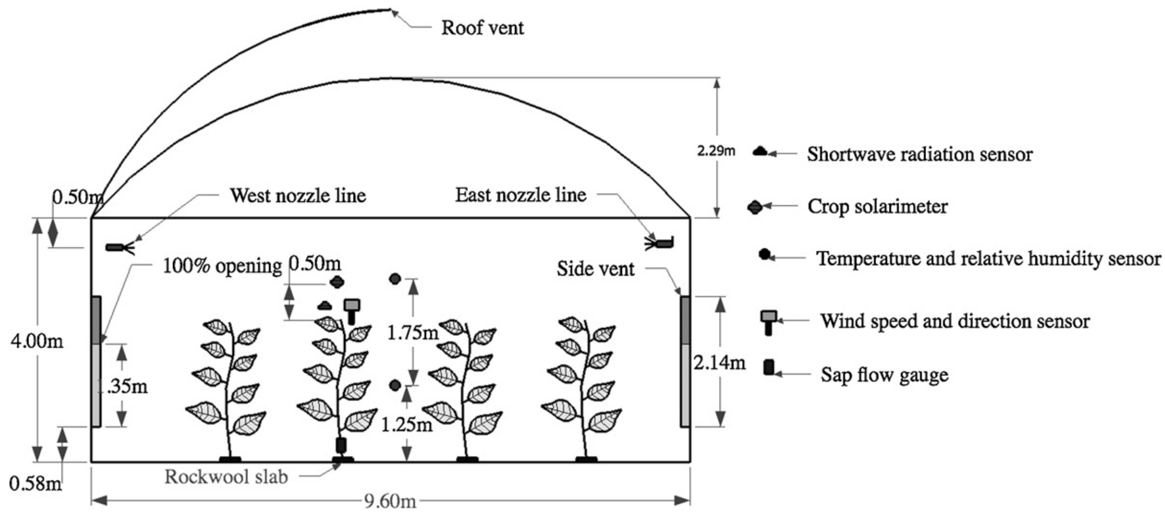

Fig. 1. Front view of the research greenhouse and sensor locations.

2.1. Variables measured

Fig. 1 illustrates the locations of all the sensors used to measure greenhouse and crop related variables. The net solar radiation and canopy surface temperature was measured with a crop solarimeter, located at 0.5 m above the canopy (Takakura et al., 2005) for ET predictions with the heat balance equation (Takakura model). Detailed specifications and working principles of this instrument are outlined in Takakura et al. (2009).

A pyranometer sensor placed above the crop canopy was used to measure incoming shortwave radiation for Stanghellini and Penman–Monteith model calculations (Model CM3, Kipp & Zonen, The Netherlands). Air temperature and relative humidity were measured both at 1.25 m and at 3.0 m heights from the ground level. The sensors (Model Vaisala HMP50, Woburn, MA, USA) were placed in a shielded and aspirated enclosure for accurate measurements. Wind speed and direction were measured within the canopy boundary layer by an ultrasonic anemometer (Model 81000, R.M. Young, Traverse City, MI, USA). Transpiration from two sampled plants was measured by means of sap flow gauges (Model SGA13-WS, Dynamax Inc., Houston, TX, USA). The amount of water applied by irrigation and the drainage from each slab containing the sap flow sampled plants were monitored with lysimeters as well. The data obtained from sap flow gauges were compared to the values measured directly from lysimeters for each day. The comparisons showed that the measurement differences between the two approaches were less than 5% and the accuracy of the sap flow gauges was found satisfactory. The three ET models were calibrated using average readings obtained from the two sap flow gauges. All the sensors were connected to a data acquisition system consisting of three different data-loggers (Models CR10x, CR23x, and CR3000, Campbell Scientific Inc., Logan, UT, USA) and were networked with an RS232 to Ethernet serial server (Model ESR904, VLINX, B&B Electronics, USA). All the sensors were scanned at 10 s time intervals and 1 min averaged readings were recorded.

Leaf areas were determined using a digital leaf area meter (Model LI-3100, LI-COR Inc., Lincoln, NE, USA). A total of 100 leaves with representative shapes and sizes were selected from different plants in the greenhouse. The length and width of the collected leaves were correlated to their respective leaf area. The length and width of all the leaves of two sample plants connected to the sap flow gauges in the greenhouse were measured weekly. Their total leaf area was determined by using the correlation between leaf length and width, and the leaf areas obtained from the 100 leaves. Leaf area index (LAI), defined as the ratio of total leaf area to the ground area, of the whole canopy was extrapolated from the sample plants and the crop density. The LAI was assumed not to change significantly within a week and a constant weekly value was used for the model predictions. This parameter was used as an input in the Stanghellini model and this procedure was performed separately for each crop.

2.2. Experimental data collection

The research greenhouse was operated under pad and fan cooling for most of the crop cycles. However, in order to collect appropriate data under natural ventilation and fogging conditions, the fans were stopped, the pad was dried, the side and roof vents were operated with 0%, 50% and 100% opening combinations, and the fog was operated at pressures of 4.83, 7.58 and 10.34 MPa, based on outside weather conditions. The greenhouse air temperature was maintained so that it would not exceed 30 °C. Table 1 illustrates the details of the tests periods, greenhouse crop and cooling system settings, duration of the tests.

2.3. Evapotranspiration models

Stanghellini, Takakura and Penman–Monteith ET models are described by Eqs. (1)–(3), respectively. Table 2 summarizes all required variables and corresponding units and symbols used in the models.

$$E\lambda = \frac{\delta \cdot R_n + ((2 \cdot LAI \cdot \rho_a \cdot C_p)/r_e)(VPD)}{\gamma \cdot (1 + (\delta/\gamma) + (r_i/r_e))} \tag{1}$$

$$E\lambda = R_n - h(T - T_w) \tag{2}$$

$$E\lambda = \frac{\delta \cdot R_n + ((\rho_a \cdot C_p)/r_e)(VPD)}{\delta + \gamma \cdot (1 + (r_i/r_e))} \tag{3}$$

Table 1
The details of the test periods during the experiments; crop type, seasons, test durations, cooling system settings, and shade curtain use.

Test	Crop	Season	Days	Cooling	Shade
1	Pepper	Summer	4	Natural ventilation + fog	No
2	Pepper	Summer	10	Pad and fan	Yes
3	Tomato	Fall	10	Pad and fan	Yes
4	Tomato	Spring	10	Pad and fan	Yes
5	Tomato	Spring	4	Natural ventilation + fog	No

Table 2
Variables used in Stanghellini (S), Penman–Monteith (PM) and Takakura (T) ET models.

Variables	Symbol	Units	Value	Model
Evapotranspiration flux	$E\lambda$	$W\,m^{-2}$		PM, S, T
Net radiation above canopy	R_n	$W\,m^{-2}$		PM, S, T
Vapor pressure deficit of the air	VPD	Pa		PM, S
Psychrometric constant	γ	$Pa\,^{\circ}C^{-1}$	66	PM, S
Slope of the vapor pressure–temperature curve	δ	$Pa\,^{\circ}C^{-1}$	$41.45 \times \exp(0.061 \cdot T)$[a]	PM, S
Density of air	ρ_a	$kg\,m^{-3}$	1.117	PM, S
Specific heat capacity of air at constant pressure	C_p	$J\,kg^{-1}\,^{\circ}C^{-1}$	1003.5	PM, S
Internal crop resistance to vapor transfer	r_i	$s\,m^{-1}$		PM, S
External crop resistance to sensible heat transfer	r_e	$s\,m^{-1}$		PM, S
Leaf area index	LAI	dimensionless		S
Convective heat transfer coefficient of air	h	$W\,m^{-2}\,^{\circ}C^{-1}$	7[b]	T
Temperature of the air	T	°C		T
Temperature of the evaporative surface	T_w[b]	°C		T

[a] ASAE Standards (1998).
[b] Takakura et al. (2009).

2.4. External crop resistance

To determine the external (aerodynamic) crop resistance (Eq. (4)) for the Stanghellini model, the Nusselt number (Nu) determined by Eq. (5) was used. This equation simulates the heat transfer through the boundary layer of leaves under mixed convection conditions, which are common in greenhouses (Stanghellini, 1987).

$$r_e = \frac{\rho_a \cdot C_p \cdot l}{\lambda_a \cdot N_u} \tag{4}$$

$$Nu = 0.37[Gr + 6.92 \cdot Re^2]^{0.25} \tag{5}$$

where Gr and Re denote the dimensionless Grashof and Reynolds numbers, respectively, r_e is the external resistance to water vapor transfer ($s\,m^{-1}$), l denotes the characteristic dimension of a leaf (m) (Parkhurst et al., 1968), which was determined to be 0.051 m and 0.043 m for pepper and tomato, respectively, and λ_a, ρ_a, C_p are the thermal conductivity ($W\,m^{-1}\,K^{-1}$), the density ($kg\,m^{-3}$) and the specific heat capacity of air ($J\,kg^{-1}\,^{\circ}C^{-1}$), respectively.

Eq. (6) was used to determine external crop resistance for the Penman–Monteith model (Monteith and Unsworth, 1991).

$$r_a = \frac{\{\ln(z - d)/z_0\}^2}{k^2 \cdot u} \tag{6}$$

where z denotes the wind speed measurement height above the ground (m). For this study, the anemometer was kept within the canopy boundary layer. d is the zero-plane displacement height (m), taken as 0.67 times the crop height (h_c). Average crop height during the experiments was 2.85 m. z_0 is the reference crop momentum aerodynamic surface roughness length (m), taken as 0.123 times the crop height, k is the von Karman constant (0.41) and u is the wind speed ($m\,s^{-1}$) at the measurement height of z.

2.5. Internal crop resistance

The stomatal resistance, a major component of the internal crop resistance (r_i), used in the Stanghellini and Penman–Monteith ET models, was measured using a diffusion porometer (Decagon Devices, Pullman WA, USA). However, poor relations were found between the measured data and the climatic factors at the time of the readings. The difficulty of obtaining reliable readings from a porometer has been reported in previous studies as well (Montero et al., 2001; Voogt and van Weel, 2008). Therefore, the internal resistance of the crop canopy was determined using Eqs. (7) (Stanghellini, 1987) and (8) (Monteith and Unsworth, 1991), for the Stanghellini and the Penman–Monteith models, respectively. The two equations represent a vapor balance between the canopy and the surrounding air.

Table 3
Polynomial parameters (C_i) used to model the internal crop resistance for pepper and tomato crop, which were determined for Stanghellini and Penman–Monteith models separately.

Model	Stanghellini		Penman–Monteith	
Crop	Pepper	Tomato	Pepper	Tomato
c_1	80.8	18.6	29.9	0.35
c_2	14.3	197.5	17	9985
c_3	0.44	0.31	−8.5	3.8
c_4	1.9×10^{-6}	1.2×10^{-6}	3.5×10^{-7}	2.61×10^{-7}

Independent measurements of plant transpiration were performed to determine r_i. Data of measured transpiration, along with all the variables required for Eqs. (7) and (8), were separated by crop (two data sets). Eqs. (7) and (8) were applied to each of the two data sets to solve for r_i separately providing four data sets of r_i values. The two data sets of r_i resulting from Eq. (7) were then fitted to Eq. (9) to determine the values of c_1–c_4 shown in Table 3, respectively. Similarly, the two data sets of r_i resulting from Eq. (8) were fitted to Eq. (10) to determine values of c_1–c_4 displayed in Table 3, respectively. With these results, r_i was modeled under all the conditions studied based on the variables different from the ET.

Eqs. (9) and (10) were obtained to consider the effect of both solar radiation and VPD. The former had the shape of a square hyperbola (Stanghellini, 1987) while the latter showed a curvilinear response (Katsoulas et al., 2001). The parameters of Table 3 were determined by using an optimization procedure based on non-linear least squares in the surface fitting toolbox of Matlab (Matlab R2010a, Mathworks Inc.).

$$E\lambda = \frac{2 \cdot LAI \cdot \rho_a \cdot C_p}{\gamma \cdot (r_i + r_e)}(VPD) \tag{7}$$

$$E\lambda = \frac{\rho_a \cdot C_p \cdot (VPD)}{\gamma \cdot (r_a + r_i)} \tag{8}$$

$$r_i = c_1 \cdot \left(\frac{(R_n/(2 \cdot LAI)) + c_2}{(R_n/(2 \cdot LAI)) + c_3}\right) \cdot (1 + c_4 \cdot VPD^2) \tag{9}$$

$$r_i = c_1 \cdot \left(\frac{R_n + c_2}{R_n + c_3}\right) \cdot (1 + c_4 \cdot VPD^2) \tag{10}$$

Net solar radiation on the canopy (R_n) for Takakura model was measured by a crop solarimeter specifically developed for this application (Takakura et al., 2009). For the Stanghellini and Penman–Monteith models, a relationship shown in Eq. (11)

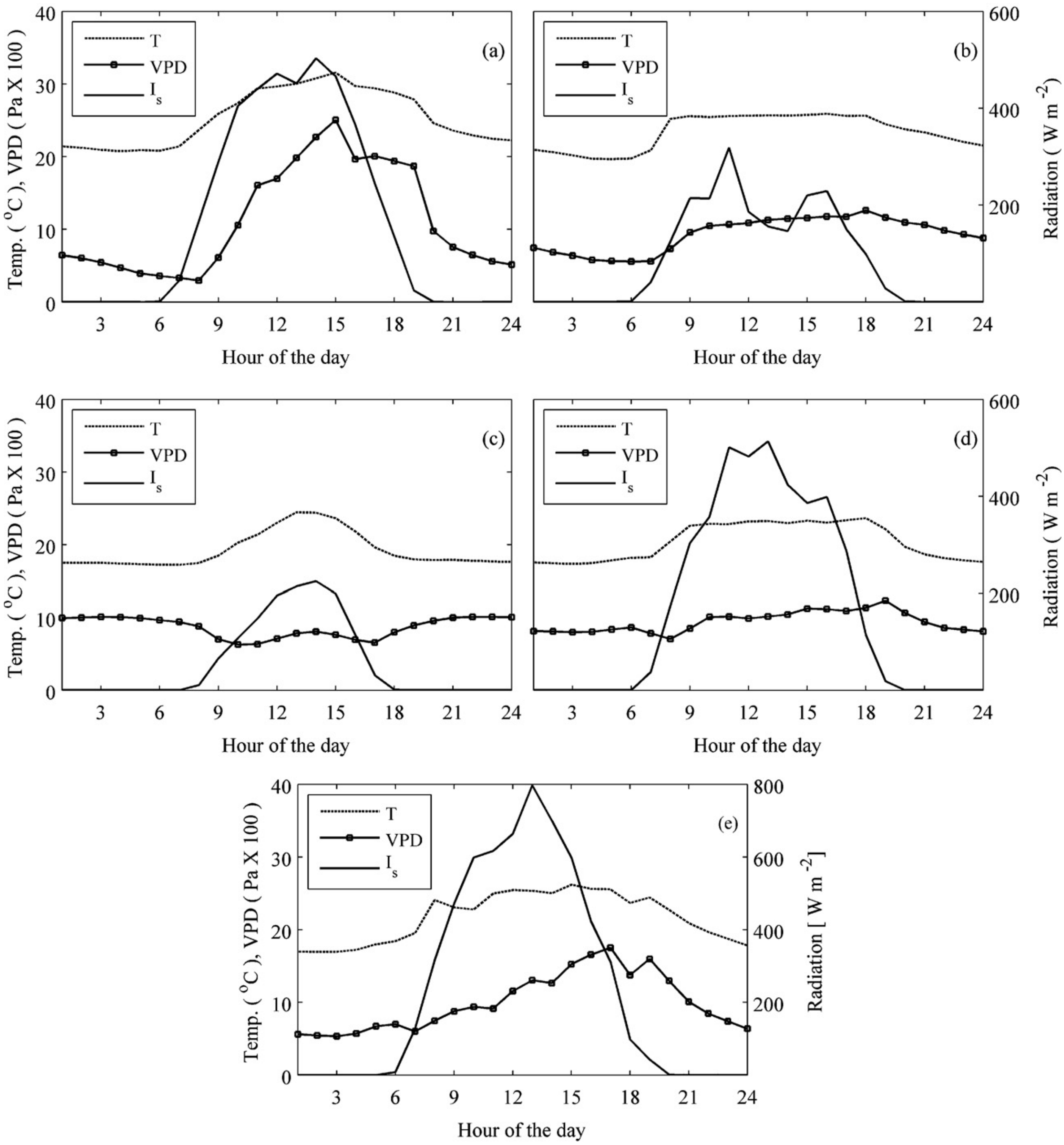

Fig. 2. Average greenhouse air temperature, VPD and incoming solar radiation above the canopy during the experiments with pepper crop under natural ventilation and fogging in Summer (a), pepper under pad and fan cooling in Summer (b), tomato under pad and fan cooling in Fall (c) tomato under pad and fan cooling in Spring (d) and tomato under natural ventilation with fogging in Spring (e).

between net radiation and incoming shortwave radiation above the canopy was used, which according to Bontsema et al. (2007), is a simplification of the formula for net radiation given by Stanghellini (1987).

$$R_n = 0.86 \cdot (1 - \exp(-0.7 \cdot LAI)) \cdot I_s \tag{11}$$

where I_s is the incoming shortwave radiation above the canopy ($\mathrm{W\,m^{-2}}$).

3. Results and discussion

3.1. Greenhouse external climatic conditions

The experiments with the bell pepper were conducted during June–August 2009 when the crop was at full maturity. The LAI of the crop during this period varied from 2.51 to 3.86. The experiments with the tomato occurred from November 2009 to May 2010 and the LAI changed from 0.38 to 4.12. Average climate data during the experimental periods in this study are shown in Fig. 2. Each data point in the figure represent an average from the days

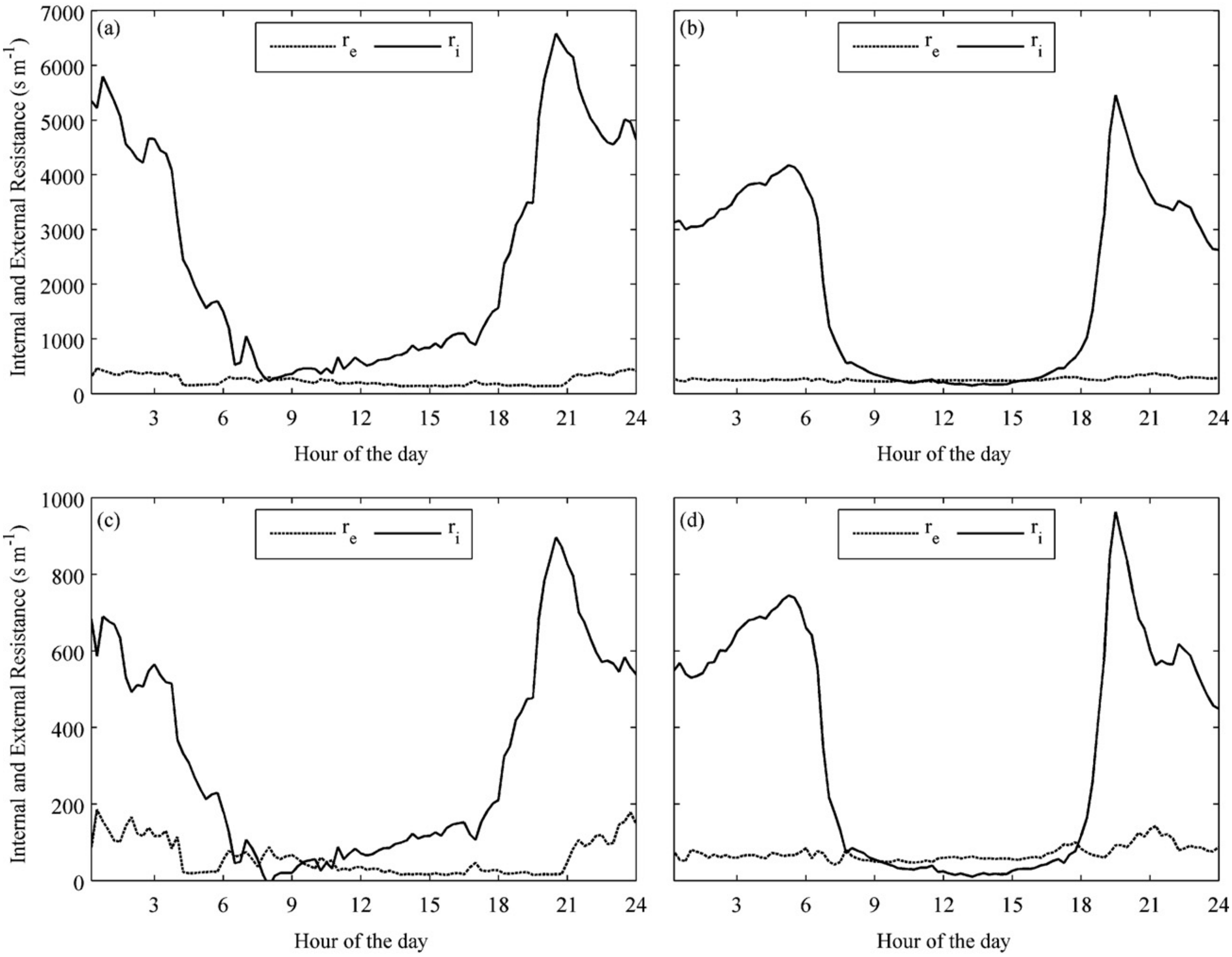

Fig. 3. Daily behavior of the internal and external crop resistances. (a) Stanghellini model, pepper (08/19/2009), (b) Stanghellini model, tomato (05/14/2010), (c) Penman–Monteith model, pepper (08/19/2009), (d) Penman–Monteith model, tomato (05/14/2010).

corresponding to each period experimented in this study. As seen in Fig. 2, solar radiation level was the highest during spring (Fig. 2d) and summer (Fig. 2a and b). The solar radiation values under pad and fan cooling conditions (Fig. 2b and c) were lower when compared to those obtained under natural ventilation and fogging (Fig. 2a and d) because a shade curtain was deployed when the solar radiation exceeded 900 W m^{-2}.

3.2. External and internal crop resistances

Relatively small variations in air movement within a greenhouse produce a fairly constant external crop resistance (Stanghellini, 1987). It has also been showed that there is not much loss of accuracy in using a constant external resistance (Fig. 3), the predicted transpiration rate is practically un-sensitive to the external crop resistance. Thus, our finding was in agreement with the previous studies evaluating transpiration with a constant external resistance (Bontsema et al., 2007; Kittas et al., 1999; Prenger et al., 2002). In the present study, and in an attempt to improve the accuracy of the ET predictions, Eqs. (4) and (5) were used to determine the external crop resistance for the Stanghellini model, for the Penman–Monteith model Eq. (6) was used. After determining the daily behavior of external crop resistances, their averages were computed. For the Stanghellini model, averages were found to be 259 s m^{-1} and 185 s m^{-1} for pepper and tomato, respectively. For Penman–Monteith model, averages were found to be 59 s m^{-1} and 70 s m^{-1}, respectively.

The use of a constant canopy conductance (inverse of resistance) value for both day and night can lead to erroneous predictions of the ET especially due to the effects of vapor pressure deficits and solar radiation (Jolliet and Bailey, 1992). In the current study, using a constant internal crop resistance produced accurate results for some days under specific climatic conditions, but it resulted in erratic outputs when the greenhouse conditions, such as radiation and humidity, changed (details not shown). Therefore, the internal resistance was calibrated for both the Stanghellini and Penman–Monteith models separately for each crop. The calibrated parameters of Eqs. (9) and (10) that yielded the best fit between the data of the internal resistance calculated according to Eqs. (8) and (9), for Stanghellini and Penman–Monteith, respectively, are presented in Table 3. Overall, the coefficients of determination were high for the four fitting procedures (R^2 = 0.93) and the average root mean square errors was 136.2 s m^{-1}. Given the nature of the internal crop resistance, varying from 40 s m^{-1} during the day to 8000 s m^{-1} at night according to the results of this study, the average root mean square error obtained in this analysis gives an acceptable accuracy for the present application.

Fig. 3a and b illustrates a typical diurnal behavior of the external and internal crop resistances obtained for the pepper and tomato, respectively, for the Stanghellini model. Fig. 3c and d shows similar results for the pepper and tomato crop, respectively, for the

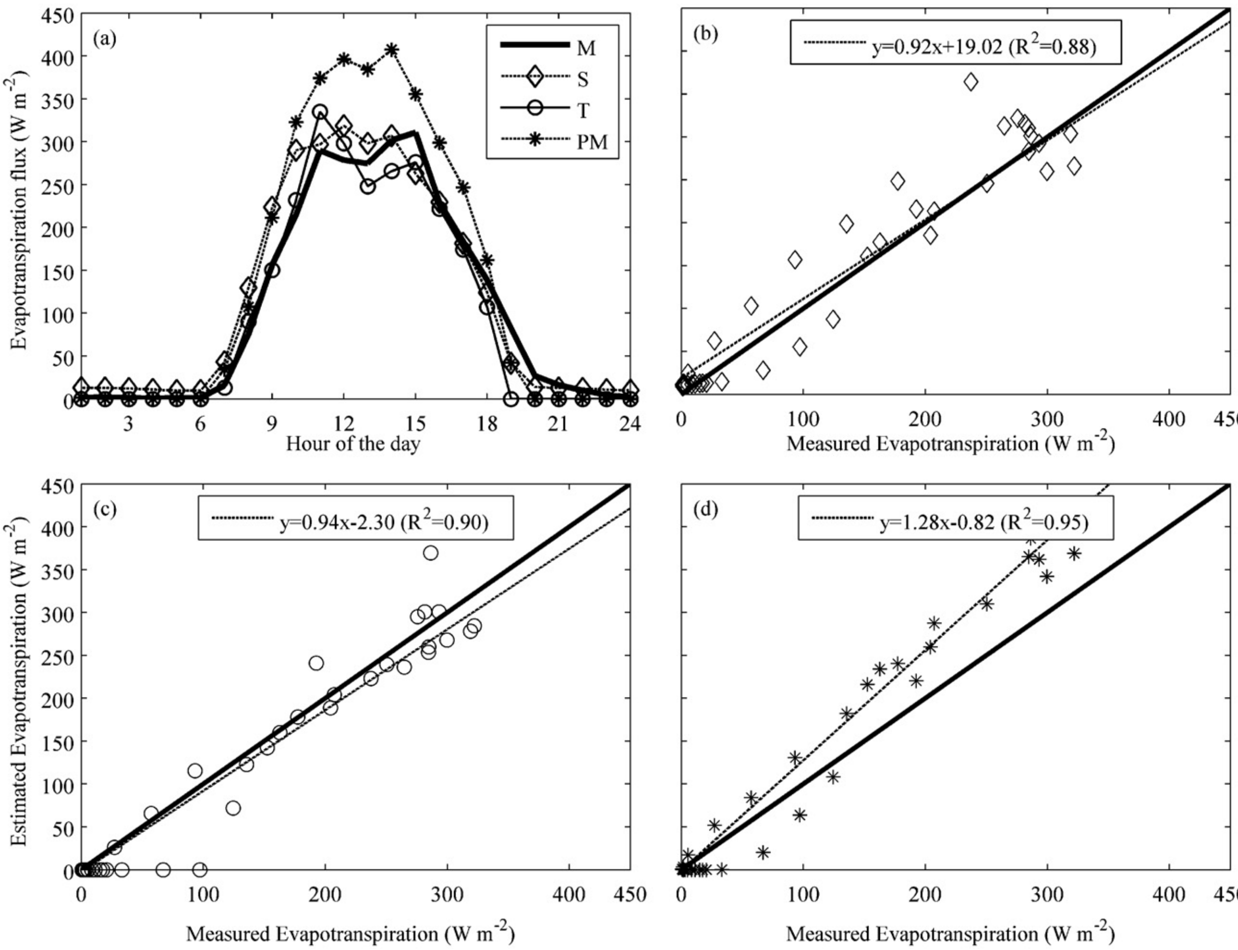

Fig. 4. (a) Pepper crop measured ET vs. estimated ET by three models under natural ventilation and fogging conditions. Each data point represents the average of four days in mid-August 2009. Linear regression fits of the measured and predicted ET by Stanghellini (b), Takakura (c) and Penman–Monteith (d). M, S, T and PM stand for Measured, Stanghellini, Takakura and Penman–Monteith, respectively.

Penman–Monteith model. For both models, the external resistance values were stable during a 24-h period. The daily external resistances found in this study were in agreement with values previously reported in the literature for greenhouse conditions (Stanghellini, 1987; Zhang and Lemeur, 1992).

The internal crop resistance was found to be high especially during early morning and later afternoon hours for both models. The main reason of this behavior can be attributed to the stomatal closures during those hours. The stomata stay closed at night resulting in higher resistances to the water vapor transfer. Under solar radiation the stomata open for the photosynthesis, which also reduces the internal resistance drastically (Montero et al., 2001; Yang et al., 1990; Zhang and Lemeur, 1992). It was observed that the internal resistance was low during the day, increased rapidly at dusk and stayed high during the dark period. The general behavior of the internal crop resistances for the two models was similar, however internal resistance values used for Stanghellini model were consistently higher, this was due to the LAI term presented in Eq. (7), which has coefficient of two in the equation and affects the output of internal resistance.

3.3. Pepper crop growing under natural ventilation and fog cooling (summer)

Hourly values of modeled and measured evapotranspiration from several days were averaged to provide a representative diurnal behavior of the three models against the measured values. Fig. 4 shows the modeled and measured transpiration of the bell pepper on mid-August 2009. The greenhouse cooling was achieved by natural ventilation coupled with high pressure fogging system during this period.

Similar to the results reported by López-Cruz et al. (2008) on tomato crop and Prenger et al. (2002) on a Red Maple tree (*Acer rubrum*), the Penman–Monteith model generally overestimated the ET (Fig. 4). The reason for this might be due the fact that this model was mainly developed for crop grown in outdoor conditions. The main difference between the Stanghellini and the Penman–Monteith model is the LAI. Thus, there is evidence that the LAI included in the second term of the equation in the Stanghellini model has significant effect on the accuracy of the ET model. The Takakura model, which accuracy relies more on the accurate measurements net radiation and evaporative surface temperatures, predicted the ET closely during the early morning, slightly overestimated in the early noon, and underestimated the measured values for the rest of the day. Regression analyses between the measured ET and the predictions of the Takakura model showed higher accuracies on the ET predictions ($R^2 = 0.9$), compared to previous studies conducted in the same experimental greenhouse ($R^2 = 0.72$) (Takakura et al., 2009). In this study, the amount of fog added to the greenhouse air was not added to the total amount of evapotranspiration. Since the average apparent temperature the crop solarimeter is measuring accounts for the canopy and floor surfaces only, it was decided to take only the transpiration from the plants as the total evaporation coming from the surface. The greenhouse

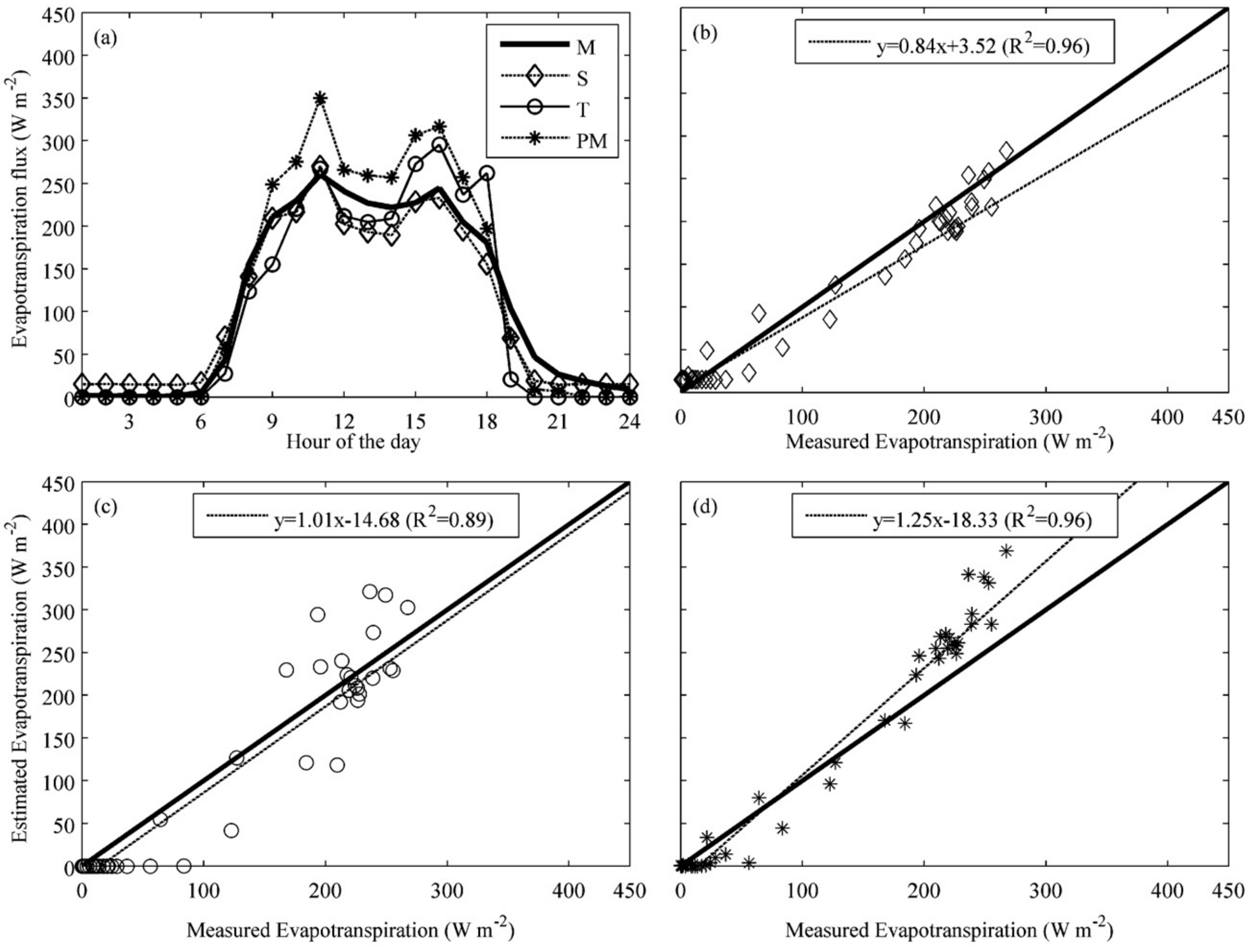

Fig. 5. (a) Pepper crop measured ET vs. estimated ET by three models under pad and fan conditions. Each data point represents the average of ten days in early-August 2009. Linear regression fits of the measured and predicted ET by Stanghellini (b), Takakura (c) and Penman–Monteith (d). M, S, T and PM stand for Measured, Stanghellini, Takakura and Penman–Monteith, respectively.

air, where the fog evaporates (assuming no wetting over the plants surface), was not part of the evaporative surface defined in this study. This change in the ET calculation may be one of the reasons of the differences in correlation coefficients between this study and Takakura et al. (2009).

3.4. Pepper crop growing under pad and fan cooling (summer)

Fig. 5a illustrates the measured ET and the predictions from the three models for the bell pepper crop growing under pad and fan cooling conditions using pad and fan evaporative cooling in the summer season. Each data point represents an average from 10 days under similar climatic conditions during summer 2009. Fig. 5 also illustrates the comparisons of measured and estimated ET rates by the Stanghellini (b), Takakura (c) and Penman–Monteith (d) models. The results showed that the Stanghellini model slightly underestimated the ET especially during the daylight periods. The Penman–Monteith model consistently overestimated the ET for most of the 24-h period, especially under high solar radiation hours, but its coefficient of determination was similar to that of the Stanghellini model. The scattering between the measured and the calculated ET was greater with the Takakura model and the model underestimated the ET early in the morning and late evening hours. This highlights the high sensitivity at low incident angles of the shortwave radiation sensors unit used in this study for the net radiation measurements exclusively for the Takakura model. The Takakura model produced the lowest coefficient of determination. It was also observed that both, the ET rates measured and estimated were slightly higher under natural ventilation conditions compared to pad and fan cooling, and this might be due to higher demand for transpiration under lower relative humidities, which were the prevailing conditions during the natural ventilation and fogging experiments (Fig. 2).

3.5. Tomato crop growing under pad and fan cooling (fall)

Measured ET and predictions from the three models for the tomato crop under pad and fan in the fall season are shown in Fig. 6. Each data point represents an average from 10 days in late November and early December, 2010. The results indicated that the ET rates predicted by the Stanghellini model were close to the measured ones during the morning, but were overestimated for the afternoon period. The Penman–Monteith model showed a similar prediction pattern, however its coefficient (R^2 = 0.51) of determination was lower than Stanghellini (R^2 = 0.72) possibly due to higher overestimations in the early afternoon hours. The Stanghellini model resulted in the most accurate ET predictions. The Takakura model underestimated ET for almost all day. With these ET models, the solar radiation effect accounts for more than 60% of the ET and the models reflected this. Thus, when the radiation in the greenhouse is significantly low, for instance during the fall experiments (Fig. 2), the ET prediction accuracy can be low as well. In general, the three models predicted less accurately under fall conditions compared to summer conditions.

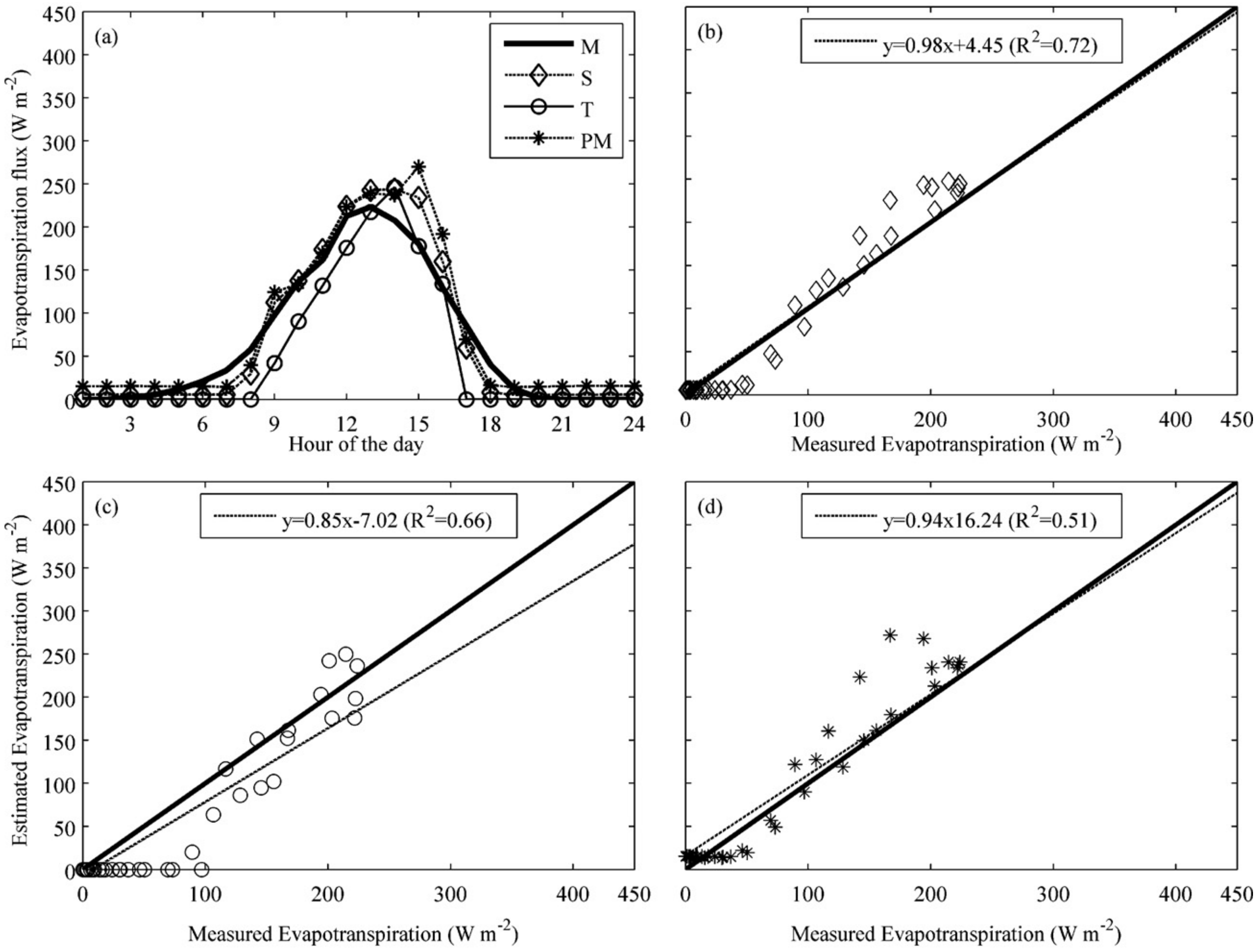

Fig. 6. (a) Tomato crop measured ET vs. estimated ET by three models under pad and fan conditions. Each data point represents the average of ten days in early-December 2009. Linear regression fits of the measured and predicted ET by Stanghellini (b), Takakura (c) and Penman–Monteith (d). M, S, T and PM stand for Measured, Stanghellini, Takakura and Penman–Monteith, respectively.

3.6. Tomato crop growing under pad and fan cooling (spring)

The experiments continued with tomato during the spring season under pad and fan cooling. In general, the predictions from the three models improved significantly (Fig. 7) compared to the predictions obtained from the fall season (Fig. 6). As shown above (Figs. 4 and 5), the three models also predicted with higher accuracies pepper ET in the summer season. This suggests that the models perform better for the ET predictions under high radiation conditions. Medrano et al. (2005) using the Penman–Monteith model with cucumbers, and Jolliet and Bailey (1992) using the Stanghellini model with tomato also reported low prediction accuracies during the periods with low radiation levels. The linear regression analysis results indicated that the measured ET was best forecasted by the Stanghellini model followed by the Penman–Monteith model while the Takakura model had the lowest prediction accuracy under these conditions.

3.7. Tomato crop growing under natural ventilation and fog cooling (spring)

Fig. 8 presents the modeled and measured ET with the tomato crop under natural ventilation with high pressure fogging in the spring season. Overall, the three models showed high coefficients of determination, which were 0.95, 0.88 and 0.94, for Stanghellini, Takakura and Penman–Monteith models, respectively. Penman–Monteith model produced the highest overestimations, followed by Stanghellini model. After 10 am, the models underestimated the measured ET, especially the Takakura model being the highest underestimating model. At that time period, the measured transpiration reached to the maximum value since the greenhouse roof vent was open and the solar radiation reached directly to the plant canopy where the experimental sap flow meter connected experimental plant was also located. This resulted in increased plant transpiration significantly (Fig. 8a). The increase in the model predicted ET rates between 10 am and 1 pm was due to the pyranometer sensor receiving direct solar radiation through the roof vent opening. It can be seen from Fig. 8a that both, the transpiration from the plants and the estimated ET rates from the models are highly sensitive to radiation levels. The results suggested that structural shade can generate noise in the data and lead to errors. The radiation inside the greenhouse could also be measured using a mobile system which could help better represent the average radiation inside the greenhouse than by the use of stationary sensors (Graham et al., 1990).

Comparing the prediction results under natural ventilation with fog cooling and mechanical ventilation with pad and fan settings for the pepper (Figs. 4 and 5) and the tomato (Figs. 7 and 8), it can be seen that the ET rates were higher under natural ventilation conditions. This is possibly due to the existence, on average, of both higher radiation and lower relative humidities during the day when the experiments under natural ventilation were conducted (Fig. 2).

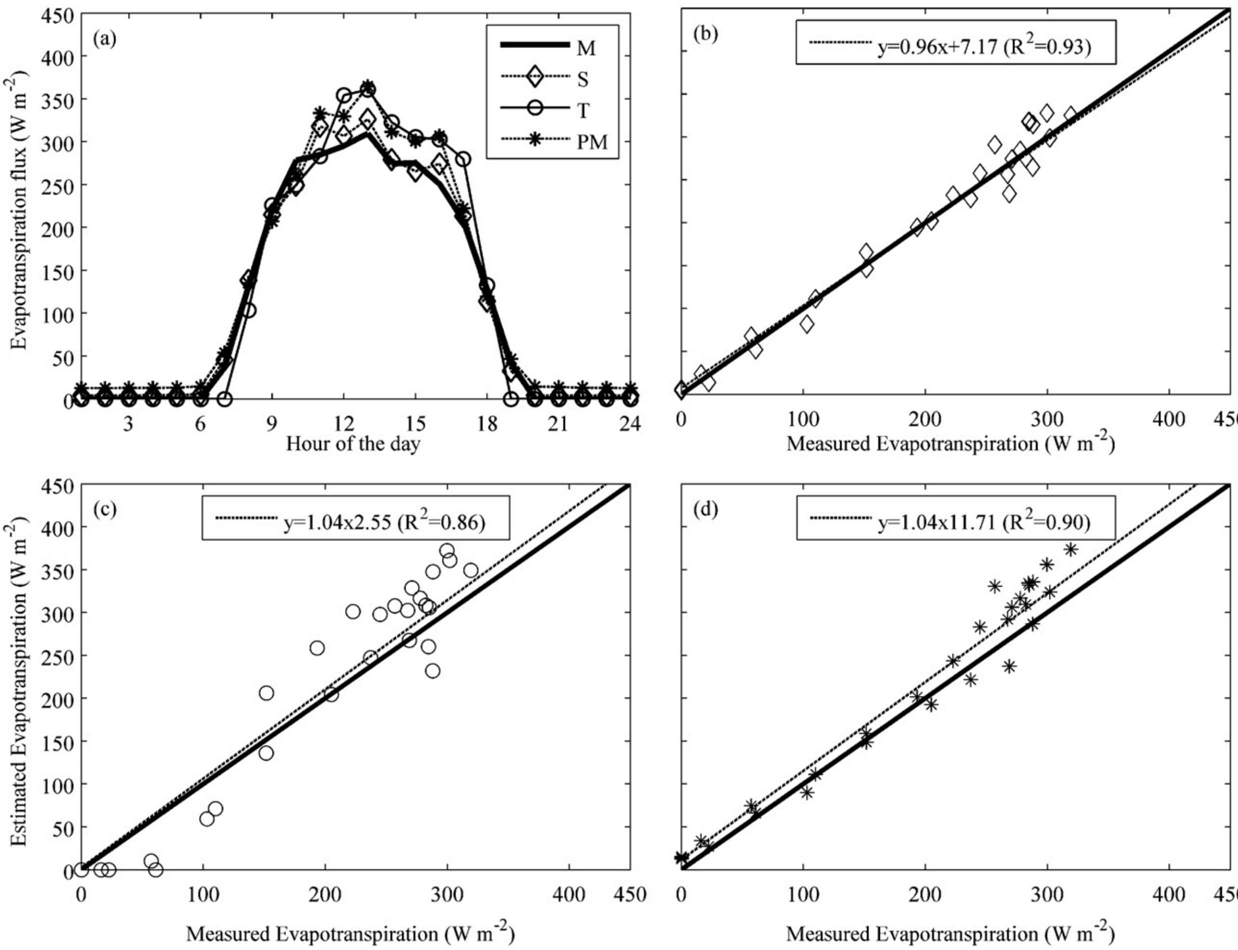

Fig. 7. (a) Tomato crop measured ET vs. estimated ET by three models under pad and fan conditions. Each data point represents the average of ten days in April 2010. Linear regression fits of the measured and predicted ET by Stanghellini (b), Takakura (c) and Penman–Monteith (d). M, S, T and PM stand for Measured, Stanghellini, Takakura and Penman–Monteith, respectively.

Lower average radiation levels were experienced with experiments under pad and fan cooling because the shade curtain was for the periods of the highest radiation incidence (around noon).

On average, the models performed with high and comparable accuracies for both mechanical and natural ventilation with fogging, under high radiation conditions (spring and summer). However, the prediction accuracy of the models was the lowest under low radiation levels (fall) (Fig. 6).

The correlation coefficients for both the Stanghellini and Penman–Monteith models were high for both the pepper and tomato crop, with the latter model having in general higher overestimations under all the cases tested in this study. However, both models require calibration and appropriate internal and external crop resistances, which require extra efforts and measurements.

The vast majorities of the existing transpiration models depend on the thermal balance of the crop canopy and are similar to the Penman–Monteith equation. However, they contrast primarily by the way solar absorption coefficients are computed, and the way the external and internal (i.e. stomatal) resistances are determined. Monteith and Unsworth (1991) and Stanghellini (1987) proposed elaborated models and procedures to determine internal resistance and Stanghellini also accounted for the energy exchange from multiple layers of leaves using the leaf area index parameter. The Takakura model is simpler and does not include parameters such as the LAI, internal and external resistances, which require measurements from the crop. These parameters are crop specific and vary depending on the growing conditions. However, the approach needs careful placement of the short and long wave radiometer sensor unit (plant solarimeter) at an appropriate height over the canopy in order to have a suitable field of view of the plants and the ground. An accurate weighted average of “canopy to ground view” is required for reliable estimations of the apparent evaporative surface temperature. Thus, the short height of a multi-span greenhouse would limit the applicability of this model.

3.8. Overall performance comparison of the models

The results showed that the performance of the three models varied depending on the crop, the greenhouse cooling settings, and the season. In some circumstances, the Stanghellini model produced the highest coefficients of determination, but in other cases, the Penman–Monteith model performed best. In order to determine which model had the best overall performance under all conditions evaluated, analysis of variance (ANOVA) was performed. The hourly deviations of the predicted ET from the measured ET were computed for each model. The squared errors were then averaged for 24-h periods to have a single value for each day. Finally, the square root of the average was computed. The data from a 60-day period including data from all the cases analyzed (i.e. crop, greenhouse cooling setting, season) in this study (Figs. 4–8) were used in the analysis of variance.

The results that are summarized in Table 4 suggested that there are no statistically significant differences between the models. Even though the Stanghellini model produced the smallest overall

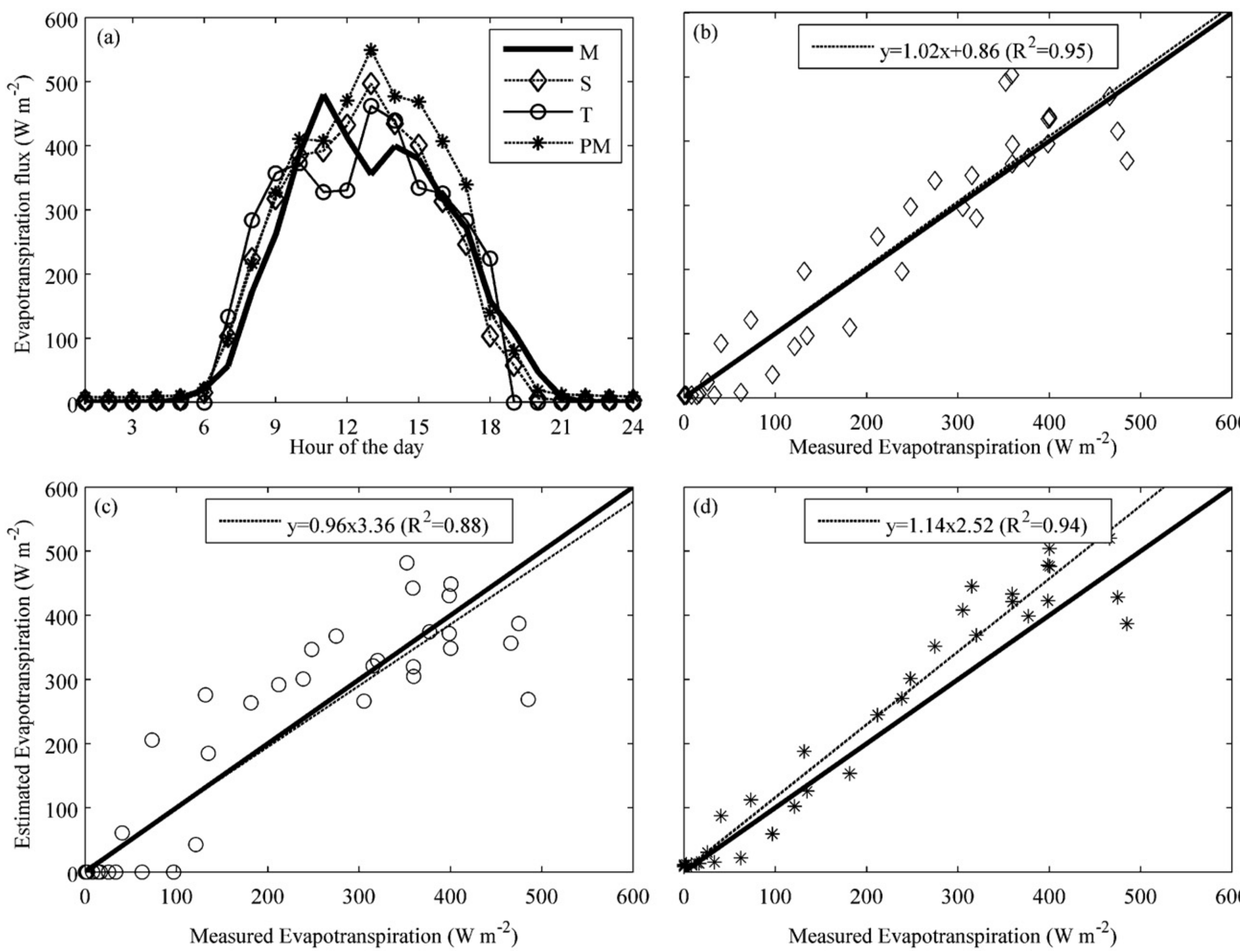

Fig. 8. (a) Tomato crop measured ET vs. estimated ET by three models under natural ventilation and fogging conditions. Each data point represents the average of four days in mid-May 2010. Linear regression fits of the measured and predicted ET by Stanghellini (b), Takakura (c) and Penman–Monteith (d). M, S, T and PM stand for Measured, Stanghellini, Takakura and Penman–Monteith, respectively.

Table 4
Analysis of variance of the daily root mean square errors from the ET models of Stanghellini, Penman–Monteith and Takakura.

Source	DF	Sum of squares	Mean square	*F* ratio	Prob > *F*
ET models	2	8988.03	4494.02	1.96	0.14
Error	171	391,968.87	2292.22		
Total	173	400,956.91			

Table 5
Comparisons for all pairs using Turkey–Kramer HSD.

Model	Mean
Penman–Monteith	54.36[a]
Takakura	46.34[a]
Stanghellini	36.77[a]

Levels not connected by same letter are significantly different ($\alpha = 0.05$).

deviations, followed by the Takakura and Penman–Monteith models, an analysis of the separation of means confirmed the ANOVA results (Table 5).

4. Conclusions

This study evaluated three evapotranspiration models with two crops, two greenhouse cooling settings and three growing seasons. The focus was on the accuracy of the models and their potential use in a greenhouse cooling control strategy. The evaluations were first made by comparing the correlation coefficients of each model under each case, and then a statistical analysis was performed to determine the best overall performing model. There was a consistent overestimation of the ET by the Penman–Monteith model for all the cases evaluated in this study. Stanghellini model, developed for crops grown in greenhouse conditions, particularly where the plant canopy consists of multi–layered evaporation surfaces, improved the ET calculation. This may be due to the leaf area index parameter and the empirical irradiance value used, which resulted in generally higher correlation coefficients. However, this study showed that even though the Stanghellini model showed the highest overall accuracies, there are no statistically significant differences between the ET predictions of the three models. Therefore, any of the three models could be considered for inclusion in an online greenhouse-cooling strategy. With this regard, the need of calibration of parameters such as crop resistances (i.e. Stanghellini and Penman–Monteith) and LAI (i.e. Stanghellini) may represent limitations because they are specific for the greenhouse settings and the crop grown. The most practical model to estimate the ET and implement in a greenhouse control strategy seems to be the Takakura model. This model does not require the adjustments and measurements of internal and external crop resistances, or LAI. However, in order to obtain accurate ET predictions special care must be paid to adjust regularly the radiation sensor position above the canopy, since proper ratio of canopy to bare-ground area is required for accurate estimations of average evaporative surface temperature. This may be a limiting factor especially when the measurement system is used in multi-span greenhouses having low gutter heights. In addition, high sensitivity of radiation sensors to low incident angles resulted in deviations from the measured ET.

Acknowledgements

This research was supported by Research Grant no. IS-4122-08R from the United States-Israel Binational Agricultural Research and Development Fund (BARD). Sincere thanks to Dr. Tadashi Takakura, Professor Emeritus of Nagasaki University (Japan), for allowing the use of the crop solarimeter unit to measure net radiation and canopy surface temperature to determine the ET by the Takakura model. UA-CEAC Paper No. D-434230-01.

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