Emir. J. Food Agric. 2014. 26 (10): 885-897
doi: 10.9755/ejfa.v26i10.18270
http://www.ejfa.info/

Plant Science

REGULAR ARTICLE

Estimation of the water requirements of greenhouse tomato crop using multiple regression models

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Abstract

Water utilization by crops, namely tomato, within greenhouses is one of the most significant factors in determining yield. Daily water consumption by tomato plants were calculated, to determine the actual evapotranspiration and transpiration rates, as well as the incorporation measurement of climatic variables and weekly determinations of fresh and dry weights of the plants. Estimations of daily evapotranspiration and transpiration rates by the tomato plants were calculated using multiple regression models. The best models for estimating, both the evapotranspiration and transpiration, had adjusted R^2 values greater than 0.9. Using the multiple obtained regression models it is possible to estimate the water needs of tomato plants under greenhouse conditions from readily available variables. The aim of this study was to generate regression models in order to determine the crop water requirements of greenhouse tomato.

Key words: Climatic conditions, Evapotranspiration, Irrigation water, Regression models, Transpiration

Introduction

Crop production in greenhouses has great importance, as it gives us an advantage over open field production, providing a barrier between the external environment and the culture. Greenhouses create near optimal microclimate conditions for growing crops, protecting them from adverse conditions (Martínez-Ruíz et al., 2012) and controlling factors, namely temperature, radiation, CO_2 concentration and relative humidity.

Tomato (*Lycopersicon esculentum* Mill.) is the most important vegetable crop in the world, being used in both fresh and processed presentations (Gad and Hassan, 2013; Mehdizadeh et al., 2013). Regarding the area under cultivation, tomato is the second most important crop after potato, but it ranks first as a processed crop (Mehdizadeh et al., 2013). In recent years, global production has increased about 10% mainly because it is a significant source of vitamins and minerals (Shalaby and El-Banna, 2013). In Mexico, tomato represents *ca*. 70% of crops grown in protected conditions, followed by pepper (16%) and cucumber (10%) (SAGARPA, 2012). Mexico is also the major international exporter, shipping the product to the United States, Canada and El Salvador. In 2011, a total of 1872000 tons were exported (MEXICOPRODUCE, 2012).

Considering the importance of tomato, it is necessary to achieve its efficient management, particularly with respect to the use of water under greenhouse conditions. Furthermore, irrigation is responsible for delivering water to the root zone (White and Folegatti, 2003), determining its correct application the crop yield (Flores et al., 2007). Therefore, the practice of irrigation should be adjusted with respect to the growth and evapotranspiration demands of the crop in focus (Fynn et al., 1989; Enriquez-Reyes et al., 2003), to avoid periods of moisture deficit or water surplus, which negatively affect crop productivity, as well as the efficient use of both water and fertilizer (Flores et al., 2007). Evapotranspiration (ET) is the process whereby water is transferred from the soil

Received 12 May 2014; Revised 31 July 2014; Accepted 12 August 2014; Published Online 02 September 2014

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and/or plant layer to the atmosphere. Transpiration (TR), on the other hand, is the flow of water from the topsoil into the atmosphere (Alkaeed et al., 2007; Verstraeten et al., 2008). Knowledge of these processes is fundamental to the management of water, allowing an adequate supply of irrigation water or its scheduling (Stöckle et al., 2004; Alkaeed et al., 2007; Verstraeten et al., 2008).

There are several studies to determine the water needs for the greenhouse tomato, some of them based on methods such as the Priestley-Taylor (PT) (Valdes-Gomez et al., 2009) which is a simplified version that combines aerodynamic and energy balance, particularly used for large evaporation surfaces, the Penman-Monteith method (Rojas et al., 2003; Salokhe et al., 2005), or in methodologies based on energy balances (Boulard and Wang, 2000). These methods, however, require sophisticated equipment to obtain the variables needed for its operation. Other studies determined the daily requirement of water via drainage lysimeters, and also considered the different phenological stages of tomato (Flores et al., 2007). Model has also been based on stem diameter measurements for generating predictions of transpiration (Lee and Shin, 1998), but this proved to be difficult to implement. Baptista et al. (2005) used lysimeters to measure evapotranspiration and transpiration of tomato, and using solely solar radiation and vapor pressure deficit as variables to create regression models. The models were effective, but the authors recommended inclusion of other influential variables, because these applications were only pertinent to the study conditions.

In considering the aforementioned, the aim of this study was to generate multiple regression models to estimate evapotranspiration and transpiration of tomato under greenhouse conditions and to determine the daily water requirements, with the particularity of using easily measured variables such as total radiation, photosynthetically active radiation, relative humidity, air and soil temperatures, and fresh weights of leaves and shoots.

Materials and Methods

Tomato development

Beef tomato (*Lycopersicon esculentum* Mill.) "Caiman" Enza Zaden with indeterminate growth was grown under a post and rafter-type greenhouse with polycarbonate cover and automatic temperature control. This took place during the years 2011 and 2012, from 3 July to 30 October and from 6 May to 23 September, respectively, in the northern region of Mexico. The culture was established in plastic pots of 12 L with a density of 3 plants m^{-2}, and in a soilless system using as substrate a mixture of peat moss and perlite in the ratio 1:1. We used an irrigation system directed to microtubing-type dripper stakes with a high flow rate for each pot. Automatic timers were also installed and set for four irrigations per day at different times (8:00, 12:00, 16:00 and 20:00 hrs.). The amount of applied irrigation was different for each phenological stage, using 2.4 L per plant per day during periods of high consumption. Crop nutrition was made with Steiner nutrient solution (Steiner, 1961) applying different concentrations in each phenological stage. Cultivation focused on a plant stem and growth was restricted by eliminating the apical bud at 13 weeks after transplantation (WAT). The experimental design was completely randomized with five replications, using a plant as the experimental unit. Furthermore, in order to determine the average fresh weight of the aerial part of the plant and average fresh weight of leaves per plant, a destructive sampling of 4 plants each week was also carried out.

Determination of water consumption by tomato plants

In order to determine the amount of water consumption of a tomato plant, 10 randomly selected pots were placed on a container to collect drained water. To prevent evaporation of collected water, the container together with the bottom of the pot were covered with black polyethylene. Furthermore, white cover wadding was placed on top of the pot of five plant samples to avoid evaporation, so that transpiration would only be allowed through the plant. For the volume of applied water a vessel connected to the irrigation system was used, whereby water was collected and measured in a receiving pot. Daily, after application of the first irrigation at 8:00 hrs, measurements were taken of the drained water and the total water accumulated from the previous day´s irrigations at 12:00, 16:00 and 20:00. To determine water evapotranspiration per plant the volume of water drained by plants in pots without the wadding cover was subtracted from the total volume of applied irrigation water. Furthermore, to determine the amount of water transpired the volume of water drained by the plants in the pots with wadding cover was subtracted from the total volume of applied irrigation water.

Measurement of climatic variables

Furthermore, climatic variables were measured in the greenhouse during crop development, for which was used a photosynthetically active radiation sensor (LI-190), a total radiation sensor (LI-200), an air temperature sensor (1400-101) and a soil temperature sensor (1400-103) connected to a datalogger (LI-1400) manufactured by LI-COR Inc. A sensor was also used to measure air relative humidity, which is included in a datalogger (K-33 ELG) from CO_2meter ®. The measurement of the data was performed every 15 minutes and stored automatically in both dataloggers for later download. These data were determined both at day and, in some cases, at night for the entire period of crop development in the two years.

Statistical analysis

The following six multiple regression models were used to generate the models of this study: 1) linear non-interactive, 2) linear interactive, 3) quadratic interactive, 4) cubic interactive, 5) quadratic non-interactive, and 6) cubic non-interactive. The input variables used were: daily average of the photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}), daily average of the total radiation (TRD, W m^{-2}), daytime average air temperature (DAT, °C) and night average air temperature (NAT, °C), daytime average soil temperature (DST, °C) night average soil temperature (NST, °C), daytime average relative humidity (RHD, %) and night average relative humidity (RHN, %), fresh weight of leaves (FWL, g) and fresh weight of aerial part (FWA, g) (sum of leaves + stem + fruits), and as response variables evapotranspiration (ml day^{-1}) and transpiration (ml day^{-1}). Data collected between 8:01 and 8:00 hrs. of the next day was considered a full day. To differentiate between day and night, the criterion was based on the TRD, which was considered as daytime when the TRD was $\geq$ 1.0 W m^{-2} and at night when the TRD was less than 1.0 W m^{-2}. The whole process of generating models was affected by using the programs add-in Regress ® within Microsoft Excel. The best model was selected for each type of regression, based on the adjusted coefficient of determination (R^2 adj.) and standard error (SE), obtaining 6 models for evapotranspiration and 6 models for transpiration for each growing season, totaling 24 models.

In order to determine the feasibility of these models, best and worst models were evaluated from the 2011 cycle with respect to each response variable obtained from the 2012 cycle, and vice versa. From this data, the Pearson correlation coefficient (R) and the standard error (SE) were calculated.

Results

Tables 1 and 2 show the multiple regressions obtained from the data for the 2011 cycle. The models of Table 1 were generated for estimating evapotranspiration, while transpiration is presented in Table 2. Tables 3 and 4 show evapotranspiration and transpiration models, respectively, corresponding to the 2012 cycle. The aforementioned Tables 1-4 also show model-generated indices, which underwent evaluation using adjusted R^2 and standard error. Models are also assigned a numerical key, each corresponding to a specific model of one multiple regressions and the order in which it was generated in the methodology.

Table 1. Models obtained from multiple regressions to estimate evapotranspiration (ET) of tomato during the 2011 cycle.

Model	R^2 adj.	SE
ET_1 = (-6.856e+02) + (0.6322*FWL) + (1.4349*PAR) + (35.657*DAT)	0.667	221.48
ET_2 = (-1.024e+02) + (1.5657e-03*PAR*FWL) + (3.377e-02*PAR*DAT) + (-3.7901e-04*FWL^2) + (0.66823*FWA) + (-2.315e-03*RHN*FWA) + (0.22637*NST*RHN)	0.764	186.60
ET_3 = (2.503e+03) + (-2.3757e-03*FWL^2) + (-1.2471e-02*DAT*FWA) + (-11.06*RHD) + (0.13312*DST*FWL) + (1.1398e-02*PAR*RHN) + (-1.056e+02*DST) + (5.2087e-04*FWL*FWA) + (-1.5734e-03*RHN*FWA) + (1.1286*DAT^2)	0.853	147.43
ET_4 = (1.037e+03) + (9.156e-05*PAR*DST*FWL) + (-9.5615e-05*DST*FWL^2) + (0.11474*DST*FWL) + (-13.28*RHD) + (1.3843e-07*FWL^2*FWA) + (-1.3870e-06*PAR*FWL^2) + (9.9898e-06*TRD^3)	0.852	147.64
ET_5 = (2.702e+02) + (3.1453*FWL) + (0.58727*PAR) + (-1.8336e-03*FWL^2) + (-14.44*RHD) + (5.4620e-05*FWA^2) + (32.522*DST) + (-0.27896*FWA)	0.824	161.33
ET_6 = (9.99e+02) + (4.4396*FWL) + (-5.8158e-03*FWL^2) + (-11.83*RHD) + (2.1197e-06*FWL^3) + (39.297*DST) + (0.13085*TRD^2) + (-21.13*TRD) + (-2.3969e-04*TRD^3) + (0.12354*FWA)	0.864	141.66

PAR: daily average of the photosynthetically active radiation (µmol m^{-2} s^{-1}). TRD: daily average of the total radiation (W m^{-2}). FWL: fresh weight of leaves (g). FWA: fresh weight of aerial part (g). DAT: average daytime air temperature (°C). RHD: daytime average relative humidity (%). DST: daytime average soil temperature (°C). RHN: night average relative humidity (%). NST: night average soil temperature (°C). R^2 adj.: adjusted coefficient of determination. SE: standard error (ml day^{-1}). Note: in the case of ET the subscript corresponds to a specific model of each multiple regression and follows the order presented in the methodology.

Table 2. Models obtained from multiple regressions to estimate transpiration (TR) of tomato during the 2011 cycle.

Model	R^2 adj.	SE
TR_1 = (-8.727e+02) + (1.023*FWL) + (1.3473*PAR) + (39.221*DAT) + (-6.613e-02*FWA)	0.727	218.37
TR_2 = (3.9163e+03) + (6.6738e-02*PAR*DAT) + (0.27117*DST*FWL) + (-4.068e+02*DST) + (7.008*DST*DAT) + (-0.1337*DAT*FWL) + (3.5952e-04*TRD*FWA) + (-3.2965e-02*RHD*FWL) + (26.134*RHD) + (-9.7497e-04*PAR*FWL)	0.866	152.83
TR_3 = (5.4405e+02) + (-4.9039e-05*DST*FWL^2) + (8.4386e-02*DAT*FWL) + (1.1551e-03*DST^2*FWA) + (-7.3665e-04*DAT*NST*FWA) + (-1.8089e-02*DAT^2*RHD) + (-1.8671e-02*TRD*DST^2) + (5.1855e-04*TRD*NST*FWL) + (7.8775e-03*PAR*DST*DAT) + (1.4619e-07*FWL^2*FWA) + (-4.0073e-06*PAR*FWL^2) + (1.2003e-02*DST*NST*RHN) + (-2.0328e-07*RHN*FWA^2) + (-2.2996e-03*DAT*NST*FWL)	0.891	138.30
TR_4 = (5.4405e+02) + (-4.9039e-05*DST*FWL^2) + (8.4386e-02*DAT*FWL) + (1.1551e-03*DST^2*FWA) + (-7.3665e-04*DAT*NST*FWA) + (-1.8089e-02*DAT^2*RHD) + (-1.8671e-02*TRD*DST^2) + (5.1855e-04*TRD*NST*FWL) + (7.8775e-03*PAR*DST*DAT) + (1.4619e-07*FWL^2*FWA) + (-4.0073e-06*PAR*FWL^2) + (1.2003e-02*DST*NST*RHN) + (-2.0328e-07*RHN*FWA^2) + (-2.2996e-03*DAT*NST*FWL)	0.891	138.30
TR_5 = (-1.718e+03) + (2.5801*FWL) + (1.7044e-03*FWL^2) + (4.6503e-03*TRD^2) + (1.6448e-05*FWA^2) + (-10.92*RHD) + (2.3222e+02*DST) + (-5.35*DST^2)	0.852	160.70
TR_6 = (-1.096e+03) + (4.1801*FWL) + (-6.3703e-03*FWL^2) + (3.4838e-03*TRD^2) + (2.4739e-06*FWL^3) + (0.41114*FWA) + (-11.03*RHD) + (1.2188e+02*DST) + (-8.2529e-02*DST^3) + (-3.719e-05*FWA^2)	0.883	142.99

PAR: daily average of the photosynthetically active radiation (µmol m^{-2} s^{-1}). TRD: daily average of the total radiation (W m^{-2}). FWL: fresh weight of leaves (g). FWA: fresh weight of aerial part (g). DAT: average daytime air temperature (°C). RHD: daytime average relative humidity (%). DST: daytime average soil temperature (°C). RHN: night average relative humidity (%). NST: night average soil temperature (°C). R^2 adj.: adjusted coefficient of determination. SE: standard error (ml day^{-1}). Note: in the case of ET the subscript corresponds to a specific model of each multiple regression and follows the order presented in the methodology.

Table 3. Models obtained from multiple regressions to estimate evapotranspiration (ET) of tomato during the 2012 cycle.

Model	R^2 adj.	SE
ET_1 = (-1.387e+03) + (0.8373*FWL) + (2.12*TRD) + (49.37*DAT) + (51.03*NAT) + (-0.0368*FWA) + (-35.86*NST)	0.897	156.55
ET_2 = (482.83) + (1.06*DAT*NAT) + (4.3913e-02*DAT*FWL) + (-1.019e-03*RHN*FWA) + (1.72*TRD)	0.903	151.71
ET_3 = (79.58) + (1.3706e-04*TRD*NAT*FWL) + (1.0203e-03*DAT^2*FWL) + (-3.8441e-06*TRD*FWL^2) + (-7.2104e-04*DST^2*FWA) + (6.168e-02*TRD*NAT) + (6.8707e-04*FWL^2) + (7.7454e-05*TRD*DST*FWA) + (-1.7629e-06*TRD^2*FWA)	0.914	142.62
ET_4 = (157.62) + (2.461e-04*TRD*NAT*FWL) + (4.684e-04*DAT^2*FWL) + (-4.7763e-06*TRD*FWL^2) + (3.6029e-02*TRD*NAT) + (4.8125e-07*FWL^3) + (1.5274e-03*TRD*FWA) + (-3.7216e-06*NAT*FWA^2) + (-1.8517e-06*TRD^2*FWA) + (-4.9778e-05*DST*RHN*FWA) + (1.729e-06*DAT*FWA^2)	0.920	138.31
ET_5 = (-2267.68) + (93.6049e-02*FWL) + (1.74*TRD) + (93.2263e-02*DAT^2) + (78.8126e-02*NAT^2) + (-6.5805e-06*FWA^2) + (-29.8924e-02*RHN^2) + (42.11*RHN)	0.902	152.58
ET_6 = (9521.33) + (75.4705e-02*FWL) + (1.65*TRD) + (18.308e-03*DAT^3) + (712.954e-03*NAT^2) + (-2.1975e-09*FWA^3) + (-30.798e-07*RHN^3) + (6.47*RHN^2) + (-445.33*RHN) + (79.545e-03*FWA)	0.910	146.60

TRD: daily average of the total radiation (W m^{-2}). FWL: fresh weight of leaves (g). FWA: fresh weight of aerial part (g). DAT: daytime average air temperature (°C). DST: daytime average soil temperature (°C). NAT: night average air temperature (°C). RHN: night average relative humidity (%). NST: night average soil temperature (°C). R^2 adj.: adjusted coefficient of determination. SE: standard error (ml day^{-1}). Note: in the case of ET the subscript corresponds to a specific model of each multiple regression and follows the order presented in the methodology.

Table 4. Models obtained from multiple regressions to estimate transpiration (TR) of tomato during the 2012 cycle.

Model	R^2 adj.	SE
TR_1 = (-2.046e+03) + (46.37*DAT) + (983.959e-03*FWL) + (2.13*TRD) + (40.44*NAT) + (-67.355e-03*FWA)	0.877	168.62
TR_2 = (581.56) + (2.20*DAT*NAT) + (42.758e-03*NST*FWL) + (376.375e-03*TRD*DST) + (-1.003e-03*RHD*FWA) + (-3.70*DST*NST) + (-5.91*TRD)	0.896	155.06
TR_3 = (-67.32) + (1.7992e-04*TRD*NAT*FWL) + (7.6717e-04*DAT^2*FWL) + (-4.0229e-06*TRD*FWL^2) + (1.2410e-03*TRD*RHD*NAT) + (6.7933e-04*FWL^2) + (4.9100e-04*TRD*FWA) + (-1.3111e-04*RHD*NAT*FWA)	0.905	148.37
TR_4 = (211.44) + (3.4140e-04*TRD*NAT*FWL) + (-5.5810e-06*TRD*FWL^2) + (8.3544e-07*FWL^3) + (7.6931e-06*TRD*RHD*FWA) + (-2.0869e-04*RHD*NAT*FWA) + (-4.2611e-06*RHD*FWA*FWL) + (2.3334e-04*DAT*RHD*FWA)	0.907	146.62
TR_5 = (1798.21) + (-263.26*DAT) + (938.238e-03*FWL) + (2.13*TRD) + (47.45*NAT) + (-8.1015e-06*FWA^2) + (5.86*DAT^2)	0.888	161.28
TR_6 = (1776.14) + (-259.75*DAT) + (912.75e-03*FWL) + (2.16*TRD) + (47.22*NAT) + (-1.2938e-09*FWA^3) + (5.74*DAT^2)	0.888	161.11

TRD: daily average of the total radiation (W m^{-2}). FWL: fresh weight of leaves (g). FWA: fresh weight of aerial part (g). DAT: daytime average air temperature (°C). DST: daytime average soil temperature (°C). NAT: night average air temperature (°C). RHN: night average relative humidity (%). NST: night average soil temperature (°C). R^2 adj.: adjusted coefficient of determination. SE: standard error (ml day^{-1}). Note: in the case of ET the subscript corresponds to a specific model of each multiple regression and follows the order presented in the methodology.

Figures 1 and 2 show a comparison between the actual data obtained during the cycle 2011 and estimates for the best and worst models selected, based on the rates mentioned above. The selection of these models was just to make a visual comparison of the results, since the seven models generated for each variable have similar effectiveness to each other (Tables 3 and 4). Figure 1 presents the comparison corresponding to evapotranspiration models and Figure 2 shows the comparison of model transpiration.

Similarly, Figures 3 and 4 are show comparisons between the actual and estimated data for the different models generated in the cycle 2012. Evapotranspiration is presented in Figure 3, and transpiration is presented in Figure 4.

Finally, derived from the verification processes for the above selected models, Figures 5 and 6 show comparisons which were made between the actual data and the estimated data for the models, but in this case in a crossed manner. The models generated from the 2011 cycle were tested with real data of the 2012 cycle (Figure 5), while models generated from the 2012 cycle data were tested with real data from the 2011 cycle (Figure 6). In both cases models for tomato evapotranspiration and transpiration are shown.

Discussion

Tables 1 and 3 shows the generated models to estimate ET for the tomato plant during the two growing seasons. It is noteworthy that in the 2012 (Table 3) the obtained models were better for estimating the obtained ET of the 2011 cycle (Table 1), according to the indices used to assess efficacy. In this case, the best model of 2012 presented an adjusted R^2 of 0.920 and a standard error of 138.1 ml day^{-1} compared to the best model of 2011, which presented an adjusted R^2 of 0.864 and a standard error of 141.66 ml day^{-1}. Also, Figures 1 and 3, present the comparison between actual and estimated data for ET, which confirms graphically the higher efficiency of the models obtained in 2012. The poorer predictive models shown for 2011 can be attributed to intermittent irregularities in watering, causing differences in the amount of water applied to each pot. Mainly, within ET is where the data shows greater variability. It is noteworthy, that the error occurred over the entire growing season. These problems were not present in the 2012 cycle, which gave a better fit between the observed and estimated data.

With respect to TR of tomato plant, Tables 2 and 4 demonstrate the patterns obtained for that variable. It is generally observed that also models for the 2012 cycle were better than 2011, but in this case, the difference was not as great as in the ET. For example, the best model of 2012 presented an adjusted R^2 of 0.907 and a standard error of 146.62 ml day^{-1} compared with an adjusted R^2 of 0.891 and a standard error of 138.3 ml day^{-1} belonging to the best model for 2011. These results show that as aforementioned, the experimental errors committed in 2011 affected ET data more notably, generating greater error in this variable than in the TR. Figures 2 and 4 graphically demonstrate the comparison between observed and estimated in the aforementioned, because in the figures it is clear that in both cases the estimated and observed data are very similar.

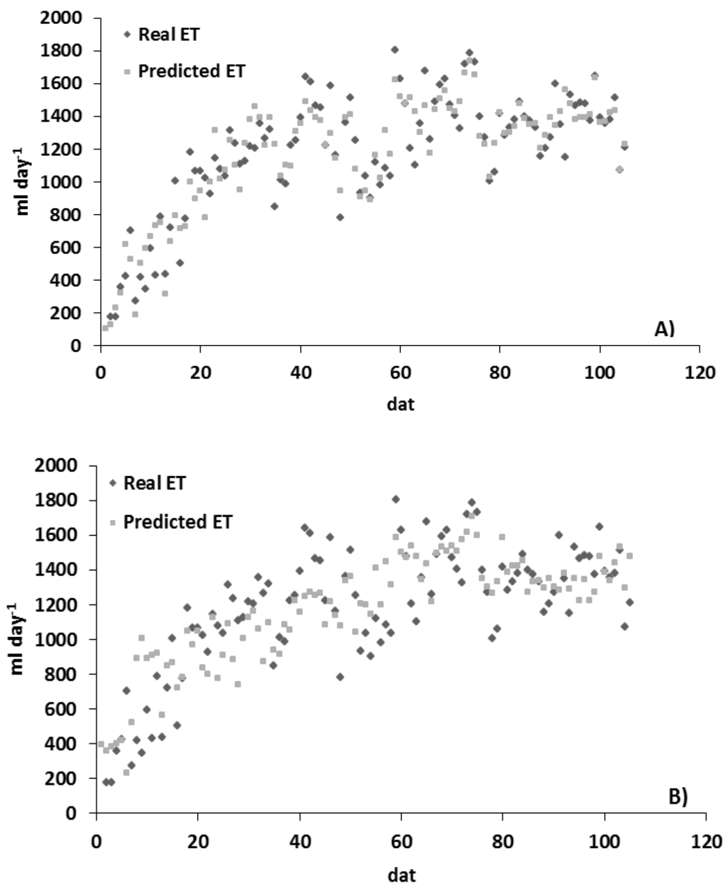


Figure 1. Comparison between real evapotranspiration (Real ET) *vs* predicted evapotranspiration (Predicted ET) for the models 6 (A) (R^2 adj.=0.864, SE=141.66) and 1 (B) (R^2 adj.=0 .667, SE=221.48), corresponding to 2011 cycle. dat: days after transplanting.

This work generated models to estimate ET and TR, in contrast to Lee and Shin (1998), who considered only a model for TR, combined with solely considering a 15 days period to calibrate and validate the model, while the models presented here cover all phenological stages and more than 100 days of evaluation are considered. In contrast with Baptista et al. (2005) who show both regression models of TR and ET with R^2 of 0.72 and 0.77, respectively, compared to 0.925 and 0.912 obtained with the best ET and TR models, respectively, from this work. Furthermore, Ortega-Farias et al. (2000) used the Penman-Monteith model to estimate daily ET in open field and greenhouse conditions and attained great precision of results (4.2% relative error). Boulard and Wang (2000) also estimated the TR with great precision and under greenhouse conditions, but the difficulty of measuring climate variables required for the model and the complexity were limiting factors and likewise with respect to the work of Valdes-Gomez et al. (2009) in using the Priestley-Taylor method. Also Martínez-Ruíz et al. (2012) estimate the TR with great precision in tomato under greenhouse conditions, but in their study is necessary leaf area index (LAI), which should be measured each 15 days using an integrator of leaf area.

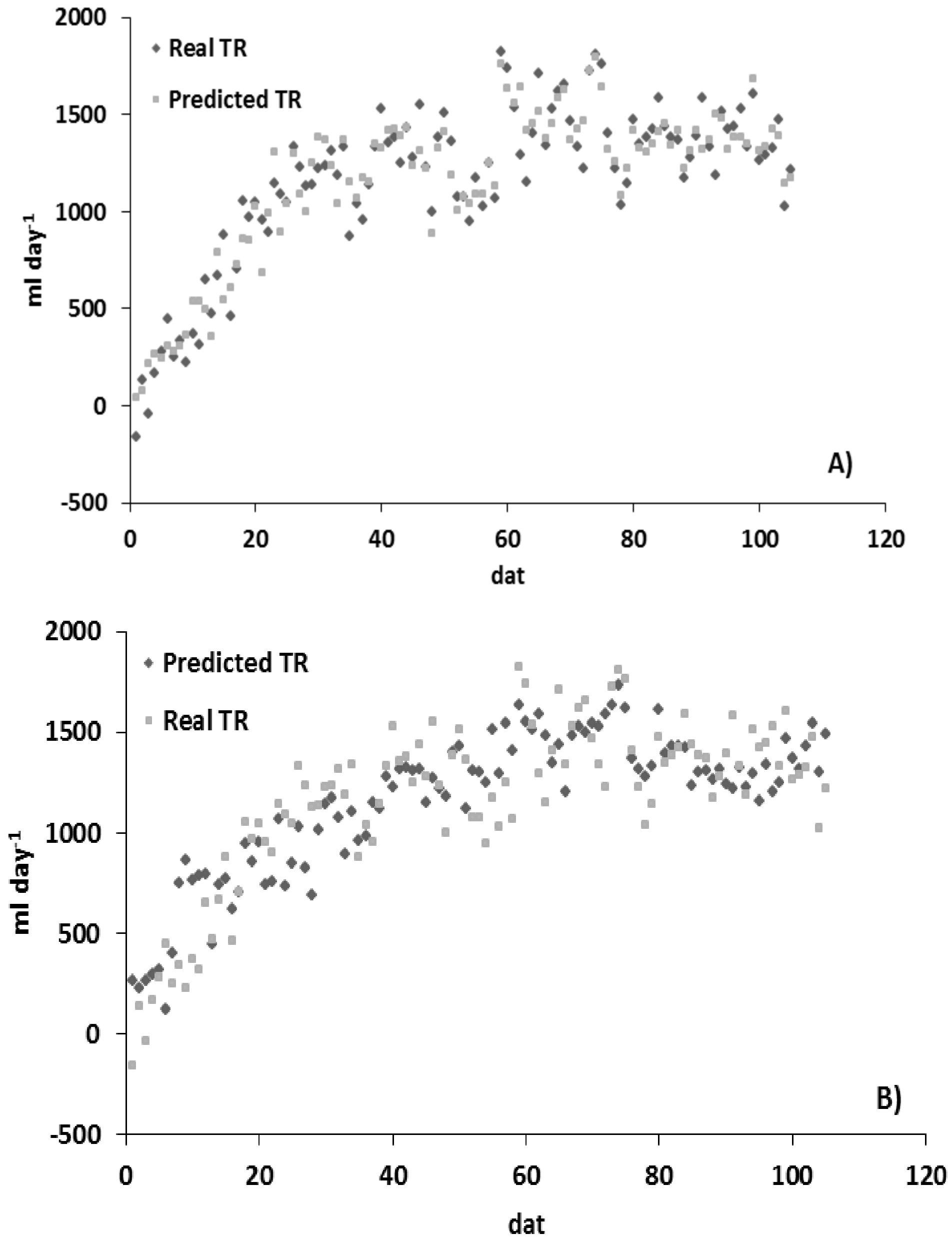
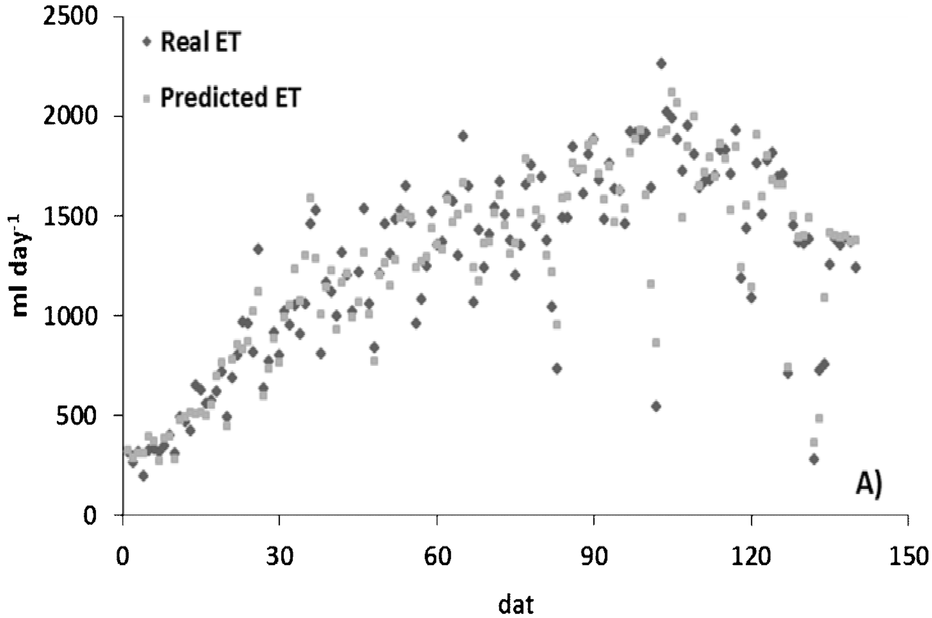


Figure 2. Comparison between real transpiration (Real TR) *vs* predicted transpiration (Predicted TR) for the models 4 (A) (R^2 adj.=0.891, SE=138.30) and 1 (B) (R^2 adj.=0.727, SE=218.37), corresponding to 2011 cycle. dat: days after transplanting.

In the obtained multiple regression models it can be seen that the models which were generated from linear regression without interaction were consistently less efficient in predictions. In contrast, the models which were generated from regression quadratic and cubic with interaction (Tables 1-4) demonstrated the highest efficiency. These results indicate that to generate multiple regression models with greater predictive capacity they must be of higher order and they should consider the interaction between variables, implying that they will be relatively more complex and incorporate more input variables.



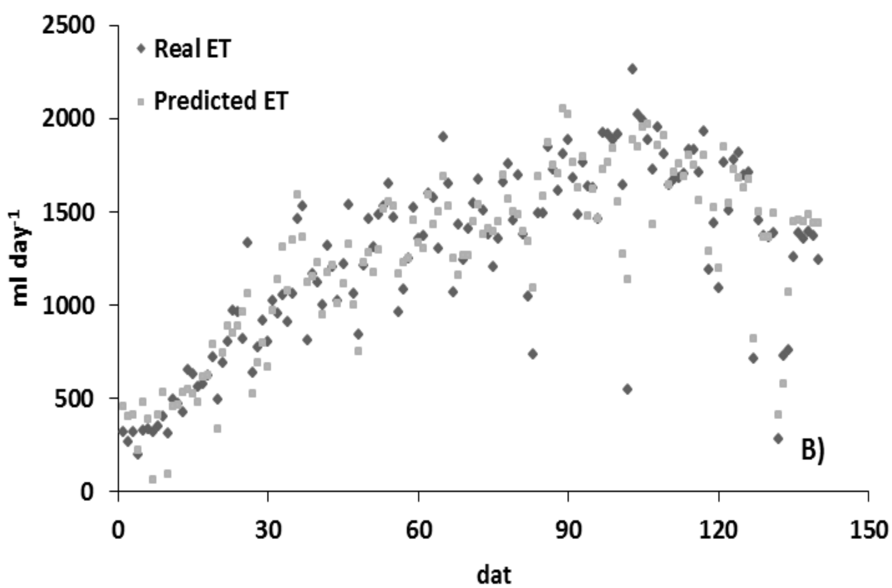


Figure 3. Comparison between real evapotranspiration (Real ET) *vs* predicted evapotranspiration (Predicted ET) for the models 4 (A) (R^2 adj.=0.920, SE=138.31) and 1 (B) (R^2 adj.=0.897, SE=156.55), corresponding to 2012 cycle. dat: days after transplanting.

Figures 5 and 6 show the cross comparison between the actual and estimated data for the models. This case presents the best and the worst models, as in Figures (1-4). With respect to the estimates corresponding to the models of 2011, Figure 5 demonstrates that ET estimation models do not adequately represent SE for models 6 and 1, with SE 349.99 ml day^{-1} and 689.98 ml day^{-1}, respectively (Figures 5A and 5B). In contrast, models 4 and 1 presented in Figures 5C and 5D, estimating TR in a more appropriate manner, with SE 385.07 ml day^{-1} and 189.94 ml day^{-1}, respectively. These results again demonstrate that experimental errors are more significantly affected by the ET data. Figure 6 shows the estimates for 2012 models and demonstrate that both the TE and TR for these models were more suitable than for 2011.

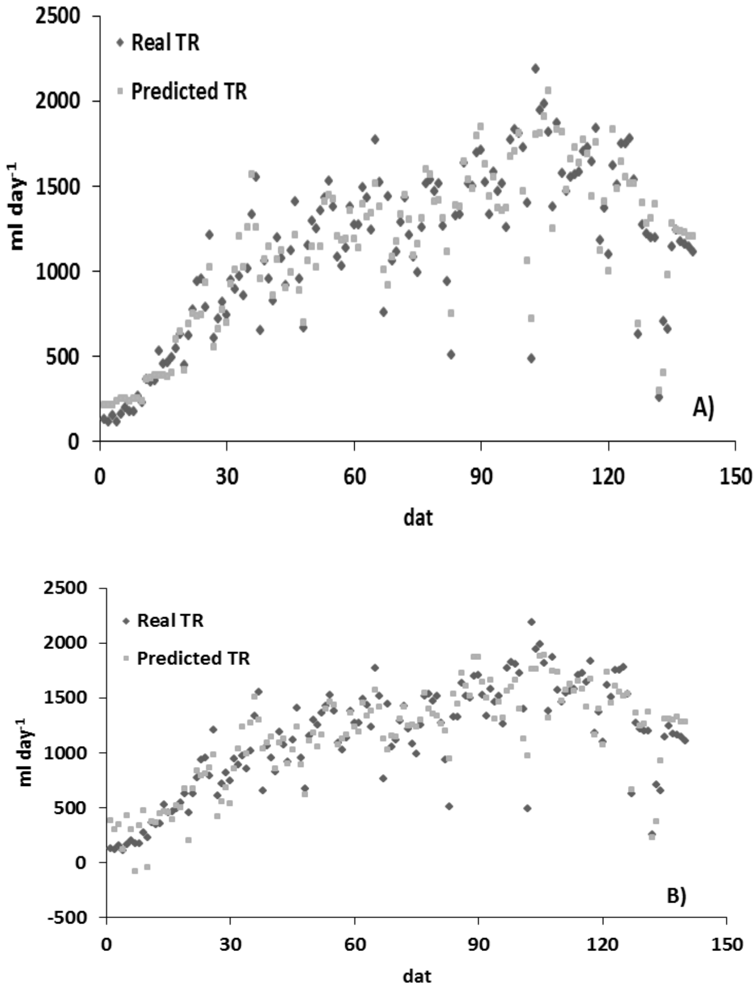


Figure 4. Comparison between real transpiration (Real TR) *vs* predicted transpiration (Predicted TR) for the models 4 (A) (R^2 adj.=0.907, SE=146.62) and 1 (B) (R^2 adj.=0.877, SE=168.62), corresponding to 2012 cycle. dat: days after transplanting.

Models 4 and 1, used for estimating ET, presented an SE of 257.91 ml day^{-1} and 212.51 ml day^{-1}, respectively (Figures 6A and 6B), while models 4 and 1, used to estimate TR, demonstrate had SE of 159.02 and 189.30, respectively (Figures 6C and 6D). Hence, although there are differences between the estimated and observed values in 2011, one can consider that the data for this cycle were generated with experimental error which may justify such differences (Figure 6).

It is important to consider that all the models are relatively simple to use with respect to the input variables. The number and availability of the input variables is a crucial factor in setting the potential use of each model. Unlike other models, where the required climatic variables are difficult to obtain, and as stand-alone are too complex to be applied (Ortega-Farias et al., 2000; Salokhe et al., 2005; Valdes-Gomez et al., 2009). Another important factor is that they are more accurate than other models that are easy to use, such as those presented by Lee and Shin (1998), or Baptista et al. (2005). Furthermore, it appears that the only variable that is required in all models is the FWL obtained (Tables

1-4), and in the case of models for 2012, FWL and TRD variables (Tables 3-4). These results demonstrate the importance of these two variables in both processes, both for ET and TR in tomato plants, which is in agreement with Flores *et al.* (2007), who worked with the total radiation used in order to very effectively determine the water needs for the tomato plant. Another advantage of the models generated in this work is directly using the FWL and FWA unlike other variables such LAI that are more difficult to measure or should be estimated (Lee and Shin, 1998; Baptista et al., 2005; Salokhe et al., 2005; Valdes-Gomez et al., 2009, Martínez-Ruíz et al., 2012).

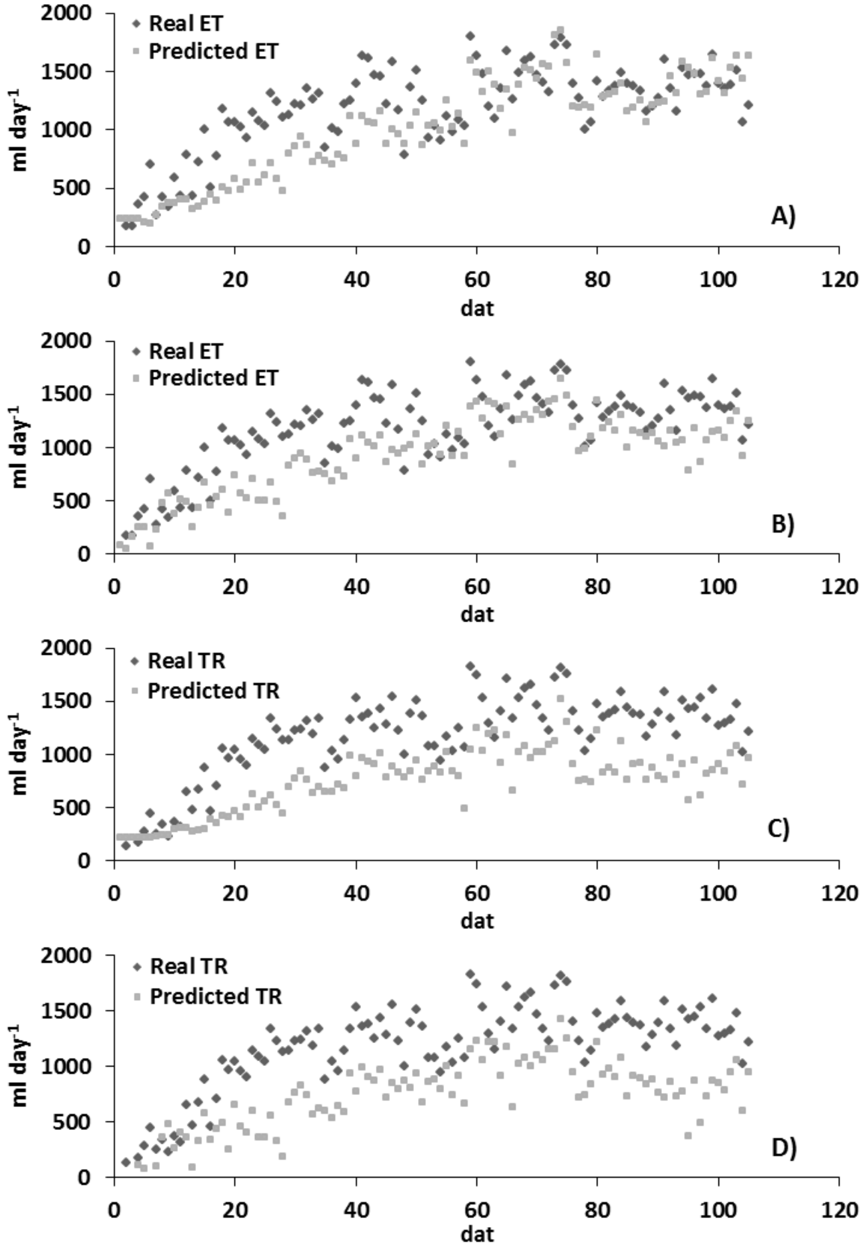


Figure 5. Comparisons for the validation process of the 2011 cycle models. Real evapotranspiration of 2012 cycle (ET 2012) *vs* predicted evapotranspiration (Predicted ET) for the models 6 (A) (R=0.238, SE=349.99) and 1 (B) (R=0.819, SE=689.98). Real transpiration of 2012 cycle (TR 2012) *vs* predicted transpiration (Predicted TR) for the models 4 (C) (R=0.803, SE=385.07) and 1 (D) (R=0.895, SE=189.94). dat: days after transplanting.

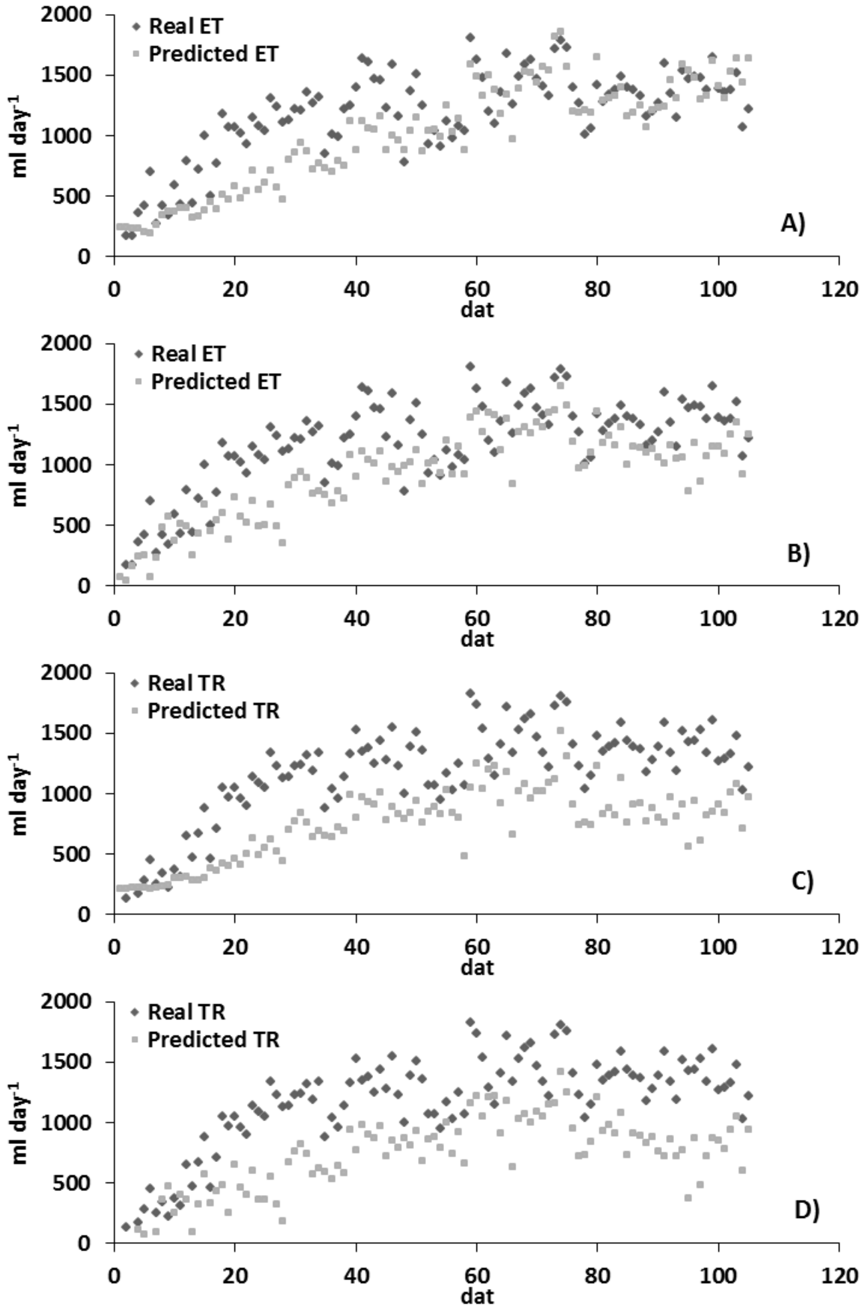


Figure 6. Comparisons for the validation process of the 2012 cycle models. Real evapotranspiration of 2011 cycle (Real ET) *vs* predicted evapotranspiration (Predicted ET) for the models 4 (A) (R=0.810, SE=257.91) and 1 (B) (R=0.811, SE=212.51). Real transpiration of 2011 cycle (Real TR) *vs* predicted transpiration (Predicted TR) for the models 4 (C) (R=0.840, SE=159.02) and 1 (D) (R=0.822, SE=189.30). dat: days after transplanting.

Conclusions

This work generated multiple regression models to estimate evapotranspiration and transpiration of tomato plants under greenhouse conditions. These models are easier to use due to the nature of the climate variables considered as inputs. These models allow the estimation of both ET and TR from different variables, providing useful tools with large applications in different scenarios. Clearly, the efficacy by which the models can be generated, aids determination of the daily water requirements for tomato plants. In this context, they can be used for different purposes such as scheduling irrigation, design of more efficient water use in growing tomatoes, avoidance of excess application of irrigation water, thereby, reducing the risk of disease incidence, among other issues.

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