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Irrigation programming applying a transpiration model for tomato crop

Programación de riegos aplicando un modelo de transpiración para el cultivo de jitomate

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Abstract

The application of transpiration models in irrigation management within agriculture has been increasing, mainly due to the great need for water by crops and its low availability. The aim of this research was to calibrate and validate a simplified model to determine water consumption in greenhouse hydroponic tomato. Therefore, an experiment of indeterminate hydroponic tomato, cv "*Rafaelo*" was established. A Campbell Scientific weather station (Campbell Scientific, INC, USA) was installed. Air temperature and relative humidity were measured with a model HMP50 sensor. Global solar radiation was measured with a model CMP3-L pyranometer. Data was stored every minute in a CR1000 model datalogger. Transpiration was measured with a weighing lysimeter using a Sartorius QA model balance, with a capacity of 120 kg, ±0.5 g precision. The best statistics found were for IAF (1.8 - 2.3), the better statistical adjustments were founded to the lower leaf area index. In the validation, the values of the statistics: RMSE, MSE and I were like those found in the calibration with 99% goodness of fitting. This model is widely recommended for practical application in determining crop water consumption.

Water uptake, water productivity, simulation models

Resumen

La aplicación de los modelos de transpiración en el manejo del riego dentro de la agricultura ha venido creciendo, debido principalmente a la gran necesidad de agua por los cultivos y a su baja disponibilidad. El objetivo de esta investigación fue calibrar y validar un modelo simplificado para determinar el consumo hídrico en jitomate hidropónico en invernadero. Por lo que, se estableció un experimento de jitomate hidropónico indeterminado, *cv* "*Rafaelo*". Se instaló una estación meteorológica Campbell Scientific (Campbell Scientific, INC, USA). La temperatura del aire y humedad relativa se midió con un sensor modelo HMP50. La radiación solar global se midió con un piranómetro modelo CMP3-L. Los datos se almacenaron cada minuto en un datalogger modelo CR1000. La transpiración se midió con un lisímetro de pesada mediante una balanza Sartorius modelo QA, con capacidad de 120 kg, ±0.5 g de precisión. Los mejores estadísticos encontrados fueron para IAF (1.8 – 2.3), a menor índice de área foliar, mejores ajustes estadísticos. En la validación, los valores de los estadísticos: RMSE, MSE e I fueron similares a los encontrados en la calibración con ajustes del 99%. Este modelo es ampliamente recomendado, para la aplicación práctica en la determinación del consumo hídrico de los cultivos.

Absorción de agua, productividad hídrica, modelos de simulación

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Introduction

Leaves lose water through their stomatal pores as an effect of the photosynthetic activity of mesophyll cells (Lambers et al., 2008). This water loss is known as transpiration, which is characterized by a gas exchange process in which water vapour leaves and carbon dioxide (CO2) enters (Maurel et al., 2016; Kim et al., 2010). It is a sequence of water transport processes from the soil through the plant and finally to the atmosphere (Maurel et al., 2016). Among the factors involved in transpiration or stomatal opening are temperature and vapour pressure deficit (VPD). The disconnection between air temperature (Ta) and transpiration can be related to the different effects of temperature and DPV on stomata, regularly increasing temperature causes increase in DPV (Hardwick et al., 2015), increased temperature will often cause plants to open stomata (Kudoyarova et al., 2011; Mäenpää et al., 2011; Sadras et al., 2012; Way et al., 2013), although this is confused with increased DPV which also often causes stomatal closure.

The degree of stomata closure is most strongly driven by Ta or VPD, in turn, may also be influenced by a process of stomata acclimation that modifies responses to Ta and VPD, further complicating the response of plants to climatic changes (Marchin et al., 2016). Another key factor to consider in the study of transpiration is solar radiation. The response to blue light is largely promoted by phototropins, with possible contributions from zeaxanthin or phytochrome under certain conditions. These blue light photo-receptors are involved in phototrophic shoot bending, chloroplast movement and negative root phototropism (Fan et al., 2004). The application of transpiration modelling in irrigation management in agriculture has been gaining momentum, mainly due to the need for water by crops and its low availability for irrigated agriculture. The major use of water resources is in the agricultural sector, and in recent times, there have been problems of profitability, requiring priority attention in irrigation scheduling (Garcia and Vazquez, 2004). One of the challenges for agricultural research is to obtain maximum yield along with optimal crop growth using as little water as possible.

Especially in conditions where the only form of input is provided by irrigation. Irrigation scheduling is a set of technical procedures developed to predict how much, when to irrigate. Irrigation management in substrates is one of the most important factors in achieving high yields and good fruit quality. This activity requires more relevance because the use of substrates is becoming more and more common in greenhouses and the amount of water they can store is relatively small. Under such conditions, it is necessary to provide small and frequent irrigation sheets, applied with the highest precision. On the other hand, transpiration dynamics in the greenhouse are subject to short-term changes in climate (Castellanos, 2009). The objective of this work was to calibrate and validate a simplified model to determine water consumption for two leaf area index intervals of a hydroponic greenhouse tomato crop.

Materials and Methods

Crop establishment

A greenhouse hydroponic tomato experiment was established within the facilities of the Universidad Autónoma de Chapingo, in the experimental field of the agricultural high school, geographically located 19º 29' north latitude and 98º 53' west longitude. Rafaelo" cv. of indeterminate growth was used, which was sown on April 7, 2011 and transplanted on May 7 of the same year at a density of 2.6 plants m^{-2}. The crop was provided with management practices similar to a cash crop under optimum irrigation and nutrition conditions. A mixture of tezontle and coconut fiber was used in a proportion (70/30%) in 45 x 45 polyethylene bags, white on the outside and black on the inside, with a three-ball planting frame with two plants per bag.

The trial was carried out in a saw-type greenhouse, with zenithal ventilation, with north-south orientation, 700-gauge plastic cover, treated against ultraviolet rays, consisting of three bays of dimensions 8.5 x 76 m, totalling an area of 1938 m^2. It has three zenithal windows of 1.6 x 76 m, covered with 24 x 40 wire/in^2 anti-aphid mesh, with semi-automated opening and closing.

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It has a drip irrigation system with stakes, with self-compensating drippers of 8 lph, with distributors with four outlets, tubing and stakes for each plant, with an automated irrigation injection system, eight irrigations per day were programmed.

Climatic variables

A Campbell Scientific weather station (Campbell Scientific, INC, USA) was installed inside the greenhouse. A sensor model HMP50 was used to measure air temperature and relative humidity, which was installed inside a 50 cm long tube with an air extractor to avoid the direct incidence of solar radiation on the sensor. Global solar radiation was measured with a pyranometer model CMP3-L (Kipp & zonen). Data from the sensors were stored in a datalogger model CR1000 at minute intervals, 39 days of data were stored.

Transpiration measurement

For the measurement of this variable, the methodology used by Sánchez et al. (2008) was used. A weighing lysimeter was installed in the central part of the greenhouse. It consisted of a Sartorius balance model QA, with a capacity of 120 kg, ±0.5 g accuracy, on which was placed a metal structure designed to isolate the experimental unit from the cultivation system, capable of containing four pots with two plants in each pot. It was covered with a plastic bench in order to avoid water loss by evaporation. The transpiration rate under this methodology was defined as the mass measured continuously by the balance in a short time interval between two successive weighing records. This variable was stored every minute, obtaining 39 days of data, in four blocks, likewise, the leaf area index was measured between each block of data every 15 days, with a LI-COR leaf area integrator model LI-3100, for which four plants were randomly selected.

Baille's model

The model proposed by Baille et al. (1994), which is based on the Penman-Monteith equation for transpiration (Monteith and Unsworth, 2008), was used in this work. This equation when applied to greenhouse crops as described by: Medrano (2005), Sanchez et al. (2008;2011), Martinez et al. (2012) is described as follows:

$$LE = Af_1(IAF)R_g + Bf_2(IAF)D \qquad (1)$$

For $f_1 = 1 - \exp\,(-\alpha IAF)$ y $f_2 = IAF$ therefore finally you have

$$LE = A[1 - \exp(-\alpha IAF)]\,R_g + B(IAF)D \qquad (2)$$

where E is the evapotranspiration rate of the crop [kg m^{-2} 15min^{-1}], R_g is the global solar radiation incident [Wm^{-2}], D D is the vapour pressure deficit [Pa], IAF is the leaf area index [m^2 m^{-2}], f_1 y f_2 are dimensionless functions of IAF. A y B are model parameters (A, dimensionless; B, [Wm^{-2}Pa^{-1}]). The parameter A refers to the radiative term and B to the aerodynamic term (sometimes called advective term). Therefore, A and B are also known as radiation coefficient and aerodynamic coefficient respectively.

The vapour pressure at saturation has an exponential relationship with the air temperature Ta [^{o}C]. The equation is as follows.

$$e_s(T_a) = 610.8 \exp\left[\frac{17.27 * T_a}{T_a + 237.3}\right] \qquad (3)$$

The actual vapour pressure of the air is commonly calculated from the relative humidity. (HR).

$$HR = 100 * \frac{e_a}{e_s(T_a)} \qquad (4)$$

Where; e_a is the current vapour pressure [Pa]; e_s (Ta) is the saturation vapour pressure [Pa] at the air temperature Ta [^{o}C].

The difference between the saturation vapour pressure and the actual vapour pressure of the air is known as the vapour pressure deficit and is denoted by the letter D.

$$D = e_s\,(T_a) - e_a \qquad (5)$$

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Calibration procedure

The calibration was carried out using the non-linear least squares method with the Levenberg-Marquardt algorithm, which consists of finding the minimum error of the square of the differences between the observed values and values predicted by the model, in a subroutine of Matlab 2016a (Mathworks) and to evaluate the quality of fit of the calibration and validation the following statistics were used: Root Mean Square Error (RMSE), Mean Absolute Error (MSE), and fit indices (I).

Results and Discussion

Figure 1 shows the sample of a block of data of 25 consecutive days, of the climatic variables measured inside the greenhouse, for a spring-summer crop cycle. Maximum radiation values of 400 Wm^{-2} for cloudy days and values of 900 Wm^{-}2 for sunny days are observed. A minimum temperature of 10 ºC and a maximum of 40 ºC were recorded. Relative humidity of 70 % for a cloudy day and a maximum value of 40 % for a sunny day.

For the transpiration rate measured with the weighing lysimeter, two blocks of data were collected (Figure 2); one block of 25 days, of which 9 days were used for calibration and 9 for the validation process and another block of 14 days (6 for calibration and 8 for model validation), the simulations were carried out with averages every 15 minutes, alluding to the fact that irrigation management in hydroponic systems, the frequency of irrigation is higher than in soil crops. It was found that for leaf area index from 2.3 to 3.02 an average transpiration of 150 g m^{-2} 15 min-1 (42.8 mL $plant^{-115}$ min^{-1}) and for leaf area index from 1.8 - 2.3 resulted in an average value of 100 g m^{-2} 15 min^{-1} (28.6 mL $plant^{-115}$ min^{-1}). For cloudy days, it is observed that the transpiration rate is reduced by half and is in correspondence with high values of relative humidity and reduction of global solar radiation, so it is clear that crop transpiration is a highly dynamic process, which responds immediately to variations or disturbances of the climatic conditions inside the greenhouse.

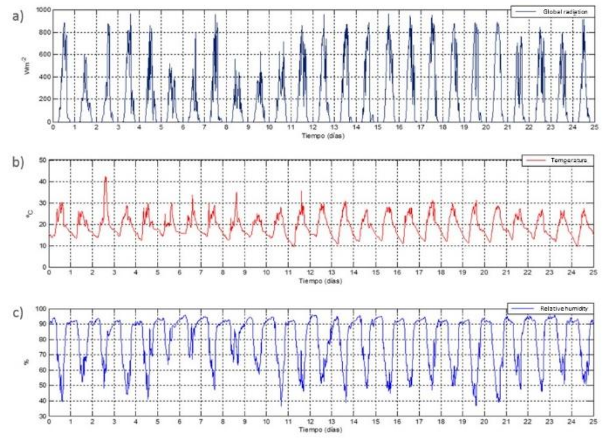

Figure 1 Meteorological variables: a) Global solar radiation, b) Temperature, c) Relative humidity, for 25 days measured inside the greenhouse.

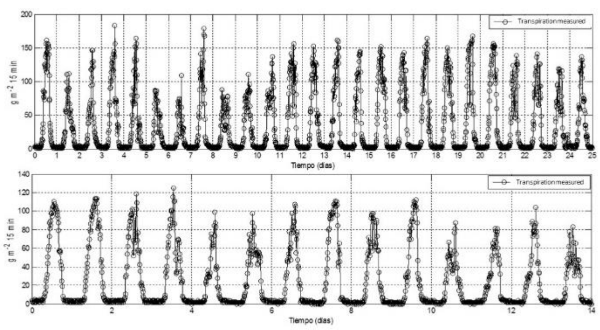

Figure 2 Measured transpiration for 25-day greenhouse tomato crop a) 2.3 - 3.02, b) IAF of 1.8-2.3

In order to find the correct values for the parameters of Baille's model, the calibration process was carried out (Figure 3) and then the validation or evaluation (Figure 4). For the radiative parameter (A) its value decreased when the leaf area index decreased, following an inverse behaviour with the other two parameters that have to do with the vapour pressure deficit (aerodynamic parameters). The parameter values resulting from the calibration (Table 1) agree with those mentioned by Martinez et al. (2012; 2019). The statistics that resulted for IAF intervals of (1.8 - 2.3), were better, as the error decreased as the leaf area index was lower (Figure 1). For the case of model evaluation (Table 2), the values of the statistics for RMSE, MSE and I were close to those found in the calibration, and 99% fits in both cases, similar results in goodness of fit were found by (Sanchez et al., 2011, Medrano et al., 2005).

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Model calibration

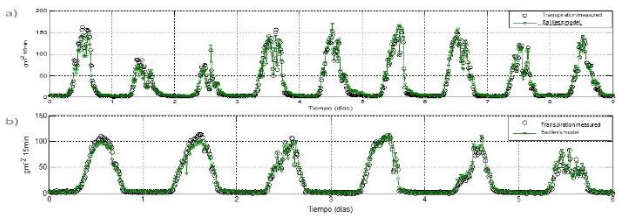

Figure 3 Calibration of the Baille model for transpiration a) for IAF 2.3 - 3.02, b) for IAF of 1.8 - 2.3

IAF	PARAMETERS		RMSE	MSE	Adjustment index
2.3 <IAF <3.02	A	0.33	8.081	65.30	0.991
	Bd	30.55			
	Bn	14.99			
1.8 <IAF ≤ 2.3	A	0.27	5.744	32.99	0.993
	Bd	32.35			
	Bn	22.00			

Table 1 Statistical parameters of the calibration of the Baille model for IAF of 2.3 - 3.02 and 1.8 - 2.3

Model validation

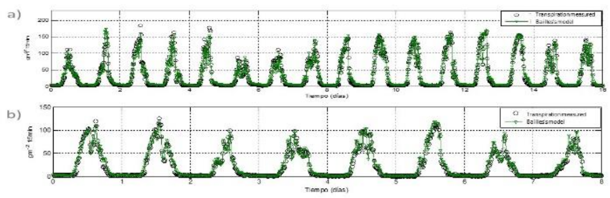

Figure 4 Validation of Baille's transpiration models, a) IAF 2.3 - 3.02, b) IAF of 1.8 - 2.3

IAF	PARAMETERS		RMSE	MSE	Adjustment index
2.3 <IAF<3.02	A	0.33	8.445	71.333	0.991
	Bd	30.55			
	Bn	14.99			
1.8 <IAF≤ 2.3	A	0.27	5.728	32.811	0.991
	Bd	32.35			
	Bn	22.00			

Table 2 Statistical parameters of the validation of Baille's model for IAF of 2.3 - 3.02 and 1.8 - 2.3

Conclusion

The Baille model is a model that has a simple mathematical structure, it comes from a simplification of the complex Penman-Monteith model, therefore, the physical laws that have to do with the balance of mass and energy are still fulfilled, according to the results found, this model is a widely recommended option for the practical application in the determination of the water consumption of crops. And it can be useful to implement control strategies in irrigation scheduling, based on the transpiration variable in interaction with the climatic conditions inside the greenhouses.

The calibration of the model parameters was performed without any complications and the predictions made by the model in both calibration and validation were satisfactory.

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