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Comparison of Vegsyst and Hortsyt models: Two models of growth of greenhouse crops

Comparación de los modelos Vegsyst y Hortsyst: Dos modelos de crecimiento de cultivos en invernadero

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Abstract

The HortSyst model is a new discrete-time model to describe the dynamics of photothermal time (PTT), dry matter production (DMP), N uptake (Nup), leaf area index (LAI) and rate of transpiration (ETc) of greenhouse crops, it has 13 parameters. The model assumes that crops do not have water and nutrient limitations. The input variables of the model are hourly measurements of air temperature, relative humidity, and the integral of solar radiation. Two experiments were carried out in a greenhouse, with hydroponic tomato cv. "CID F1" at a density of 3.5 plants m^{-2}, autumn-winter and spring-summer cycle, in Chapingo, Mexico. The first experiment was transplanted on August 21, 2015 and the second experiment on April 24, 2016. A weather station was installed inside the greenhouses, temperature and relative humidity were measured with a model S-TMB-M006 sensor and radiation global sensor S-LIB-M003. The objective of this research is to compare two growth models for tomato in greenhouses. According to the adjustment of its predictions against the measurements it can be of help in the supply water and nitrogen.

Wáter consumption, Water use efficiency, Nutritional extraction

Resumen

El modelo HortSyst es un nuevo modelo de tiempo discreto para describir la dinámica del tiempo fototérmico (PTT), la producción de materia seca (DMP), la absorción de N (Nup), el índice de área foliar (LAI) y la tasa de transpiración (ETc) de cultivos de invernadero, cuenta con 13 parámetros. El modelo asume que los cultivos no tienen limitaciones de agua y nutrientes. Las variables de entrada del modelo son mediciones horarias de la temperatura del aire, la humedad relativa y la integral de la radiación solar. Se realizaron dos experimentos en invernadero, con jitomate hidropónico *cv*. "CID F1" a una densidad de 3.5 plantas m^{-2}, de ciclo otoño-invierno y primavera-verano, en Chapingo, México. El primer experimento se trasplantó el 21 de agosto de 2015 y el segundo experimento el 24 de abril de 2016. Se instaló una estación meteorológica dentro de los invernaderos, se midió temperatura y humedad relativa con un sensor modelo S-TMB-M006 y la radiación global sensor S-LIB-M003. El objetivo de esta investigación es comparar dos modelos de crecimiento para jitomate en invernadero. De acuerdo con el ajuste de sus predicciones frente a las mediciones puede ser de ayuda en el suministro de agua y N.

Consumo hídrico, Eficiencia del uso del agua, Extracción nutrimental

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Introduction

Plant growth modelling has become a key research activity, particularly in the fields of agriculture, forestry and environmental sciences. Due to the growth of computer power and resources and the sharing of experiences between biologists, mathematicians and computer scientists, the development of plant growth models has progressed enormously during the last two decades. The use of an interdisciplinary approach is necessary to advance research in plant growth modelling and simulation (Thornley and France, 2007; Fourcaud *et al.,* 2008).

The efficient management of intensive agriculture demands consideration of the factors that determine the crop production potential and their interactions. The integration of these factors under the systems approach and based on growth simulation models is an approximation that allows the design of practices of management aimed at increasing productivity by minimizing the environmental impact caused by agricultural activity (Stockle *et al.,* 1994).

To increase knowledge of cropping systems and to look for practical applications, several models have been developed for greenhouse crops. Specifically for tomatoes have been proposed TOMGRO (Jones *et al*., 1991), TOMSIM (Heuvelink *et al*., 1999), TOMPOUSSE (Abreu *et al*., 2000) models, which have helped to simulate the behavior of production systems. However, some of these models are too complex because they involve too many state variables, input variables or model parameters, which make their implementation difficult. For example the model TOMGRO ver. 1.0 has 69 state variables, TOMGRO ver. 3.0 has 574 state variables, or the simplified version of this same model that presents 5 state variables and 29 parameters (Vazquez *et al*., 2014). Other models for greenhouse crops, although simpler, have been developed for crop systems specific to a region such as the VegSyst model (Gallardo *et al*., 2011; Gimenez *et al*., 2013; Gallardo *et al*., 2014; Gallardo *et al*., 2016).

In order to have an optimal control in the management of productive systems, it is necessary to develop models with the capacity to represent the interactions that exist between the development of the crop, climatic conditions and physiological processes of water and nutrients uptake. Thus, to find the concentration of the optimal nutrient solution, is the most desirable in a production system, this fact considers an important effect of the transpiration and irrigation management on the nutritional absorption since the dissolved ions in the nutrient solution are transported from the root through mass flow, in which transpiration is the process that provides the necessary force for the movement to occur (Mengel *et al*., 2001).

Therefore, with the use of a mathematical model, the perfect synchronization between the amounts of water required for growth and the nutritional demand of the crop depending on the environmental conditions, allows efficient use of water in the greenhouse crops. Nowadays, some of the scheduling of irrigation of hydroponic culture mode used in greenhouses is based either on time clock or by radiation method, but some of these are not flexible enough to satisfy the varying crop water requirements through the day and during de season, in case of time clock, and another as, the radiation method does not take into account the influence of vapor pressure deficit so this method is an approach of the reality, but not the complete solution according to (Lizarraga *et al*., 2003).

The HortSyst model is a new discrete time dynamic model that predicts: photo-thermal time, dry matter production, N uptake, leaf area index and crop transpiration rates. The development of this model started by modifying the structure of the VegSyst model (Gallardo *et al*., 2011; Gimenez *et al*., 2013; Gallardo *et al*., 2016) proposed for greenhouse crops. However, these modifications became increasingly large and ended up being a new model considerably simpler and with predictive quality equal or greater than the VegSyst model. The objective of this work is to describe the mathematical model HortSyst that was developed as a tool capable of being used by producers in the decision making on the nitrogen supply from the simulation of biomass production and irrigation programming using the transpiration in a crop of hydroponic tomato (*Solanum lycopersicom* L.) in greenhouse

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Materials and methods

HortSyst Model Description

The HortSyst model is a nonlinear dynamic growth model for hydroponic systems, for tomato (*Solanum lycopersicom* L.) in greenhouses. This model was developed to be used as a tool for decision support systems in Mexican greenhouses. The model assumes that crops have no water and nutrient limitations, also that the crop is free of pests and diseases, and under management in cultural activities like commercial greenhouses.

The HortSyst model predicts crop biomass production ($DMP, g\, m^{-2}$), N uptake ($Nup, g\, m^{-2}$), photo-thermal time ($PTI, MJ\, d^{-1}$) as state variables and the crop transpiration rates (ETc, kgm^{-2}) and leaf area index ($LAI\, , m^2 m^{-2}$) as output variables. The model inputs variables are hourly measurements of air temperature (°C), relative humidity (%), and integral of solar radiation (Wm^{-2}). It has thirteen parameters (Table 1) besides initial conditions of dry matter production and photo-thermal time. The HortSyst model was developed based on the VegSyst model (Gallardo *et al*., 2011; Gallardo *et al*., 2016; Gallardo *et al*., 2014; Giménez *et al*., 2013; Granados *et al*., 2013; Gallardo *et al*., 2016).

The following Forrester diagram (Figure 1) summarizes the functional relationship that exists between the components of the model as input, output, parameters and state variables.

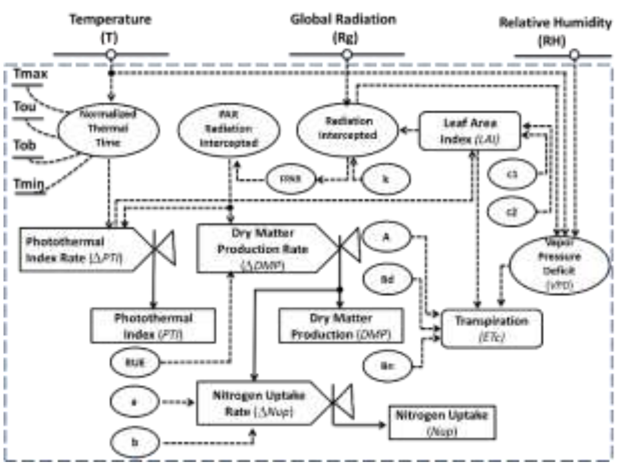

Figure 1 Forrester diagram for HortSyst model

The HortSyst model predicts in discrete time, namely, by means of difference equations the behavior of the three state variables: the photo-thermal time (eq.1), the dry matter production (eq.2) and the nitrogen uptake (eq.3).

$$PTI(j+1) = PTI(j) + \Delta PTI \quad (1)$$

$$DMP(j+1) = DMP(j) + \Delta DMP \quad (2)$$

$$N_{up}(j+1) = N_{up}(j) + \Delta N_{up} \quad (3)$$

where the values of each variable in discrete time $j+1$ are calculated by adding the values of the variables in the previous discrete time j plus the rate of change Δ corresponding to each variable.The variable photo-thermal time ($PTI, MJ\, d^{-1}$) is defined as the state variable since it couples the effect of radiation and temperature on the crop and from the point of view of the climate of the greenhouse, these variables are not strongly correlated as they are in the open field (Reffye *et al*., 2009; Xu *et al*., 2010). In contrast to other researchers who have modeled the leaf area index as a function of time or as a function of the day degrees (Carmassi *et al*., 2013; Chin *et al*, 2011; Incrocci *et al*., 2008; Massa *et al*., 2011; Medrano., 2008; Montero., 2001; Orgaz *et al*., 2005) or others who have used the days after transplant (Carmassi *et al*., 2007; Medrano., 2005; Medrano *et al*., 2011; Ta *et al*., 2011) or the specific leaf área (Bechini *et al*, 2006; Stockle *et al*, 2003), in the HortSyst model, the photo-thermal time state variable as the independent variable of the leaf area of the crop. In the VegSyst model, the thermal time is the state variable that drives the daily calculation of biomass production, nitrogen uptake and crop evapotranspiration (Gallardo *et al*., 2011; Gimenez *et al*., 2013). In addition, radiation directly influences crop growth (dry matter production) and affects development (morphogenesis) (Sergio *et al*., 2003).

The rate of change of the photo-thermal time (ΔPTI) depends on the photosynthetically active radiation(PAR), normalized thermal time (TT) and the intercepted fraction of radiation($f_{i-PAR)}$.

$$\Delta PTI(j) = \left(\sum_{i=1}^{24} TT(i,j) \right) / 24 \times PAR(j) \times f_{i-PAR}(j) \quad (4)$$

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where the index i represents hourly calculations, index j represents daily level, PAR is photosynthetically active radiation and is calculated from daily global radiation above the crop (R_g,$W\ m^{-2}$).

$$PAR = 0.5 \times R_g \quad (5)$$

TT °C is the normalized thermal time as used by other researchers (Bechini *et al*., 2006; Soltani *et al*., 2012), which is defined as the ratio of the rate of growth under real conditions of optimal temperatures, and is calculated as follows:

$$T = \begin{cases} 0 & (T_a < T_{min}) \\ (T_a - T_{min})/(T_{ob} - T_{min}) & (T_{min} \le T_a < T_{ob}) \\ 1 & (T_{ob} \le T_a \le T_{ou}) \\ (T_{max} - T_a)/(T_{max} - T_{ou}) & (T_{ou} < T_a \le T_{max}) \\ 0 & (T_a > T_{max}) \end{cases} \quad (6)$$

where T_a (°C) is the temperature of the air, T_{min} (°C) is the minimum temperature, T_{max} (°C) is the maximum temperature, T_{ob} (°C) is the lower optimal temperature and T_{ou} (°C) is the upper optimal temperature. The intercepted fraction of the radiation is calculated by the exponential function:

$$f_{i-PAR} = 1 - exp(-k \times LAI(j)) \quad (7)$$

where k is the light extinction coefficient, and LAI is the leaf area index which in turn is calculated from the leaf area value A_f (m^2) which depends on the daily photo-thermal time (ΔTPI) by an equation type Michaellis-Menten

$$LAI(j) = \left(\frac{c_1 PTI(j)}{c_2 + PTI(j)}\right) d \quad (8)$$

where c_1 (m^{-2}) and c_2 are parameters of the Michaellis-Menten equation and d (plants m^{-2}) is the density of the crop.

The model uses a classical concept approach, efficient radiation applications (Kang *et al*., 2008; Lemaire *et al*., 2008; Reffye *et al*., 2009) which allows the calculation of daily dry matter production (ΔDMP) as a function of the photosynthetically active radiation (PAR) eq. (5), crop characteristics such as leaf area index (LAI) eq. (8) and the radiation use efficiency parameter (RUE, gMJ^{-1}) as has proposed by several researchers (Gallardo *et al*., 2016; Shibu *et al*., 2010; Soltani and Sinclair, 2012).

$$\Delta DMP(j) = RUE \times f_{i-PAR} \times PAR(j) \quad (9)$$

The value of (ΔDMP) accumulates day by day as in equation (2) Once the daily dry matter production is calculated, it is possible to calculate the nitrogen uptake daily by the equation(10, 11) (Le Bot *et al*., 1998; Tei *et al*., 2002) which, when accumulated with equation (3), allows the calculation of the nitrogen extraction throughout the crop growing period (ΔDMP).

$$\%N(j) = a \times (DMP(j))^{-b} \quad (10)$$

$$N_{up}(j) = (\%N(j)/100) \times DMP(j) \quad (11)$$

where ΔN_{up} is the daily uptake nitrogen ($g\,m^{-2}$), a and b are parameters of the equation and ΔDMP is the increase of daily dry matter produced ($g\,m^{-2}$).

Finally, crop transpiration ($ETc, kg\,m^{-2}$) is calculated every hour using the equation proposed by (Baille *et al*., 1994), which has been widely used to schedule greenhouse irrigation (Carmassi *et al*., 2013; Martínez-Ruiz *et al*., 2012; Massa *et al*., 2011; Medrano *et al*., 2011). The Baille transpiration model requires the global radiation data, vapor pressure deficit, which is calculated with values of air temperature and relative humidity and leaf area index equation (8). The equations that in HortSyst estimate the transpiration of the crop are:

$$ETc(i) = A \times (1 - \exp(-k \times LAI(j))) \times Rg(i) + LAI(j) VPD(i) B_{(d,n)} \quad (12)$$

$$ETc(j+1) = \sum_{i=1}^{24} ETc(i) \quad (13)$$

where $ETc(j+1)$ ($kg\,m^{-2} d^{-1}$) is the daily accumulated transpiration, $ETc(i)$ ($g\,m^{-2} h^{-1}$) is the hourly transpiration rate, R_g is the hourly incident solar radiation ($W\,m^{-2}$), VPD is the vapor pressure deficit and A (dimensionless) refers to the radiative parameter; and B_d, B_n ($Wm^2 kPa^{-1}$) are parameters of the aerodynamic term of equation (28) for day and night, respectively. All the parameters of HortSyst are described in Table 1.

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The computational model

The HortSyst is currently programmed in the Matlab computer environment. The dynamic equations are coded inside a Matlab subroutine (function). Two iterative loops allow computing daily and hourly calculations. The outputs of the subroutine are the variables; photo-thermal time, crop biomass, nitrogen uptake, crop evapotranspiration and leaf area index. The input variables of the subroutine are the model parameters (Table 1) and climatic variables. A main program (Matlab script) calls the subroutine and generating graphs or other calculations necessary to run the simulations.

Tomato growth experiments description

Two experiments were carried out under greenhouse conditions, during the autumn-winter, and spring-summer season, located at the University of Chapingo, Mexico. Geographical location: 19° 29' LN, 98° 53' and 2240 msnm. A tomato (*Solanum lycopersicom* L.) crop cultivar "CID F1" was grown in a hydroponic system using volcanic sand as substrate and fertilized with Steiner nutrient solution (Steiner, 1980). Plants were distributed with a density of 3.5 plants m^{-2}. For the first experiment tomato seeds were sown on 18 July 2015 and the plants were transplanted on 21 August 2015 in a glass greenhouse type chapel with 8 x 8 m dimension, and the second experiment were sown on 24 March 2016 and transplanted on 24 April 2016 in a plastic greenhouse with overhead ventilation with dimension of 8 x 15 m.

A weather station (Onset Computer Corporation) was installed inside of the greenhouses. Temperature and relative humidity were measured with a S-TMB-M006 model sensor placed at a height of 1.5 m. Global radiation was measured with a S-LIB-M003 sensor and was located 3.5 m above the ground.

Both sensors were connected to a datalogger U-30-NRC model, which recorded data every minute. In each experiment, three plants were chosen randomly for the sample each 10 days to measure dry matter, nitrogen uptake accumulation and leaf area index. Plants were dried out during 72 h at 70 °C. And nitrogen was determined by Micro-Kjeldahl method (Chapman and Pratt, 1974).

Leaf area Index were determinate by a nondestructive method, it consisted in taking 4 plants randomly to get measurements of width and length of the plants leaves and also the total leaf area and a plant canopy analyzer LAI-3100 (LICOR, USA) was used. From the measurements, nonlinear regressions models were fitted in order to estimate this variable. The crop transpiration rate was measured every minute by means of a weighing lysimeter located in a central row of the greenhouses, the device includes an electronic balance (scale capacity =120 kg, resolution ±5 g equipped with a tray carrying 4 plants for both experiments. The weight loss measured by the electronic balance was assumed equal to the crop transpiration. To compare the predictive quality of the HortSyst and VegSyst models we used the nominal parameters listed in Table 1 for the HortSyst model and the parameters used for the simulation VegSyst model were taken from (Gallardo *et al*.,2014, Gallardo *et al*., 2016). And MAE and RMSE statistics were considered to evaluate the performance of simulation of both models.

No	Parameter	Symbol	Units	Nominal Value (autumn-winter)	Nominal Value (spring-summer)	source
1	Top upper temperature	T_{max}	°C	35.00	35.00	Peet and Welles (2005), Chu *et al*., (2009)
2	Top bottom temperature	T_{min}	°C	10.00	10.00	Peet and Welles (2005), Chu et al., (2009)
3	Optimum minimum temperature	T_{ob}	°C	17.00	17.00	Peet and Welles (2005)
4	Optimum maximum temperature	T_{ou}	°C	24.00	24.00	Peet and Welles (2005)
5	Radiation Use Efficiency	RUE	g MJ^{-1}	4.01	3.1	Gallardo *et al*., (2014), Challa and Bakker (1998)
6	Extinction coefficient	k	---	0.70	0.70	
7	N concentration in the dry biomass at the end of the exponential growth period	a	g m^{-2}	0.755	7.55	Gallardo *et al*., (2014)
8	Is the slope of the relationship	b	---	-0.15	-0.15	Gallardo *et al*., (2014)
9	Slope of the curve	c_1	m^{-2}	2.82	3.07	Estimated
10	Intersection coefficient	c_2	---	74.66	175.64	Estimated
11	Radiative coefficient	A	---	0.59	0.24	Montero *et al*., (2001), (Medrano *et al*., (2008)
12	Aerodynamic coefficient during day	B_d	Wm^{-} $2kPa^{-1}$	19.10	37.6	Montero *et al*., (2001),Medrano *et al*., (2008)
13	Aerodynamic coefficient during night	B_n	Wm^{-} $2kPa^{-1}$	25.00	26	Montero *et al*.,(2001), Medrano *et al*.,(2008)

Table 1 Model parameters used for HortSyst model during greenhouse growing condition.

Results

Simulation of HortSyst Model: Input variables

The global solar radiation (Rg), air temperature (Ta), and relative humidity (RH) used in the simulations of the HortSyst and VegSyst model for both growing periods autumn- Winter (O-W) and spring summer (S-S) crop cycle are showed in Figure 2, 3 and 4, respectively.

The nominal values of the model parameters are given in Table 1. According to measured data it is clear that the amount of global radiation in the spring summer season is a more than twice the one is reached in the autumn-winter season. Furthermore, during autumn-winter we observed greater cloudy days. This fact has its effect on the accumulation of dry matter, nitrogen uptake, leaf area index and water uptake (transpiration).

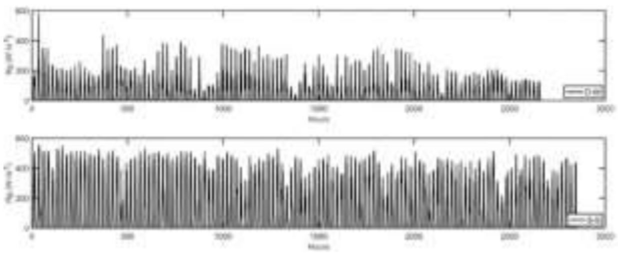

Figure 2 Global radiation measured hourly inside of the greenhouse located in Chapingo, Mexico during outum-winter (O-W), 2015, and Spring-Summer (S-S), 2016

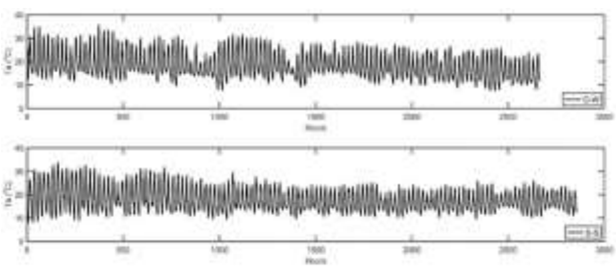

Figure 3 Air temperature measured hourly inside of the greenhouse, located in Chapingo, Mexico, during outum-winter (O-W), 2015 and Spring-Summer (S-S), 2016

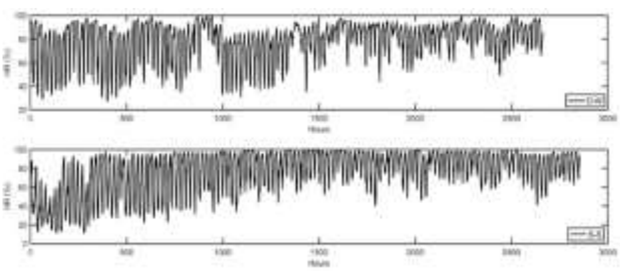

Figure 4 Relative Humidity measured hourly inside of the greenhouse located in Chapingo, Mexico, during outum-winter (O-W), 2015 and Spring-Summer (S-S), 2016

Dry matter Production (DMP)

Figure 5 shows the values of the simulation for dry matter production using RUE values of 4.01 g MJ^{-1} for the autumn-winter and RUE of 3.01 g MJ^{-1} for the spring summer, where it is observed that during the spring summer season for both HortSyst and VegSyst models, there was approximately twice the biomass with respect to the autumn-winter, this is due to the fact that it is the cycle in which there is more solar radiation (Figure 2).

It was found that the simulation follows the trend of the measured values in laboratory having as accumulated final value of simulated biomass in the autumn-winter cycle of 587.37 g m^{-2} against a measured value of 673.38 g m^{-2} which represents an underestimation of the model of 12.77% of the measured value. In case of the spring-summer period, the simulated value at the end of the cycle is 1336.59 g m^{-2} against the measured 1304.118 g m^{-2}, resulting in an overestimation error of 2.49%. This means that the RUE value considered could be used for the simulation of the biomass.

In both experiments total dry matter production shows an exponential growth and then an approximately linear growth phase, which is a growth pattern, expected under constant climate conditions.

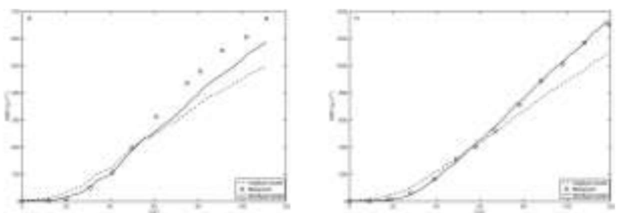

Figure 5 Time course of the simulated and measured values of dry matter production of a greenhouse tomato crop grown in Chapingo, Mexico, for a) autumn-winter, 2015 and b) spring-summer, 2016 for HortSyst and VegSyst models

Nitrogen Uptake (Nup)

On the other hand, Figure 6 shows a comparison between the values measured and predicted by the HortSyst model and VegSyst model, for the nitrogen uptake variable for both crop seasons.

In both cases a good fit between simulations and measurements is observed for the case of nitrogen uptake in autumn-winter, the final value predicted by the simulation is 19.98 g m^{-2} against the measured value of 13.71 g m^{-2} which represents an error of 45.78%. In case of Spring-Summer the value simulated was 40.23 g m^{-2} and the measured was 27.4 g m^{-2}. In both periods error of predicted value by the model is approximately of 46% above measurements (Figure 6).

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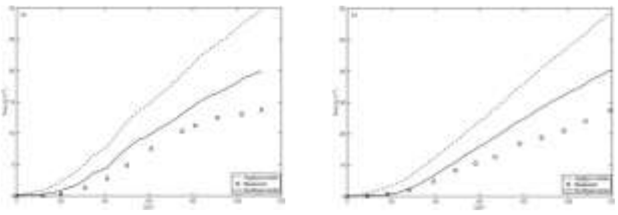

Figure 6 Time course of the simulated and measured values of Nitrogen uptake of a greenhouse tomatocrop grown in Chapingo, Mexico, for a) autumn-winter, 2015 and b) Spring-Summer, 2016, for HortSyst and VegSyst models

Leaf Area Index

Because the lack of information in the literature of the parameters values of this variable (c_1 and c_2) a manual calibration was carried out in order to determine the possible values could be used in the simulation for each growing period. It is possible that, this variable plays central role in the model since, from these simulated values is predicted photo-thermal time, dry matter production, transpiration and indirectly nitrogen uptake. The considered values for the parameters are showed in Table 1. Their values are longer for spring-summer than for autumn-winter.

The simulated LAI values are similar to the measured values 5.85 m^2m^{-2} with an error of 0.4% between the measured and simulated data (5.83 m^2m^{-2}), during autumn-winter and during spring-summer, the measured LAI was 7 m^2m^{-2}, against 6.86 m^2m^{-2} with an error of 2.17% for the measured and simulated data as shown in the figure 7.

LAI is only simulated by the HortSyst model. The VegSyst model does not take in account the computation of LAI, because it uses another concept like heat units and intercepted PAR radiation for two stages of the crop.

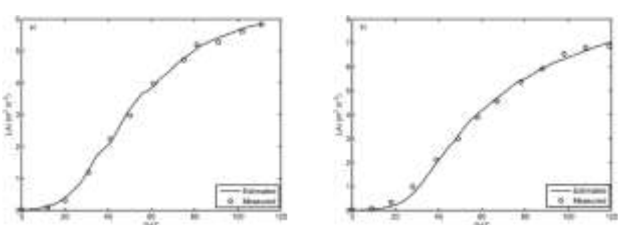

Figure 7 Time course of the simulated and measured values of the Lea Area Index of a greenhouse tomato crop grown in Chapingo, Mexico for, a) Autumn-Winter, 2015 and b) Spring-Summer, 2016, for HortSyst model.

Crop transpiration rate

For the transpiration variable (Figure 8), it was found that using the parameters values shown in Table 1 for A, Bd and Bn, it is acceptable to estimate with an error of 2. 62%, for an accumulated simulated value of 183.68 kg m-2 and measured values and 188.49 kg m-2 at the end of the cycle autumn-winter and measured value of 291.69 kg m-2 against simulated of 294.2 kg m-2 with error of 0.88% for spring and summer, respectively.

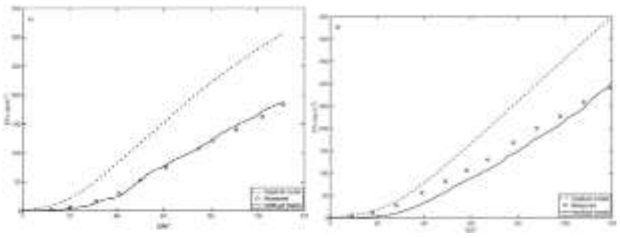

Figure 8 Time course of the simulated and measured values of crop transpiration of a greenhouse tomato crop grown in Chapingo, Mexico a) Autumn-Winter, 2015 and b) Spring-Summer, 2016, for HortSyst and VegSyst models

Photo-thermal time

Figure 9 shows the photo-thermal time variable that uses this model to calculate the leaf area index which presents a behavior similar to that previously reported by Xu *et al.*, (2010). It is important to emphasize that this simulation is intended to demonstrate the ability of the model to predict the most important variables related to the production of a hydroponic tomato crop under greenhouse conditions and using volcanic sand ("tezontle") as substrate. Using the temperature at 1.5 m above ground and PAR above canopy this photo-thermal model eq. (4) gave satisfactory prediction of leaf area index eq.(8)

The amount of photo-thermal time accumulated in autumn winter was 108.97$MJ\ d^{-1}$ and for spring summer of 327.56 $MJ\ d^{-1}$ representing a 3 times greater difference in spring- summer. Like LAI variable the HortSyst model simulates PTI during the crop cycle this is the main difference between HortSyst and VegSyst model.

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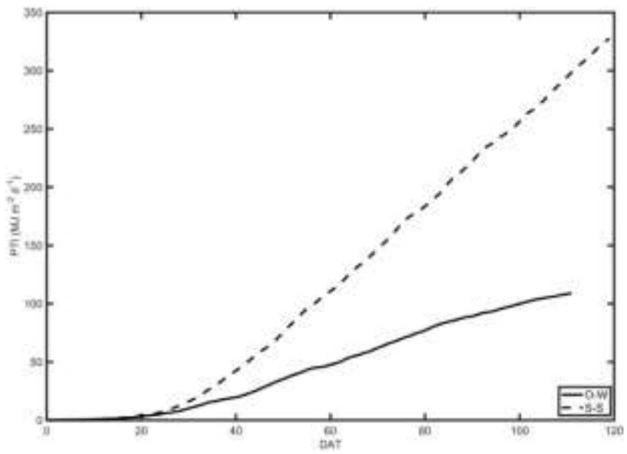

Figure 9 Time course of the predicted of photo-thermal time by HortSyst model, accumulated since plant date for Autumn-Winter (O-W) and Spring-Summer (S-S)

From the simulations carried out for the HortSyst and VegSyst model, the HortSyst model provides better predictive quality for dry matter production, nitrogen uptake and transpiration than the VegSyst model, this is confirmed by the higher values of the statistics; MAE and RMSE (Table 2) for this last model for both crop season, spring-summer and autumn-winter, with the highest errors for the case of transpiration in the VegSyst model. The variable leaf area index was not compared since both models do not share the simulation of this variable in its mathematical structure.

	HortSyst Model		VegSyst Model	
	Autumn-Winter			
OUTPUT	MAE	RMSE	MAE	RMSE
DMP	39.35	53.60	69.70	93.04
Nup	2.56	3.19	7.29	8.82
ETc	3.51	4.37	67.77	80.49
LAI	0.09	0.10		
	Spring-Summer			
DMP	12.93	16.71	70.14	101.17
Nup	5.25	7.03	13.54	16.99
ETc	15.94	18.16	59.96	79.53
LAI	0.12	0.14		

Table 2 Summary of results of the statistical indices (MAE and RMSE) used to evaluate the performance of the HortSyst model and VegSyst model for simulation of DMP, Nup, ETc and LAI during Autumn-Winter, 2015 and Spring-Summer, 2016

In order to show a potential use of the HortSyst model to predict the concentration of nitrogen uptake by the crop as a function of the transpiration, in figure 10 shows daily N absorbed concentration, considering the amount of water absorbed daily by the process of transpiration predicted by the model, for the spring-summer and autumn-winter crop cycles.

Where in the first 35 days, the uptake concentration by crop exceeds the concentration of 12 me L^{-1} (168 mgL^{-1}) recommended by Steiner (1980), after 40 days of cultivation, the concentration decreases approximately half of the concentration applied to the crop. With the evaluation of performance of the model, it was found that it would be a waste of approximately 50% of the applied fertilizer considering an efficiency of 100% of the system production under soilless culture.

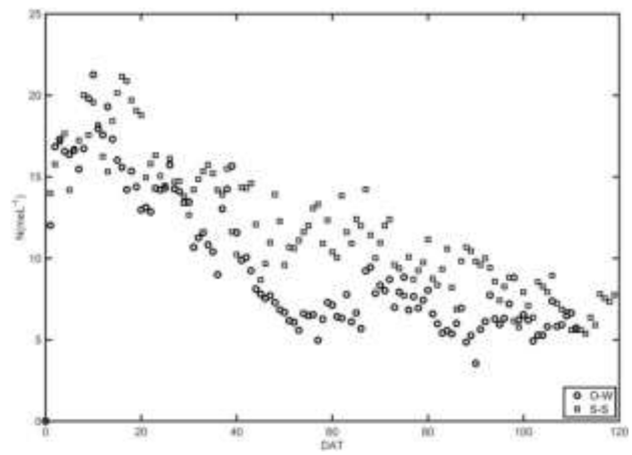

Figure 10 Time course of simulation of daily value of N concentration (meL-1) nitrogen uptake during Autumn-Winter (O-W), 2015 and Spring-Summer (S-S), 2016

Discussion

The crop simulation models HortSyst and VegSyst were simulated to show its performance for tomato for Mexican greenhouses. HortSyst model predicts correctly crop biomass, photo-thermal time and predicts accurately leaf area index and transpiration crop, however the quality of prediction of N uptake is poor using the nominal parameter values. This means that to improve the predictive quality of the model not only for N uptake but also for the other variables parameter estimation of model calibration is required by using experimental data. The quality of the simulated values of dry matter production are acceptable, because of the results obtained in the simulation using the RUE value of 4.01 g MJ^{-1} for prediction of biomass reported by (Gallardo *et al*., 2016) and RUE 3.01 g MJ^{-1} reported by (Challa and Bakker, 1998), for tomato crop, biomass values at the end of cycle are slightly lower than those reported by Gallardo *et al*., (2014) for autumn-winter. The value of this parameters are different due to differences in climatic conditions between one region and another or to different crop cycles (Villegas - Cota *et al*., 2014).

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The measured N uptake values were quite similar to those results reported for tomato crop by Gallardo *et al*., (2016); Gallardo *et al*. (2014). The differences in the values accumulated for nitrogen uptake between both cycles at the end of these are because in each cycle the environmental conditions are not the same at least in the levels of radiation and maybe the temperature variation between the day and night. The parameters used in the model for these variables were the same for the two crop cycles reported by Gallardo *et al*. (2016); Gallardo *et al*. (2014) since no values were found for each different cultivation period, in both cases the model did not show a satisfactory fit because the authors calibrated the model for nitrogen in a different culture system.

The modeling of LAI is one of the important differences with respect to the VegSyst model proposed by (Gallardo *et al*., 2011, 2016, 2014; Giménez *et al*., 2013; Granados *et al*., 2013), since these authors did not include the simulation of this variable in their model.

The final accumulated measured of evapotranspiration value for the autumn- winter is similar to those reported by (Gallardo *et al*., 2016; Gallardo *et al*., 2014). It is important to mention that the methodology to model water consumption by these authors was different since they used the Penman-Monteith model with crop coefficients. The values of the parameters in the HortSyst model are slightly similar to those reported by (Martínez-Ruiz *et al*., 2012) since these authors performed the calibration using frequent climatic data of 15 minutes and hourly.

In case of photo-thermal time Xu *et al*. (2010) found that modeling the leaf area index using this concept gave better predictions than degrees days model as (Gallardo *et al*., 2016) the latter type of models overestimate the predictions because of the fact that inside of the greenhouse the global radiation is not synchronized with the temperature behavior (De Reffye *et al*., 2003; Xu *et al*., 2010).

On the other hand, when comparing the estimation of leaf area index using the specific leaf area as used in Stockle *et al*. (1994) presents a poorest predictions due to the large variation of the specific leaf area among different growing seasons and the data of this latter variable can only be obtained by destructive measurements, this limits the application of models based on specific leaf area to greenhouse crops and climate management practice (Xu *et al*., 2010).

The advantage of using a model to make fertilization recommendations is that it considers factors as; environment conditions, physiological processes such as transpiration and characteristics of the crop as leaf area index and biomass production. The results found that with the model without calibration the simulation are quite similar to those reported (Gallardo *et al*., 2014) for the Autumn-winter season, who evaluated the use of the model VegSyst under three scenarios of recommendation of fertilization.

Conclusions

The HortSyst model can be used as a decision-making tool in greenhouse production systems, since according to the presented simulation it predicts in an acceptable way the biomass, absorbed nitrogen, leaf area index and transpiration. To model the leaf area index, a new concept called the photo-thermal time, which represents the effect of temperature on leaf expansion and the effect of radiation on crop growth, which, may be used as an alternative to simulate leaf area index in crop models. In fact, there are few models that include the variable transpiration in order to be used in irrigation management, in this case, was used a model that was derived from the simplification of Penman-Monteith and for its simplicity can be used to predict the consumption of water by the crop, in addition it needs climatic variables that are commonly measured in greenhouses.

It is necessary to carry out a calibration of the model to find the values of the parameters that help to improve its predictive quality. Also is necessary carrying out an evaluation (validation) of the model, with data of another experiment of the same cycle or different crop cycle to evaluate its behavior under different scenarios.

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Due to the small number of parameters (13 parameters) involved in the HortSyst model it is feasible to use it for irrigation management and nitrogen application in hydroponic tomato under greenhouse.

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