

MODELING TOMATO GROWTH FOR OPTIMIZING GREENHOUSE TEMPERATURES AND
CARBON DIOXIDE CONCENTRATIONS

J.W. Jones	E. Dayan	H. Van Keulen	H. Challa
Ag. Engineering	ARO, Ha-Bsor	Center for Agro.	Dept. of
Department	Res. Stat.	Biol. Res.	Horticulture
University of Florida	Hanegev,	Wageningen	Wageningen
Gainesville, Florida	ISRAEL	The Netherlands	Agr. Univ.
USA 32611			Wageningen,
			The Netherlands

Abstract

Predictions of crop yield response to a dynamic environment are essential to the development of optimal control strategies for greenhouses. A dynamic tomato growth and yield model (TOMGRO) was developed specifically for coupling to physical models of the greenhouse environment for optimizing temperature and carbon dioxide concentrations for tomato production. The model is based on development and growth components. Experiments were conducted in outdoor, computer-controlled plant growth chambers to parameterize the development, carbon exchange, and growth submodels under combinations of two CO₂ (350 and 950 vpm) and three night temperatures (12, 16, and 20 C). Daytime temperatures were held to 28 for all treatments. The model successfully described development, growth, and yield for all combinations of temperature and CO₂ in this experiment.

1. Introduction

The cultivation of crops inside greenhouses provides growers with the capability to control the aerial environment of crops to conditions favoring growth when outside conditions are not favorable. Various researchers have suggested that an economic optimization approach be used to determine how to operate the environmental control devices for maximum profit, taking into account the costs of operation and increased crop value under the modified environment (Udink ten Cate et al., 1978; Challa and van de Vooren, 1980; Seginer and Raviv, 1984). This approach requires physical models of the greenhouse environment and control devices, biological models of crop growth and yield as affected by environment, economic information on the crop and operation of the greenhouse devices, and a method to integrate these models and determine the most profitable control operations.

In recent years, greenhouse production of tomatoes has steadily increased in the southern U.S. and Israel where sunlight is abundant, temperatures are high, and primary harvest occurs in the winter months. It is quite likely that greenhouse control strategies developed under more northerly climates are not optimal for greenhouse tomatoes growing in high sunlight, moderate winter climates. A research project was undertaken in 1984 to study this problem, using the approach suggested by authors cited above. One of the major requirements of this study was a tomato growth and yield

model sensitive to the dynamic greenhouse environment. A relatively simple tomato growth and development model, TOMGRO, was developed to meet this need. The purpose of this paper is to provide an overview of this model and its responses to temperature, CO₂, and light.

2. Model overview

Few previous tomato modeling efforts have included fruit yield. Wolf et al. (1986) developed a model to predict the development of the tomato plant from planting through flowering and harvest maturity of the fruit. Temperature was the major environmental variable in their model. Acock et al. (1978) developed a canopy photosynthesis model dependant on light and CO₂. Gent and Enoch (1983) developed a vegetative growth model for tomato in which photosynthesis and dry matter growth depended on light, CO₂ and temperature. Kano and van Bavel (1988) briefly described a deterministic model for greenhouse tomatoes in which light, CO₂, and temperature affected photosynthesis, respiration, development of fruit clusters and other processes. The ultimate goal of this latter model was for use in studying greenhouse environment control.

The model developed in this research (TOMGRO) was designed to respond to temperature, solar radiation, and CO₂ concentration that change dynamically within each day. It is written in Microsoft FORTRAN V4.01 for use on IBM and compatible microcomputers. The model is modular in design and consists of a main program and 12 subroutines. One subroutine is included to set inside greenhouse conditions for simulation experiments.

The tomato plant in the model is represented by seven state variable vectors consisting of physiological age classes of plant components: numbers of leaves, stems, and fruit; dry weight of leaves plus petioles, stems, and fruit; and area of leaves. Plant growth occurs through changes in these numbers, weights, and areas in each age class of each component. Other variables, such as total plant weight, leaf area index, etc., are computed from these seven state variable vectors.

Time in the model is updated by two loops. The main loop increments time daily and a "fast" loop increments time hourly or more frequently within each day. Within the fast loop, inside greenhouse conditions are computed for that instant in time, and development, photosynthesis and respiration rates are computed and accumulated. Growth of the plant occurs in the daily loop where, at the end of the day, state variables are updated.

2.1. Organogenesis/Development

The changes in the numbers of plant organs occur through initiation of new leaves, stems, and fruit, abortion of leaves and fruit, and physiological development of numbers from one age class to the next. The rate of initiation of new nodes (leaf or truss) is determined by temperature and adjusted slightly for elevated CO₂ levels. The rate of new leaf appearance is equal to the rate of node

initiation until the first truss is formed, then it is reduced by the ratio $1/(1+TPL)$, where TPL is number of trusses per number (no./ leaf (0.33 in the variety used in this study). After a delay of FRLG nodes, new fruit initiation rate is equal to rate of node formation multiplied by the ratio of new fruit to new nodes, varying with node position on the plant, and by the ratio of carbohydrate supply to demand (R_c). When new plant organs are initiated, their numbers (no./m²), initial masses (g/m²) and area (m² leaf/m² ground) are placed into the first (youngest) age class for that component. Flowers are not accounted for explicitly.

After entering the first age class, numbers of leaves, stems, and fruit move from one age class to the next based on development rates for each component that depend on temperature and CO₂. Weights and areas also move through the age classes, and within any day, new weight and area can be added to each class by new growth. Abortion of leaves occur when they reach maturity (the oldest age class) and when the leaf is heavily shaded (when Leaf Area Index (LAI) is greater than 5.0).

Mathematically, the time rate of change of the number of leaves in a particular age class, $N_L(i)$, is given by the following equation:

$$\frac{dN_L(i)}{dt} = r(T,C)*n_1*N_L(i-1) - r(T,C)*n_1*N_L(i) - P_1 \quad (1)$$

where $r(T,C)$ is the overall rate (day⁻¹) of development of leaves under the current temperature (T) and carbon dioxide concentration (C), and n_1 is the number of leaf age classes. The last term, P_1 , accounts for losses due to shading or abortion caused by insects or disease. The product $r(T,C)*n_1$ represents the proportion of the number of leaves in class i that move to the next class ($i+1$) in one day.

The equation for mass and area rates of growth contain an extra term each for the new growth in mass or area that occurs in a given day. For example, the net rate of change in weight of fruit ($W_f(i)$) in the i^{th} age class (g/m²-day) is given by:

$$\frac{dW_f(i)}{dt} = g_f(i) + f(T,C)*n_f*W_f(i-1) - f(T,C)*n_f*W_f(i) \quad (2)$$

where $g_f(i)$ is the dry weight growth rate of fruit in the i^{th} age class, (g/m²-d), $f(T,C)$ is the overall rate (day⁻¹) of development of fruit under the current temperature and CO₂ levels, and n_f is the number of fruit age classes.

2.2. Sink strength

Sink strength is computed by calculating the potential rate of dry weight growth by each age class of each plant component. For

leaves, it is assumed that potential leaf area expansion rate depends only on physiological age of the leaf, temperature, and CO₂. This rate is divided by specific leaf area (SLA, m²/g leaf), which depends on light, CO₂, and temperature, to obtain a demand for each age class (L_{dem}(i)), taking into account the petiole growth as well. Stem growth demand (S_{dem}(i)) is assumed to be proportional to leaf growth demand. Fruit growth demand (F_{dem}(i)) depends on physiological age, temperature, and CO₂. Total sink strength for each organ is then computed by adding demand by each age class. Total dry weight growth demand (DEMAND) of the tomato (above ground) is the sum of L_{dem}, S_{dem}, and F_{dem}.

2.3. Source of carbon for growth

Carbohydrate availability for growth is computed using a carbon balance. Photosynthetic rate, P_g, is computed at each time step within a day for the whole canopy using the model of Acock (1978):

$$P_g = \frac{D \cdot LF_{\max}}{K} \ln \left[\frac{(1-m)LF_{\max} + Q_e \cdot K \cdot \text{PPFD}}{(1-m)LF_{\max} + Q_e \cdot K \cdot \text{PPFD} \cdot \text{EXP}(-K \cdot \text{LAI})} \right] \quad (3)$$

where D = coefficient to convert P_g from μM/m²-s to g/m²-d,
 K = light extinction coefficient,
 m = leaf light transmission coefficient,
 LF_{max} = maximum leaf photosynthesis, μM/m²-s,
 Q_e = leaf quantum efficiency, μM (CO₂ fixed)/μM (photon),
 PPFD = photosynthetic photon flux density μM/m²-s, and
 LAI = canopy leaf area index.

Maintenance respiration is computed by:

$$R_m = Q_{10}^{(0.1) \cdot T - 2.0} (R_L (W_L + W_S) + R_F (W_F)) \quad (4)$$

where R_m = maintenance respiration, gCH₂O/m²-d,
 Q₁₀ = sensitivity to temperature,
 R_L, R_F = respiration requirement for vegetative tissue and fruit, respectively, g CH₂O/g tissue-d and w_L, w_S, w_F = leaf, stem and fruit weight, respectively, g/m².

Total respiration is computed by:

$$\text{Resp} = (1-E) \cdot P_g + R_m \quad (5)$$

where (1-E) is the loss of CH₂O due to growth respiration.

It is assumed that root growth is a fraction of the above ground growth potential. This fraction (P_{root}, depending on physiological age of the plant), is subtracted from photosynthesis to obtain the overall supply of carbon for above-ground growth:

$$\text{SUPPLY} = (P_g - R_m) \cdot E + (1 - P_{\text{root}}) \quad (6)$$

In the model, P_g is computed as $\mu M(CO_2)/m^2-s$, then converted into $g\ CH_2O/m^2-d$. Units on E are $g\ tissue/g\ CH_2O$, so that SUPPLY and DEMAND are in the same units of $g\ tissue/m^2-d$.

2.4. Growth rates

Final growth rates by each age class of each organ depend on the ratio of carbon supply to demand, R_c . If $R_c \geq 1.0$, supply was greater than demand and growth rates are $L_{dem}(i)$, $S_{dem}(i)$, and $F_{dem}(i)$ for all i , and photosynthesis is reduced to exactly meet the sink strength in a feedback loop. If $R_c < 1$, carbohydrate is limiting, and weight and area growth rate by each age class are computed by multiplying demand by R_c . For fruit in age class i ,

$$g_f(i) = F_{dem}(i) * R_c \quad (7)$$

in g/m^2-day . Leaf area expansion is reduced similarly.

3. Material and Methods

Experiments were conducted in Gainesville, FL, in six outdoor environmentally controlled growth chambers exposed to natural sunlight. The chambers were 2 x 1 m in area and 1.5 m in height and were placed on 1 m deep steel lysimeters. Temperature, dew point temperature, and CO_2 concentration of the air in the closed chambers were controlled by a central computer (Jones et al., 1984). Light level in the chambers was about 85% of that outside the chambers.

On 4 February 1986, tomato seedlings, an indeterminate Israeli variety (K-111), were transplanted into the chambers in rows 0.50 m apart, 0.08 m between plants, resulting in 44 plants in each chamber (22 plants/ m^2). At the end of February, a steel plate was placed in the chambers to separate the soil from the chamber top, and slits between plants and steel plates were sealed with closed-cell polyurethane strips. Every 2 or 3 weeks, one or more plants were sampled from each chamber such that at the end of the experiment (May 15), 6 plants remained in each chamber (3 per m^2). Vegetative branches were pruned weekly so that plants were grown by one stem. Twice per week, flowers were shaken with a hand-held vibrator to enhance pollination. Irrigation was done about every two days to prevent water stress. Nutrients were supplied with irrigation, the amounts based on monthly soil analysis. Diseases and insects were controlled to minimal levels with preventative applications of pesticides. Treatments in the chambers consisted of combinations of 3 night time temperatures (20, 16, and 12 C) and 2 CO_2 levels (350 and 950 ppm). Daytime temperature was held constant at 28 C in all chambers for 13 hours each day. Night time dewpoint temperature was 8 C in all chambers whereas it was 21 C in the day.

Canopy carbon dioxide exchange rates were recorded every 5 minutes and used with the chamber leakage rate (measured by N_2O depletion) to compute net canopy photosynthesis on hourly intervals. Photosynthetic photon flux density (PPFD), above and below canopy, were measured every 20 s and accumulated to provide hourly values.

Days were selected during the season for estimating parameters for the photosynthesis model. These days were selected when all control and measurement operations were performing as expected, the chambers remained closed all day, and no auxiliary experiments were being conducted. Twelve days, grouped into 4 groups of about the same age, were selected (March 29, 30, 31, April 2; April 9, 10, 11; April 23, 24, 26, 27; and May 2). A nonlinear regression procedure was used to estimate LF_{max} and Q_e for each chamber and each group of data. Light extinction coefficient, K , was computed for each chamber from the PPFD measurements using Beer's law.

Plant samples were taken into the laboratory for measuring area of each leaf, counting nodes, trusses, and fruit, and drying and weighing component parts (leaves, stems, fruit, and mature fruit) of the plants. These data were used as the basis for quantifying the effects of temperature and CO_2 on development rates of leaves and fruit, on initiation rate of new nodes, and on fruit, leaf, and stem dry matter growth rates for table look-up functions in TOMGRO for the ranges of these variables in the experiment. Data were recorded on a per plant basis and used to compute LAI and values per m^2 based on the plant density on each sampling date.

4. Results

4.1. Photosynthesis

When K values were computed for each chamber, there was little difference when the five minute-interval data were averaged over the day. Using the data from all chambers and all selected days, an average value of K of 0.58 was computed. A value of $m=0.1$ was assumed for fitting the other parameters in the model, equation 3. Apparent gross photosynthesis was computed from the data by adding dark respiration, R , an unknown variable that was also estimated in the procedure along with LF_{max} and Q_e . LAI was interpolated for each chamber for the day of photosynthesis observations from successive sampling date data. Results showed a high correlation between LF_{max} and Q_e . A linear regression analysis of Q_e showed that neither canopy age nor treatment had a significant effect on its value, so an overall average Q_e of $0.0645 \mu M(CO_2)/\mu M$ photon was computed. Fixing K , Q_e , m , and knowing LAI allowed the regression procedure to estimate only LF_{max} and R . A linear relationship was found to exist between LF_{max} and CO_2 , or

$$LF_{max} = r * CO_2 \quad (8)$$

where r was found to be $0.0665 \mu M(CO_2)/m^2$ -s per vpm CO_2 concentration, or 1.49×10^{-3} m/s, which compares favorable with the value of $1.6 \pm 0.7 \times 10^{-3}$ m/s for tomato reported by Acock et al. (1978). Figure 1 shows an example of the photosynthesis data and model fit for the first group of data, 350 vpm CO_2 concentration and for the 28/20 C temperature. There were no apparent differences in model parameters for temperature treatments.

4.2. Development and growth

A linear reduction in rate of node initiation was assumed between 12 and 28 C, with the rate at 12 C being 55% of that at 28 C. Also, a relative increase in the rate was assumed for increased CO₂. At 28 C and 350 vpm CO₂ concentration, the rate of node formation was one node every two days. Based on literature (Wolf et al., 1986), the development rate of leaves (and fruit) was assumed to be linearly related to temperature between 9 C and 28 C.

Leaf area expansion rate for leaves of different ages was based on data taken on 29 March for area per leaf vs truss. Numbering the trusses from the top of the plant and grouping all (usually 3) leaves between trusses, the rate of expansion per truss could be determined (figure 2). This process normalized the development to a physiological time scale and there was little difference in the timing of development or maximum area of leaves. Using two physiological days between nodes and one truss out of four nodes, it was estimated that area expansion was completed after 56 physiological days (7 trusses) and that leaves started aborting after 72 physiological days (9 trusses). The area expansion rate per truss was computed directly from these data and normalized to 100% development to provide an input function of potential area expansion rate vs development. SLA varied from about 0.02 to 0.04 m²/g, and linear functions were used to compute SLA from temperature and CO₂ to compute leaf sink strength in the model. Figure 3 shows the resulting development of LAI for three treatments. Very little difference existed between LAI for low and high CO₂, but LAI development for low night temperature lagged behind the 20 C treatment by about 10 days until full canopy was reached.

Individual fruit (starting after flowers aborted and fruit were greater than 5 mm in diameter) developed toward maturity faster than leaves. The maximum rate of development was estimated to be 0.032 per day resulting in a minimum time to develop of 32 days under constant 28 C temperatures. Figure 4 shows number of mature fruit for 20/350, 12/350, and 20/950 treatments. Sink strength of fruit was small when fruit was young and reached a maximum value of 0.27 g/fruit per day. Sink strength was also assumed to depend on temperature. More research is needed to define this temperature function.

5. Discussion

The model developed in this study was shown to predict tomato growth and development accurately for the range of temperature and CO₂ concentrations tested. After determining model parameters using three of the treatments, results of the other combinations of temperature and CO₂ were predicted well by the model. In preliminary sensitivity analyses, the model simulated reductions in fruit yield over 200 days of 30% when temperatures were dropped from 28/16 C day/night to 20/12. An 18% increase in yield was simulated when CO₂ was increased from 350 to 950 vpm for 200 days, with temperatures of 28/16 C. More development and testing is needed to

gain confidence in its usefulness for optimizing greenhouse environmental control over a wider range of temperatures. In particular, the functions used in the model for temperatures above 28 and below 12 C must be improved.

References

- Acock, B., D.A. Charles-Edwards, D.J. Fitter, D.W. Hand, L.J. Ludwig, J. Warren-Wilson, and A.C. Withers, 1978. The contribution of leaves from different levels within a tomato crop to canopy net photosynthesis: An experimental examination of two canopy models. *J. Exp. Bot.* 29(111):815-827.
- Challa, H., and J. van de Vooren, 1980. A strategy for climate control in greenhouses in early winter production. *Acta Hortic.* 106:159-164.
- Gent, M.P.N., and H.Z. Enoch, 1983. Temperature dependence of vegetative growth and dark respiration: A mathematical model. *Plant Phys.* 71:562-567.
- Jones, Pierce, J.W. Jones, L.H. Allen, Jr., and J.W. Mishoe, 1984. Dynamic computer control of closed environmental plant growth chambers. Design and verification. *Trans. ASAE* 27:879-88.
- Kano, A., and C.H.M. van Bavel, 1988. Design and test of a simulation model of tomato growth and yield in a greenhouse. *J. Japan Soc. Hort. Sci.* 56:408-416.
- Seginer, I., and M. Raviv, 1984. Optimal night temperatures for greenhouse seedlings. *Sci. Hort.* 23:203-216.
- Udink ten Cate, A.J., G.P.S. Bot, and J.J. van Dixhoorn, 1978. Computer control of greenhouse climates. *Acta Hortic.* 87:265-272.
- Wolf, S., J. Rudich, A. Marani, and Y. Rekah, 1986. Predicting harvesting date of processing tomatoes by a simulation model. *J. Amer. Soc. Hort. Sci.* 111(1):11-16.

Acknowledgements. This research was supported in part by the Binational Agricultural Research and Development fund, BARD No. US-871-84. Approved as Florida Agricultural Experiment Station Journal Series No. 9200.

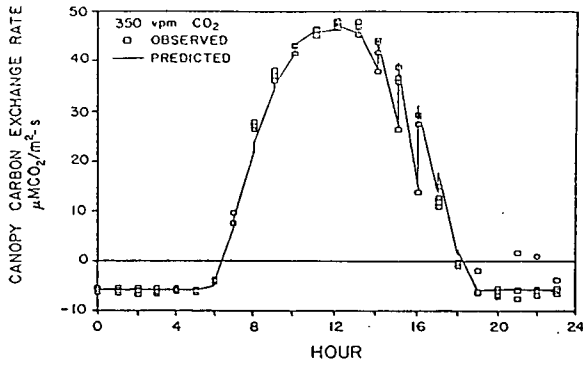


Figure 1. Tomato canopy CO₂ exchange rate for the 350 vpm CO₂, 28/20 C temperature treatment. Observed data were for the time period March 29 - April 2, 1986, Gainesville, FL.

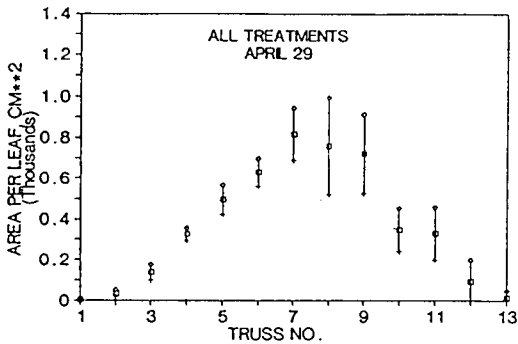


Figure 2. Area per leaf vs. truss number, measured from the top of the plants. Average and standard deviation limits from all treatments, April 29, 1986, Gainesville, FL.

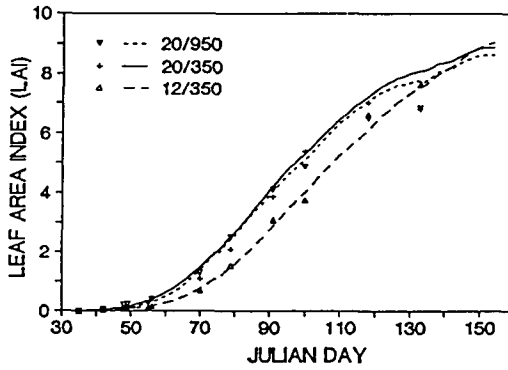


Figure 3. Simulated and observed tomato leaf area index for plants from three treatments in the 1986 experiment in Gainesville, FL.

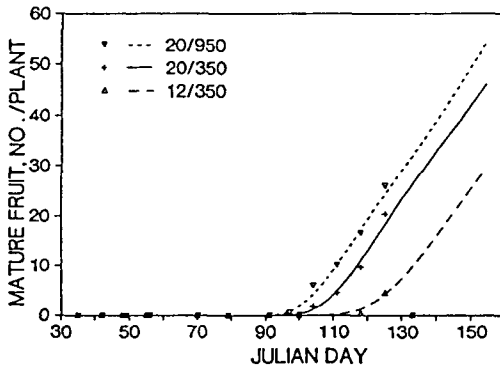


Figure 4. Simulated and observed number of tomato fruit per plant (cumulative) for three treatments from the 1986 experiment in Gainesville, FL.