Modeling tomato growth and production in a photovoltaic greenhouse in southern Italy

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Abstract

The aim of this work was to calibrate CROPGRO-Tomato model, included in the Decision Support System for Agrotechnology Transfer (DSSAT) software, for a cherry tomato genotype grown in a photovoltaic greenhouse in southern Europe (39°19’59”N; 8°59’19”E). The experiment was carried out in Decimomannu, Sardinia, in an East-West oriented pitched-roof greenhouse with two spans (50×9.6 m each) covering an area of 960 m². Silicon photovoltaic panels were used to completely replace the south-oriented roof of each span, resulting in a 50% roof cover ratio. Tomato was grown hydroponically with a plant density of 2.3 plants m^{-2}. An autumn-winter tomato crop cycle was carried out from August 2011 to January 2012. Microclimatic conditions were monitored for the whole lifespan of the experiment (e.g., internal global and PAR radiation and greenhouse internal temperature). Phenology was monitored at weekly interval. Leaf area, aboveground biomass, and fresh fruit production was determined at fifteen day interval. CROPGRO-Tomato model was calibrated over the uncovered roof data and it was evaluated over the covered roof data. The genotype file (cultivar), including the main parameters of crop phenology and plant growth, was adapted to the cherry tomato cultivar ‘Shiren’. The first flowering date showed a good agreement between simulated and observed data. The model fitted well the observed leaf area index data with an index of agreement (D-Index) of 0.87 and an average root mean square error (RMSE) of 0.53. Good agreement was observed between the measured and simulated plant development parameters as biomass and fresh weight yield. Overall, the CROPGRO-Tomato model proved to be suitable for predicting tomato growth and yields inside PV greenhouses and under different light intensity conditions. However, model validation is also necessary to show how the model works under a spring-summer cycle and with supplementary lighting system.

Keywords: *Lycopersicum esculentum* Mill., DSSAT model, genetic coefficients, phenology, leaf area, fresh weight yield

INTRODUCTION

Simulation modeling can be a powerful tool to analyze the relationships among soil, plants, air, and other components in agricultural systems, particularly through studying the relationships between system components over time (Zamora et al., 2009; Lenz-Wiedemann et al., 2010). In the last decades, several tomato models have been focused on different research topics e.g., TOMGRO (Dayan et al., 1993), TOMSIM (Heuvelink, 1995), TOMPOUSSE (Gary et al., 1997), the model of Marcelis et al. (2009), and CROPGRO-Tomato (Boote and Scholberg, 2006; Boote et al., 2012). These models were developed, not only to understand the processes and interactions involving system components and their effects upon overall production, but also for their usefulness as decision support tools for identifying best management options for attaining optimal production. Under potential production scenarios where water and nutrients are available for plant growth, the level of light transmittance to

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crop canopies largely determines production (Kropff, 1993, 1994). Several studies in alley cropping systems or in controlled environment have indicated that shading affects morphological development in plants, with consequences on photosynthesis and biomass production. Shading can also affect carbon allocation patterns in plants. In the recent years, farmers in southern Europe regions adopted solar photovoltaic (PV) greenhouses due to the abundance of solar energy and the advantageous public policy support for renewable electricity generation (Cossu et al., 2014, 2017), and notwithstanding they may assume that shading affects crop performance. While this may be true in some circumstances, there exists a need for better understanding of the complexities of such systems with regard to optimizing light use. In this regard, application of a process-based model (e.g., CROPGRO) can be useful for understanding the effects of light on production, which, in turn, can provide a basis for determining whether or not to promote adoption of a PV greenhouse. CROPGRO, a member of the DSSAT (Decision Support System for Agrotechnology Transfer), is a dynamic simulation model that simulates growth and development of most common agronomic crops (e.g., *Glycine max* L., *Arachis hypogaea* L., *Brassica napus* L. var. *oleifera* D.C.) grown under varying environmental conditions. CROPGRO is widely used in temperate and tropical regions because of its precision in simulating production when compared to actual field data, provided that the model is calibrated based on site-specific conditions. CROPGRO-tomato (Tsuji et al., 1994; Jones et al., 2003; Hoogenboom et al., 2010) model, which has been used predominantly in field-grown systems, can also be used to evaluate biophysical interactions in controlled environment systems, including interactions involving light (Jones et al., 2003). The relationships of plant morphological parameters (i.e., leaf area index) with light levels have been well established in CROPGRO models. Variations in leaf area index (LAI) due to differences in environmental growth conditions can significantly influence production. Accordingly, the main objective of the paper was to calibrate the CROPGRO-Tomato (Boote and Scholberg, 2006; Boote et al., 2012) model to predict the production of tomato grown under different light conditions in a photovoltaic greenhouse where interspecific competition for water and nutrients was experimentally removed.

MATERIALS AND METHODS

The experiment was conducted inside an east-west oriented greenhouse in Decimomannu, Sardinia, Italy (39°19’N; 8°59’E). The south-oriented roof of each span was covered by silicon photovoltaic panels resulting in a 50% coverage. The experiment was carried out over autumn–winter season (AW), from August 2011 to January 2012. The planting area (960 m^2) was laid out into four equal areas (A, B, C, D; Cossu et al., 2014). Two areas (A, and C) were subjected to supplementary lightning system. Each area included six plants rows (39 plants each), three rows under uncovered roof (UCR), and three rows under covered roof (CVR). For the purposes of simulation modeling, only AW in two areas without supplementary lighting system (B and D) were considered in this paper. Seedlings of a cherry tomato cultivar ‘Shiren’ (Hazera Seeds, USA) were transplanted on August 22, 2011, and grown hydroponically at a plant density of 2.3 plants m^{-2}. The final harvest date was January 25, 2012. The experiment was well managed to obtain optimum conditions for plant growth and development, and to avoid any stresses due to water, pests, disease and other crop limiting factors that could affect any reduction in yield. Thus, the major driving force in the production of tomato was assumed to be the level of light transmittance to the canopy. Detailed experimental set-up is described by Cossu et al. (2014, 2017). Data were collected on plant growth and development, soil, microclimate and crop management as required for determining the cultivar coefficients of a new tomato cultivar (Boote et al., 1998; Jones et al., 2003; Hoogenboom et al., 2010).

Microclimatic conditions

The greenhouse internal maximum and minimum temperatures were obtained from four thermometers (Mela KPC2-ME, Galtec, Germany), two per span, placed at 1.5 m height. The internal global and PAR radiation were measured both under UCR and CVR using 4 photoradiometers (HD 2102.2, Delta Ohm, Italy) (Cossu et al., 2014). The weather data files varied according to the amount of solar radiation that each plants row in UCR and CVR had received as indicated earlier.

Measurements

To measure different development stages, ten plants selected for each area (5 plants in CVR, and 5 plants in UCR, respectively) were tagged and weekly monitored from anthesis to physiological maturity according to BBCH scale (Lancashire et al., 1991). Crop growth data were collected at a fifteen day interval. Ten plants were harvested from each area under both roofs. All plants used for destructive measurements were replaced by spare plants, which were grown in similar micro-environmental condition at the heading of the PV greenhouse. The individual samples were separated into leaf, stem, and fruits. The samples were oven dried at 70°C until constant weight. To determine total leaf area, in each sample, leaves were measured by a leaf area meter (LI-COR 3100C Lincoln, Neb.).

Calibration and evaluation of CROPGRO-Tomato model

Crop models must be calibrated such that model parameters truly represent cultivar characteristics and crop responses to soil and atmospheric conditions. Calibration was based on separate dataset of the experimental phenology and yield data of the cultivar 'Shiren' obtained in 2011 from UCR. Calibration was carried out first by adjusting each phenological characteristic (emergence to end of juvenile, flowering to maturity, etc.) and then followed by adjusting the growth and yield characteristics based on available measured or estimated data. Evaluation of a model is the process of comparing the simulated output by the model with the observed data. This includes evaluation of model performance using various statistical techniques. For model evaluation, we used tomato phenological, growth and yield data obtained from CVR in 2011. Such use of separate evaluation data sets of the same year other than model calibration is not uncommon although not optimal (e.g., Kassie et al., 2014). The observed phenological data (days to anthesis and maturity), LAI, biomass and fresh fruit yield were compared with simulated data. Model evaluation for development, and time-course of growth (LAI, fruit and biomass yield) was performed using RMSE and index of agreement (D-index) as suggested by Willmott et al. (1985). The RMSE summarizes the root mean sum of squares differences in the units of observed and predicted values, while the D-index is a descriptive index that measures dispersion of the simulated and observed data.

RESULTS AND DISCUSSION

Micro-environmental conditions

According to Cossu et al. (2014), the highest reduction of solar radiation was observed in autumn (averagely 71%), followed by winter (69%), and summer (60%). Significant differences were found between the spans: the areas in the North span received averagely 7% less solar radiation than the South span areas. This difference was detected mainly on the rows placed under CVR of the South span, which received averagely 33% more solar radiation than the same rows placed under UCR of the North span, resulting in a higher standard deviation (averagely 78 MJ m^{-2}), compared to the one observed on the rows under UCR (averagely 9 MJ m^{-2}). No statistical differences were found among data from the sensors inside the greenhouse, indicating a homogeneous temperature on the whole area.

Model calibration

The ecotype (.ECO) and cultivar (.CUL) coefficients in Tables 1 and 2 were modified from the default values available in DSSAT v. 4.6. The simulated phenology, time-series growth, biomass, and yield were compared with data observed in UCR, following the procedures outlined by Boote et al. (1998). The model's species file was the standard default for version 4.6. For the UCR condition, 'Shiren' flowered in 16 d and reached physiological maturity in 157 d (Table 3). The simulated time to first flower was set to 15.5 photothermal days (PD) by slightly decreasing the default time between emergence and flower appearance

(EM-FL) coefficient of 'Sunny' (default) cultivar. A small increase in the coefficient for the time between beginning seed and physiological maturity (SD-PM) from 45.2 to 56 PD was need for a correct simulation of physiological maturity (Tables 2 and 3). Days to beginning pod addition was achieved by setting the coefficient for time between first flower and beginning pod (FL-SH) to 11 PD, and onset of pod-plus-seed mass was delayed by increasing the FL-SD from the default of 19 to 27 PD.

Table 1. Genetic coefficients as defined in the ecotype file of CROPGRO-tomato model for tomato cherry group cultivar.

Variable	Coefficient	Default	Calibrated
Time between planting and emergence (V0) (TD)	PL-EM	6	0
Time required from emergence to first true leaf (V1), TD	EM-V1	22	2
Proportion of time between first flower and first pod for first peg	PM06	0.55	0.05
Time from first flower to last leaf on main stem (PD)	FL-VS	24.5	54.5
Rate of appearance of leaves on the main stem (leaves per TD)	TRIFL	0.45	0.85
Relative width of this ecotype in comparison to the standard width per node (YVSWH) defined in the species file	RWDTH	1	0.3
Relative height of this ecotype in comparison to the standard height per node (YVSHT) defined in the species file	RHGHT	1	1.2

TD = thermal days, PD = photothermal days.

Table 2. Genetic coefficients as defined in the cultivar file of CROPGRO-tomato model for tomato cultivar 'Sunny' (default) and cherry tomato cultivar 'Shiren'.

Variable	Coefficient	Sunny	Shiren
Time between emergence and flower appearance (PD)	EM-FL	24.4	15.5
Time between first flower and beginning pod (PD)	FL-SH	3	11
Time between first flower and beginning seed (PD)	FL-SD	19	27
Time between beginning seed and physiological maturity (PD)	SD-PM	45.2	56
Time between beginning seed and end of leaf expansion (PD)	FL-LF	52	89
Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	SLAVR	300	475
Maximum fraction of daily growth that is partitioned to seed-shell	XFRT	0.73	0.85
Seed-filling duration for pod cohort under standard conditions (PD)	SFDUR	26	37
Duration of pod addition under standard conditions (PD)	PODUR	58	88
Threshing percentage (seed (seed + shell)$^{-1}$)	THRSH	8.5	7.5

PD = photothermal days.

Table 3. Simulated and observed number of days to phenological events, fresh fruit and aboveground biomass yields, and maximum leaf area index (LAI) for cultivar 'Shiren' under uncovered roof. Root mean square error (RMSE), and the index of agreement (D-index) were also reported.

Variable	Simulated	Observed	RMSE	D-Index
Days to first flower (dap)	17	16	0.23	0.98
Days to first pod (dap)	32	32	0.11	0.99
Days to physiological maturity (dap)	157	157	0.12	0.99
Fresh fruit yield (kg ha^{-1})	39192	45091	9788	0.75
Biomass yield (kg ha^{-1})	2145	2230	602	0.93
LAI maximum	1.77	2.13	0.59	0.86

dap = days after planting.

The time course of LAI was generally well simulated (RMSE of 0.59 and D-Index of

0.86; Table 3) after calibration of three traits. In the .CUL file, the specific leaf area (SLAVAR) coefficient was increased from 30.0 to 47.5 m^2 kg^{-1}; and the time from beginning flower to end leaf coefficient (FL-LF) was adjusted from 52 to 89 PD to make the peak of LAI occur later and be somewhat higher (Table 2). In the .ECO file, relative width (RWDTH) and relative height (RHGHT) were modified in order to take into account the different canopy characteristics of a cherry tomato cultivar with respect to default value (Table 1). Biomass yield was well simulated throughout the season (RMSE of 602 kg ha^{-1} and D-Index of 0.93) by setting soil fertility value (SLPF, in the soil file) to 0.9 (assumes fertile soil), and without changing the maximum leaf photosynthesis (LFMAX) from the default of 1.36 mg CO_2 m^{-2} s^{-1}. To fit the growth of fruits and seeds, in the .CUL file (Table 2), the coefficient PODUR was increased of 30 PD and SFDUR was increased of 11 PD. In addition to give more priority to shell (fruit) growth over seeds growth, the threshing percentage (THRSH) was slightly decreased from 8.5 to 7.5.

Model evaluation

For the CVR condition, the model predicted phenology, growth and yields quite satisfactorily (Figures 1-4). The CROPGRO-Tomato model was able to simulate phenology well for both anthesis and physiological maturity (Figure 1). Statistical indices very close to the optimal values confirm these outcomes.

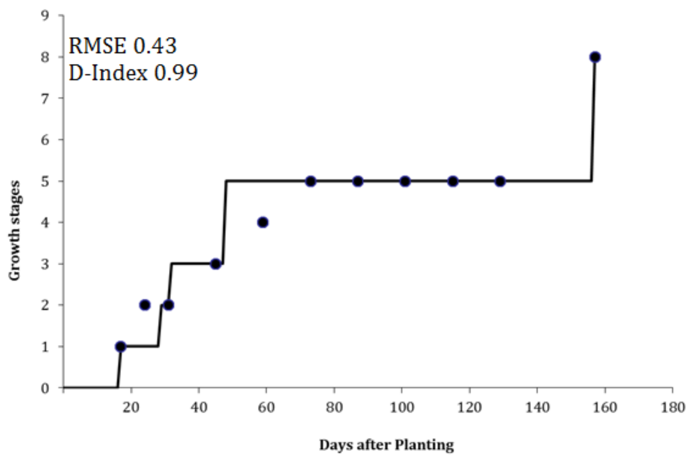

Figure 1. CROPGRO simulated (lines) and measured (points) tomato growth stages in 2011 autumn-winter growing season and under covered roof. On y-axis, stages 0-1 refer to vegetative development, stage 1 to first flower; stages 2-3 to first pods; stages 4-5 to first seed and end pod addition; stage 8 to last harvesting date.

The simulation curve of LAI followed the classic course that in tomato decreases very slowly at the end of cycle, when leaf senescence occurred. Simulated LAI fitted the measured data during initial growth but failed to match the LAI maximum (Figure 2). The simulated LAI peak was 1.94, but observed LAI peak reached 2.47 means that the real crop had a somewhat extended ability to exploit low light condition. Model evaluation indices for LAI confirm the slight underestimation of leaf area index.

The simulated biomass yield agrees well with observed values (Figure 3). However, there was a slight overestimation by the model, averaging over the growing season, simulated biomass yield was 1843 kg ha^{-1} and experimental biomass yield was 1537 kg ha^{-1}.

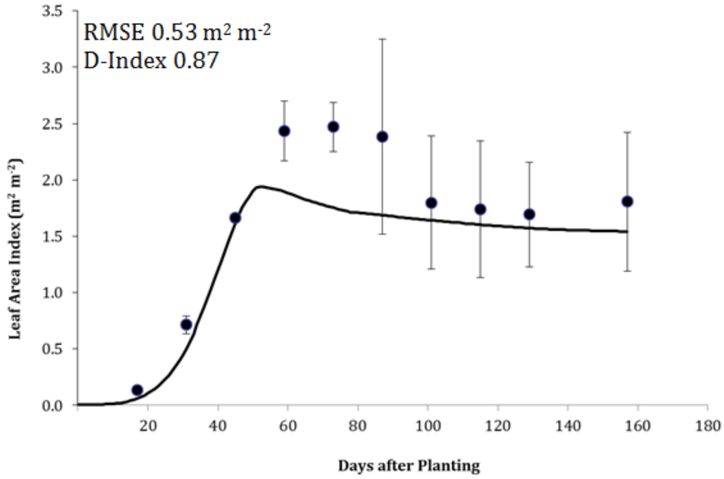

Figure 2. CROPGRO simulated (lines) and measured (points) tomato leaf area index in 2011 autumn-winter growing season and under covered roof. Bars indicate standard deviation of measured data.

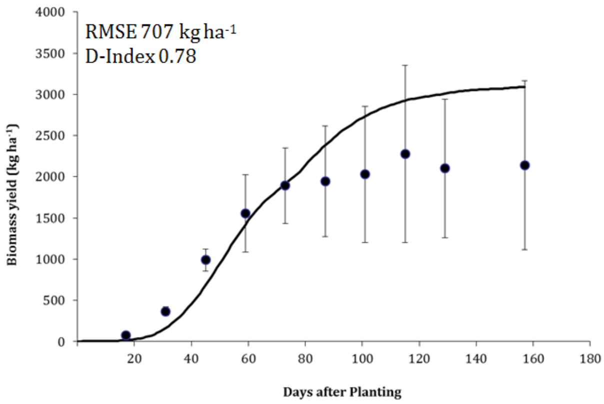

Figure 3. CROPGRO simulated (lines) and measured (points) tomato biomass yield in 2011 autumn-winter growing season and under covered roof. Bars indicate standard deviation of measured data.

The modelling efficiency decreased for the simulation of fresh fruit yield. The prediction was good initially, but was overestimated later in the season (Figure 4). Averaging over the growing season, the model predicted 34776 kg ha^{-1} of fresh fruit yield despite the observed 28760 kg ha^{-1}. There were lower D-index and higher RMSE values for fresh fruit yield in CVR, associated with model overprediction. Thus, while LAI and total biomass were comparable under UCR and CVR conditions, the average fruit yield was twice lower under CVR condition. The discrepancy between simulated and observed data was probably due very low photosynthetic rates recorded for most part of the growing cycle (Cossu et al., 15). According to Cossu et al. (2017) the homogeneous distribution of the fertigation solution in a crop with a high variability of the transpiration rate can cause the wrong estimation of the water and nutrients requirements at row level. Indeed, the conventional distribution may cause plant water stress on some rows and, conversely, an excess on other rows, leading to reduction of water and nutrient use efficiency. The light is the most important factor affecting the productivity of tomato and a complete review was written by Papadopoulos and Pararajasingham (1997). Heuvelink (1995) found that the average tomato crop growth rate is highly related (R_2=0.87; $p<0.001$) to the photosynthetically active radiation (PAR).

The same trend that we observed in our study on the prediction of LAI by the model (underestimation) was also observed by other authors (Boote et al., 2012) in a tomato field-grown study. Boote et al. (2012) suggest that to improve the performance of the model, it may be useful to adjust a species coefficient that affects remobilization of N (NMOBMX) from vegetative to reproductive tissues.

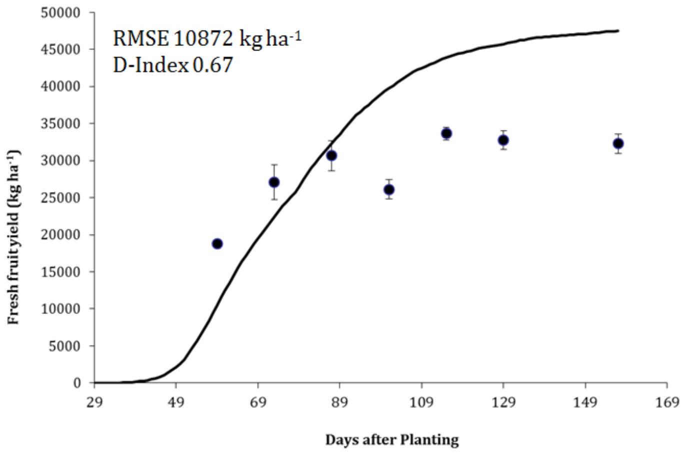

Figure 4. CROPGRO simulated (lines) and measured (points) tomato fresh fruit yield in autumn-winter growing season and under covered roof. Bars indicate standard deviation of measured data.

CONCLUSIONS

Parameters were calibrated from UCR, and the simulated results fitted reasonably well with the measured independent data obtained for CVR. The phenology, leaf area index, and the dynamics of dry matter accumulation simulated by the model demonstrate its ability to explain and predict tomato growth also in light-limiting conditions. Therefore, further investigation needs to be done to validate the model against a spring-summer cycle and with supplementary lighting system. Until now, the model has only been calibrated with field data using near determinate cultivars growing in open field, and, therefore, assumptions regarding the behavior of the model in greenhouse conditions cannot be made until an appropriate validation is performed. However, as the model was able to produce reasonable outputs under shading conditions over time, it can be considered a tool with a high potential for practical applications.

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