

Design and Test of a Simulation Model of Tomato Growth and Yield in a Greenhouse¹

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Summary

A deterministic model of the growth of greenhouse tomatoes (*Lycopersicon esculentum* Mill), written in Pascal computer language, was developed based on a leaf assimilation model, a respiration theory, and a theory that the photosynthesis rate is controlled by both environmental conditions and leaf carbohydrate level. The model was applied to estimate the effect of carbon dioxide enrichment on tomato fruit yield, and tested with data obtained from two experiments conducted in College Station, Texas, U. S. A. in 1983 through 1984. Tomatoes were grown at 340, 700, and 1000 ppm (on a volume basis) of carbon dioxide (CO₂) in three 2×2×10 m translucent chambers inside a double-layered, polyethylene greenhouse.

The measured values of the CO₂ assimilation rate and the dry mass accumulation rate of tomatoes were consistently higher than the calculated ones, but the prediction of the fruit growth and yield were rather accurate. The potential use of the model is in predicting the effects of environmental factors, or in estimating the effect of a new climate control method under a variety of environmental conditions. It could possibly also be a subroutine in an integrated greenhouse model, which predicts growth and yield of the crop in the greenhouse as well as the energy, water, and CO₂ requirements, all from the environmental conditions outside.

Introduction

It is difficult to improve upon the judgement of an experienced greenhouse grower when it comes to forecasting yields in familiar circumstances, *e. g.* for a given location, type of greenhouse, and production method. However, when a rather new production variable is introduced, one would prefer to try a prediction method that, while subject to eventual improvement, would not require many years of experimentation and experience. Thus, theoretical models are helpful when a greenhouse crop is to be grown in an unfamiliar climate, a new type of greenhouse, or in an unusual interior environment. A case in point of the latter is the use of a controlled and augmented level of

carbon dioxide.

There have been a number of greenhouse models reported in the last 20 years as the use of computers has become more common. Most are energy budget models that predict the temperature inside the greenhouse, or estimate heat requirements at night from the environmental conditions outside the greenhouse(3, 6, 18). Some include crop growth in the greenhouse, as those reported by Inoue(11), Horie(9), Van Bavel and Sadler(22), but few of them predict the yield of the crop.

We have formulated a method to calculate tomato yield as a function of greenhouse carbon dioxide concentration, temperature, and light level. To make its application possible at the most general level, *i. e.* by extension specialists and growers themselves, it has been prepared for use on the IBM-PC, using the Turbo Pascal Language(2). Pascal has the advantages of having a transparently logical structure, a standardized code and,

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hence, a high degree of machine independence. It also fully exploits the growing memory capabilities of the current generation of microcomputers.

We also conducted two experiments, in a set of three ventilated compartments, located inside a standard greenhouse, to test the ability of the model to make adequate predictions.

Model Design

The model is not a greenhouse model, in the sense that it does not calculate the greenhouse climate from the outside environment and from the climate control functions such as heating, cooling, and carbon dioxide enrichment. Preliminary calculations of such a nature have indicated that the amount and cost of carbon dioxide required might well be the largest single production cost element (20). Hence, the input/output relation is all the more interesting.

The following are the physical inputs to the model.

- 1.1 Solar radiation level, Wm^{-2} (variable with time of day),
- 1.2 Air temperature inside, $^{\circ}\text{C}$ (variable with time of day),
- 1.3 Carbon dioxide concentration inside, gm^{-3} (constant),
- 1.4 The mass exchange coefficient between crop and the bulk air ms^{-1} (constant).

The following are the descriptors of the tomato crop.

- 2.1 The total dry matter per m^2 of space, gm^{-2} , and its rate of change, $\text{gm}^{-2}\text{s}^{-1}$,
- 2.2 The maintainable dry matter per m^2 of space, gm^{-2} , and its rate of change, $\text{gm}^{-2}\text{s}^{-1}$,
- 2.3 The dry matter in the photosynthate pool per m^2 of space, gm^{-2} ; its rate of change, $\text{gm}^{-2}\text{s}^{-1}$; and the maximum pool size, gm^{-2} ,
- 2.4 The leaf area index as a function of (2.2),
- 2.5 The time of appearance and harvest of fruit clusters, d ,
- 2.6 The photosynthate sink capacity as a function of the number and age of

fruit clusters,

- 2.7 The relative size of the photosynthate pool,
- 2.8 The pool efflux rate as a function of (2.7), $\text{gm}^{-2}\text{s}^{-1}$,
- 2.9 The maximum relative growth rate, s^{-1} ,
- 2.10 The maintenance and growth respiration requirements, $\text{gm}^{-2}\text{s}^{-1}$,
- 2.11 The photoxynthesis rate, $\text{gm}^{-2}\text{s}^{-1}$.

All values of parameters and functions were taken from previously reported results, or were estimated, except the following.

- 3.1 Leaf mass per unit leaf area, gm^{-2} ,
- 3.2 The maximum total plant mass for a tomato plant with five clusters after topping, gm^{-2} .
- 3.3 The first day of anthesis, d ,
- 3.4 Leaf resistance to the water vapor diffusion as a function of light and CO_2 level, sm^{-1} .

The relations between these variables are documented fully in the program and its glossary in Kano(12). In the following, some of the principal features are explained.

The amount of light actually absorbed by the leaves of the crop is calculated from measured or estimated light levels inside the greenhouse, as a function of time of day. The absorption function was constructed using the Stewart model(1). Leaf temperature was assumed to be equal to air temperature but 1°C higher when the light level exceeded 50 Wm^{-2} . Air temperature was estimated from daily maximum and minimum values.

The aerodynamic resistance of the crop foliage was set at a constant level of 150 sm^{-1} , implying that the relative importance of stomatal movement is limited under greenhouse conditions. Values between 50 (ventilated) and 250 sm^{-1} (unventilated) have been reported for the resistance in a greenhouse(17).

The basic photosynthesis equation (Eq.1) was taken from Van Bavel(19). It is essentially a double Michaelis-Menten relation in terms of light energy absorbed and of the CO_2 level in the leaf. A term for the temperature effect was added to the equation using results from El-Sharkawy and Hesketh

(7).

$$P_{\text{pot}} = P_{\text{max}} \left(\frac{I}{(P_{\text{max}}/E_i + I)} \right) \cdot \left(\frac{(C_i - C_c)}{(1/E_c + (C_i - C_c))} \right) \cdot f(T_1) \quad (\text{Eq. 1})$$

P_{pot} : Potential photosynthesis rate, $\text{gm}^{-2}\text{s}^{-1}$

P_{max} : Maximum photosynthesis rate, $\text{gm}^{-2}\text{s}^{-1}$

I : Absorbed incident, photosynthetically active radiation, Wm^{-2} ,

E_i : Efficiency of light utilization, Jg^{-1} ,

C_i : CO_2 concentration in the leaf, gm^{-3} ,

C_c : CO_2 compensation point, gm^{-3} ,

E_c : Efficiency of CO_2 utilization, m^3g^{-1} ,

$f(T_1)$: Temperature function.

The above equation defines the potential value of the photosynthesis rate, P_{pot} , as determined by environmental conditions only.

The model also embodies a negative feedback from the degree of photosynthate pool saturation on the rate of photosynthesis; in other words, the actual rate is found from a proposed relation between the pool size relative to the maintainable dry matter and the potential photosynthesis rate(8). This relation is shown in Fig. 1, in which all values are normalized by dividing by the maintainable dry matter. It is necessary to point out that the reality of this mechanism has not been clearly demonstrated from experiments.

The growth rate is also a function (Fig. 1) of the pool size, having a maximum value (16), as was done by Horie(10).

The respiration rate is defined in the following way.

$$R = aP + bW$$

R : Total respiration rate, $\text{gm}^{-2}\text{s}^{-1}$,

P : Photosynthesis rate, $\text{gm}^{-2}\text{s}^{-1}$,

W : Maintainable dry matter, gm^{-2} ,

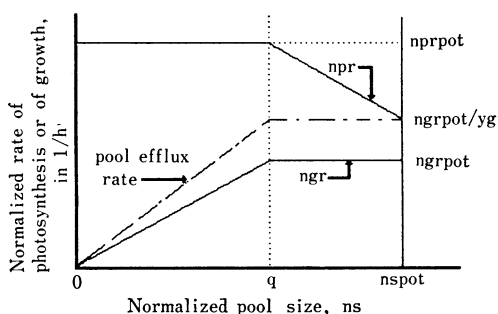


Fig. 1. Relation between pool size (ns) and photosynthesis (npr); also, between pool size and growth rate (ngr). Y_g is the yield of growth.

a : Coefficient, constant,

b : Coefficient, function of leaf temperature.

McCree(14) experimentally validated the above relation as the carbon budget for a whole day. The same equation is applied to the instantaneous rates in our model. An expression for the coefficient b was taken from McCree(15).

It was assumed, as a working hypothesis, that, during the fruit development, the fruit cluster had a maximum sink capacity equal to half that of the vegetative part, and that, at most, three clusters could develop simultaneously.

The overall organization of the carbon accumulation model is given in the diagram of Fig. 2. Change in leaf area must be considered because the potential photosynthesis rate per unit leaf area is, first, calculated using the absorbed radiation per unit leaf area. It is later converted to the value per unit floor area and used for calculating the actual rate.

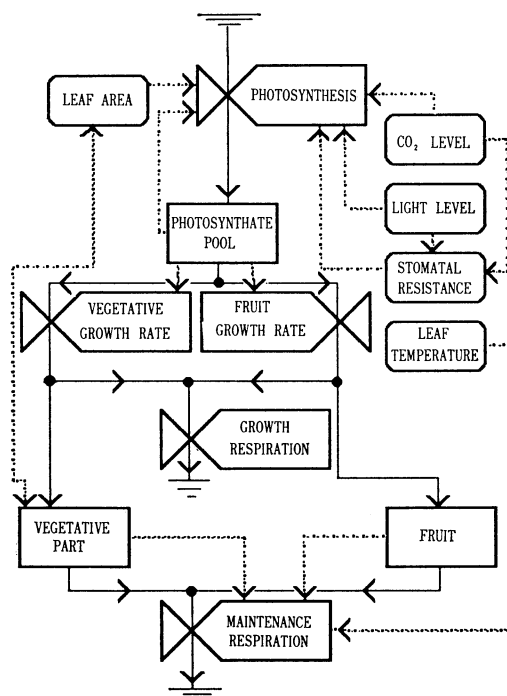


Fig. 2. System diagram of carbon flow as CO_2 or photosynthate used in simulation model, as indicated by solid lines. Dotted lines indicated control actions.

Materials and Methods

Model application.

Since two experiments were done, each at three levels of carbon dioxide, a total of 6 simulation runs were made, with the total dry matter, the fruit mass, and the leaf area index as outputs, all three as a function of time. The carbon dioxide assimilation rate was also simulated for a comparison with measured data taken on selected days.

On experiment was carried out from August 1983 to February 1984, and the second from July 1984 to November 1984. Carbon dioxide levels were maintained at ambient (340 ppm), at 700 ppm, and at 1000 ppm. Measured values for light and temperature were entered as data in the simulations.

Experimental methods.

In the first experiment, tomatoes (variety 'TVT 2') were transplanted on August 20, 1983 into a quonset-type, double inflated polyethylene film greenhouse. Three 2×2×10 m chambers made of 0.1 mm polyethylene were built inside the greenhouse, each with a double row of plants with 45 plants in each chamber. The light level in the chambers was about 60% of that outside the greenhouse. Inside temperatures and humidities were monitored continuously. The chambers were ventilated at a constant rate of 20 air changes per hour with greenhouse air, which was heated or evaporatively cooled as needed. Fresh air was always introduced into the greenhouse except on a few very cold days.

The three chambers were maintained at ambient (340 ppm) and two enriched levels (700 and 1000 ppm) during the day. From the measured ventilation rate and the decrease of the CO₂ level between intake and outlet, the carbon dioxide assimilation rate could be measured.

The tomato plants were grown in the sand floor and drip irrigated with a nutrient solution with 170 ppm (on a mass basis) N, 50 ppm P, and 320 ppm K. The plants were topped to 5 clusters and harvested twice weekly. The experiment was terminated on February 9, 1984, even though some fruits had not fully matured.

In the second experiment, tomato plants (variety 'Tropic') were directly seeded on July 25, 1984 in 7 liter pots filled with an artificial medium (fritted clay) whose physical properties were reported by Van Bavel, *et al.* (21). The plants were drip irrigated with the same nutrient solution as in the first experiment. We did not top the tomatoes, and the experiment was terminated on October 29, 1984 with 5 clusters having developed, but without mature fruits. The chamber treatments were as in the first experiment, though the CO₂ concentration in the chamber was more closely controlled by continuous feed-back. Initially, there were 240 plants in each chamber. Through bi-weekly harvesting for leaf area development and dry matter accumulation, the number was reduced to 30 per chamber at the end of the experiment.

The principal purpose of the first experi-

Table 1. Leaf resistance to water vapor diffusion in sm^{-1} at different CO₂ concentrations.

Date	Time	Leaf Resistance to Water Diffusion sm^{-1}		
		CO ₂ Concentration		
		340 ppm	700 ppm	1000 ppm
09/25/84*	12 : 30	34.3 (1.00)*	64.9 (1.89)	78.8 (2.30)
09/30/84 ^y	11 : 30	51.5 (1.00)	104.1 (2.02)	170.8 (3.32)
10/17/84 ^y	9 : 44	61.2 (1.00)	182.9 (2.99)	373.8 ^w (6.11)
	14 : 00	26.5 (1.00)	62.0 (2.34)	90.3 (3.41)
	15 : 20	96.8 (1.00)	98.1 (1.01)	176.4 (1.82)
Average	—	54.1 (1.00)	102.4 (1.89)	129.1 (2.39)

* : Numbers in parentheses are values relative to those at 340 ppm.

^y : Harmonic mean of 10 measurements.

* : Harmonic mean of 5 measurements.

^w : This value was excluded from the calculation of the average.

ment was to test the model for its adequacy in predicting fruit yield, whereas the purpose of the second experiment was primarily to test the prediction of dry matter accumulation and of the rate of CO_2 assimilation during the daytime. Although both objectives could be attained simultaneously, this did not appear to be practical.

In both experiments, temperature, humidity, carbon dioxide level, and light level were monitored. Generally, temperatures varied between 33 and 20°C, and the maximum irradiance was about 550 W m^{-2} in the chambers. Occasional measurements of the CO_2 assimilation rate of each chamber were made on selected days by measuring the difference in CO_2 concentration of incoming and

outgoing air using an infrared gas analyzer (ADC Corporation, Series 225).

Leaf epidermal resistance was measured with a steady-state leaf porometer (Li-Cor, Model LI-1600) on selected days during the second experiment.

Results

Table 1 shows the measured leaf resistance to water vapor diffusion. The numbers were for both sides of the leaf. A value of 30 sm^{-1} was taken for the minimum leaf resistance as closest round number to the value at 340 ppm at 14:00 on October 17, 1984, while the maximum, or cuticular, resistance was assumed to be 2000 sm^{-1} (24). The multiplier for the effect of CO_2 level on leaf

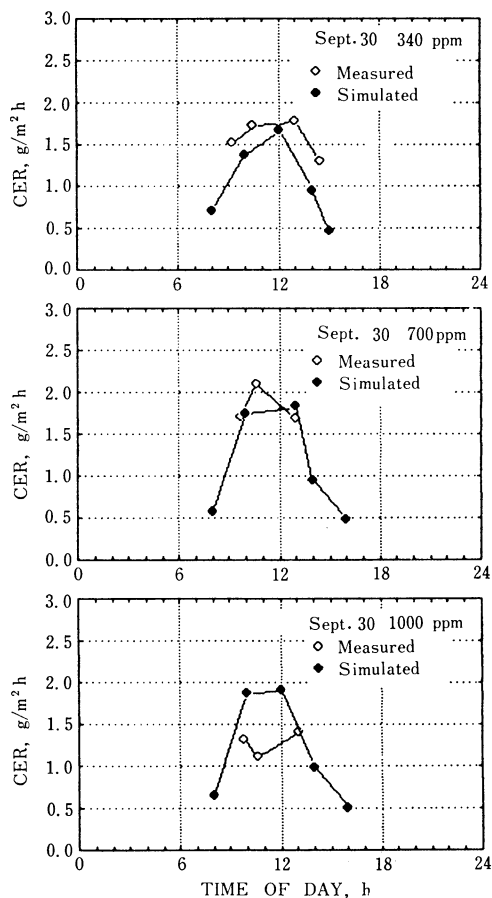


Fig. 3. Measured and calculated rates of CO_2 assimilation by the tomato crop at three levels of ambient CO_2 level, September 30, 1984.

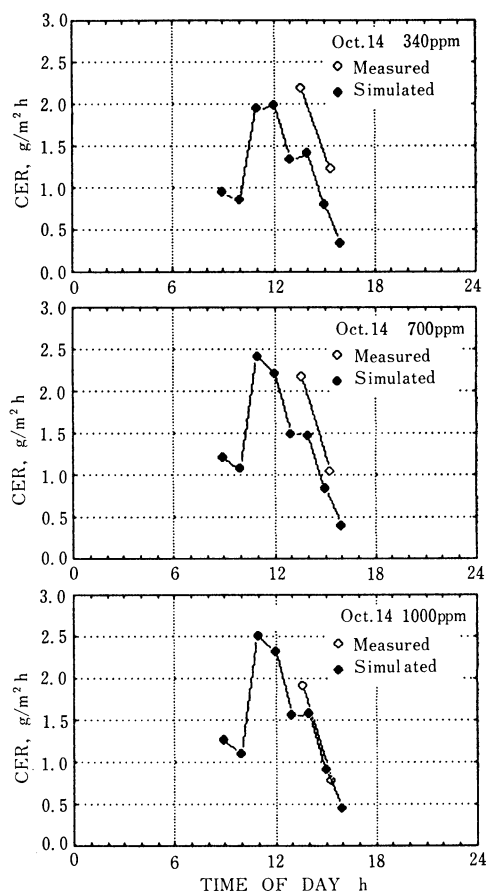


Fig. 4. Measured and calculated rates of CO_2 assimilation by the tomato crop at three levels of ambient CO_2 level, October 14, 1984.

resistance was estimated as 2.0 for 700 ppm and 2.5 for 1000 ppm. Both sets of numbers were used in the model.

The results of the measurement of carbon dioxide assimilation rate, taken in the second experiment, will be shown first. Only a few measurements could be taken in each chamber on the same day, as it was necessary to have a nearly clear sky during a major part of the day, and since only one chamber could be measured at a time. There were only two days with suitable conditions for the measurements because of an unusually long cloudy period in October, 1984.

The rate of carbon dioxide assimilation was measured over a period of about one hour.

The calculated value was found from the simulation procedures 'photosynthesis' and 'respiration', using hourly measured values for the environmental variables and a LAI (leaf area index) value measured immediately before and after the assimilation measurements. The output of this test is given as Fig.3 for September 30, 1984 and as Fig.4 for October 14, 1984.

The measured and simulated accumulation of dry matter by the entire above-ground plants and by the fruits alone during the second experiment (1984), is given in Figs.5 and 6, respectively.

Finally, the comparison of the calculated and measured yield of harvested fruits from

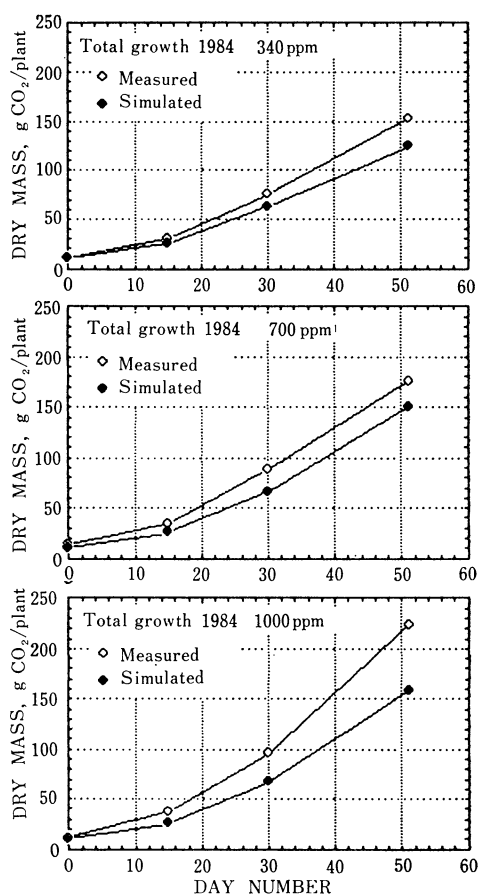


Fig. 5. Measured and simulated total dry mass of the tomato crop, in g CO₂ per m², during Fall, 1984, at three levels of ambient CO₂. Day number zero refers to September 8, 1984.

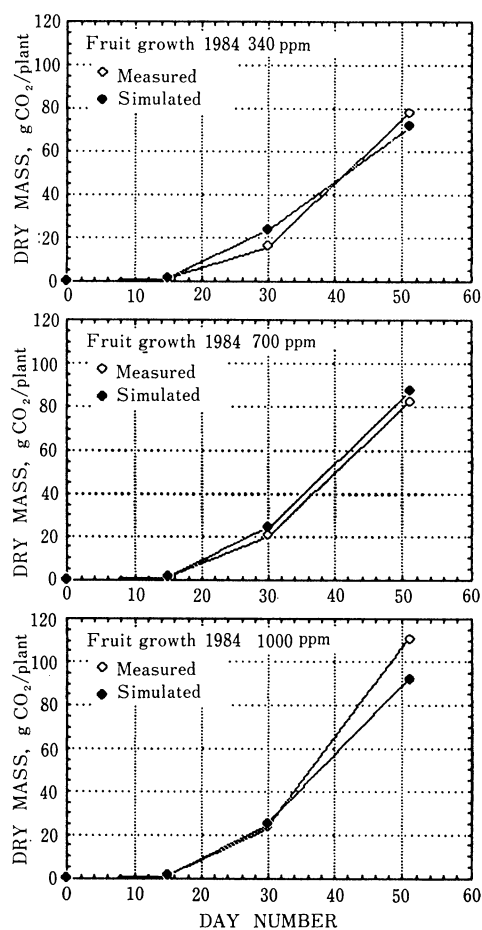


Fig. 6. Measured and simulated total dry mass of all fruits, in g CO₂ per m², during Fall, 1984, at three levels of ambient CO₂. Day number zero refers to September 8, 1984.

the first experiment (1983/1984) is shown in Fig. 7. The final yield from 5 clusters for the standard treatment in terms of fresh weight was estimated at 5.3 kg m^{-2} .

In judging the adequacy of the simulation program, it should be kept in mind that a number of parameters had to be arbitrarily chosen or estimated from data by others. However, all values, except the anthesis date of the first cluster, were selected before any experimental data were obtained. One adjustment was made afterward, in estimating the LAI as 15% higher than actually measured with a leaf area meter (Li-Cor, model LI-3100), since the "green" surface of the tomato plant is not fully measured with

the standard optical projection of leaflets.

Difficulty was experienced in maintaining and recording the ambient carbon dioxide level over periods of many weeks in the first experiment. Also, the measurement of CO_2 assimilation rate from direct differential CO_2 analysis proved unreliable at times.

It is seen from Figs. 3 and 4, that predicted and measured CO_2 assimilation rates agreed in magnitude, but that the accuracy of prediction leaves much to be desired. Therefore, the differences are not likely significant as the random error is large. Overall, both data and simulation imply that the effect of CO_2 enrichment is one of diminishing returns. More precise work on whole plants on a leaf area basis, rather than on single leaves, seems in order.

The prediction of total and of fruit dry matter accumulation (Figs. 5 and 6) showed good agreement for the fruits, but not for the entire plants (the root dry mass had to be ignored and was estimated to less than 10% of total dry mass in any event). Both measured and predicted values for the fruits suggest a significant, but not overly strong effect of CO_2 enrichment on eventual yields of mature fruit.

This conclusion was borne out by both predicted and measured yields in the first experiment, as shown in Fig. 7. In yield prediction, the simulation appears to give accurate results, but, as a practical matter, the effect of enrichment, a 31% increase as measured and 36% as calculated at the 850 ppm level, as the average of the effects at 700 and 1000 ppm, is not large. Similar magnitudes of tomato yield increase by CO_2 enrichment have been reported by Calvert(4), Calvert and Slack(5), Kimball and Mitchell(13), and Wittwer and Robb(23).

Often, the justification for enrichment is the avoidance of depletion caused by the tightness of modern, energy efficient greenhouses. To explore this effect we show, in Fig. 8, a comparison of predicted fruit yields at 150, 250, 340, and 1000 ppm for the first experiment. It shows that CO_2 depletion below 250 ppm seriously depresses the yield and explains the practical experience of

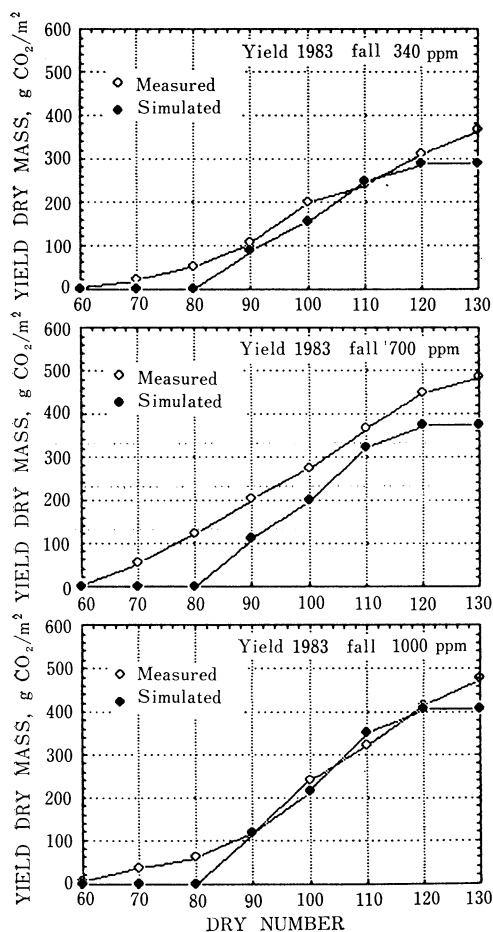


Fig. 7. Measured and simulated yield of fruits, in $\text{g CO}_2 \text{ per m}^2$, during Fall, 1983, at three levels of ambient CO_2 . Day number zero refers to September 18, 1983.

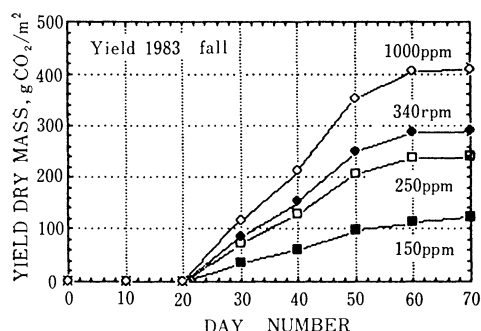


Fig. 8. Simulated yield of fruits, as g CO₂ per m², during Fall, 1983, at five levels of ambient CO₂, showing the effects of depletion and enrichment. Day number zero refers to September 18, 1983.

commercial greenhouse growers.

Discussion

The accuracy of the proposed method for tomato yield prediction could be improved by adjusting some parameters in the model, but such is outside the scope of the present study. Replacing the fundamental equations, such as the photosynthesis equation, by other relations such as polynomials, neglecting fundamental plant functions, should be avoided. Improving the model by making each sub-model more general could also be possible by eliminating empirical expressions and adding new components in the CO₂ flow algorithms, for example. However, one must be aware that the model already contains many parameters, each with inevitable uncertainty and that introducing new parameters may actually result in larger errors in the output of the simulation. Thus, further development must be guided by error analysis and sensitivity tests, as well as subjective value judgments as to the balance between complexity and practical usefulness.

As the model is not a greenhouse model, it requires measured environmental conditions as inputs. Combined with a greenhouse model, which predicts the greenhouse climate from the conditions outside, it would be one of the few recorded mechanistic and deterministic greenhouse models which predict the yield of the crop in a greenhouse from the outside weather conditions and the

control actions of the greenhouse itself.

One of the present uses of the model, as it stands, is to estimate the magnitude of effects on growth and yield of environmental factors, such as light, CO₂ concentration, and temperature, to help producers to make decisions in greenhouse management.

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温室トマトの生育と収量を予測するシミュレーションモデルの開発と試験

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摘 要

温室トマトの決定論的生長モデルを 1) 葉の光合成モデル, 2) 生長と呼吸の理論, および 3) 光合成が環境条件と葉中光合成産物の濃度に律速されているという仮説に基づいて開発した。モデルは Pascal 言語で記述され, トマトに対する二酸化炭素 (CO₂) 増与の効果をシミュレートするのに用いられた。1983年から1984年にかけてアメリカ合衆国テキサス州カレッジステーションにて行なった2回の栽培実験の結果とモデルの出力を比較した。この栽培実験のために, 著者らは3つの2×2×10 mのポリエチレンチャンパーを二重ポリエチレン温室内に構築し, チャンパー内空気のCO₂濃度をそれぞれ340,

700, 1000 ppm (容量) に制御してトマトを栽培した。

モデルはトマトのCO₂同化速度を低めに出力したが, 果実の生育量とその収量はかなり正確に予測した。

このモデルを用いて, 環境条件がトマトに与える影響を予想したり, いろいろな栽培環境における温度制御法の効果を推定したりすることが可能なことがわかった。また, このモデルが温室モデルに組み込まれることにより, 温室内で栽培されたトマトの生育や収量, 暖房熱, 水やCO₂の必要量などを温室外環境から推定するのに役立つと思われる。