Application and evaluation of Stanghellini model in the determination of crop evapotranspiration in a naturally ventilated greenhouse

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Abstract: Stanghellini model is one of the few models primarily developed to predict the evapotranspiration of crops (ET_c) in naturally ventilated greenhouses. However, there are insufficient data on the model regarding its use, particularly in China where solar greenhouses without heating systems are fast spreading for vegetable growth and production. The application of Stanghellini model and the evaluation of its performance using meteorological and tomato plant data generated inside an unheated and naturally ventilated multi-span Venlo-type greenhouse is exploited in this study. Model capability was evaluated by utilizing data from sap flow measurements, meteorological and crop data. Measured meteorological data included solar radiation (R_s), air temperature (T_a), relative humidity (*RH*) and net radiation (R_n). Average leaf area index (LAI) values measured during the experimental period were 1.00, 3.30, 4.05 and 2.93; while determined crop coefficients (K_c) changed from 0.40, 0.62, 1.12 to 0.83 for the initial stage, development stage, mid-season stage and late-season stage, respectively. Results from the study indicated that the average hourly ET_c values of tomato plants using sap flow measurements were 0.165 mm/h, 0.148 mm/h, 0.192 mm/h and 0.154 mm/h for the initial stage, development stage, mid-season stage and late-season stage, respectively. Meanwhile, the ET_c values obtained from calculation using Stanghellini model were 0.158 mm/h, 0.152 mm/h, 0.202 mm/h and 0.162 mm/h for the initial stage, development stage, mid-season stage and late-season stage, respectively. These ET_c values calculated by the Stanghellini model were close to the measured values within the same period. The coefficients of correlation (R^2) based on hourly ET_c for the calibration data was 0.94 and that of the validation dataset was 0.90. Scatter plots of the estimated and measured hourly ET_c revealed that the R^2 and the slope of the regression line for May, June and July were 0.94, 0.90, 0.96 and 1.15, 0.97, 1.10 respectively. These data were well represented around the 1:1 regression line. A model sensitivity analysis carried out illustrates how the changes in R_s and T_a affect greenhouse ET_c. Stanghellini model was therefore proven to be suitable for ET_c estimation with acceptable accuracy in unheated and naturally ventilated greenhouses in the Northeast region of China.

Keywords: calibration, verification, crop evapotranspiration, naturally ventilated greenhouse, sap flow
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1 Introduction

Greenhouse crops require adequate irrigation at the right time in order to minimize water stress, and maximize yield and quality of production. Proper irrigation scheduling and water supply are very important to improve crop yield. Scheduling water application is critical since inaccurate irrigation, especially excessive irrigation may cause waterlogging, root damage and water losses below the root zone[1], and limited irrigation leads to weaker plants and poor crop yield[2,3]. Scarcity of water resources requires greenhouse growers to put more emphasis on improving their irrigation strategies so as to provide crops with exact water requirements, effectively reduces water consumption and ensure production. This calls for a better knowledge and understanding of the evapotranspiration process, adapting the water inputs to meet the plant needs. Prediction of ET_c depends solely on meteorological and plant data generated in greenhouse, and accurate estimation of ET_c is required to support efficient irrigation design, planning and scheduling in the greenhouse as well as other models which simulate or attempt to simulate the water-soil budget and improving water use efficiency, in arid and semi-arid regions that rely on irrigation for agricultural production[4]. Applying ET_c models to quantify crop water use in the greenhouse has been a reliable and effective tool in irrigation scheduling[5]; greenhouse ventilation design[6]; on-line climate control[7,8]; and, for irrigation and climate control strategy[9,10]. Meanwhile, quantification of

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greenhouse ET_c must provide timely information for the implementation of greenhouse water management.

Generally, the most accurate measurement of ET_c is gravimetric method under field conditions, weighing lysimeters-an isolated soil tank mounted on a load cell (electronic weighing balance) that directly measures the evaporation of water from the soil and the loss of water from plant leaves (transpiration) is employed for such purposes[11]. Many greenhouse models have been formulated using either the physical model (i.e. a combination method based on energy balance) - e.g. FAO Penman, 1948; FAO Penman-Monteith, 1998, or the empirical model (i.e. a radiation-based or radiation-temperature based) - e.g. Priestly-Taylor, 1972; FAO Radiation, 1975; Hargreaves-Samani, 1985- to evaluate ET_c and its practical applications in the open field and greenhouse irrigations is to boost vegetable production worldwide.

Greenhouse ET_c models commonly used in China to evaluate crop water requirement included pan evaporation methods for cucumber; tomato in an unheated greenhouse; and Penman-Monteith method for tomato[12-15]. In the open fields, Penman-Monteith method for ET_c in maize and buckwheat fields; FAO Penman and Priestley-Taylor models for vegetation have been reported[16-20]. All these models differ in the availability of data needed for calculation and their accuracy. Additionally, the coefficients of these greenhouse simplified models depend on wind speed, temperature and stage of crop development. However, in the naturally ventilated greenhouse, wind speed is virtually zero and can lead to large differences in errors in predicted ET_c. Thus, the validity of these models can be compromised and therefore, needed to be checked. However, to date, available data on Stanghellini[21] method for naturally ventilated and unheated greenhouse ET_c is scanty. Stanghellini revised the first evapotranspiration model developed by Penman[22] with the inclusion of the leaf area index (*LAI*) term mainly for greenhouse microclimatic conditions. Stanghellini proposed a more elaborate model where the stomatal resistance depends on solar radiation, leaf vapour pressure deficit, leaf temperature and CO_2 concentration. The model is a combination equation, which includes the internal and external resistances of the canopy consisting of multi-layers meant for surface evaporation. Available literature on ET_c models in greenhouses records that the best option for the ET_c estimation in a naturally ventilated, medium and high technology greenhouses with no heating systems is the Stanghellini model. This is because the influence of both solar radiation and vapour pressure deficit on the stomatal conductance was taken into account in the formulation of the model[23-25]. Several greenhouse studies including comparison of ET_c models using green pepper[26]; *acer rubrum* tree[27]; and tomato[28,29] have shown higher accuracies with the Stanghellini approach predicting ET_c of greenhouse crops.

However, in all these studies, the influence of wind speed was important in the high performance levels of the model. This study specifically focuses on the application of Stanghellini model to determine ET_c under naturally ventilated greenhouse conditions where wind speed is near or close to 0 in the northeast subtropical region of China; and also evaluate the model's performance using meteorological and crop data.

2 Materials and methods

2.1 Experimental site

The experiment was conducted in an unheated and naturally ventilated multi-span Venlo-type greenhouse at Jiangsu University (31°56′N, 119°10′E) located in Zhenjiang City, Jiangsu Province, China, from March 2016 to July 2016. The experimental site is in a humid sub-tropical monsoon climatic zone with an average annual air temperature of 15.5°C and a mean annual precipitation (rainfall) of 1058.8 mm, relative humidity is 76 % at 26 m above sea level. The rectangular greenhouse structure has an area of 32 m long × 20 m wide in horizontal dimensions, 3.8 m high with the longer side in an east-west orientation, which is the prevailing wind direction. Greenhouse operates on natural ventilation for the exchange of hot exhaust air from the inside of the greenhouse to the outside. Heating system available in the greenhouse is non-functional. The planting medium used in the greenhouse was a soil-biochar mixture with mean bulk density of 1.266 g/cm^3, field capacity of 0.408 cm^3/cm^3 and permanent wilting-point water content of 0.16 cm^3/cm^3 in the depth of 0-60 cm.

2.2 Design, materials and greenhouse meteorological data measurements

Tomato (*Lycopersicon esculentum* L. cv. *Jinzuan-3*), which is one of the main cultivars of tomato in the province, was used for this study and planted in 9 plots with 54 plants planted in two rows between March to July 2016 (as shown in Table 1). Each soil box was 0.65 m long × 0.45 cm wide. Seedlings were sowed 30 days before transplanting. Prior to transplanting, the soil-biochar planting medium was prepared to ensure proper uniform mixture of soil and biochar in the soil boxes. Transplanting was done with a planting density of 2 plants per soil box evenly spaced at 0.40 m apart. For a better establishment and to ensure seeding growth, the transplanted seedlings were immediately irrigated with the same volume of water (25 mm). Thereafter, the plants were watered by drip irrigation and the spatial interval of the emitters in each drip tape was 0.35 m. The designed discharge rate of each drip tape was 100 mL/min. Drip surface irrigation application was initiated 3 days after transplanting (*DAT*) together with 200 ppm fertilizer solution applied directly to the tomato plants. Specific concentrations of NPK were 25 % N, 5 % P_2O_5 and 5 % K_2O. All treatments were given the same agronomic management practices such as pruning branch stem, fertilization, pest control and trellised support. Following the FAO-56 approach, the growth season of the tomato crop is divided into four stages: the initial stage, the crop development stage, the mid-season stage and the late season stage[30]. The divided growth stages for the tomato crop, main features and the duration of each stage are presented in Table 1.

Meteorological data inside the greenhouse were measured using a standard automatic weather station located inside the greenhouse. Solar radiation (R_s), air temperature (T_a), relative humidity (*RH*) and net radiation (R_n) were the meteorological parameters collected over the whole growing season inside the greenhouse. The elements of air temperature and relative humidity were measured both at 1.20 m and at 2.90 m heights from the ground level, respectively (as shown in Figure 1). Humidity and temperature sensors HMP155 (Vaisala HUMICAP, Vaisala Oyj, Finland) were used for the measurements. A silicon pyranometer sensor S-LIB-MOO3 (OnsetCom, USA) placed above the tomato crop canopy was used to measure the incoming shortwave solar radiation and net radiation measured by a net radiometer, NR Lite 2 (Kipp & Zonen, Delft, The Netherlands) with sensitivity of 15.3 μV/(W m^{-2}). Sensor specifications for T_a, *RH*, R_n, and R_s are –20°C-60°C, 0-100%, 0-2000 W/m^2 and 0-2000 W/m^2, with the precision values of ±0.1°C, ±2%, ±2% and ±5%, respectively. All the data were continuously sampled every

10 s, averaged every 10 min and recorded by two computer-controlled data loggers CR1000 (Campbell Scientific, USA) and HOBO U30 (Station Remote Monitoring Systems, OnsetCom, USA).

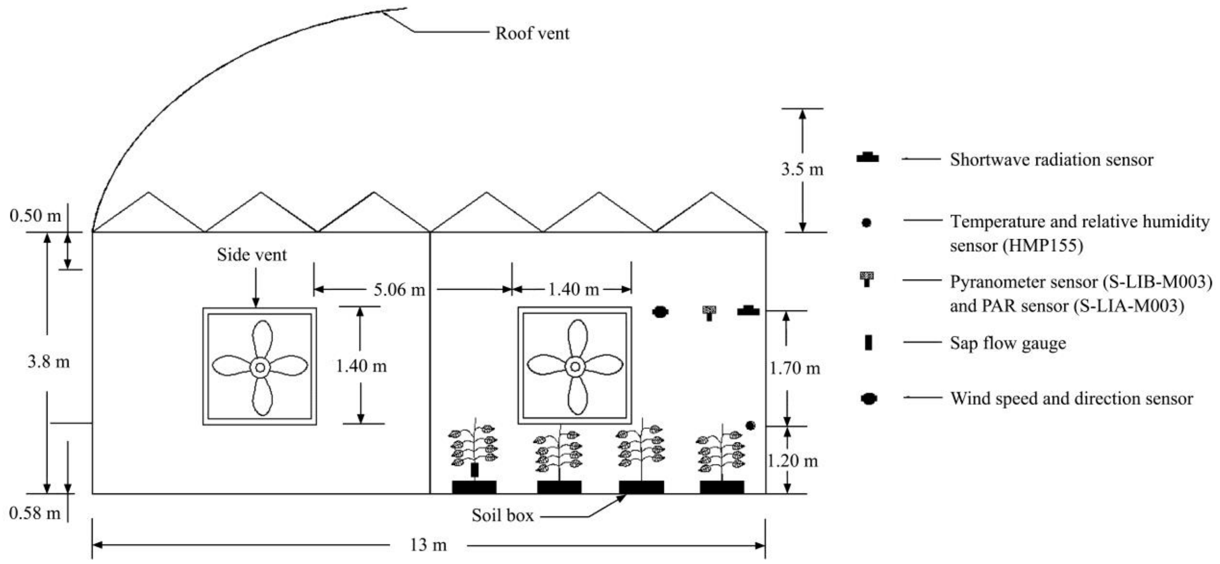


Figure 1 Schematic description of the research greenhouse and the arrangement of the sensors and instruments

2.3 Tomato crop transpiration measurements

Tomato crop transpiration was determined using a sap flow system (Flow32-1K Sap Flow System, Dynamax Inc., Houston, TX, USA). In each plot, the SGA-WS gauges of the sap flow (Dynamax Inc., Houston, TX, USA) were installed at representative plants of the tomato crops. Twelve healthy plants were selected and their stem diameters were measured prior to installation of gauges. Stem diameters measured ranged from 5.07 mm to 12.47 mm. The SGA2-WS, SGA5-WS, SGA7-WS and SGA9-WS gauges were used to measure the sap flow, gauges were fixed on the stems 20 cm above the ground surface to avoid the effect of surface heat flux[23,24]. Sap flow from 23 May to 23 July, 2016 were measured, and the sap flow data was collected after every 10 min by a data logger CR1000 (Campbell Scientific Inc., USA).

Table 1 Growth stages for tomato during the entire experimental period

Growth stage	Main feature	Date	Duration /d
Initial	Seedling and vegetative stage	03/03/16-18/03/16	15
Development	Flowering and fruit formation	19/03/16-20/04/16	42
Mid-season	Fruit development and maturation	21/04/16-23/06/16	63
Late season	Breaker to full ripe and final harvest stage	24/06/16-23/07/16	29

The sap flow of each individual plant was then converted to plant transpiration using the following formula by Gong et al.[25]:

$$T = \frac{1}{1000}[\sum_{i=1}^{n} \frac{f_i / LA_i}{n}] \times LAI \tag{1}$$

where, T is the plant transpiration after normalizing the sap flow data by the leaf area, mm/h; f_i is the stem flow, g/h; LA_i, the leaf area, m^2; n is the number of plants measured; and LAI, leaf area index, m^2/m^2.

2.4 Leaf area index, plant height and crop coefficients

Manual non-destructive method of *LAI* measurements were done at an interval of 5-14 days. Eighteen healthy plants were sampled from the 9 plots. The leaf length (L) and the highest leaf width (W_L) were measured with a measuring tape, and the conversion coefficient of 0.657 for the leaf area was derived by fitting the measured results to the one drawn using CAD software[31]. *LAI* was determined as follows:

$$LAI = \sum_{i=1}^{n} \left(\frac{[L \times W_L] \times 0.657}{I_R \times I_P} \right) \tag{2}$$

where, I_P is the average distance between two closest or neighbouring plants (inter-plant distance = 0.40 m), and I_R is the average row space (inter-row distance = 0.45 m). Leaf area index was defined as the ratio between total leaf area and the ground area of the whole canopy, it was extrapolated from the above formula and used as an input in the Stanghellini model calibration and validation. Plant height was measured with the 18 healthy tomato plants at same time of leaf area measurements.

The crop coefficient (K_c) values for the tomato crop for any period of the growing season were determined on the assumption that K_c is constant and equal to the K_c value of the growth stage during the initial and mid-season stages. In addition, during the crop development and late season stages, K_c varies linearly between the K_c at the end of the previous stage ($K_{c\,prev}$) and the K_c at the beginning of the next stage ($K_{c\,next}$), that is, $K_{c\,end}$, in the case of the late season stage. Thus, K_c values were determined as follows:

$$K_{c\,i} = K_{c\,prev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}} \right](K_{c\,next} - K_{c\,prev}) \tag{3}$$

where, i is day number within the growing season (L…length of growing season); $K_{c\,i}$ is the crop coefficient on day i; L_{stage} is length of the growing stage under consideration (days); $\sum(L_{prev})$ is sum of the lengths of all previous stages (days)[30]. Equation (3) can be applied to all four growth stages outlined in Table 1.

2.5 Stanghellini model based on hourly time scale

The hourly Stanghellini model of the crop evapotranspiration, ET_c is basically a revised Penman-Monteith model representing greenhouse microclimatic conditions of typically low wind speed (u<1.0 m/s; for naturally ventilated greenhouses, u≈0 m/s) and low solar radiation. Hourly climatic data measured inside a Venlo-type greenhouse with natural ventilation was used to calculate the hourly ET_c. The Stanghellini model includes calculations of the solar radiation heat flux derived from the empirical characteristics of short wave and long wave radiation absorption in a multi-layer canopy[26,32]. This model was developed specifically for the conditions of a greenhouse utilize *LAI* to account for energy exchange from multiple layers of leaves on the greenhouse tomato crop. According to Villarreal-Guerrero et al.[29], the *LAI* in the Stanghellini model has significant effect on the accuracy of the model. The Stanghellini equation for hourly ET_c (mm/h) is defined by Donatelli et al.[33] and described as follows:

$$ET_c = K_c 2LAI\frac{1}{\lambda}\left[\frac{\Delta(R_n - G) + K_t\left\{\frac{VPD\cdot\rho\cdot C_p}{r_R}\right\}}{\Delta + \gamma(1+\frac{r_C}{r_a})}\right] \quad (4)$$

$$R_n = 0.07\frac{R_{ns} - 252\rho C_p(T_a - T_0)}{r_R} \quad (5)$$

$$R_{ns} = 0.07R_s \quad (6)$$

$$r_R = \frac{\rho c_p}{4\sigma(T_a + 273.15)^3} \quad (7)$$

where, ET_c is crop evapotranspiration under standard conditions,(mm/h; R_n is net radiation at the crop surface, (MJ m^2)/h; R_{ns} is net short wave radiation, (MJ m^2)/h; R_s is ground level solar radiation, (MJ m^2)/h; K_t is time unit conversion factor equal to 3600 s/h; T_a is mean hourly air temperature at 2 m height, °C; T_0 is leaf temperature, °C; *VPD* is hourly vapour pressure deficit, kPa; *LAI* is leaf area index, m^2/m^2; *G* is soil heat flux density, (MJ m^2)/h; Δ is slope of the saturation vapour pressure curve, kPa/°C; *γ* is psychrometric constant; *ρ* is mean atmospheric density, kg/m^3; *λ* is latent heat due to water vaporization, kJ/kg; c_p is specific heat capacity of air at constant pressure, MJ/(kg °C); r_R is radiative resistance, s/m; r_a is aerodynamic resistance, s/m; r_c is canopy (stomatal) resistance, s/m; *σ* is Stefan-Boltzman constant, MJ/(m^2 K^4 h), and K_c is the crop coefficient mainly affected by crop type, crop height, albedo (reflectance) of the crop-soil surface, aerodynamic properties, leaf properties and crop stages[30].

A summary of Stanghellini model input variables used in the calculation[33] is shown in Table 2.

Table 2 Variables used in the Stanghellini model

Variable	Unit	Symbol	Equation
Latent heat of vaporization	MJ kg^{-1}	λ	λ=2.501–0.002361T_a
Soil heat flux	MJ m^2 h^{-1}	G	G = measured values
Net radiation	MJ m^2 h^{-1}	R_n	$R_n = 0.07\frac{R_{ns} - 252\cdot\rho\cdot C_p\cdot(T_a - T_0)}{r_R}$
Net short wave radiation	MJ m^2 h^{-1}	R_{ns}	$R_{ns} = 0.77R_s$
Specific heat of the air	MJ kg^{-1} °C^{-1}	C_p	$C_p = 0.001013$
Mean atmospheric density	kg m^{-3}	ρ	$\rho = \frac{100000}{R(T_a + 273.16)}$
Specific gas constant	J kg^{-1} K^{-1}	R	$R = 287$
Actual vapour pressure	kPa	e_a	$e_a = e_s\frac{RH}{100}$
Saturation vapour pressure	kPa	e_s	$e_s = 6.894757e^{f(R)}$
Function of air temperature	-	$f(R)$	$f(R) = \frac{-10440}{T_a} - 11.29 - 0.02702T_a + 1.289\times10^{-5}T_a{}^2 - 2.478\times10^{-9}T_a{}^3 + 6.546\ln(T_a)$
Air temperature	°C	T_a	T_a = measured values
Leaf temperature (Daytime)	°C	T_0	$T_0 = T_a + 1.67R_s - 0.25\frac{VPD}{\gamma}$
Leaf temperature (Nighttime)	°C	T_0	$T_0 = T_a - 0.1\left(\frac{VPD}{\gamma}\right)$
Slope of the saturation vapour pressure curve	kPa °C^{-1}	Δ	$\Delta = 0.04145e^{0.06088T}$
Vapour pressure deficit	kPa	VPD	$VPD = e_s - e_a$
Psychrometric constant	kPa °C^{-1}	γ	$\gamma = \frac{C_p\rho}{\varepsilon\lambda}$
Water to dry molecular weight ratio	-	ε	$\varepsilon = 0.622$
Aerodynamic resistance	s m^{-1}	r_a	Refer to Equations (8)-(10)
Internal resistance	s m^{-1}	r_i	Refer to Equation (11)
Radiative resistance	s m^{-1}	r_R	$r_R = \frac{\rho C_p}{4\sigma(T_a + 273.15)^3}$

2.6 Estimation of aerodynamic resistance

In greenhouse, the heat and mass transfer between vegetation and interior air are largely dependent on the aerodynamic resistance (r_a). The determination of the transfer of heat and water vapour from the evaporating surface into the air above the canopy is referred to as r_a. The r_a is mainly related to a mean interior air speed, assumed constant in most energy balance models. However, this is only true when the greenhouse is closed or when natural ventilation is maintained at a small and constant value as reported by Wang et al.[34] The r_a, mainly depends on the aerodynamic regime that prevails in the greenhouse. Considering that the buoyancy force can be ignored with respect to the wind force, r_a can be directly expressed with respect to the average interior air speed expressed by Boulard and Wang[35] as follows:

$$r_a = 220\frac{d^{0.2}}{V_i^{0.8}} \quad (8)$$

where, *d* is the characteristic length of the leaf (m); V_i, the mean interior air speed, m/s, can be considered to be proportional to the ventilation flux Φ_v divided by A_c, m^2, the vertical cross-section area perpendicular to the average direction of the inside air flux, in this case the greenhouse axis, expressed as[36]:

$$V_i = \frac{v}{A_c} \quad (9)$$

Boulard and Baille[36] explained that the relationship accounting for the combination of thermal and wind effects used to calculate the ventilation flux (Φ_v in m^3/s) is given as:

$$v = \frac{L_0 C_d T_e}{3g\Delta T}[(\frac{g\Delta T}{T_e}h + C_w U_e^2)^{3/2} - (C_w U_e^2)^{3/2}] \quad (10)$$

where, C_d and C_w are empirical discharge and wind effect coefficients, identified for this greenhouse as 0.644 and 0.09[36], respectively; *g* is acceleration due to gravity constant, m/s^2; *h* is the vertical height of the vent opening, m; L_0 is the length of the continuous vents, m; T_e and ΔT are the exterior air temperature and the interior-exterior air temperature difference (K) and U_e is the external wind speed, m/s.

2.7 Estimation of internal resistance

The internal resistance, r_i refers to the average resistance of an individual leaf and is influenced by climate and by water availability. This resistance is crop-specific and differs among crop varieties and crop management. It usually increases as the crop ages and begins to ripen. Avissar et al.[3] have reported that the internal resistance can be considered to be dependent on the inside level of global radiation and inside air temperature and humidity based on exponential laws. For greenhouse tomato crops, the effects of radiation on internal resistance are the most crucial and obey the relationship given by Boulard and Wang[35] as follows:

$$r_i = 200(1 + \frac{1}{\exp(0.05(\tau R_g - 50))}) \tag{11}$$

where, τ is the transmittance of the greenhouse cover; and R_g is the outside global solar radiation, W/m^2.

2.8 Model calibration and verification

The entire measurement period was divided into sky-clear and cloudy days. Calibration (8-31 May 24 consecutive days); verification (2-24 June 24 consecutive days); and model sensitivity analysis were carried out only in the sky-clear days to show the model response to variations in the major meteorological variables like T_a, R_s and *VPD*. Data obtained during the calibration period were used to derive a set of regressions related to the calculated variables: measured $R_{s,}$, T_a and ET_c were regressed against their corresponding calculated values. During the verification period calculated values of $R_{s,}$, T_a and ET_c were verified against their corresponding measured ones by linear regression.

2.9 Sensitivity analysis

A model sensitivity analysis was carried out to further validate and evaluate the model response to variations in the major meteorological variables (in this case solar radiation, R_s, *VPD* and air temperature, T_a). In order to simulate the performance of the model under different monthly climatic conditions, the sensitivity of the model to simultaneous changes in R_s, *VPD* and T_a was examined.

2.10 Statistical analysis

The measured and calculated ET_c were compared by using simple error analysis and linear regression. For each month, the following parameters were calculated: mean absolute error (*MAE*), root mean squared error (*RMSE*), and the percent deviations of average measured and calculated ET_c (% Deviations). Additionally, maximum, minimum, mean and standard deviations for each month were also calculated. For validation of the Stanghellini model, the statistical error between measured and calculated ET_c was calculated and two-tail *t*-test statistical analysis method was used with the data from July, 2016.

3 Results and discussion

3.1 Variations of plant height and *LAI*

The active *LAI* describes the index of the leaf area or healthy leaves actively contributing to the surface heat and vapour transfer. The variations of crop height and *LAI* of tomato during the experiment is shown in Figure 2. The tomato plant reached a maximum height of 1.84 m at approximately 90-110 d after transplanting (*DAT*). The maximum plant height was higher than the value (=1.56 m) reported by Harmanto et al.[38] using Troy 489 tomato variety. The measured *LAI* exceeded 1.0 around 50 *DAT* and reached a maximum value of 4.05 in the experimental duration. The *LAI* was assumed not to change significantly within a week and a constant weekly value was used for the model calibration and validation.

3.2 Daily crop coefficients

Crop coefficients (K_c) determined using Equation (3) as suggested by Allen et al.[30], ranged from 0.40 to 1.12. At the start of the experimental study, $K_{c\ (initial)}$ was 0.40. During canopy development (crop development stage), $K_{c\ (dev.)}$ increased rapidly reaching 0.95 at mid-season stage of crop development. $K_{c\ (mid)}$ remained relatively constant, varying from 0.95 to the peak of 1.12 (as shown in Figure 3). The average mid-season K_c was similar to values reported by Phene et al.[39] for tomato plants grown under similar conditions. The daily crop coefficient data showed well-defined late-season growth stages ($K_{c\ (end)}$) with values decreasing from 0.92 to 0.83. Initially, the K_c was increased almost linearly from 0.40 to reach a maximum value of 1.12 ($K_{c\ (mid)}$) when *LAI* was slightly above 4.0. Finally, K_c decreased slightly down to 0.8 at the end of the growth season which was associated with a decline in *LAI* as illustrated in Figure 3.

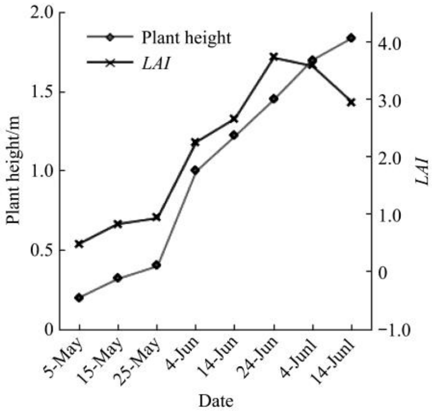


Figure 2 Evolution of tomato plant height and *LAI* during the experimental period

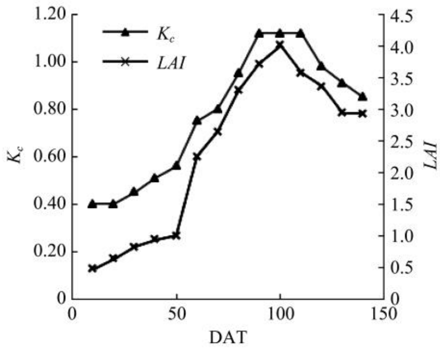


Figure 3 Curves of crop coefficient (K_c) and *LAI* of tomato plant during the experimental period (March to July, 2016)

3.3 Evaluation of aerodynamic and internal resistances

Stanghellini[21] reported that relatively small variations in wind movement within the greenhouse result in a fairly constant aerodynamic resistance. However, previous reports have shown that authors often choose a constant value for the aerodynamic resistance since there is not much loss of accuracy in using a constant value[29,40]. The predicted ET_c was found to be practically ‘not sensitive’ to the leaf aerodynamic resistance. This finding is in agreement with results reported for the evaluation of transpiration with a constant aerodynamic resistance[10,27]. In the present study, Equations (8)-(10) were employed for the determination of the aerodynamic resistance in an attempt to improve the accuracy of the ET_c predictions. Results indicated that the average aerodynamic resistance (Figure 4) is 145 s/m with values varying between 75 and 172 s/m. These values are relatively closer to the average value of 185 s/m reported by Villarreal-Guerrero et al[29] using a greenhouse cooling strategy with natural ventilation. The aerodynamic resistances obtained in this study were found to be in strong agreement with values reported for tomato in greenhouse conditions[21,29,41].

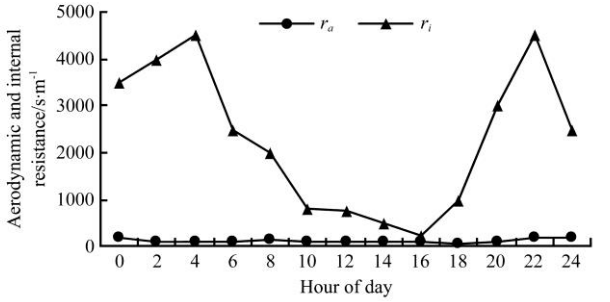


Figure 4 Hourly behaviour of aerodynamic and internal resistances

The internal resistance was calculated using Equation (11). Solar radiation has strong and effective impact on internal resistance and was found to be high during the early hours of the day and in the night hours. The main reason for this pattern can be attributed to the stomatal closures during those hours. During the night, stomata remain closed resulting in higher resistances to the water vapour transfer. In the presence of solar radiation, the stomata open for photosynthesis, thus drastically reduce the internal resistance[29,41-43]. The internal resistance values determined in this study were high due to the *LAI* term prevalent in Equation (4) with coefficient of 2, thus, affecting the output of the internal resistance. The consistently higher values of the internal resistance obtained were in agreement with values reported in literature for a greenhouse cooling strategy with natural ventilation[29].

3.4 Evaluation of greenhouse meteorological variables

Table 3 is the summary of the maximum, minimum, mean and standard deviations of hourly averages for the three consecutive months May, June, and July of all meteorological parameters measured in the greenhouse (RH, T_a, R_n and R_s) from 8 May to 23 July, 2016. The average minimum R_n remained constant at 0.60 W/m^2 for the 3 months whereas the average maximum recorded values were 403.9 W/m^2, 497.9 W/m^2 and 589.4 W/m^2 for May, June and July, respectively. Average minimum values for R_s were 19.6, 11.9 and 12.4 with the maximum of 726.9 W/m^2, 598.0 W/m^2 and 621.5 W/m for May, June and July, respectively. The average minimum T_a recorded values were 14.1, 20.2 and 22.9, and the maximum were 43.4°C, 42.8°C and 52.3°C for May, June and July. Average minimum RH values were 25.6%, 43.0% and 37.3% for May, June and July, respectively, whilst the maximum was 100 % for all the 3 months. The differences were mainly due to varied solar radiation during the experimental period in the greenhouse.

Table 4 present the estimated and measured hourly ET_c using the sap flow measurements from 23 May to 23 July 2016. The calculated ET_c was derived from Stanghellini model calculations using meteorological and crop data. The measured ET_c was obtained from sap flow measurements when the soil surface was almost covered by canopy and after normalizing the sap flow data by the leaf area. The hourly ET_c calculated for May, June and July increased linearly as R_s (ET_c = 0.35R_s – 0.67, R^2 = 0.90), T_a (ET_c = 0.25T$_a$ – 2.67, R^2 = 0.76), R_n (ET_c = 0.41R_n– 2.25, R^2 = 0.79), and RH (ET_c = 1.35RH + 0.25, R^2 = 0.63). The hourly ET_c was significantly influenced by R_s, R_n, T_a and RH ($p<0.001$), and the correlation between hourly ET_c and R_s was higher compared with R_n, and T_a, but inversely with RH. The R_s appeared to be the main meteorological variable determining the greenhouse ET_c. Similar assessments were made by Qiu et al.[23], Fernández et al.[44] and Jiao et al.[45] with the conclusion that the relationship between R_s and R_n varies with greenhouse T_a. The measured and calculated diurnal variations of R_n for May, June and July are shown in Figures 5a-5c.

Table 3 Greenhouse maximum, minimum, mean and standard deviations of *RH*, R_n, T_a and R_s of hourly averages for May, June and July 2016

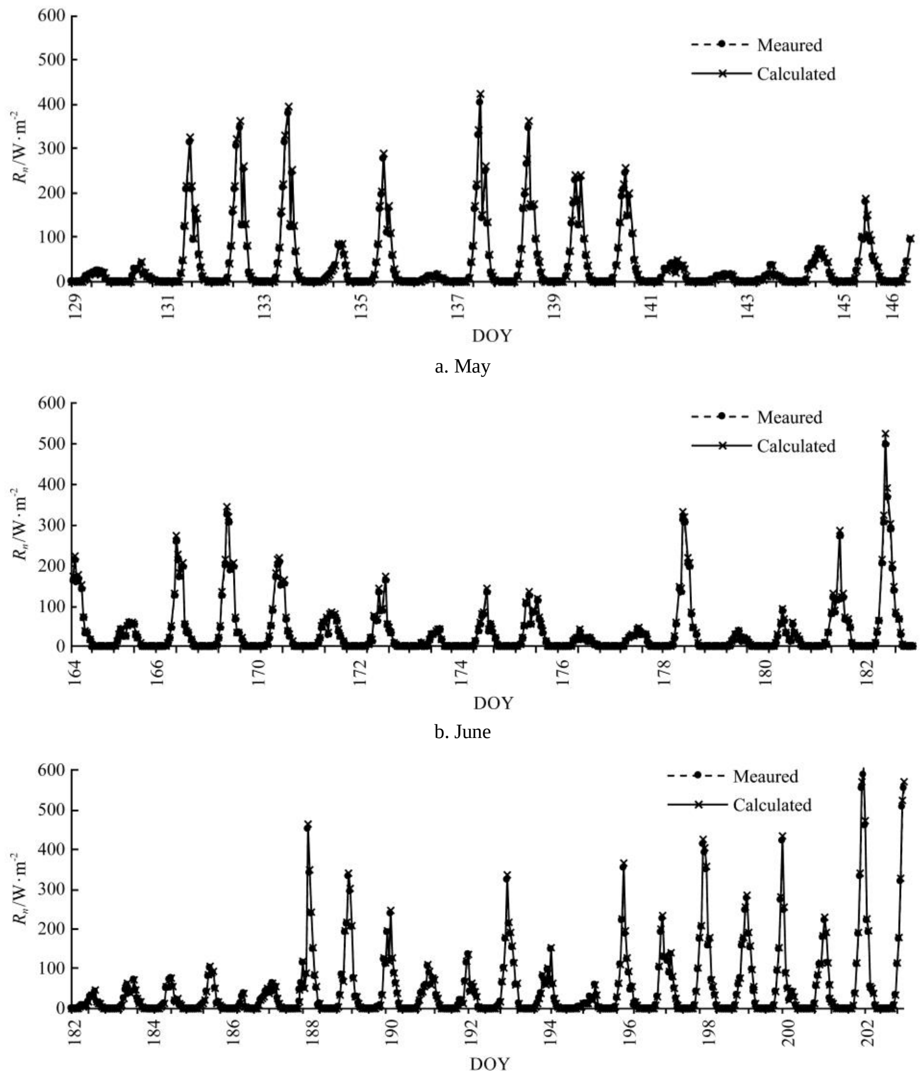
Parameter	May				June				July			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
R_n /W m^{-2}	0.60	403.97	37.82	70.84	0.60	497.92	37.25	67.30	0.60	589.38	57.60	105.10
R_s /W m^{-2}	19.56	726.90	65.66	130.87	19.56	726.90	65.66	130.87	12.45	621.50	62.36	115.19
T_a /°C	14.10	43.36	22.66	7.02	20.16	42.81	28.77	5.55	22.93	52.33	31.51	6.88
RH /%	25.63	100.00	73.46	21.45	43.03	100.00	83.94	15.68	37.28	100.00	82.16	18.63

Note: Min, Max and SD are minimum, maximum, and the standard deviations, respectively, of hourly averages of all meteorological data recorded for May, June and July 2016 in the greenhouse during the experiment.

Table 4 Error analysis statistics of the comparison between measured and calculated ET_c during the experiment in May, June and July 2016

	May	June	July
Measured ET_c /mm h^{-1}	0.192	0.148	0.154
Calculated ET_c /mm h^{-1}	0.223	0.164	0.171
Slope	1.15	0.97	1.10
Coefficient of correlation /R^2	0.94	0.90	0.96
RMSE /mm h^{-1}	0.037	0.019	0.020
MAE /mm h^{-1}	0.032	0.018	0.018
Deviations /%	14.16	10.08	9.91

Note: *RMSE* is root mean square errors; *MAE* is mean absolute error and R^2 is coefficient of correlation.



a. May

b. June

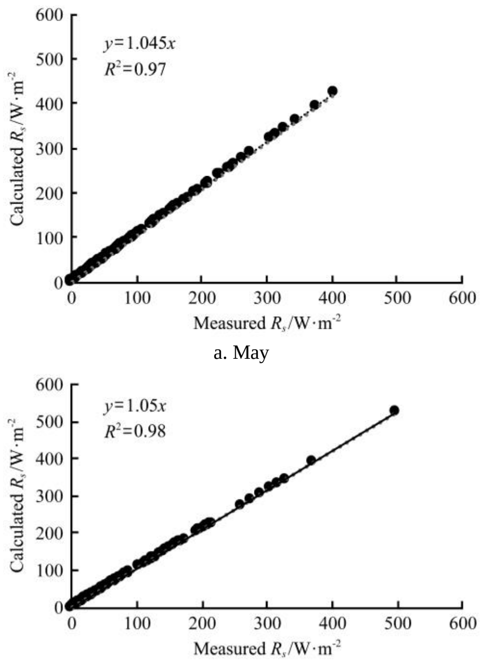
c. July

Figure 5 Diurnal courses of net radiation (R_n) for May, June and July

3.5 Calibration and verification of model input data

The results of calibration and verification of the major model parameter R_s are presented in Figures 6a, 6b. Figure 6a represents the model calibration regression equations using R_s data during the 24 consecutive days in May. Similarly, Figure 6b shows the verification linear regression between the calculated and the measured values using R_s data during the 24 consecutive days in June. All the calculated variables were well correlated with the corresponding measured variables inside the greenhouse during May and June with the $R^2 \geq 0.97$.

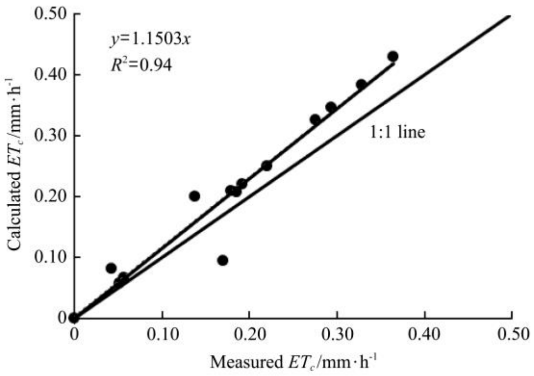
The results of the error analysis statistics of the comparison between hourly measured and calculated ET_c data for May and June, 2016, are shown in Table 4. Figure 7a shows the comparison between measured and calculated ET_c for May. There was high correlation between measured and calculated ET_c. The regression lines were close to 1:1, which indicates the calculated ET_c were close to the measured values. The coefficient of determination (R^2) was 0.94. Figure 7b represents the comparison between measured and calculated ET_c for June. A high correlation between measured and calculated ET_c resulted in a high coefficient of determination (R^2) of 0.90. Table 4 shows the other statistical parameters, such as mean absolute errors (*MAE*), root mean squared errors (*RMSEs*), deviations and regression equations. According to two-tail *t*-test statistical analysis (significant level α = 0.05), there were no significant differences between measured and calculated ET_c values in all the months under consideration.



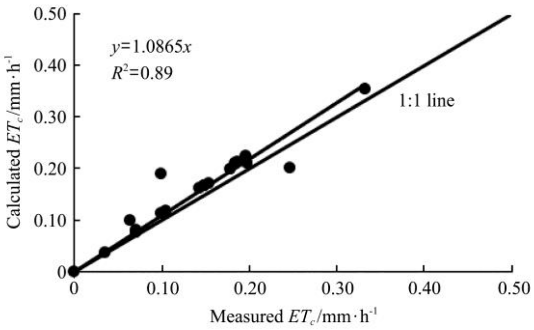
a. May

b. June

Figure 6 Comparison of calculated R_s with measured using average hourly data for May and June



a. May

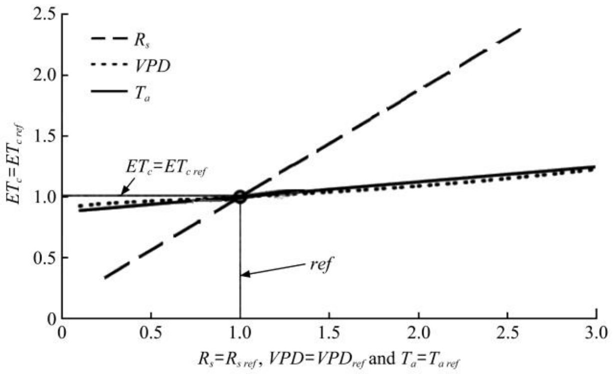


b. June

Figure 7 Comparison of daily ET_c between Stanghellini model (calculated ET_c) and sap flow measurements (measured ET_c) in: May and June based on only sky-clear days within the months under consideration

3.6 Sensitivity analysis

Sensitivity analysis further evaluated the performance of the model and indicated the change in the ET_c due to variations in T_a and R_s. Figure 8 illustrates the sensitivity test for calculated ET_c obtained by employing Stanghellini model calculations with measured values derived by sap flow measurements in July. The sensitivity coefficient of determination, R^2 of 0.96 is in agreement with the calibration and verification R^2 of 0.90 and 0.96, respectively. Higher sensitivity of a model suggests that small errors in the measurements of the meteorological parameters may result in larger errors in the ET_c prediction[1]. As anticipated from Equations (4) and (5), ET_c increases linearly with R_n and hence R_s and non-linearly towards T_a. Since sensitivity of the model increases with increasing ET_c and R_s and decreases with T_a, it implies that the model is more susceptible to changes in the radiation levels in the greenhouse. The model was found to be most sensitive to the level of incoming R_s, followed by T_a and then



Note: *ref* means $R_s = R_{s\,ref}$, $VPD = VPD_{ref}$ and $T_a = T_{a\,ref}$. The relative change of ET_c (i.e. $ET_c/ET_{c\,ref}$) is plotted against the relative variations of R_s, *VPD* and T_a.

Figure 8 Result of sensitivity analysis

VPD as shown in Figure 8. Model sensitivity analysis indicated that reduced R_s and T_a were the main meteorological factors influencing transpiration in the greenhouse.

4 Conclusions

This study calibrated and tested the potential performance of the Stanghellini model for prediction of ET_c using meteorological and crop data generated inside an unheated and naturally ventilated multi-span Venlo-type greenhouse in a sub-tropical climatic environment. Stanghellini model was developed primarily for crops grown under greenhouse microclimatic conditions, particularly where the plant canopy consists of multi-layered surfaces for evaporation. Tomato was used in this study, and results indicated that the hourly ET_c measured values were close to the values predicted by the Stanghellini model during the experimental period. The calibration data had coefficient of correlation (R^2) to be 0.94 and that of the verification dataset was 0.90.

Scatter plots revealed that the hourly calculated values from Stanghellini model and measured ET_c data were well represented around the 1:1 regression line. Sensitivity analysis, which evaluated the performance of the model resulted in sensitivity coefficient of determination R^2 of 0.96, which was in agreement with the calibration and verification R^2 of 0.90 and 0.96, respectively. Model sensitivity analysis showed reduced R_s and T_a mainly influenced transpiration in the greenhouse. A two-tail *t*-test statistical analysis (significant level α = 0.05) revealed that there were no significant differences between measured and calculated ET_c. This study revealed that the application of Stanghellini equation from detailed meteorological data for estimation of ET_c in an unheated and naturally ventilated greenhouse was feasible.

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