Numerical Estimation of Evapotranspiration Rate in a Greenhouse

Tomokazu HARAGUCHI^{*}, Satyanto K. SAPTOMO^{**}, Koji INOSAKO^{***}, Kozue YUGE^{****},
Ken MORI^{*} and Yoshisuke NAKANO^{*}

^{*}Faculty of Agriculture, Kyushu University, Fukuoka, 812-8581, Japan

^{**}Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, Fukuoka, 812-8581, Japan

^{***}Faculty of Agriculture, Tottori University, Tottori, 680-8553, Japan

^{****}Faculty of Engineering, Kyushu-Kyoritsu University, Fukuoka, 807-8585, Japan

Abstract

A simulation model constructed in this study consisted of three sub models, i.e. the radiation environment model, the crop transpiration model, and the soil water and heat transfer model. The radiation model was used for simulating the distribution of short- and long-wave radiation in a greenhouse. Amounts of short-wave radiation in several processes such as transmission on a plastic film, interception by crop plant, arrival on soil surface were estimated. The distribution of short-wave flux on soil surface was obtained by reproducing the process that short-wave radiation passes through foliages. Crop transpiration rate was calculated via a heat balance on surfaces of a single big-leaf. The processes of water and heat transfer in the soil were calculated for the two-dimensional plane. The accuracy of the sub models was confirmed by comparing estimates with measurements. The short-wave radiations arriving on a canopy and soil surface were estimated well. Then, the reproduction of a short-wave radiation environment around a canopy could be successful. The estimates of temperature of leaf and soil surfaces also agreed with measurements. This simulation model would be useful to estimate evapotranspiration rate by distinguishing into transpiration and soil evaporation.

Key words: Evapotranspiration, Greenhouse, Radiation environment, Simulation model

1. Introduction

In recent years, greenhouse culture has come into wide use all over the world, especially in the middle latitudes because it makes it possible to control the meteorological condition voluntarily. Since rainfall is intercepted by the roof of a greenhouse, water must be applied by irrigation even in rainy regions. The effective use of water resource is required in industry, agriculture, and also our daily life because water resource has been coming tight. Thus saving irrigation should be introduced in greenhouse culture. For evaluating the effects of water saving, the procedure to quantify the amount of water consumption under various irrigation methods should be established. Taking evaporative environment changes depending on a type of greenhouse and region into account, the introduction of a simulation model might be effective for this purpose of the quantification.

Many studies have simulated micrometeorological environment in a greenhouse numerically. Kozai and Sugi (1972), Kozai (1974), Heuvelink et al. (1995) have developed an analytical method for evaluation of the solar radiation environment. These studies have treated glasshouses with flat roof. Kimball (1973) has estimated the energy balance of a greenhouse considering heat exchange processes on a cover, vegetation and soil surface. Takakura et al. (1971) have simulated the effects of micrometeorological environment on the plant leaf within a greenhouse.

In this study, the short-wave radiation environment in a single-span plastic greenhouse with semicylindrical roof was estimated. The predicted short-wave radiation environment was used for estimating the evapotranspiration rate.

2. Simulation Model

A simulation model to estimate the evapotranspiration rate in a semicylindrical plastic greenhouse was constructed. The simulation model consisted of three sub models, i.e. the radiation environment model, the crop transpiration model, and the soil water and heat transfer model (Fig. 1).

2.1 Radiation environment model

The radiation model was used for simulating the short- and long-wave radiation environment in a greenhouse. Amounts of short- and long-wave radiation in several processes such as passage on a plastic film, interception by crop plant, arrival on soil surface were estimated by this sub model (Fig. 2). Sky-radiation outside the greenhouse was calculated by Brunt's formula.

For estimating the flux of short-wave radiation transmitted on a flat or semicylindrical wall, the curved roof was divided into six flat walls (Fig. 3).

To calculate the transmittance of short-wave radiation on each wall, the incident angle was calculated with the directional vector of sunlight ray and the normal vector of a wall. The frame rate of each

wall was obtained from size and number of metal frame and plastic tape on the wall, and considered to estimate the actual transmittance (Fig. 4).

Attenuation of short-wave radiation by transmission through foliage was expressed as

$$R_{SO}=R_{SI} \exp(-G LAI), \quad (1)$$

where R_{SI} and R_{SO} are the short-wave radiation which incident to and pass through foliage, respectively, G is an extinction coefficient, and LAI is a leaf area index.

The transmission of the long-wave radiation on a foliage was calculated as follow (Lascano et al., 1987),

$$R_{LO}=R_{LI}(1-F_{ss}) \quad (2)$$

where R_{LI} and R_{LO} are the long-wave radiation which incident to and pass through foliage, respectively, and F_{ss} is the view factor of canopy from the soil surface.

2.2 Crop transpiration model

Crop transpiration rate (latent heat flux) was calculated via a heat balance on surfaces of a single big-leaf,

$$R_{np}=T_r+H_p, \quad (3)$$

where R_{np} is net radiation on a big-leaf and calculated as

$$R_{np}=R_{Sp}+R_{Lp}. \quad (4)$$

R_{Sp} is the short-wave radiation absorbed by foliage and R_{Lp} is the net long-wave radiation. R_{Lp} results from the balance between the absorbed one and the long-wave radiation emitted depending on leaf temperature. T_r is latent heat transfer and H_p is sensible heat flux,

$$T_r = 2\ell A \frac{0.622\rho_a}{P} \frac{e_s(T_l) - e_a}{r_{la} + r_s} \quad (5)$$

$$H_p = 2A\rho_a c_p \frac{T_l - T_a}{r_{la}} \quad (6)$$

where ℓ is the latent heat of vaporization of water, A is the area of a Big leaf, ρ_a is the density of air, c_p is the specific heat of air at constant pressure, P is the air pressure, T_l is the leaf temperature, T_a is the air temperature, $e_s(T_l)$ is the saturated vapor pressure at T_l , e_a is the vapor pressure of air, r_{la} is the leaf boundary layer resistance, r_s is the stomatal resistance. Since T_r , H_p and R_{np} are functions of leaf temperature, T_l , these parameters are obtained successively.

Fig. 1 Structure of simulation model with three sub model.

Fig.2 Schematic diagram of radiation environment.

Fig.3 Division of walls.

Fig.4 Distribution of frame and plastic tape.

2.3 Soil water and heat transfer model

The processes of heat and water transfer in the soil were expressed equations (7) and (8), and calculated for the vertical two-dimensional plane.

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (D_{\theta} \nabla \theta) + \nabla \cdot (D_T \nabla T) + \frac{\partial k}{\partial z} \quad (7)$$

$$C_v \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + \rho \ell \nabla \cdot (D_v \nabla \theta) \quad (8)$$

The short-wave radiation flux on soil surface was obtained by reproducing the process with equation (1) that short-wave radiation passes through foliages of the crop canopy. The net radiation on soil surface predicted by the radiation environment model applied into the energy balance on soil surface, and the boundary condition was determined.

3. Materials and Methods

3.1 Measurements

Micrometeorological data for simulation were obtained from an N-S direction single-span plastic greenhouse from September 1 to 15 in 1997. The greenhouse was maintained under side-opening condition. Soybean was planted inside and outside the greenhouse. There were three rows of soybeans inside the greenhouse and the ground was covered fully. Irrigation water was applied using a perforated pipe which was set beside roots. Irrigation was planned to initiate when the matric potential which was measured using a tensiometer at 0.15 m in depth beneath center crop row goes down to 60 kPa. Irrigation was conducted once during this experiment period.

Solar radiation was measured with solarimeters inside and outside the greenhouse. Air temperature and humidity were measured with a psychrometer at three heights in the center of the greenhouse. Leaf temperature was measured at three heights of 0.2, 0.6 and 0.9 m in the center. Soil surface temperature was measured beneath the center crop row and the middle of the center and western rows. Wind speed was measured at the height of 1.1 m in the center. Net radiation above the canopy was measured in the center. Evapotranspiration was measured by a weighing lysimeter that was placed in the center of the greenhouse.

3.2 Simulation

Simulation was conducted for 15 days from September 1. The height of canopy was about 1 m and LAI was over 3.6 in this period. The measured air temperature and vapor pressure were used for estimating latent and sensible heat transfer between crop surface and air.

Fig.5 Time courses of net radiation above the canopy.

Fig.6 Time courses of leaf temperature.

Fig.7 Time courses of soil surface temperature.

4. Results and Discussion

The accuracy of the sub models was confirmed by comparing the estimates with the measurements. The net radiation on the canopy was well estimated well (Fig. 5). The estimates of temperature of leaf also agreed with measurements (Fig. 6). The measured leaf temperature was the average of three heights. Figure 7 shows soil surface temperatures at two points, i.e. beneath the center row and between center and western rows. The soil surface temperature by the simulation showed good agreement with measurements. These results reveal that the short- and long-wave radiation

Fig.8 Daily evapotranspiration and capillary rise rate.

and thermal environment around a crop canopy can be well estimated with the model.

Figure 8 shows the daily evapotranspiration rates measured and estimated by the simulation model with capillary rise rate calculated in the simulation. Simulated evapotranspiration rate agreed with measurements.

These results suggest that this simulation model would be useful to estimate evapotranspiration rate by distinguishing transpiration and soil evaporation.

References

- Heuvelink, E., Batta, L.G.G., Damen, T.H.J., 1995: Transmission of solar radiation by a multispan venlo-type plasshouse: validation of a model. *Agric. For. Meteorol.*, **74**, 41-59.
- Kimball, B.A., 1973: Simulation of the energy balance of a greenhouse. *Agri. Meteorol.*, **11**, 243-260.
- Kozai, T., 1974: Numerical experiments on light transmission in greenhouses (2). *J. Agric. Meteorol.*, **29**, 239-247.
- Kozai, T., and Sugi, J., 1972: Studies on the solar irradiation in greenhouses (2). *J. Agric. Meteorol.*, **27**, 105-115.
- Lascano, R.J., van Bavel, C.H.M., Hatfield, J.L., and Upchurch, D.R., 1987: Energy and water balance of a sparse crop: Simulated and measured soil and crop evaporation. *Soil Sci. Soc. Am. J.*, **51**, 1113-1121.
- Takakura, T., Jordan, K.A., and Boyd, L.L., 1971: Dynamic simulation of plant growth and environment in the greenhouse. *Trans. ASAE*, **14**, 964-971.