Evapotranspiration Model Analysis of Crop Water Use in Plant Factory System

Agung Putra PAMUNGKAS, Kenji HATOU and Tetsuo MORIMOTO

Department of Bio-mechanical Systems, Faculty of Agriculture, Ehime University,
3–5–7 Tarumi, Matsuyama, Ehime 790–8566, Japan

(Received May 9, 2014; Accepted June 19, 2014)

An estimation based on a mathematical model to predict hourly evapotranspiration (ET) rates that occur inside a plant factory system was made using the Stanghellini model. The Stanghellini model is considered more appropriate for estimating the rate of ET inside the soilless culture of greenhouse tomatoes. The model requires some climatic data (e.g., solar radiation, air temperature, relative humidity, and wind speed) and plant growth parameters (leaf area index) as inputs. In this study, the observed data were obtained from an experimental greenhouse located at the Ehime University, Japan. The ET rate of tomato (Lycopersicon esculentum Mill.) crop was measured using a weighing method. Accurate determination of ET is essential to precisely compute crop water use and to assist growers for applying good irrigation management. The results showed that solar radiation and vapor pressure deficit are important factors driving the ET rate. The model’s output showed good results for determining the ET rate and depicted crop water requirements on an hourly basis.

Keywords : evapotranspiration, MATLAB/Simulink, plant factory, Stanghellini model

INTRODUCTION

Environmental control of plant production systems affects crop productivity and quality. The efficiency of plant production in plant factories or greenhouses significantly depends on adjusting several components, particularly the internal temperature, relative humidity, carbon dioxide (CO₂) concentration, and water management. Optimization of these components can lead to better cultivation systems. The “speaking plant approach” is a concept that controls and manages the optimal environment for cultivation on the basis of the diagnosis of the growth status of a plant (Hashimoto, 1989).

A major component in water management is the irrigation system. Good irrigation management can help sustain the life of crops and result in good quantity and quality of yield. Inaccurate watering is the main cause of excess irrigation; however, this is not the main problem, particularly in a “closed system” of cultivation. However, reducing excess irrigation can help growers to minimize chemical usage and improve on-farm water use efficiency.

Crop water use is related to evapotranspiration (ET). ET is the total loss of water to the atmosphere through evaporation and transpiration (the loss of water from the plant). Evaporation and transpiration occur simultaneously, and there is no easy way of distinguishing between the two processes. The estimation of ET often involves calculating the reference evapotranspiration (ET₀). Subsequently, a suitable crop coefficient (Kc) is applied. Crop coefficients vary with the crop type and growth stage. There are four growth stages: initial, crop development, midseason, and late season stages. Midseason crop coefficients (during the period of the highest ET) have been developed from previous experimental data and range from 1.05 under subsurface drip irrigation (Phene et al., 1985) to 1.25 under sprinkler irrigation (Pruit et al., 1972). More recently, the recommended midseason coefficients were 1.10–1.15 (Allen et al., 1998), although the source of these coefficients was not identified (Hanson and May, 2006). Predicting hourly ET₀, which is the basis for estimating hourly ET, is essential for real-time irrigation forecasting (Xu et al., 2012) and for assessing water availability and plant requirements (Allen et al., 1998).

Measuring the water lost by transpiration is a way of determining the plant’s water requirement. The estimation of transpiration in different species grown in greenhouses has been made, e.g., for ornamentals (Baille et al., 1994), for tomatoes (Stanghellini, 1987; Jemaa et al., 1995), for geranium crops (Montero et al., 2001), for cucumbers (Medrano et al., 2005), for rose cultivation (Suay et al., 2003), for chrysanthemums (Voogt et al., 2000), and for gerbera pots (Schmidt and Exarchou, 2000).

Implementing the correct volume of irrigation water is an important task for growers to support optimal crop growth and to conserve fertilizer use during the cultivation season so that production costs can be reduced. The purpose of the present study was to evaluate the performance of the ET model on the basis of the Stanghellini equation (Stanghellini, 1987), which represents the plant water requirements inside the greenhouse system to prevent nutrient leaching, thereby reducing production costs.
MATERIALS AND METHODS

Plant material and water treatments

The data used in the present study were obtained from a plant factory located at the Faculty of Agriculture, Ehime University, Japan (33°50'N, 132°47'E). The greenhouse orientation was east–west, and the crop rows were aligned north–south.

Tomato plants (Lycopersicon esculentum Mill. cv. Taiankichijitsu) were grown in rows (density of four plants per slab) beginning in August 2013. The plants were planted in standard rock-wool slabs and were regularly irrigated 15 times by drip systems from 8 AM to 4 PM. Water application per irrigation event was 75–150 mL/plant on sunny days and a half ratio of irrigation volume on rainy days.

Greenhouse climatic parameters such as air temperature, relative humidity, and solar radiation (Rs) were continuously monitored. The air temperature and relative humidity were measured 2.5 m from the ground level using a type-T thermocouple (copper-constantan) and humidity sensor (HIOKI Z2000, HIOKI, Tokyo, Japan), respectively. Photosynthetically active radiation was measured at the top of the plant canopy using a quantum sensor (MIJ-14PAR, Environmental Measurement Japan Co., Ltd., Tokyo, Japan). All greenhouse climatic data were recorded every 2.0 m heights using an anemometer (Kanomax Climomaster 6531 series, Tokyo, Japan). Wind velocities inside the greenhouse were measured at 2.0 m heights using an anemometer (Kanomax Climomaster 6531 series, Tokyo, Japan). All greenhouse climatic data were recorded every minute and stored using a data logger (HIOKI LR8400-20, HIOKI, Tokyo, Japan). Wind velocities inside the greenhouse were measured at 2.0 m heights using an anemometer (Kanomax Climomaster 6531 series, Tokyo, Japan). All greenhouse climatic data were recorded every minute and stored using a data logger (HIOKI LR8400-20, HIOKI, Tokyo, Japan). Wind velocities inside the greenhouse were measured at 2.0 m heights using an anemometer (Kanomax Climomaster 6531 series, Tokyo, Japan). All greenhouse climatic data were recorded every minute and stored using a data logger (HIOKI LR8400-20, HIOKI, Tokyo, Japan).

The leaf area index (LAI, m² m⁻²) was defined as the ratio of total leaf area (m²) to ground area (m²). We estimated leaf areas using a nondestructive method as per Hatou et al. (2006) at the same experimental site. The leaf area was determined using the correlation between the length and width of the leaf. LAI was assumed to not change significantly within 1 week, and a constant value was used for the model predictions.

Water balance and crop water use in the greenhouse

ET can be related to the water supplied by an irrigation system, the change in water stored in substrate media, and the volume of water drained out of the greenhouse. The water stored in the artificial substrate is constant; therefore, it was ignored when calculating ET in the present study owing to its limited influence.

The observations for measuring crop water use were conducted over a 13-day period between February and March 2014. The plants were fully grown with an average height of approximately 2 m. Plant ET and the volume of both irrigation and drainage water were periodically measured during the experiment. The weight of the whole plant was measured using an electronic scale (A&D GP-32K, capacity=31 kg; resolution=1 g, A&D Company Ltd., Tokyo, Japan) connected to a personal computer. The ET rate was calculated as the weight difference between two consecutive times. Units of ET were converted to millimeters considering a density of 4 plants m⁻². A water content sensor (WCM-control, Grodan, the Netherlands) was also placed on the growth media so that the water content could be monitored.

ET mathematical model

A standardized form of the FAO-56 implementation of the Penman-Monteith equation was used to estimate daily or hourly ET from a hypothetical grass reference surface (0.12 m in height, with surface resistance of 70 s m⁻¹ and albedo of 0.23) (Allen et al., 1998). The Penman-Monteith equation is presented in Eq. (1) as follows:

$$ET = \frac{1}{\lambda} \left[ \Delta (R_e - G) + K_t \frac{VPD \cdot p_c}{R_e} \right] \Delta + \gamma \left( \frac{1 + \frac{r_a}{R_e}}{1 + \frac{r_a}{R_e}} \right)$$

where Δ is the slope of saturation vapor pressure curve at an air temperature in kPa °C⁻¹, Kt is a unit conversion (86,400 s⁻¹ for ET, in mm d⁻¹; 3,600 s h⁻¹ for ET, in mm h⁻¹).

Stanghellini (1987) revised the Penman-Monteith model to represent greenhouse conditions, where wind speeds are typically <1.0 m s⁻¹. The Stanghellini model includes calculations of Rs heat flux derived from the empirical characteristics of shortwave and longwave radiation absorption in a multilayer canopy (Stanghellini, 1987; Prenger et al., 2002). The crop growth parameter is also an important factor for determining crop water use. The Stanghellini model requires LAI for calculating the ET rate. LAI is used to account for energy exchange from multiple layers of greenhouse plants. During the observation period, LAI of the tomato crop grown inside the experimental site was 2.8–2.9 m² m⁻². The model proposed by Stanghellini (1987) is presented in Eq. (2) as follows:

$$ET = 2.2 LAI \frac{1}{\lambda} \left[ \Delta (R_e - G) + K_t \frac{VPD \cdot p_c}{R_e} \right] \Delta + \gamma \left( \frac{1 + \frac{r_a}{R_e}}{1 + \frac{r_a}{R_e}} \right)$$

where ET is the reference ET (mm d⁻¹ and mm h⁻¹ for a daily and hourly basis, respectively), LAI is the leaf area index in m² m⁻², and Kt is a unit conversion (86,400 s d⁻¹ for ET, in mm d⁻¹; 3,600 s h⁻¹ for ET, in mm h⁻¹). The component of the ET equation is given in Table 1.

The ET estimates were calculated using Eq. (2). Figure 1 shows the block diagram of the hourly ET model on the basis of a previously proposed method, which was constructed using MATLAB/Simulink. One of the advantages of MATLAB/Simulink is the ability to model and simulate systems with easy to operate and fast responses. Five data inputs were used in this model: air temperature, relative humidity, Rs, wind speed, and LAI. The constructed ET system consisted of some subsystems, which were represented as blocks. Detailed information of the subsystems, which defines the model components, is listed on Table 1. The line on the Simulink diagram represents the transfer signals from one block to another or the relationship between the blocks and ET components.
CROP-WATER REQUIREMENTS

<table>
<thead>
<tr>
<th>Variable</th>
<th>MATLAB/Simulink</th>
<th>Expression</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor pressure deficit (VPD)</td>
<td>( VPD = e_c - e_a )</td>
<td>kPa</td>
<td></td>
</tr>
<tr>
<td>Saturation vapor pressure (es)</td>
<td>( e_s = 0.61078 \exp \left( \frac{17.269 T}{237.3 + T} \right) )</td>
<td>kPa</td>
<td></td>
</tr>
<tr>
<td>Actual vapor pressure (ea)</td>
<td>( e_a = \frac{e_c R_h}{100} )</td>
<td>kPa</td>
<td></td>
</tr>
<tr>
<td>Slope of the saturation vapor pressure curve (s)</td>
<td>( \lambda = 0.04145 \exp \left( 0.006088 T \right) )</td>
<td>kPa °C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Atmospheric pressure (P)</td>
<td>( P = 101.3 \left( \frac{293 - 0.00654 T}{293} \right)^{2.52} )</td>
<td>kPa</td>
<td></td>
</tr>
<tr>
<td>Latent heat of vaporization (Lamb)</td>
<td>( L = 2.501 - 0.002361 T )</td>
<td>MJ kg⁻¹</td>
<td></td>
</tr>
<tr>
<td>Specific heat of air (cp)</td>
<td>( c_p = 1.013 \times 10^{-3} )</td>
<td>MJ kg⁻¹ °C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Psychrometric constant (Gamma)</td>
<td>( \gamma = \frac{c_p P}{c_v} )</td>
<td>MJ m⁻³ °C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Atmospheric density (ρ)</td>
<td>( \rho = \frac{R e}{f(U)} )</td>
<td>kg m⁻³</td>
<td></td>
</tr>
<tr>
<td>Leaf temperature (Ts)</td>
<td>( T_s = 2.52 + 0.84 T_a - (0.54 \times VPD) )</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Canopy resistance (rc)</td>
<td>( r_c = \frac{0.5 \times LAI}{100} )</td>
<td>s m⁻¹</td>
<td></td>
</tr>
<tr>
<td>Aerodynamic resistance (ra)</td>
<td>( r_a = \frac{K}{f(U)} )</td>
<td>s m⁻¹</td>
<td></td>
</tr>
<tr>
<td>Wind speed function (FogU/2)</td>
<td>( f(U) = 1 + 0.54 U )</td>
<td>m s⁻¹</td>
<td></td>
</tr>
<tr>
<td>Net radiation (Rs)</td>
<td>( R_s = R_e - R_a )</td>
<td>MJ m⁻² h⁻¹</td>
<td></td>
</tr>
<tr>
<td>Net shortwave radiation (Rns)</td>
<td>( R_{ns} = 0.07 R_s )</td>
<td>MJ m⁻² h⁻¹</td>
<td></td>
</tr>
<tr>
<td>Net outgoing longwave radiation (Ron)</td>
<td>( R_{on} = 0.16 K_s \rho \epsilon_c (T - T_a) )</td>
<td>MJ m⁻² h⁻¹</td>
<td></td>
</tr>
<tr>
<td>Radiative resistance (Rr)</td>
<td>( R_r = \frac{4 \sigma (T + 273.16)^4}{\epsilon_c} )</td>
<td>s m⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

\( \epsilon_c \), ratio of molecular weight of water to dry air (equal to 0.622); \( R_s \), specific gas constant (287 J kg⁻¹ °C⁻¹); \( \sigma \), Stefan-Boltzmann constant (5.669 \times 10⁻⁸ MJ K⁻¹ m⁻² s⁻⁴); \( G \), soil heat flux (MJ m⁻² h⁻¹); \( E T \), reference evapotranspiration, 3,600 s⁻¹

RESULTS AND DISCUSSION

The climate data measured from inside the greenhouse system are shown in Fig. 2. Net radiation and soil heat fluxes (\( G \)) can be measured or estimated from climatic parameters. The value of \( G \) is very small under greenhouse conditions owing to the isolated floor (no open area exists); therefore, the \( G \) value for this case was neglected. Besides \( Rs \), wind speed is an important factor affecting \( ET \), particularly for open-field cultivation. The greenhouse environment is typically characterized by lower wind speed values (< 1 m s⁻¹) and higher relative humidity. During the experiments, the wind speed recorded inside the greenhouse was very low (< 0.5 m s⁻¹). The daily mean temperature during the observation period fluctuated from 23°C to 31°C. At high temperatures, plants tend to increase transpiration, which also increases the \( ET \) rate or vice versa. Another measure called vapor pressure deficit (VPD) is gaining popularity in the greenhouse industry because it combines both temperature and humidity effects in a way that better reflects how the plant feels (Humidity Control in greenhouses, http://www.autogrow.com/general-info/humidity-and-vpd, June 14, 2014). The lowest VPD was found (± 0.7 kPa) at midday during the observations, when hourly leaf and air temperatures were similar. \( Rs \) and VPD are the principal meteorological variables driving transpiration in this calculation. The range of leaf to air VPD varied between 0.2 and 2.36 kPa during the experiments. The highest \( ET \) of 0.24 mm h⁻¹ was recorded when \( Rs \) reached 1.01 MJ m⁻² h⁻¹ accompanied by air heating and VPD of 2.08 kPa.

Figure 3 shows the hourly (24-h) example of \( Rs \) and VPD measured from above the plant canopy and the \( ET \) rate for sunny and rainy days, respectively. \( Rs \) and VPD were very low in the morning. However, both the values increased when the sun rose; therefore, transpiration reached its maximum during midday. \( Rs \) values were the minimum at night and early morning. Water loss continued during this time, as observed in the graph. It was assumed that \( ET \) was driven by VPD at this specific time. \( ET \) tended to be more proportional to \( Rs \) on sunny days (Fig. 3A). However, \( ET \) tended to be more proportional to VPD on rainy days (Fig. 3B).

The diurnal variations in leaf temperature and air temperature are presented in Fig. 4. Leaf temperature and air temperature were similar during sunrise and sunset hours; however, leaf temperature was consistently lower than air temperature during the rest of the day, indicating that a high \( ET \) rate associated with high \( Rs \) and high VPD is responsible for the phenomenon and that leaves are cooler than the surrounding air.

The relationships between \( Rs \) and measured \( ET \) and between VPD and measured \( ET \) are presented in Fig. 5A and B, respectively. The results showed a good linear relationship, according to the regression determination coefficient (\( P < 0.05 \) and 0.01).

Hourly crop water use was measured with data from the irrigation event and from drainage and compared with data estimated by the crop water use model (Fig. 6). In the present study, the estimation of water use by tomato plants grown in a greenhouse environment was made using the method proposed by Stanghellini (1987). As explained before, \( ET \) was estimated by multiplying the crop coefficient

Vol. 52, No. 3 (2014) (69) 185
A. P. PAMUNGKAS ET AL.

Thus, crop coefficients ($K_c$) were calculated as the ratio of these two ($ET/ET_{0}$). Crop coefficients were nearly equal to 1 ($K_c = 1.10 \pm 0.04$), indicating that $ET$ was nearly equal to $ET_{0}$. These average midseason coefficients were similar to those found by Phene et al. (1985) and Hanson and May (2006) but smaller than found by Pruit et al. (1972).

The $ET$ curve in Fig. 6 is slightly overestimated, which is thought to be due to the strong dependence of $Rs$, which can lead to error in the estimate. However, the differences are acceptable considering that the curve obtained by linear regression showed a good coefficient of determination ($P<0.05$).

Information on crop use is essential for growers to provide an overview about the most effective way of sustaining crops, particularly in regions with water resource limitations. As shown in Fig. 6, the results indicate that the model estimated crop $ET$. In conclusion, the $ET$ data calculated from the Stanghellini equation provided a good estimate of the values of actual $ET$. 

Fig. 1 Implementation of the evapotranspiration ($ET$) model on the basis of Stanghellini equations in the MATLAB/SIMULINK environment.
Fig. 2  Mean hourly values of solar radiation, air temperature, relative humidity, and vapor pressure deficit (VPD) during the observation time (February 26–March 10, 2014).

Fig. 3  The effect of solar radiation (Rs) and vapor pressure deficit (VPD) on the evapotranspiration (ET) rate of tomato crops as measured on a sunny day (A; March 6, 2014) and a rainy day (B; March 1, 2014), respectively.

Fig. 4  Diurnal variation of air temperature and leaf temperature of tomato crops as measured on a sunny day (A; March 6, 2014) and a rainy day (B; March 1, 2014), respectively.
REFERENCES


