The Journal of Animal & Plant Sciences, 25 (3 Suppl. 1) 2015 Special Issue Page: 141-145
ISSN: 1018-7081

SIMULATION OF REFERENCE CROP EVAPOTRANSIRATION IN A PLASTIC SOLAR GREEN HOUSE USING A SIMPLIFIED ENERGY BALANCE APPROACH

X. F. Liu [1*], Z. G. Liu[1*], A. W. Duan[1*], J. S. Sun[1#], H. Liu[1], Z. F. Chen[1], J. Y. Zhang[1], X. J. Shen, U. P. Adaobi[1] and V. N. E. Uzokwe[2]

Jiyang Zhang[1], Xiaojun Shen, Uzokwe Pauline Adaobi[1], Veronica NE Uzokwe[2]
1.Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences/Key Lab of Crop Water Requirement and Regulation of Ministry of Agriculture 453002, Xinxiang, China.
2. International Institute of Tropic Agricultural, Dares Salaam-P.O. Box 34441, Tanzania.
*These authors equally contributed to this paper. Both are considered as first author.
[#]Corresponding Email: jshsun623@aliyun.com

ABSTRACT

With larger planting areas being used in greenhouses, evaluating crop evapotranspiration in a greenhouse has garnered greater attention. Currently, calculating the reference crop evapotranspiration for a greenhouse crop through using the Penman-Monteith formula recommended by FAO is difficult because the wind speed in a greenhouse is approximate zero. In order to calculate reference crop evapotranspiration in a greenhouse by the Penman-Monteith modified formula, a simplified model for calculating reference crop evapotranspiration in a greenhouse was proposed based on the energy balance equation, which was the correlative function between reference crop evapotranspiration and radiation and temperature. The model's parameters were obtained through meteorological data taken from the inside of a greenhouse in 2011. Then, the model was validated by using meteorological data within the greenhouse in 2012, and the fitted value of the model agreed with the calculated value of the formulas with a determination coefficient (R^2) of 0.9554. This model is an easy means of calculating the reference crop evapotranspiration in a greenhouse because less meteorological factors are needed. Furthermore, the model provides a theoretical basis for crop irrigation in greenhouses.

Key words: Greenhouse, water requirement, reference crop evapotranspiration, simulation.

INTRODUCTION

As a kind of inverse season cultivation, vegetables that are planted in greenhouses are capable of making full use of light, temperature, and other meteorological elements for plant growth; therefore, greenhouses not only benefits farmers, but they also solve the shortage of slack season vegetables. Furthermore, with the promotion of greenhouse crop cultivated area, the crop water requirement in a greenhouse has become an important focus area for research. Greenhouses have a special environment that supports the growth of crops, unlike in fields where the water requirement varies greatly.

Extensive research into this area of study has been conducted both at home and abroad. For example, Wu *et al.* (2005) summarized the study progress of soil water and heat transport in greenhouses. Katsoulas *et al.* (2001) investigated the effect of greenhouse moisture on canopy conductance of crop evapotranspiration. In addition, Li *et al.* (2001) reported the effects of electrolysis and transpiration on the yield of greenhouse tomato under saline irrigation. Cecilia Stanghellini *et al.* (2011), Medrano *et al.* (2005), and Rouphael *et al.* (2005) analyzed the radiation effects on transpiration of greenhouse crops. Moreover, Boulard *et al.* (2004) and Kichah *et al.* (2012) simulated crop evapotranspiration in a greenhouse based on the mechanism model of leaf stomatal conductance and the computational fluid dynamics model, respectively. The aforementioned research work primarily estimated the evapotranspiration of greenhouse crops from its physiological mechanism. However, there is a need to measure the physiological parameters of greenhouse crops, but this method for estimating the evapotranspiration of greenhouse crop is not easily or widely used.

Crop water requirements are generally calculated via the water balance method (test methods) and the reference crop method (theory of empirical formula). In using the reference crop method to calculate the crop water requirements, the first step is to calculate the reference crop evapotranspiration and crop coefficients. The reference crop evapotranspiration is calculated using a modified Penman-Monteith formula that is recommended by FAO in 1998 (Allen *et al*., 1998) and is mainly suitable for weather information in the field. With the development of protected agriculture as well as an increase in greenhouse planting area, studies conducted on the water consumption, yield, and quality of greenhouse crops are becoming major issues for investigation. The Penman-Monteith formula for calculating the reference crop evapotranspiration in a greenhouse as recommended by FAO is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (1)$$

Where:

ET_o –reference evapotranspiration, mm d^{-1}; Rn - net radiation at the crop surface, MJ m^{-2} d^{-1}; G — soil heat flux density, MJ m^{-2} d^{-1}; T — mean daily air temperature at 2 m height, °C; u_2—wind speed at 2 m height, $m.s^{-1}$; e_s —saturation vapor pressure, kPa; e_a—actual vapor pressure, kPa; e_s-e_a —saturation vapor pressure deficit, kPa; Δ —slope of vapor pressure curve, kPa°C^{-1}; r—psychrometric constant, kPa °C^{-1}.

However, because greenhouses have a high temperature, a highly wet environment, and little wind effects, using the latest Penman-Monteith formula recommended by FAO to calculate the reference crop is difficult. In calculating air dynamics impedance, Wang *et al.* (2006) and Chen *et al.* (2007 a, b) proposed that the air boundary layer within a daylight greenhouse belongs to a non-neutral stable stratification. They adopted the formula of calculating air dynamics impedance (ra) from Thom and Oliver (1977) to replace the impedance formula amended by Allen *et al.* (1994) in the Penman-Monteith formula, which was adapted to consider the air boundary layer as belonging to a neutral stable stratification. Furthermore, the ET_0 correction formula, which is suitable for greenhouse crops, was proposed and then subsequently validated using both the pan evaporation method and the water balance method. However, this corrected formula requires more meteorological factors, and therefore, calculating the formula can be cumbersome. Thus, the formula cannot be used in a solar greenhouse with incomplete meteorological data. Based on the above reasons, it is important to seek a simple approach of calculating the reference crop evapotranspiration in a greenhouse. Accordingly, an amended formula was proposed by Wang Jian and is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{1713(e_a - e_d)}{T+273}}{\Delta + 1.64\gamma} \quad (2)$$

The meaning of the symbols and units in formula (2) are the same as above. The formula is explained as follows:

The corrected Penman-Monteith formula primarily consists of two parts. The first part is the radiation item, and the second is the aerodynamics item. In a greenhouse, the wind speed is close to 0, and by substituting U_2=0 into formula (1), the aerodynamics item of the reference crop evapotranspiration is 0. Therefore, this does not clearly match the physical meaning of formula (1), and as such, formula (1) cannot be used for a direct calculation of the reference crop evapotranspiration in a greenhouse. Wang *et al.*(2006) and Chen *et al.* (2007 a, b) cited the formula for calculating the aerodynamic resistance proposed by Thom and Oliver and avoided the situation at which the wind speed is close to 0 and the aerodynamic resistance is infinity. The corrected formula for calculating the reference crop evapotranspiration in a greenhouse is more reasonable through experimental verification. The model described above also requires weather information and crop physiological indices, which are difficult to apply. Based on the energy balance, the equation for estimating the reference crop evapotranspiration in a greenhouse with less meteorological data were derived.

MATERIALS AND METHODS

Process of deriving model: The heat balance equation for evapotranspiration is as follows:

$$Q - rQ - F \pm G - LE - H = 0 \quad (3)$$

Where:

Q— the total solar radiation, $k.cm^{-2}d^{-1}$; r — reflectivity (dimensionless); F —effectivelongwave radiation, $k.cm^{-2}d^{-1}$; G — the soil heat storageor soil heat loss, $k.cm^{-2}d^{-1}$; L — the latent heat of evaporation, which is $590k.g^{-1}$; E — evapotranspiration rate, $mm.d^{-1}$; H — the heat exchange of near-surface vertical turbulent, $k.cm^{-2}d^{-1}$.

By dividing both sides of the above equation by Q, it becomes:

$$LE/Q = 1 - r - F/Q - G/Q - H/Q \quad (4)$$

Jin and Yang (1981) synthesized the following formula form through plotting E/Q～T:

$$E = (0.019T + 0.08)Q/59 \quad (5)$$

We assume that there is a linear relationship between the reference crop evapotranspiration (ET_0) in the greenhouse and E:

$$ET_0 = kE + c \quad (6)$$

Inserting formula (5) into formula (6), we obtain:

$$ET_0 = k[(0.019T + 0.08)Q/59] + c \quad (7)$$

As long as the coefficientsof k and c are obtained, ET_0 has a function ofglobal solarradiation, Q,and mean temperature, T.

Calibration of the model's parameters: The water requirement of tomatoes in a solar greenhouse was studied at the crop water requirement observation site at the Farmland Irrigation Research Institute of CAAS (North latitude 35.19°, longitude 113.53°, altitude 72.7m), from April to September 2011. The greenhouse was 40m long and 8.5m wide with a 273m^2 planting area. Moreover, it had sandy loam soil that was covered with a drip-free polyethylene film, while the outer cover was a thermal keeping quilt. Each day, it was opened at 8:00 am and closed at 18:30 pm. Additionally, the greenhouse had no heating devices. It consisted of a 3.6m-high roof ridge, a 2.88m-high back wall, and a 0.42m-thick wall, with ventilation holes (24cm × 24cm) that were 1.2m above the ground with a horizontal spacing of 3m. Its wall structure consisted of 12cm of red brick, a 6cm thermal insulation layer, and 24cmof red brick in thickness. Moreover, the wall foundation was a brick-concrete structure that was 76cm below ground, and the roofing skeleton was pre-galvanized steel pipes with Φ 1.0 inch-formed arch beams with 1.0m spacing. The front end of the arch beam had foam heat insulation panels that were 30cm deep and 6cm thick, and below the panels, there was a 10cm lime-soil cushion layer. Weather data was obtained by an automatic weather station located within the greenhouse.

By adopting the equation of calculating the reference crop evapotranspiration in a greenhouse that was proposed by Wang *et al.*(2006), combining the global solar radiation Q and mean temperature T in the greenhouse, the coefficients of k and c were estimated according to formula (7):

K=1.2 c= -0.8

Calculating the reference crop evapotranspiration in a greenhouse was then simplified to the following:

$$ET_0 = 0.02Q(0.019T + 0.08) - 0.8 \quad (8)$$

RESULTS AND DISCUSSION

The simplified formula (8) above and formula (2) that was presented by Wang *et al.*(2006) were validated as follows:

The meteorological data collected while growing tomatoes in a greenhouse from March 14 to July 6, 2012, were used to validate the above formula. Figure 1 shows a scatter chart of the simulated values and actual calculated values of the reference crop evapotranspiration for a greenhouse crop. The simulated values represent the calculated values of formula (8), and actual values were the calculated values of formula (2). As can be seen from Figure 1, there is a linear correlation between the simulated values and the actual calculated values ($Y = 1.0702X$), with a correlation coefficient of R^2=0.9661 (n=155). Through statistical analysis, it was determined that t=9.94, $t_{0.05}$ (114), =1.99, and $t_{0.01}$ (114) = 2.64.Thus, the correlation was very significant both at the level of α = 0.05 and α = 0.01. Table 1 reveals that the model had a mean deviation (MD) of 0.18, a mean prediction error (MPE) of 0.20, a mean prediction square deviation (MSPE) of 0.07, a root-mean-square deviation (RMSE) of 0.27, and a skewness of 7.02.

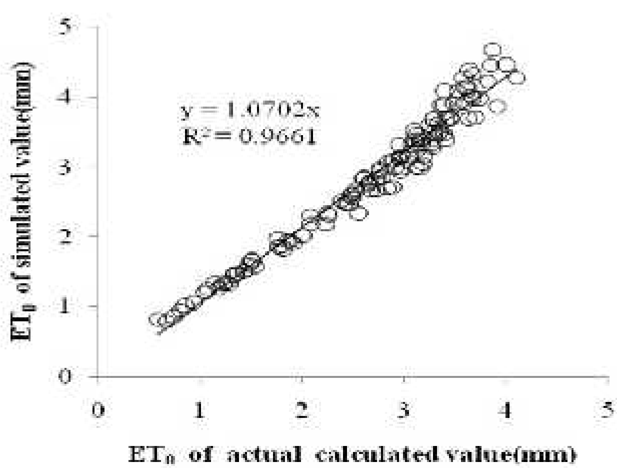

Figure 1. ET0 mapping between actual calculated values and simulated values

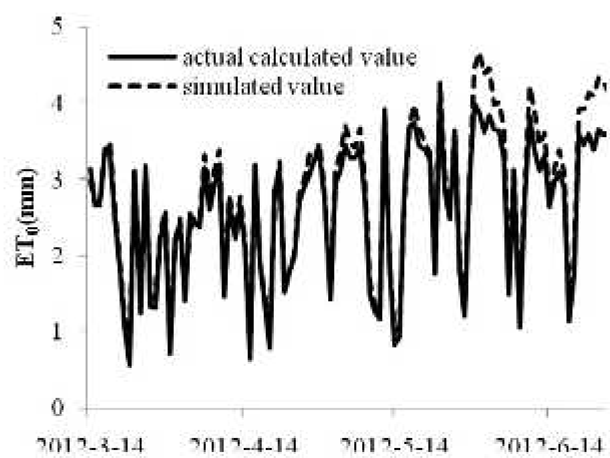

Figure 2. Change in ET0 trend over time

Figure 2 presents the changes in the ET_0 curves of the simulated value and actual calculated value with time. From Figure 2, the ET_0 of both the simulated and actual calculated values increased over time, as did both the average temperature and sunlight intensity. Before June, there was little difference in the ET_0 between the simulated values and actual calculated values, but after June, there was a greater deviation, which was consistent with the results of Chen *et al.* (2007 a, b).

Table 1.The error statistics of the model

Error name	MD	MPE	MSPE	RMSE
Numerical value	0.18	0.20	0.07	0.27

In March, April, and May, the heat generated by the total solar radiation was small, and the temperature changes in the greenhouse were not obvious. However, unique meteorological conditions appeared in the greenhouse in June, July, and August as there was both high humidity and high temperatures present. Additionally, the total radiation items increased greatly in the greenhouse due to the radiation reflected from the ground and plastic cover, which then raised the temperature in the greenhouse, and the greenhouse effect was obvious. This led to greater simulated values. In addition, the high temperature and high humidity caused the gradient of aerodynamic items to be reduced, which also resulted in great deviation in the simulated values.

Furthermore, the simulation results of the reference crop evapotranspiration in a greenhouse that were obtained by different researchers(Möller *et al.*, 2004; Tanny *et al*., 2006; Dicken *et al*., 2013; Pirkner *et al.*, 2013) were different, but these differences were caused by differences in methods, climate, and planting crops.

Through simulating the reference crop evapotranspiration of a greenhouse crop based on energy balance, the simplified equation was proposed with fewer data and high simulation accuracy, which results in a simple, easy, and accurate simulation of the reference crop evapotranspiration of greenhouse crops.

At present, there is not a common international standard for simulating the reference crop evapotranspiration in greenhouse water requirements, and it was validated using different standards. Therefore, in future research, a generic model will be established to improve the simulation precision like the Penman-Moteith equation proposed by FAO in 1998. After establishing a generic model, the crop coefficients in a greenhouse can be further calculated, which will play an important role in developing the irrigation scheduling of greenhouse crops.

Acknowledgments: This project was co-funded by Project supported by the National High Technology Research and Development Program of China (Grant No.2011AA100502 and 2011AA100509), the Special Public Interest Fund for Agro-scientific Research (Grant No.201203077), Innovation Project of CAAS and the Joint Funds of the National Natural Science Foundation of China (Grant No. U1404528).

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith (1998). Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO-Food and Agriculture Organization of the United Nations, Rome.

Allen, R.G., M. Smith, and L.S. Pereira (1994).An update for the calculation of reference evapotranspiration. ICID Bulletin. 43(2): 35−92.

Boulard, T., H. Fatnassi, and J. Lagier (2004). Simple Indirect Estimation of Ventilation and Crop Transpiration Rates in a Greenhouse. Biosyst. Eng. 88(4):467-478.

Chen, X.M., H.J. Cai, H.X. Li, J. Wang and W.J. Du (2007). Calculation of crop evapotranspiration in greenhouse. Chinese J. Applied Ecology. 18(2):317-321. (in Chinese)

Chen, X.M., H.J. Cai, H.X. Li, and J. Wang (2007). Calculation and verification of crop evapotranspiration in greenhouse. Advances in Water Science. 18(6):812-815. (in Chinese)

Dicken, U., S. Cohen, and J. Tanny (2013). Effect of plant development on turbulent fluxes of a screenhouse banana plantation. Irrig. Sci. 31 (4): 701–713.

Jin, D.L. and S.C. Yang (1981). Method of calculating soil evaporation using general weather information. Yangtze River. (4): 30-35. (in Chinese).

Katsoulas, N., A. Baille,and C. Kittas (2001). Effect of misting on transpiration and conductances of a greenhouse rose canopy. Agric. For. Meteorol. 106(3): 233-247.

Kichah, A., P. Bournet, C. Migeon, and T. Boulard (2012). Measurement and CFD simulation of microclimate characteristics and transpiration of an impatiens pot plant crop in a greenhouse. Biosyst. Eng.112 (1):22-34.

Li, Y.L., C. Stanghellinia, and H. Challa (2001).Effect of electrical conductivity and transpiration on production of greenhouse tomato (lycopersiconesculentuml.). Sci. Hortic. 88(1):11-29.

Medrano, E., P. Lorenzo, and M. Sánchez (2005).Evaluation and modelling of greenhouse cucumber-crop transpiration under high and low radiation conditions. Sci. Hortic. 105(2):163-175.

Möller, M., T. Tanny, Y.Li, and S.Cohen (2004). Measuring and predicting evapo-transpiration in an insect-proof screenhouse. Agric. For. Meteorol. 127 (1–2):35–51.

Pirkner, M., U. Dicken, and J. Tanny (2013). Penman–Monteith approaches for estimatingcrop evapotranspiration in screenhouses—a case study with table-grape. Int. J. Biometeorol. 58(5):725-737.

Rouphael, Y.and G. Colla (2005). Radiation and water use efficiencies of greenhouse zucchini squash in relation to different climate parameters. Eur. J. Agron. 23(2): 183-194.

Stanghellini, C., J. F. Dai, and F. Kempkes (2011). Effect of near-infrared-radiation reflective screen materials on ventilation requirement, crop transpiration and water use efficiency of a greenhouse rose crop. Biosyst. Eng.110 (3):

261-271.

Tanny, J., L. Haijun, and S. Cohen (2006). Airflow characteristics, energy balance and eddycovariance measurements in a banana screenhouse. Agric. For. Meteorol. 139 (1-2): 105–118.

Thom, A.S. and R. Oliver H. (1997). On Penman's equation for estimating regional evaporation. Quart. J. Roy. Meteor. Soc. 103(436):345 - 357.

Wang, J., H.J. Cai, H.X. Li, and X.M Chen (2006). Study and evaluation of the calculation methods of reference crop evapotranspiration in solar-heated greenhouse. J. Irrigation and Drainage.25 (6):11-14.(in Chinese)

Wu, W. Y., P. L. Yang, and H. L. Liu (2002). Retrospect and prospect on researches of water and heat transfer in Soil-Plant-Environment Continuum (SPEC) in greenhouse. J. Irrigation and Drainage. 21(1): 76-78. (in Chinese).