

TOMGRO - a greenhouse-tomato simulation model

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1. Introduction

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Increasing international competition necessitates tomato growers to cut the costs of production, among others, by economizing on resource use. To this end, new growing techniques are required, including use of new varieties, climate control, and extension of the growing period. Growth of tomato plants in a greenhouse is a complex process, governed by the interactions between plant genetic properties and environmental conditions, as modified by climate control inside the greenhouse. It is therefore difficult to predict intuitively the management measures necessary to create crop growing conditions that will lead to optimal resource use (Challa and van de Vooren, 1980).

Dynamic crop growth models in which the insights in plant physiological processes and their dependence on environmental conditions are combined (Seligman, 1990), may provide a practical aid in management decision making, so that the effects of alternative management strategies can be examined.

In this report such a model for a tomato crop, TOMGRO, is presented. In Chapter 2 a description of the model is presented, in Chapter 3 calibration of the model under controlled conditions and in Chapter 4 field calibration and validation. In Chapter 5 suggestions are given for further model development, and in Chapter 6 for model application. Its application for economic optimization of greenhouse control is described elsewhere (Seginer and Shina, 1989).

The model was designed to describe growth of an indeterminate tomato variety under the specific conditions of greenhouse cultivation in Israel. Timing, quantity and quality of tomato fruit yield are affected by climate conditions in the greenhouse, controlled by cooling, heating and CO₂ enrichment. The model describes the effects of these management measures through their influence on total dry matter accumulation and distribution.

Effects of water or nutrient deficiency are not treated in the model, as near-optimum levels of nutrient and water supply are maintained under greenhouse conditions. Weeds are supposed not to influence crop performance, and effects of pests and diseases are treated in a rudimentary way. Under the intensive management practices common in greenhouses, weeds, pests and diseases hardly interfere with the growth of commercial crops.

An important criterion in model development was robustness in view of its application for economic optimization of greenhouse management as part of an overall decision support system.

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2. Description of the model

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2.1. Construction of the model

2.1.1. General

The model describes growth of the tomato crop quantitatively, both by number of and dry matter accumulation in the various plant components (roots, stem nodes, leaves and fruits). Organ numbers are derived from the order and rate of appearance, ageing, death and disappearance. Dry matter accumulation is derived from the canopy carbon balance and the partitioning of dry matter among plant organs.

The plant described in the model is composed of a series of successive sympodia, the first sympodium having 7-15 nodes with leaves, followed by a truss, the following sympodia 3 nodes with leaves preceding the truss. Each truss carries 5-12 flowers, resulting in 3-12 fruits (Picken et al., 1986; Atherton and Harris, 1986).

Time step of the model

The time interval of integration of the model is one day, in accordance with the time constant of the system. However, some of the processes like assimilation and respiration react rapidly to varying environmental conditions such as light intensity and CO₂ concentration. Hence, these rates are calculated in a so-called 'fast loop', that is executed at hourly time intervals during day-time. Integrated values are then used to update the state variables once a day.

State variables and age classes

The model calculates the time course of both weight and number of aerial plant components (stem nodes, leaves and fruits), while root growth is only treated superficially. Only the main stem is considered, as side shoots are supposed to be removed (van de Vooren et al., 1986). Each of the aerial plant components is subdivided in 'uniform' classes (cohorts), consisting of individuals, having on average, the same physiological age.

Some of the cohorts can be identified with specific morphological stages in the plant's life cycle, like flower buds, flowers and ripe fruits. Each cohort of each component is characterized by two state variables, representing its number and its weight. Leaf cohorts are further characterized by their green area. The total crop is thus represented by seven cohorts of state variables: number of leaves, number of stem nodes, number of fruits, dry weight of leaves, dry weight of stem nodes, dry weight of fruits, and area of leaves (Fig. 1). The growth and development of each of these plant components are described as cohort changes, i.e.

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development means movement of number and weight of cohorts from one age class to another, describing physiological ageing, while growth refers to changes within one age class. The rate of transfer between age classes depends on the development rate of the components. The average residence time within each age class equals total lifetime of that

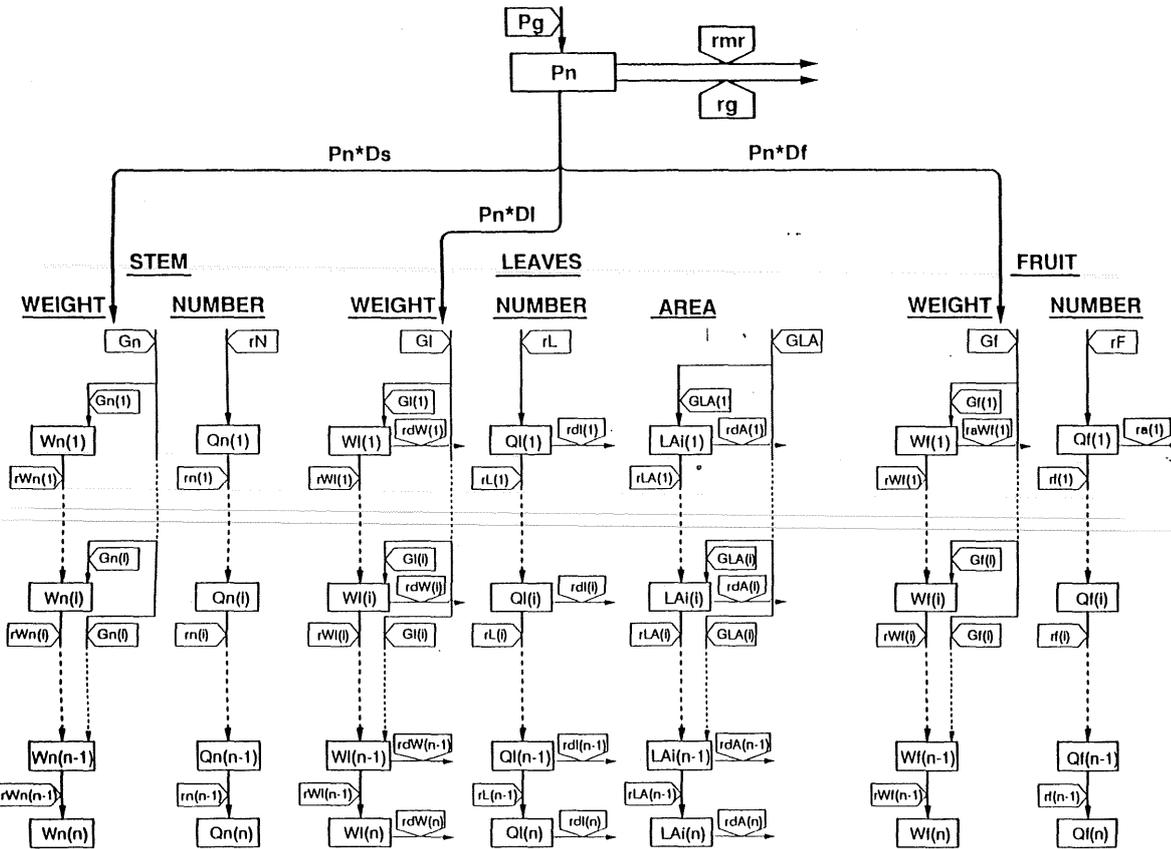


Figure 1 Schematic representation of state variables and flows in the simulation model TOMGRO, symbol convention after Forrester (1961)

P_g : gross rate of assimilation; r_{mr} : rate of maintenance respiration; r_g : rate of growth respiration; P_n : net rate of assimilation; D_s : demand for assimilates of the stem nodes; D_l : demand for assimilates of the leaves; D_f : demand for assimilates of the fruits; G_n : rate of increase in total dry weight of stem nodes; G_l : rate of increase in total dry weight of leaves; G_f : rate of increase in total dry weight of fruits; r_N : rate of increase in number of stem nodes; r_L : rate of increase in number leaves; GLA : rate of increase in total leaf area; r_F : rate of increase in number of fruits; $W_n(i)$: weight of stem nodes in age class i ; $G_n(i)$: rate of increase in dry weight of stem nodes in age class i ; $r_{Wn}(i)$: rate of transfer of stem node weight among age classes; $Q_n(i)$: number of stem nodes in age class i ; $r_n(i)$: rate of transfer of number of stem nodes among age classes; $W_l(i)$: weight of leaves in age class i ; $G_l(i)$: rate of increase in dry weight of leaves in age class i ; $r_{Wl}(i)$: rate of transfer of leaf weight among age classes; $rdW(i)$: rate of death of leaf weight in age class i ; $Q_l(i)$: number of leaves in age class i ; $r_L(i)$: rate of transfer of leaf number among age classes; $rdl(i)$: rate of death of leaf number in age class i ; $LAI(i)$: leaf area in age class i ; $GLA(i)$: rate of increase of leaf area in age class i ; $rLA(i)$: rate of transfer of leaf area among age classes; $rdA(i)$: rate of death of leaf area in age class i ; $W_f(i)$: weight of fruits in age class i ; $G_f(i)$: rate of increase in dry weight of fruits in age class i ; $raWf(1)$: rate of weight loss by abortion; $r_{Wf}(i)$: rate of transfer of fruit weight among age classes; $Q_f(i)$: number of fruits in age class i ; $r_f(i)$: rate of transfer of fruit number among age classes; $ra(1)$: rate of abortion of fruits

organ, divided by the number of age classes defined. Rapid development shortens total lifetime, and hence the residence time in each of the classes.

The rate of change of number of organs, either leaves, stem nodes or fruits, in a particular age class (r_x), can be presented by:

$$r_x = R \cdot N \cdot (Q(i-1) - Q(i)) - rd(i) \quad (1)$$

where,

$Q(i)$ = number of organs (no m^{-2}) in age class i , for $1 < i < N$

R = rate of development of organs (d^{-1}), function of ambient temperature and CO_2 concentration.

N = total number of age classes.

$rd(i)$ = rate of death of plant organs (no $m^{-2} d^{-1}$).

This mathematical description is an overall representation of the rates of change of most of the state variables, except for some specific modifications, depending on organ, mainly in the first and last age class of each component.

The physiological age of the crop is described by the current node number (referred to in this report as plastochron index). This description can be used because each sympodium has a fixed number of nodes and successive sympodia appear along the main stem (Coleman and Greyson, 1976).

The rate of new stem node formation, r_N , which is basically genetically controlled, is affected by crop age, characterized by the current node number, ambient temperature and ambient CO_2 concentration (Klapwijk, 1981).

$$r_N = r_M \cdot f_T \cdot f_c \cdot d_p \quad (2)$$

where,

r_M = maximum rate of stem node initiation per plant, function of plastochron index (no $plant^{-1} d^{-1}$).

f_T = factor accounting for the effect of suboptimum temperatures on stem node initiation.

f_c = factor accounting for the effect of ambient CO_2 concentration on stem node initiation.

d_p = plant density (plants m^{-2}).

Nodes are considered stable elements in the system, that are retained till the end of the growth cycle, hence no death rate is defined.

During the initial period of plant growth, the rate of new leaf appearance along the first sympodia (r_L), is equal to the rate of node appearance. After 7-15 nodes per plant have been formed, the first trusses appear. From then on, truss to leaf initiation ratio, usually 3 leaves per truss, is taken into account (Calvert, 1965):

$$r_L = r_N / (1+a) \quad (3)$$

where,

a = ratio of new trusses to new leaves.

$$a = 0, N_n < N_t \quad (4)$$

$$a = \text{trl}, N_n > N_t$$

where,

N_n = current stem node number.

N_t = number of stem node at which first truss is formed.

trl = truss to leaf initiation ratio.

In all age classes the number of leaves may decrease. The rate of decrease is determined by leaf physiological age, degree of shading (Tucker, 1981) and local agricultural practice like pruning (Van de Vooren et al., 1986). Leaves not prematurely removed, are considered mature when they reach the last age class, N (Peat, 1970; Ludwig and Withers, 1984). Hence, for leaves not susceptible to death by shading:

$$\text{rdl}(i) = \text{rdr}(i) \cdot Q(i) \quad 1 < i < N \quad (5)$$

For mature leaves, susceptible to leaf shedding due to shading:

$$\text{rdl}(N) = \text{rdr}(N) \cdot Q(N) + \text{rdrs} \cdot (L_a - L_{ax}) \quad L_a > L_{ax} \quad (6)$$

where,

$\text{rdr}(i)$ = relative death rate of leaves in age class i (d^{-1}), forcing function.

rdrs = maximum relative death rate due to shading (d^{-1}).

L_a = leaf area index of the canopy.

L_{ax} = critical leaf area index, above which leaves die because of shading.

Each truss consists of several flowers, in which several fruits are set and develop. The number of flowers initiated per node is a varietal characteristic, modified by physiological age of the plant (Vriesenga and Honma, 1974) and environmental conditions, e.g. low temperatures result in splitting of the truss and initiation of more fruits per truss (Hurd and Cooper, 1967; Calvert, 1959). The degree of splitting and hence the number of fruits per truss is assumed to be positively correlated with time of exposure to lower than critical temperatures. Hence, the rate of fruit formation, r_F , equals:

$$r_F = r_M \cdot F_t \cdot c_s \cdot f_{tl} \quad (7)$$

where,

r_M = maximum rate of stem node initiation per plant, function of plastochron index (Eqn. 2)

F_t = factor accounting for the effect of plastochron index on the number of fruits per truss.

c_s = factor accounting for the effect of low temperatures on truss splitting.

f_{tl} = factor accounting for the effect of sub-optimum temperatures on fruit set.

Both high and low temperatures reduce fruit set (Levy et al., 1978; Rylski, 1979; Sawhney, 1983; Picken, 1984). Hence, in the model, the rate of fruit initiation is negatively correlated with the duration of the period of exposure to above- or below-critical temperatures. After setting, the young fruits are still sensitive to sub-optimal conditions and some may be aborted (Atherton and Othman, 1983; Russel and Morris, 1982). The number of aborted young fruits is calculated as a function of sink/source ratio (Calvert and Slack, 1975), which will be discussed later. Hence, the rate of fruit abortion, R_a , equals:

$$R_a = rra \cdot F \quad (8)$$

where,

$$rra = \text{relative rate of fruit abortion (d}^{-1}\text{)}.$$

All mature fruits are picked and removed from the system.

2.1.2. Dry matter production

Calculation of biomass accumulation of the crop is based on a quantitative description of the carbon balance, comprising gross carbon assimilation, maintenance respiration and growth respiration. Gross assimilation, as well as maintenance and growth respiration are determined by the instantaneously variable combination of the environmental conditions temperature, radiation and CO_2 level and the morphology, size and physiological age of each plant component (Hurd and Thornley, 1974). As environmental conditions inside the greenhouse vary over short periods of time, assimilation and respiration are calculated with hourly time steps, in the 'fast loop'.

Daily gross assimilation is obtained by integration of instantaneous assimilation rates, calculated as a function of the prevailing levels of PAR (Photosynthetically Active Radiation) and CO_2 , ambient temperature and crop characteristics, such as leaf area index, leaf angle distribution, light extinction coefficient, etc.

Calculation of instantaneous gross photosynthesis rate, P_g , is based on Acock's equation (Acock et al., 1978):

$$P_g = \frac{(D \cdot P_m / K) \cdot \ln(((1-m) \cdot P_m + Q_e \cdot K \cdot R_m) / ((1-m) \cdot P_m + Q_e \cdot K \cdot R_m \cdot \exp(-K \cdot L_a)))}{T_a} \quad (9)$$

where,

- D = conversion factor from $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$
- K = canopy light extinction coefficient for PAR.
- m = leaf light transmission coefficient.
- P_m = light saturated leaf CO_2 assimilation rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)
- Q_e = leaf quantum efficiency ($\mu\text{mol CO}_2 \mu\text{mol}^{-1}$ photons).
- R_m = photosynthetic photon flux density ($\mu\text{mol photons m}^{-2} \text{ s}^{-1}$).
- L_a = active canopy leaf area index ($\text{m}^2 \text{ leaf m}^{-2} \text{ surface}$).
- T_a = factor accounting for the effect of ambient temperature on gross assimilation.
- \exp = takes the exponent of the argument in brackets

The value of P_m is determined by physiological crop age, ambient temperature and ambient CO_2 concentration (Thornley et al., 1981):

$$P_m = P_{mc} \cdot f_{tp} \cdot f_{pi} \quad (10)$$

where,

P_{mc} = light saturated leaf CO_2 assimilation rate, function of ambient CO_2 concentration ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

f_{tp} = factor accounting for the effect of ambient temperature on light-saturated leaf CO_2 assimilation rate.

f_{pi} = factor accounting for the effect of leaf age on light-saturated leaf CO_2 assimilation rate.

The value of P_{mc} is calculated from ambient CO_2 concentration:

$$P_{mc} = t_1 \cdot C_a + \max(0, t_2 \cdot (C_a - 350)) \quad (11)$$

where,

C_a = ambient CO_2 concentration ($\mu\text{mol mol}^{-1}$).

t_1, t_2 = empirical constants.

\max = takes the maximum value of the arguments in brackets.

Daily maintenance respiration is also obtained by integration of the instantaneous rates, calculated according to (Penning de Vries, 1975):

$$r_{mr} = (W_{tv} \cdot r_{rv} + W_{tf} \cdot r_{rf}) \cdot T_m \quad (12)$$

where,

r_{mr} = daily total maintenance respiration ($\text{kg CH}_2\text{O m}^{-2} \text{ d}^{-1}$).

W_{tv} = total dry weight of live aboveground vegetative plant organs, comprising leaves, petioles and stem nodes (kg m^{-2}).

r_{rv} = maintenance respiration coefficient of vegetative plant material ($\text{kg CH}_2\text{O kg}^{-1}(\text{dry matter}) \text{ d}^{-1}$).

W_{tf} = total dry weight of fruit on the crop (g m^{-2}).

r_{rf} = maintenance respiration coefficient of fruit material ($\text{kg CH}_2\text{O kg}^{-1}(\text{dry matter}) \text{ d}^{-1}$).

T_m = factor accounting for the effect of temperature on maintenance respiration, (Gosiewski et al., 1982).

Growth respiration represents the energy used in the conversion of primary photosynthates into structural dry matter (Penning de Vries et al., 1983).

$$r_g = c_p (P_g - r_{mr}) \quad (13)$$

where,

r_g = rate of growth respiration ($\text{kg CH}_2\text{O m}^{-2} \text{ d}^{-1}$).

c_p = carbon production value ($\text{kg dry matter kg}^{-1} (\text{CH}_2\text{O})$)

Total assimilate (expressed in terms of dry matter) available for growth of structural plant material, P_n , equals thus:

$$P_n = P_g - r_{mr} - r_g \quad (14)$$

2.1.3. Assimilate distribution

Partitioning of dry weight increase among plant organs can be described by their relative sink strengths (Hurd and Thornley, 1974; Tanaka et al., 1974a; 1974b; Hurd et al., 1979; Thornley et al., 1981; Starck, 1983).

In the model, first a fraction, f_{rt} , of the available assimilates, defined as a function of the physiological age of the plant (plastochron), modified by temperature and the source/sink ratio, is partitioned to growth of the root system (Nourai, 1980; Russell and Morris, 1983). The total sink strength of leaves and fruits is calculated by adding the sink strengths of the various cohorts, each of which is a function of the number of organs in the cohort and the genetically determined 'potential growth rate' per individual, i.e. its growth rate under non-limiting carbohydrate supply (Mihailov, 1975).

The actual sink strength of the fruits, D_f , is obtained as the sum of the sink strengths of all fruit cohorts, calculated in dependence of the number of fruits in the cohort and the potential growth rate per individual (Walker and Ho, 1977; Ho et al., 1983), modified by the effects of ambient temperature and CO_2 concentration (Fisher, 1977; Ho, 1980):

$$D_f = \sum_{i=1}^N (N_f(i) \cdot P_f(i) \cdot T_f \cdot f_C) \quad (15)$$

where,

$N_f(i)$ = number of fruits in age class i .

$P_f(i)$ = maximum rate of dry matter accumulation per fruit in age class i ($\text{g fruit}^{-1} \text{d}^{-1}$).

T_f = factor accounting for the effect of temperature on potential fruit dry matter accumulation rate.

f_C = factor accounting for the effect of ambient CO_2 concentration on potential fruit dry matter accumulation rate.

For leaf blades, potential dry matter accumulation rate is assumed to be controlled by potential leaf area expansion rate in each cohort, $r_{LA}(i)$, (Hussey, 1963a; 1963b; 1965; Cooper, 1966; 1967; Klapwijk, 1981), defined as:

$$r_{LA}(i) = N_l(i) \cdot P_l(i) \cdot T_l \cdot f_C \quad (16)$$

where,

$N_l(i)$ = number of growing leaves in age class i (no m^{-2}).

$P_l(i)$ = maximum rate of leaf area expansion of an individual leaf in age class i at optimum temperature and $350 \mu\text{mol mol}^{-1} \text{CO}_2$ concentration ($\text{m}^2 \text{leaf}^{-1} \text{d}^{-1}$).

- TI = factor accounting for the effect of ambient temperature on leaf area expansion rate.
 fc = factor accounting for the effect of ambient CO₂ concentration on leaf area expansion rate.

Dry matter demand of each leaf age class ('sink strength') is derived from its potential expansion rate, taking into account its specific leaf area:

$$rDp(i) = rLA(i)/Ls(i) \quad (17)$$

where,

- rDp(i) = potential rate of increase in dry weight of leaves in age class i (g m⁻² d⁻¹).
 Ls(i) = specific leaf area of leaves in age class i (m² g⁻¹).

Specific leaf area for each leaf cohort is defined as a function of ambient temperature and CO₂ concentration and the prevailing photon flux density (Hurd and Thornley, 1974; Charles-Edwards and Ludwig, 1975):

$$Ls(i) = Lss \cdot fc \cdot TsL \cdot fR \quad (18)$$

where,

- Lss = 'standard' specific leaf area (m² g⁻¹).
 fc = factor accounting for the effect of ambient CO₂ concentration on specific leaf area.
 TsL = factor accounting for the effect of ambient temperature on specific leaf area.
 fR = factor accounting for the effect of photosynthetic photon flux density on specific leaf area.

The effect of ambient CO₂ concentration on specific leaf area is defined as a linearly increasing function of CO₂ concentration (Goudriaan and de Ruiter, 1983):

$$fc = 1/(1+Bc(Ca-350)) \quad (19)$$

where,

- Bc = change in specific leaf area per μmol mol⁻¹ change in ambient CO₂.

Temperature has a differential effect on leaf area expansion and dry matter production, i.e. leaf thickness decreases with increasing temperatures (Friend, 1966; Hurd and Thornley, 1974):

$$fT = 1/(1+BT(24-T)) \quad (20)$$

where,

- BT = change in specific leaf area per °C change in temperature (Hurd and Thornley, 1974).
 T = ambient temperature (°C)

The reference temperature of 24 °C was chosen rather arbitrarily, based on the results of controlled condition experiments (Jones et al., 1989b).

Because of the relative independence of leaf area development and leaf weight increase, higher assimilation rates, induced by increased photon flux density, lead to thicker leaves (Cooper, 1966; 1967; Thornley and Hurd, 1974; Klapwijk, 1981). In the model a modified version of an empirical equation developed by Boote et al. (K.J. Boote, J.W. Jones and G. Hoogenboom, unpublished data) is used:

$$fR = L_{sm} + (L_{sx} - L_{sm}) \cdot \exp(-0.417 \cdot R_m) \quad (21)$$

where,

L_{sm}, L_{sx} = minimum and maximum value of specific leaf area, respectively (g m^{-2}).

R_m = photosynthetic photon flux density ($\mu\text{mol photons m}^{-2} \text{s}^{-1}$).

Total dry matter demand for leaf growth, DI , is obtained by adding the demands of all age classes, and taking into account the requirements for growth of the petioles, that are assumed to be part of the leaf blades:

$$DI = (1 + pf) \sum_{i=1}^N (rDp(i)) \quad (22)$$

where,

pf = fraction petiole in total leaf blade weight.

Total dry matter demand of the growing stem nodes is derived from the demand of the leaves by assuming a fixed ratio between leaf and stem node sink strength (Heuvelink and Marcelis, 1989):

$$D_s = \sum_{i=1}^N (rD_s(i)) \quad (23)$$

$$rD_s(i) = rD_p(i) \cdot N_s(i) / N_l(i) \cdot f_s \quad (24)$$

where,

D_s = total dry matter demand for stem growth ($\text{g m}^{-2} \text{d}^{-1}$).

$rD_s(i)$ = dry matter demand for stem growth in age class i ($\text{kg plant}^{-1} \text{d}^{-1}$).

$N_s(i)$ = number of growing stem nodes in age class i .

f_s = ratio of dry matter demand of leaf blade and stem node.

Total dry matter demand for growth of the aerial plant parts is the sum of the demands of the components:

$$TD = DI + D_s + D_f \quad (25)$$

The actual growth rates of all cohorts of leaves (plus petioles), stem nodes and fruits are derived from the potential rate by multiplying with the ratio P_n/TD , i.e. the supply/demand ratio:

$$R(p) = P(p) \cdot P_n/TD \quad (26)$$

where,

$R(p)$ = actual growth rate of each cohort of organs ($\text{kg m}^{-2} \text{d}^{-1}$).

$P(p)$ = potential growth rate of each cohort of organs ($\text{kg m}^{-2} \text{d}^{-1}$).

If net assimilation exceeds total crop demand for assimilates, assimilation is instantaneously adjusted to satisfy demand exactly, i.e. surplus assimilates are not stored in a reserve pool for later use (Walker and Ho, 1977; Walker et al., 1978; Gosiewski et al., 1981).

2.2. Discussion

The present model is based on the assumption that assimilate availability is the major constraint for growth and yield of greenhouse tomato crops. For many situations in the temperate zone a linear relation between light interception and dry matter production has been established (Monteith, 1977; Walker et al., 1978; Gosiewski et al., 1981; Van Keulen and Stol, 1991). Under winter conditions in Israeli greenhouses this phenomenon was also observed (Dayan et al., 1986). Therefore, the present model is based on limited assimilate availability, hence a strong internal competition for assimilates between vegetative and reproductive plant organs and no accumulation of reserve carbohydrates.

The model described here is very similar to others in calculating dry matter accumulation in the crop from a quantitative description of the carbon balance, i.e. gross photosynthesis minus losses through respiration for growth and maintenance. The principle of dry matter partitioning among the various plant organs, based on a source/sink approach is also similar to some other models (Dayan et al., 1981; Van Keulen and Seligman, 1987; Marcelis et al., 1989). In models for determinate crops, the variable sink/source relations are often described in terms of fixed development stages (Jones et al., 1984b; Van Keulen and Seligman 1987) and partitioning is directly related to these development stages by empirical functions (Heuvelink and Marcelis, 1989; Spitters et al., 1989). In indeterminate crops, growth of vegetative and reproductive organs proceeds simultaneously and continuously, hence the plant's life cycle does not have a fixed length, so that development has to be related to the life cycle of the component organs. Therefore, in the model presented here, the physiological age of the crop as a whole is described in terms of the life cycle of the various organs, stem nodes, leaves and fruits. The physiological age of each of the organ populations, present at any moment, is defined by its number and the physiological age of its individuals. The physiological age of each individual is described by the integrated and interactive effect of the environmental conditions, temperature, light and CO_2 concentration since its appearance. Basically, this description is similar to the one using accumulated heat sum, as in other models, except that the heat sum between initiation and physiological maturity is modified by radiation level and CO_2 concentration, conditions that generally under greenhouse conditions can be controlled.

Defining sink strength on the basis of number and physiological age of the various organs results in variable sink strength, both total and for the different organs, in the course of the plant's growth cycle, which is in accordance with the observed pattern of growth of vegetative and reproductive plant organs.

Use of a dynamic supply/demand ratio to govern dry matter partitioning, rather than physiological age only, leads to variable partitioning patterns in the course of the plant's growth cycle. Moreover, it affects initiation and abortion of organs, thus influencing also the growth pattern.

Although the present model performs satisfactorily, both under Israeli greenhouse (Dayan et al., 1986) and controlled chamber conditions (Jones et al., 1989a), several physiological and physical aspects warrant further attention.

Leaf appearance and leaf area development are treated descriptively, by using empirical functions, relating specific leaf area to environmental conditions, thus disregarding number and rate of development of leaflets on the composite leaf. A more mechanistic approach based on cell number, cell expansion rate and carbohydrate availability as affected by environmental conditions and leaflet position would be preferable (Ho and Shaw, 1977). Description of fruit initiation and fruit development requires more detail, as the pattern of fruit initiation within the truss, and environmental effects on flowering and fruit set, e.g. viability of the pollen, transfer of pollen from the anther to the ovaries, etc. (Levy et al., 1978; Rylski, 1979; Sawhney, 1983; Picken, 1984) are not taken into account. These processes may have considerable effects on fruit numbers under greenhouse conditions.

Dry matter allocation to the roots and root activity are treated in a rudimentary way, as in most published crop growth models (cf. Van Keulen and Seligman, 1987). A more explanatory description, that would take into account the interactions between above ground and below ground plant organs, as well as the effects of environmental conditions on root growth and functioning would widen applicability of the model, especially for soilless cultures, where root functioning may be a constraint for optimum crop performance (Crapo and Ketellapper, 1981).

Plant genetic characteristics, either directly or through their response to environmental conditions, govern the pattern of growth and development of the crop. These characteristics are cultivar-specific, so that the model needs re-calibration for application with each different variety (Augustine et al., 1979; Bangerth and Ho, 1984)

Also some physical processes are treated rather superficially. Effects of air humidity are not treated at all. This could be an over-simplification, especially under greenhouse conditions, as high humidities, such as may occur during closing of the windows either to allow CO₂ enrichment or to reduce heat dissipation during cold nights, may interfere with various processes, such as ion uptake, assimilation, fertilization, fruit set, etc. (Klapwijk, 1975; Picken, 1984).

Exchange processes of energy, water and carbon dioxide within the canopy are not considered in the model, hence temperature and carbon dioxide concentration are assumed constant throughout and extinction of photosynthetically active radiation is based on a homogeneous crop, and does not take into account the row structure (Goudriaan, 1977; Gijzen and Goudriaan, 1989)

Organ formation is described explicitly in the model, and provides the physiological age distribution of the existing leaf mass, hence it also allows evaluation of the position of the leaves relative to each other and, if combined with information on stem node length, also in absolute terms. This characterization of the canopy within the model may provide a good starting point for the improvement of model descriptions for leaf area development, fruit initiation and development, energy balance, etc., earlier described as non-satisfactory in the present model.

The modular setup of the model provides flexibility as new modules can easily be added (e.g. transpiration) and modules for specific processes (e.g. assimilation, organ formation) can easily be replaced if improved descriptions become available.

The model provides a consistent schematic description of the tomato crop, which facilitates simplification, generalization, adaptation to other crops or applications and transfer to other software and incorporation in other software systems, e.g. economic optimization and greenhouse climate control.

3. Calibration of the model under fully controlled conditions

J.W. Jones³⁾, E. Dayan¹⁾ & B. Jacobson³⁾

3.1. Materials and methods

Experiments were conducted in Gainesville, Florida - USA, 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 CO₂ concentration of the air in the closed chambers were controlled by a central computer (Jones et al., 1984a). Light level in the chambers was about 85% of that outside the chambers.

On February 4, 1986, tomato seedlings, of 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 inserted 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 2-3 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 plants m⁻²). Vegetative side shoots were pruned weekly, so that plants consisted of a main stem only. Twice per week, flowers were shaken with a hand-held vibrator to enhance pollination. Irrigation was applied 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 minimum levels by preventive applications of pesticides. Treatments in the chambers consisted of combinations of 3 night-time temperatures (20, 16 and 12 °C) and two CO₂ levels (350 and 950 μmol mol⁻¹). Daytime temperature was constant at 28 °C in all chambers for 13 hours each day. Dew point temperature was 8 °C in all chambers at night and 21 °C during the day.

Canopy carbon dioxide exchange rates were recorded every 5 minutes, from which, combined with the chamber leakage rate (measured by N₂O depletion), net canopy photosynthesis was calculated at hourly intervals. Photosynthetic photon flux density (PPFD), above and below the canopy, was measured every 20 seconds and integrated to provide hourly values.

Parameters for the photosynthesis model were derived from measurements on days that 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 sets representing 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 non-linear regression procedure was used to estimate P_m and Q_e (Chapter 2, Equation 9) for each chamber and each group of days. Light extinction coefficient, K, was computed for each chamber from the PPFD measurements, using Beer's law.

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Plant samples were taken to the laboratory for measuring the area of each leaf, counting nodes, trusses and fruits, and, after drying, weighing component parts (leaves, stems, fruits and mature fruits). These data were used as the basis for quantifying the effects of temperature and CO₂ on development rates of leaves and fruits, initiation rate of new nodes, and fruit, leaf and stem dry matter growth rates for forcing 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 unit area, based on plant density at each sampling date.

3.2. Results

Photosynthesis

K-values computed for each chamber separately, on the basis of average daily values, showed very little variation. Averaged over all chambers and all selected days, a value of 0.58 was computed. A value of $m=0.1$ was assumed for fitting the other parameters in the model (Chapter 2, Equation 9). Apparent gross photosynthesis was calculated from the data by adding dark respiration, R, which was also estimated in the procedure in addition to P_m and Q_e. LAI was interpolated for each chamber for the day of photosynthesis observations, from successive sampling dates. Results showed a high correlation between P_m 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 μmol (CO₂) μmol⁻¹ photons was computed. Fixing K, Q_e, m, and knowing LAI allowed estimation of P_m and R in the the regression procedure. A linear relationship was found between P_m and CO₂, or:

$$P_m = r * CO_2 \quad (27)$$

with r equal to 0.0665 μmol (CO₂) m⁻² s⁻¹ per μmol mol⁻¹ CO₂ or 1.49 * 10⁻³ μmol mol⁻¹ m⁻² s⁻¹, which compares favourable with the values of 1.60-0.7 * 10⁻³ m s⁻¹ for tomato reported by Acock et al. (1978). Figure 2 shows an example of the photosynthesis data and model results for the first group of dates, 350 μmol mol⁻¹ CO₂ concentration and the 28/20 °C temperature regime. Model parameters for different temperature treatments were not significantly different.

Development and growth

A linear relation between temperature and rate of node initiation was assumed in the range of 12 to 28 °C, with the rate at 12 °C set at 55% of that at 28 °C. Moreover, the rate was assumed to increase at elevated CO₂ levels. At 28 °C and 350 μmol mol⁻¹ CO₂ concentration, the rate of node formation was set at one node per two days. Based on literature data (Wolf et al., 1986), the development rate of leaves (and fruits) was assumed to be linearly related to temperature between 9 and 28 °C.

Leaf area expansion rate for leaves of different March 29. Numbering the trusses from the top of the plant downwards, and grouping age classes was derived from experimental data for area per leaf versus truss number from all (usually 3) leaves between trusses, the rate of leaf area expansion per truss number could be determined (Fig. 3)

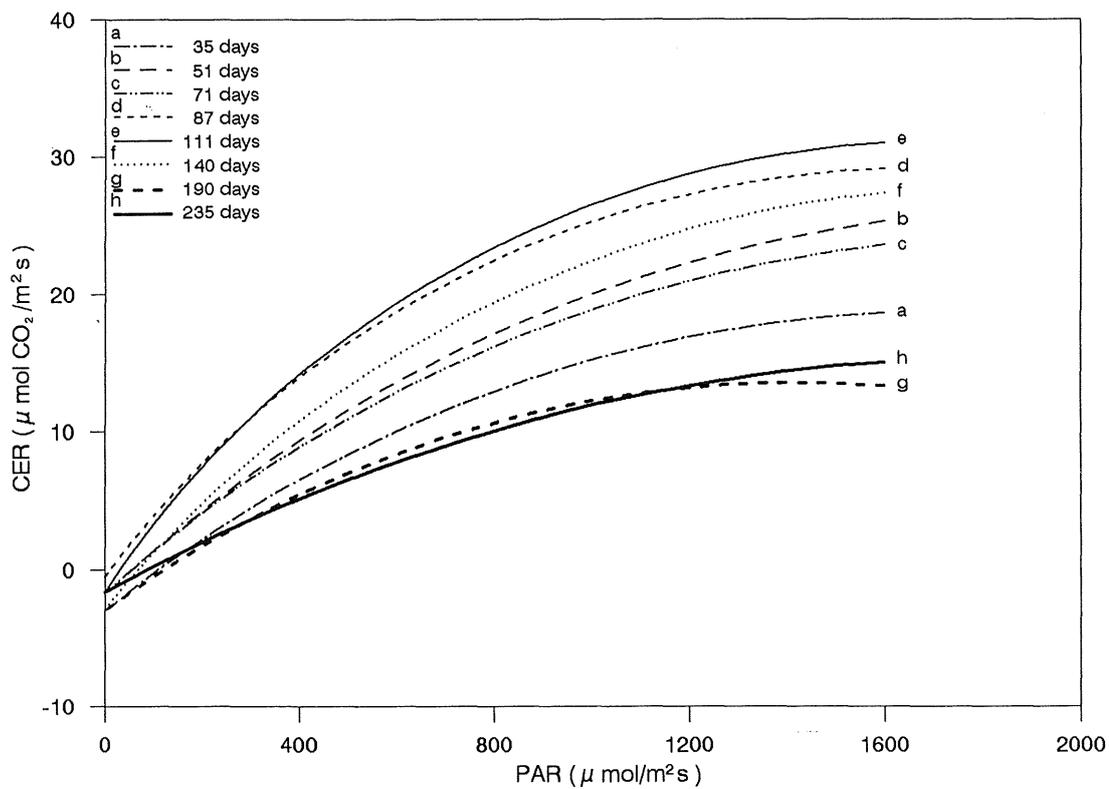
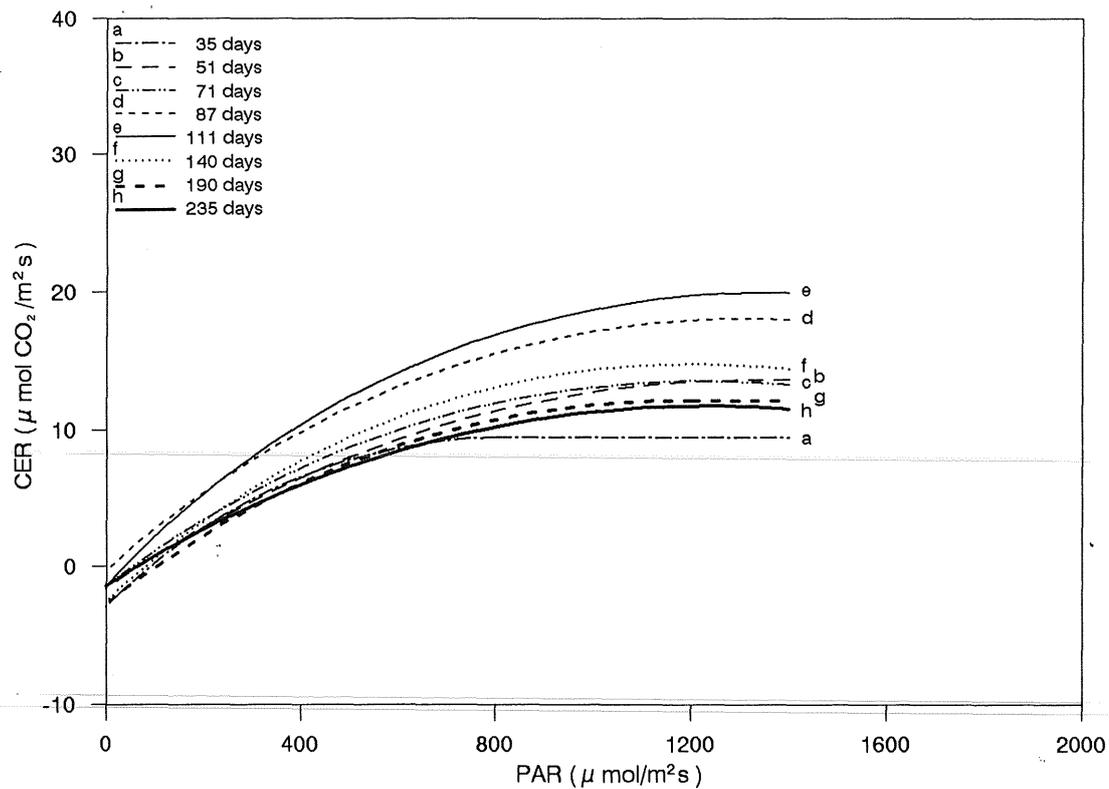


Figure 2 The fitted relations between CER and PAR for a tomato canopy at different days after planting

a at low CO_2 level

b at elevated CO_2 level

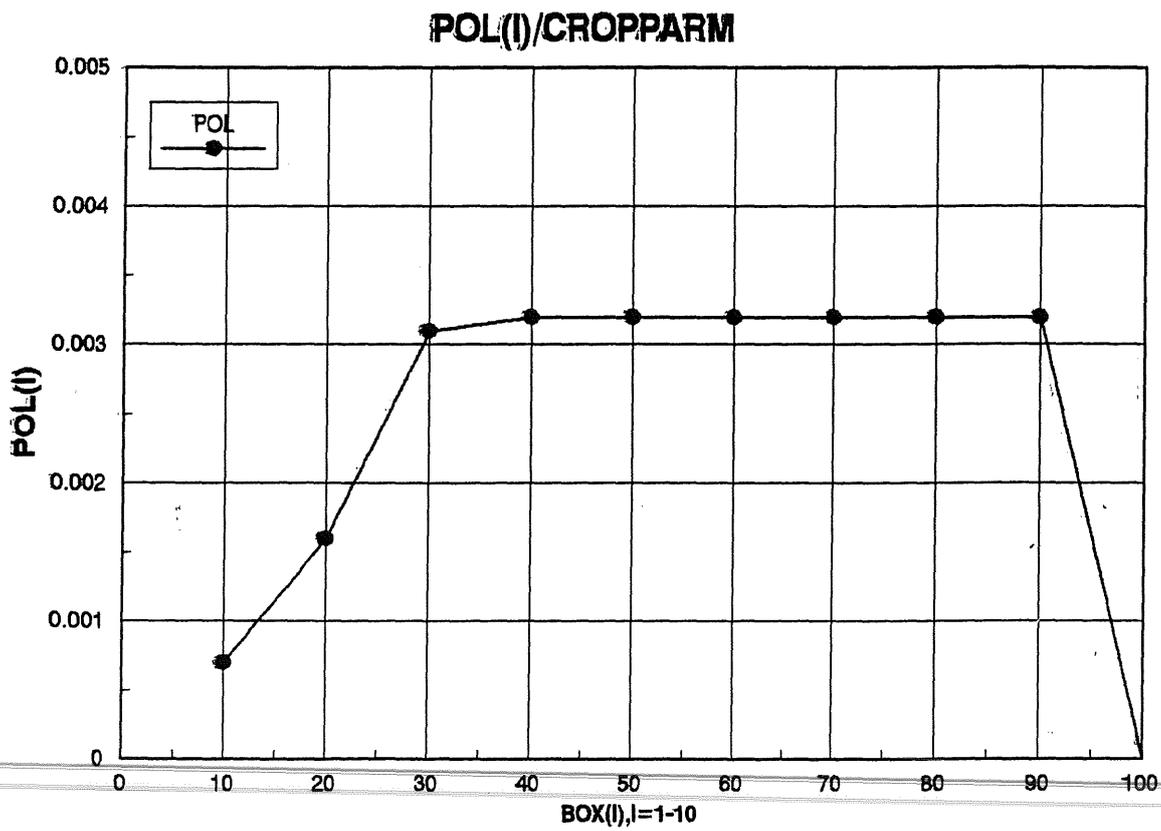


Figure 3 Potential leaf area expansion rate (POL in $\text{m}^2 \text{m}^{-2} \text{d}^{-1}$) as a function of leaf age class

Hence, development was normalized to a physiological time scale and there was little difference in the timing of development or maximum area of leaves among treatments. Using two physiological days between nodes and one truss per four nodes, it was estimated that leaf area expansion was completed after 56 physiological days (7 trusses) and that leaf abortion started after 72 physiological days (9 trusses). The area expansion rate as a function of truss number was calculated directly from these data and normalized to 100% development to describe the relation between potential area expansion rate and development. Specific leaf area (SLA, $\text{m}^2 \text{g}^{-1}$) varied from about 0.02 to 0.04 and linear functions were assumed to relate SLA to temperature and CO_2 concentration, to compute leaf sink strength in the model. LAI development was very similar for the high and low CO_2 levels, but at low night temperatures full canopy cover was reached about 10 days later. Figure 4 shows the calculated development of LAI for three treatments.

Individual fruits (starting after flower abortion and fruits were greater than 5 mm in diameter) developed toward maturity faster than leaves. The maximum rate of development was estimated at 0.032 per day, resulting in a minimum time to develop of 32 days under constant 28 °C temperatures. Figure 5 shows the time course of number of mature fruits for the 20/350, 12/350 and 20/950 treatments.

Sink strength of fruits was small when fruits were young and reached a maximum value of $0.27 \text{ g fruit}^{-1} \text{ d}^{-1}$. Sink strength was also assumed to depend on temperature, but more research is needed to quantify the functional relationship.

3.3. Discussion

The model developed in this study accurately predicted tomato growth and development under controlled conditions, for the range of temperatures and CO_2 concentrations tested. After determining model parameters using three of the treatments, results of the other combinations of temperature and CO_2 were predicted well by the model. In preliminary sensitivity analyses, the model simulated reductions in fruit yield of 30% over a growing period of 200 days, when the temperature regime changed from 28/16 °C day/night to 20/12 °C. An 18% increase in yield was simulated when CO_2 was increased from 350 to 950 $\mu\text{mol mol}^{-1}$ for 200 days, at temperatures of 28/16 °C. Further development and testing is needed to increase confidence in its applicability 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.

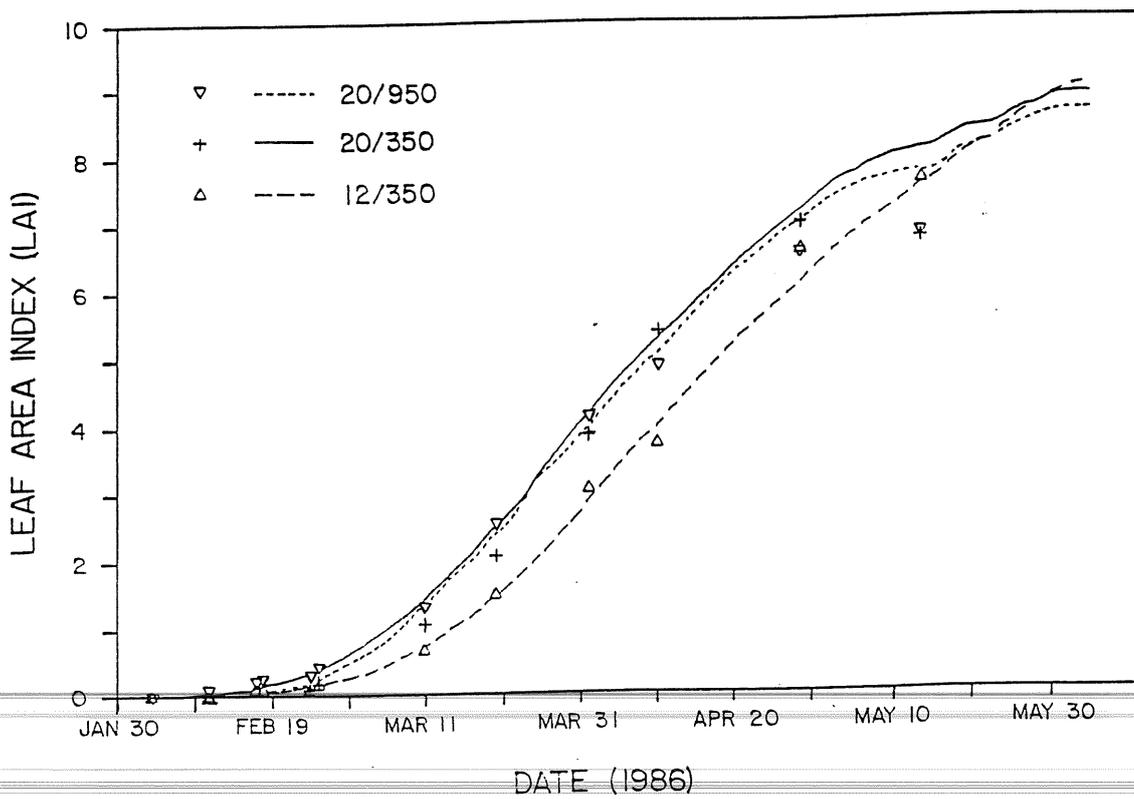


Figure 4 Simulated course of leaf area index for three treatments

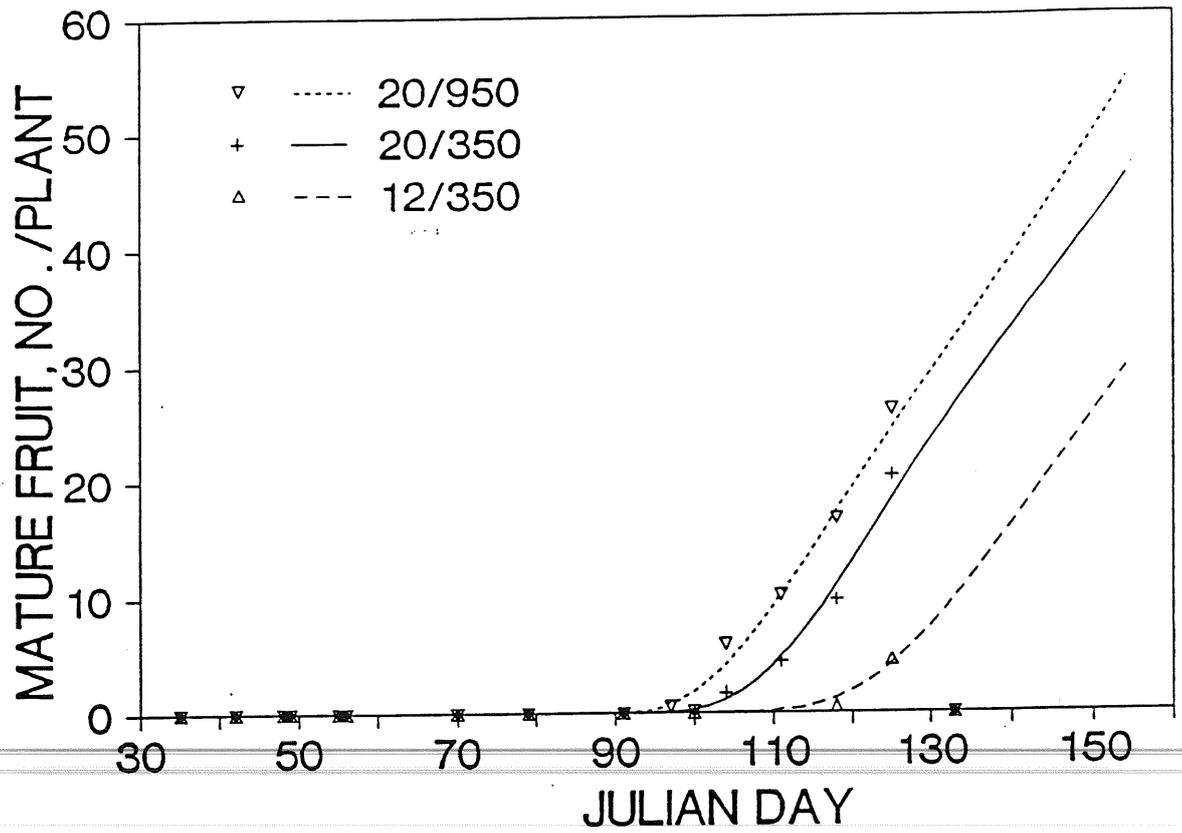


Figure 5 Measured number of mature fruits per plant under three temperature /CO₂ regimes for tomatoes grown under controlled conditions

4. Field calibration and validation of the model

E. Dayan¹⁾, H. van Keulen²⁾, J.W. Jones³⁾, I. Zipori⁴⁾, D. Shmuel⁴⁾ & H. Challa⁵⁾

4.1. Introduction

In Chapter 2 of this report, a tomato crop growth model was described, developed to simulate yield potentials under the specific conditions and agrotechnical practices of greenhouses in Israel, including varietal characteristics and climate control. One version of the model was calibrated on the basis of data collected under controlled conditions in Florida (Chapter 3), and was used for developing an economic optimization method (Seginer and Shina, 1989) and as a basis for a decision support system (Jacobson et al., 1987; Jones et al., 1988; 1989a; 1989b). In this chapter, field calibration and validation of the model are described.

4.2. Materials and methods

Development, calibration and validation of the model was based on data collected in commercial greenhouses at Habsor Experimental Station in Israel (31.16 NL, 32.24 EL), during the period 1979/83. These greenhouses, each with an area of about 600 m², consist of glass roofs, three double-layered polyethylene walls and one corrugated fibreglass wall. Each greenhouse comprises three bays, 9 m in width and 23 m in length. The height of the gutter is 3.2 m, that of the gable 5.5, with the orientation of the gutter and plant rows north-south. A sliding window, 1.5 by 2.0 m, is installed at the top of each gable, on the southern side. A 1.2 m fan with a ventilation capacity of about 40 000 m³ h⁻¹ is installed on the northern wall, facing the window. The three polyethylene walls can be opened by rolling up. Each greenhouse is equipped with a CO₂ injector with a maximum capacity of 20 kg h⁻¹ and with an air heater convector with a capacity of 0.756 MJ h⁻¹. In each greenhouse a blower is installed with a capacity of 80 000 m³ h⁻¹, that removes air from the inside and forces it back through perforated polyethylene tubes along the plant rows. Tomato seeds were sown in a nursery. Seedlings, at the age of three weeks were transplanted into the greenhouses at the beginning of October. Each greenhouse was divided into subplots planted with two indeterminate varieties: K-111 and K-121. Seedlings were planted in pairs of rows at distances of 0.4 m between rows in a pair and 1.5 m between the centers of two adjacent pairs. Distance between plants in the row was 0.45 m, resulting in 3 plants m⁻². Water and plant nutrients (N, P, K and micro elements) were applied through an

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automatically-controlled drip-irrigation system. Side shoots were removed weekly, so that plants consisted of a single stem. The plants grew along vertical wires till a height of 2.2 m, after which the stem was guided down till it reached ground level and was cut. Twice a week flowers were vibrated to promote pollination. Diseases and insects were controlled by application of pesticides.

Various climate treatments were imposed in the different greenhouses during different seasons:

- I. Control: During day-time, the side walls were rolled up and the gables opened, whenever greenhouse temperatures exceeded 27 °C or condensation occurred on the leaves. During night-time, starting about one hour before sunset, the greenhouses were fully closed.
- II. CO₂ enrichment, intermittent with ventilation: Whenever greenhouse temperatures were below 28 °C during day-time, CO₂ was injected, up to a level of 1000 µmol mol⁻¹. When temperatures exceeded 28 °C or condensation occurred, enrichment was stopped and ventilation started. CO₂ enrichment was applied from mid-November (appearance of the first fruits) until the end of March (end of the main growth period). Outside that period, the greenhouse was operated similarly to the control (Zipori et al., 1986).
- III. Heating to a constant night temperature: The day-time regime under this treatment was similar to the control. Minimum night temperatures, however, were maintained above 11 °C until the end of March.
- IV. Cooling: This was achieved by applying wet pads and forced ventilation, whenever greenhouse temperatures exceeded 28 °C.
- V. CO₂ enrichment combined with heating and cooling: A combination of treatments II, III and IV.

Weather data were collected in each greenhouse by means of sensors connected to a data-logger, (Campbell-CR5). Air temperature and humidity were measured through T-type thermocouples within aerated psychrometers, installed between the plants and PAR fluxes by Li-Cor LI190SA-type sensors installed above the canopy.

In each subplot, fresh fruit yields were estimated by weekly harvests of ripe fruits, picked from approximately 40 pre-selected plants. Each fruit sample was weighed and the number of fruits counted. Dry matter content was determined from sub-samples, after drying for several days at 65 °C. Fresh and dry weight of other plant parts were determined by monthly sampling of two to three plants per treatment. The plants were separated in leaves, stems, trusses and fruits, and each of the components weighed fresh. Dry weights were determined after drying at 65 °C for several days. Leaf area was determined on one of these plants through calibrated visual estimates.

Morphological development was recorded by monthly measurements on two pre-selected typical plants in each treatment. Plant length, total number of leaves, and number of dead and missing leaves, total number of trusses and trusses with flowers, and with fruits, were recorded separately. The rate of leaf appearance (1/plastochron) and leaf length were determined by measuring, every three to four days, one pre-selected leaf per sympodium on three pre-selected plants. Plastochron was derived from these data as the time interval between successive leaves reaching 2 cm length (Dayan, in prep.). Fruit growth rate was determined on the same plants by measuring the diameter of one pre-selected fruit per truss. During the growing season, approximately once per month, canopy net photosynthesis (P_n) rates were determined. Measurements were conducted during a continuous period of 36 hours under stable weather conditions (clear sky and low wind speeds). Air from the greenhouses and outside air were sampled continuously by means of sampling pumps. The air was dried and CO₂ concentration recorded by infrared gas analysis. Air exchange rate

between the greenhouse and the outside air were estimated by injecting N_2O into the greenhouse and monitoring its depletion by IRGA. Net photosynthesis rates, at three minute intervals, were calculated from the differences between inside and outside CO_2 concentrations and air exchange rate (Dayan et al., 1985).

4.3. Results

Calibration

The parameters and functions used for calibration of the model were derived from measurements in '85/'86 in the 'control' treatment of variety K-111. The photosynthesis rate under elevated CO_2 was determined in treatment II during the same growing season.

The photosynthesis model, based on Acock's photosynthesis equation (Acock et al., 1978), was calibrated using data collected in treatments I and II: The values of the light extinction coefficient (K) and the light transmission coefficient of leaves (m) were adopted from the work by Jones et al. (1989b). Measured values of leaf area index (LAI) and photon flux density were used. Dark respiration (R) was estimated by averaging CER-values during night-time. The parameters P_g (light-saturated photosynthesis rate of individual leaves, in $\mu mol CO_2 m^{-2} s^{-1}$) and Q_e (the quantum efficiency at low light intensities) in $\mu mol CO_2 \mu mol^{-1}$ (photons) (Dayan et al., 1993a) were estimated on the basis of CER (Carbon Exchange Rate) measurements under different photon flux densities within greenhouses on crops of different LAI under high and low ambient CO_2 . Best-fitting values for P_g and Q_e were derived using the optimization procedure PROC NLIN of SAS (SAS, 1979) for each measured light response curve.

The best fit between measured and calculated crop carbon exchange rates was achieved with a value for Q_e of 0.056 and values for P_g of 45 at $350 \mu mol mol^{-1} CO_2$ and of 200 at $1000 \mu mol mol^{-1} CO_2$, respectively (Fig. 6)

The relation between P_g and CO_2 -level derived from this procedure is given in Fig. 7.

An effect of ageing on P_g was introduced in the model, to account for the observed decrease in canopy photosynthesis at later stages of crop development (Schapendonk et al., 1990). Simulated canopy photosynthesis using these values, in comparison to measured values is illustrated in Fig. 8.

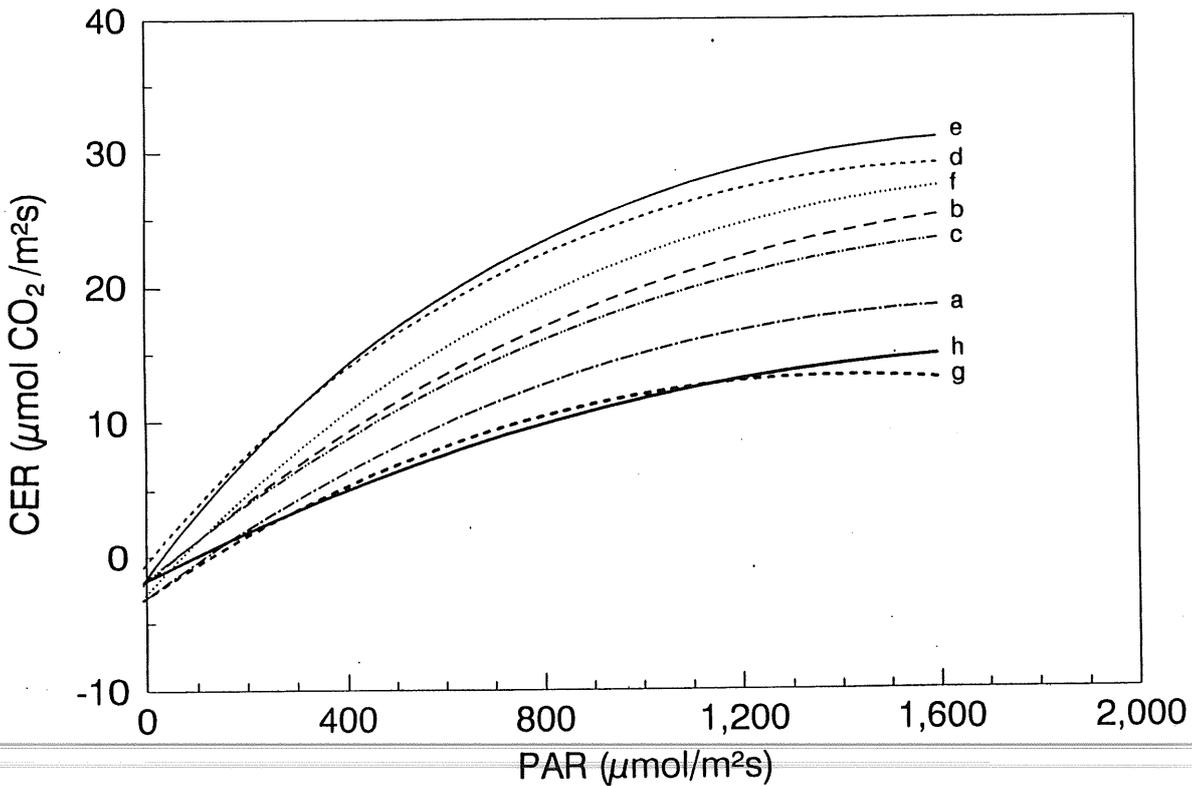
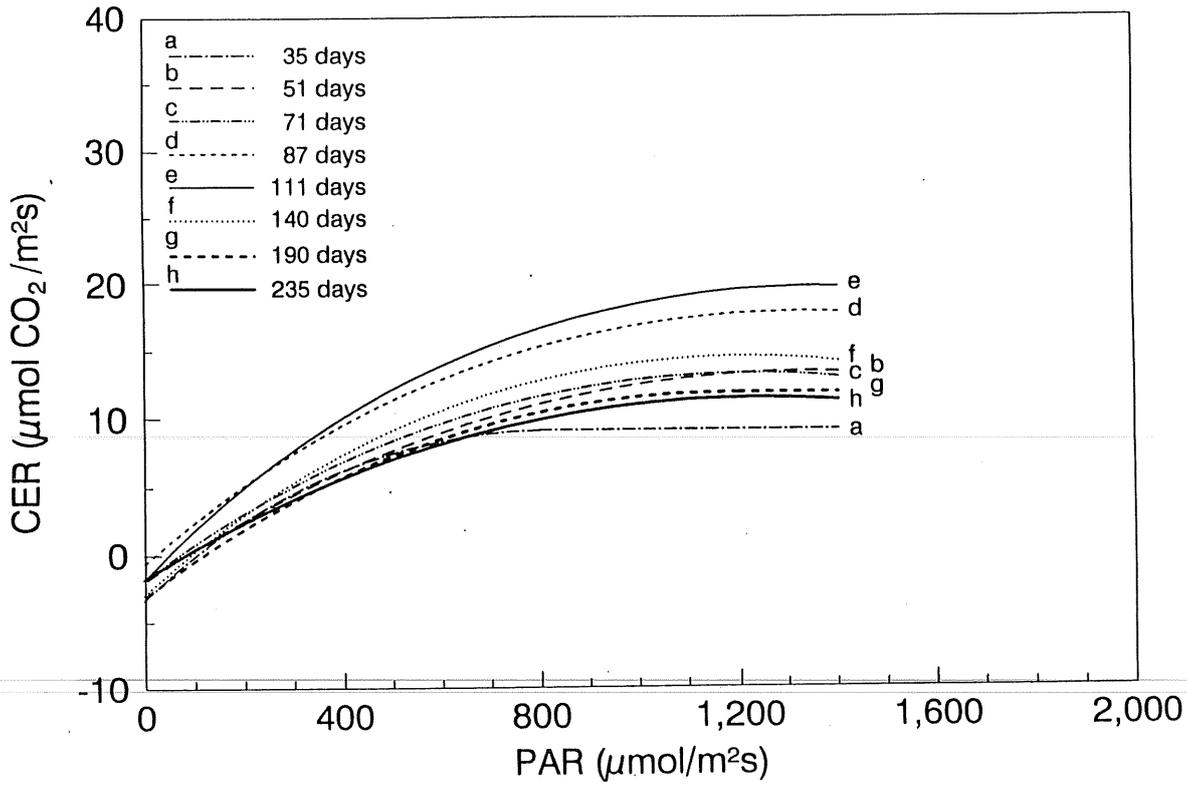


Figure 6 The fitted relation between carbon exchange rate (CER) and incident photosynthetically active radiation (PAR) for a tomato canopy at different days after planting. (a) at low CO₂ level, (b) at elevated CO₂ level

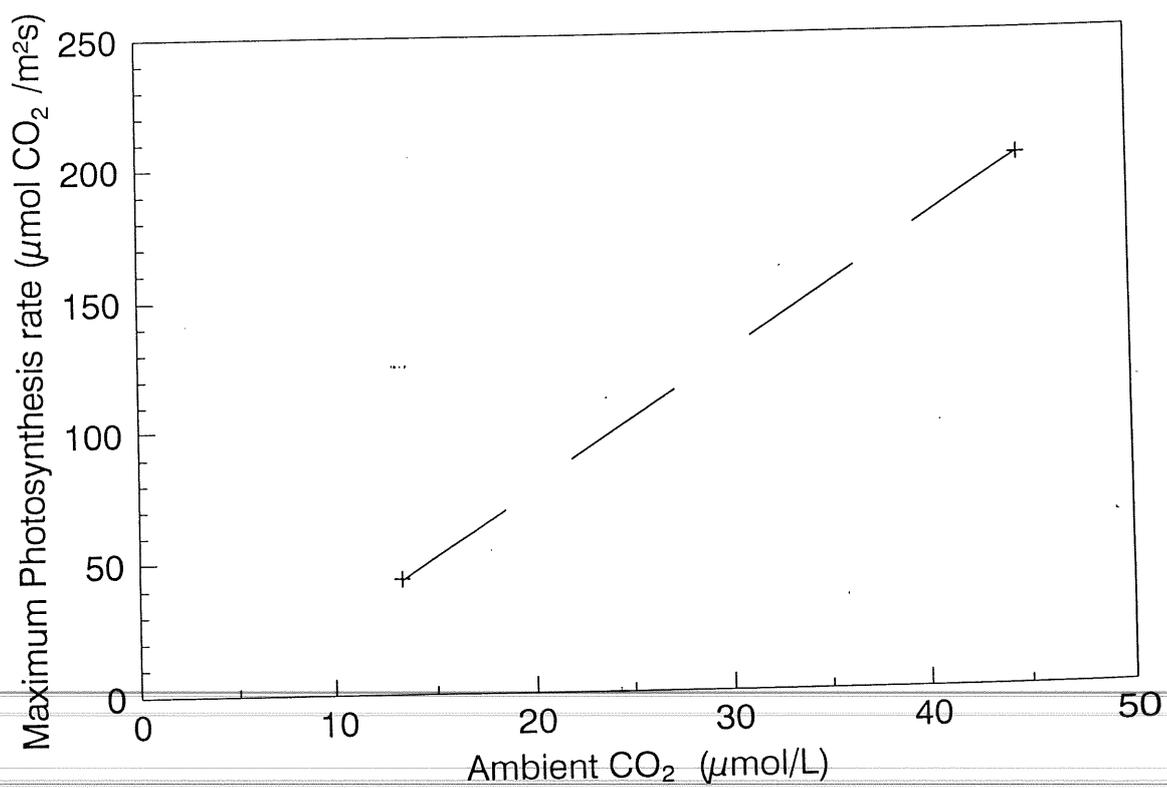


Figure 7 The relation between light-saturated gross canopy assimilation rate and ambient CO₂ level

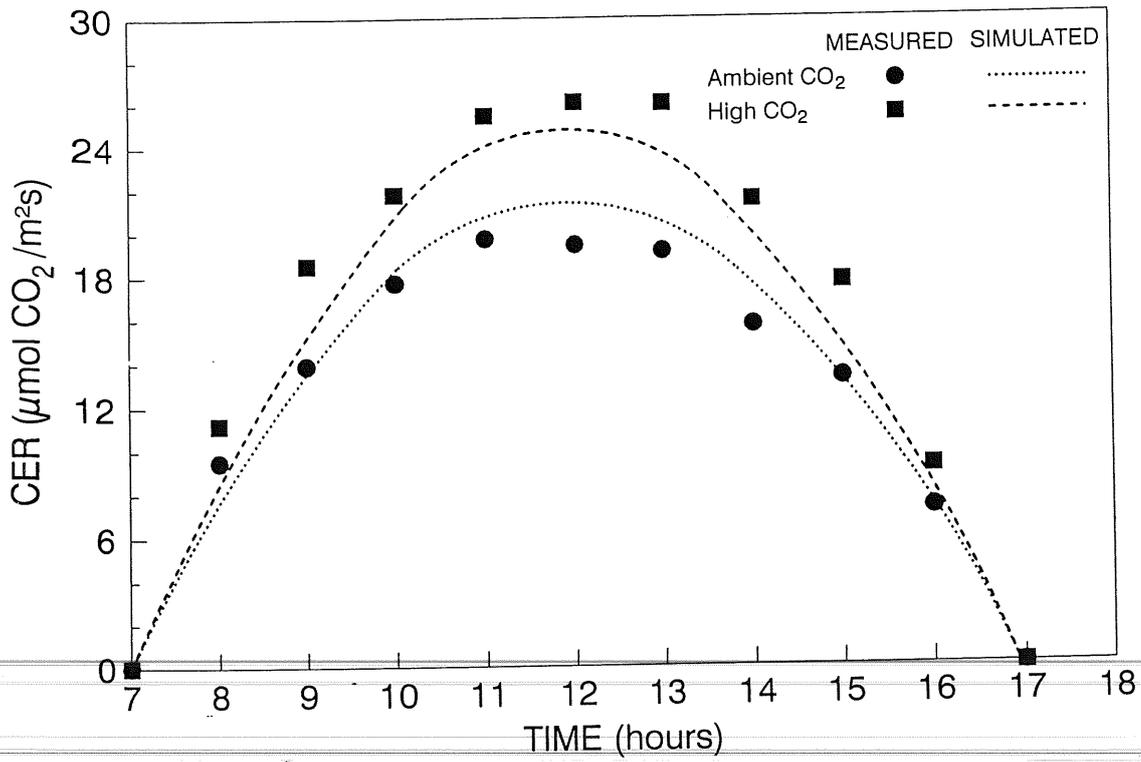


Figure 8 Measured and simulated CER at high and low CO₂ levels in the course of a typical day. (106 days after planting: Jan. 21, 1986)

The effect of temperature on maintenance respiration was described by an exponential function (Penning de Vries, 1975) with a Q_{10} of 1.4, hence somewhat lower than the value of 2, reported by Gosiewski et al. (1982).

The effects of temperature, light and CO_2 concentration on plastochron, fruit and leaf development rates, leaf expansion rate, and specific leaf area were derived from field measurements, assuming known biological response functions such as optimum functions, either minimum or maximum, or Michaelis-Menten or other rectangular hyperbolic functions (Goudriaan, 1979). The parameters describing the various response functions were derived through iterative procedures. As an example, the relative sink strength of each age group of organs was derived from the measured rate of change in leaf length and fruit diameter (Fig. 9).

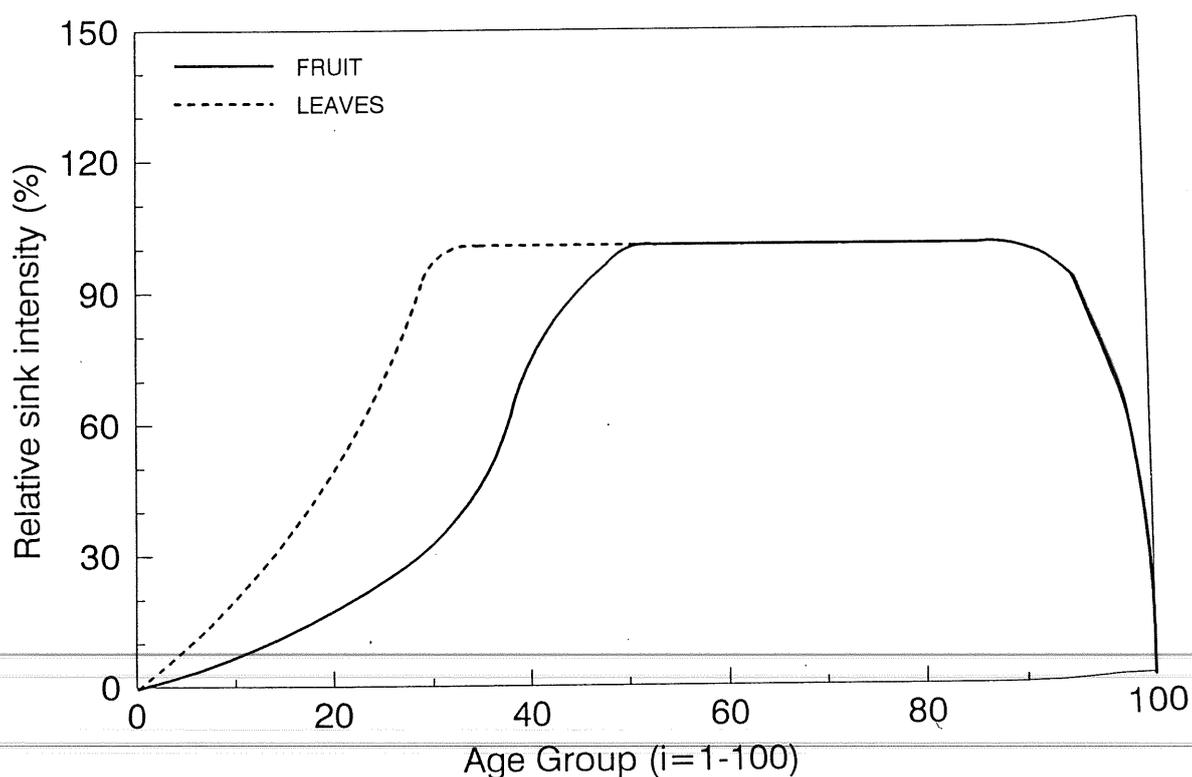


Figure 9 Relative sink strength of fruits and leaves as a function of physiological crop age

For fruit development, the basic observations were that it requires 65 days from flowering till maturity during summer time, i.e. under conditions of high temperatures and high radiation levels and 135 days during winter time, i.e. under low temperatures and low radiation levels. Elevated CO_2 levels accelerate the process. In the model, the effect of temperature on fruit development rate was defined as an optimum function (Fig. 10), that of CO_2 as a linear function.

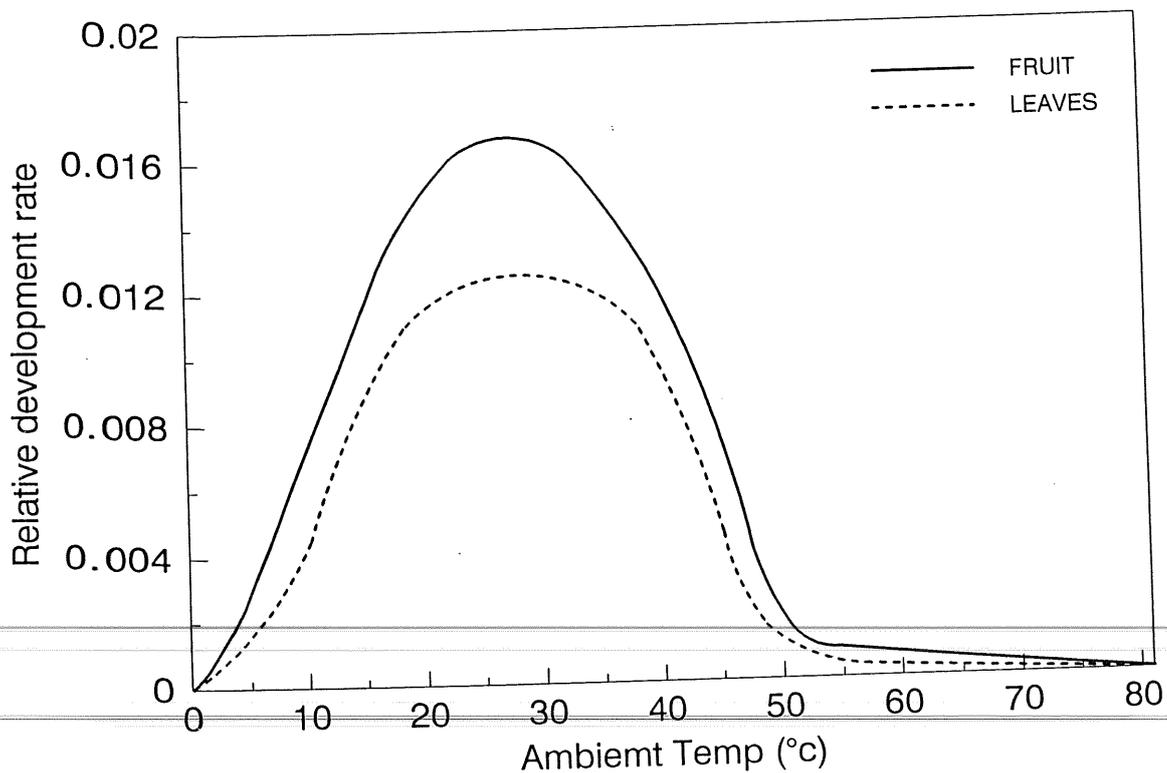


Figure 10 The effect of temperature on the rate of development of fruits and leaves

Another example refers to specific leaf area, for which typical values for winter-grown and summer-grown leaves are 0.024 and $0.075 \text{ m}^2 \text{ g}^{-1}$, respectively. Higher temperatures stimulate leaf area expansion, relative to assimilation, leading to thinner leaves. Radiation has the opposite effect, resulting in thicker leaves with increasing radiation levels, while high CO_2 concentrations, by stimulating assimilation, also lead to thicker leaves (Fig. 11). These response functions were assumed to be exponential and linear, respectively.

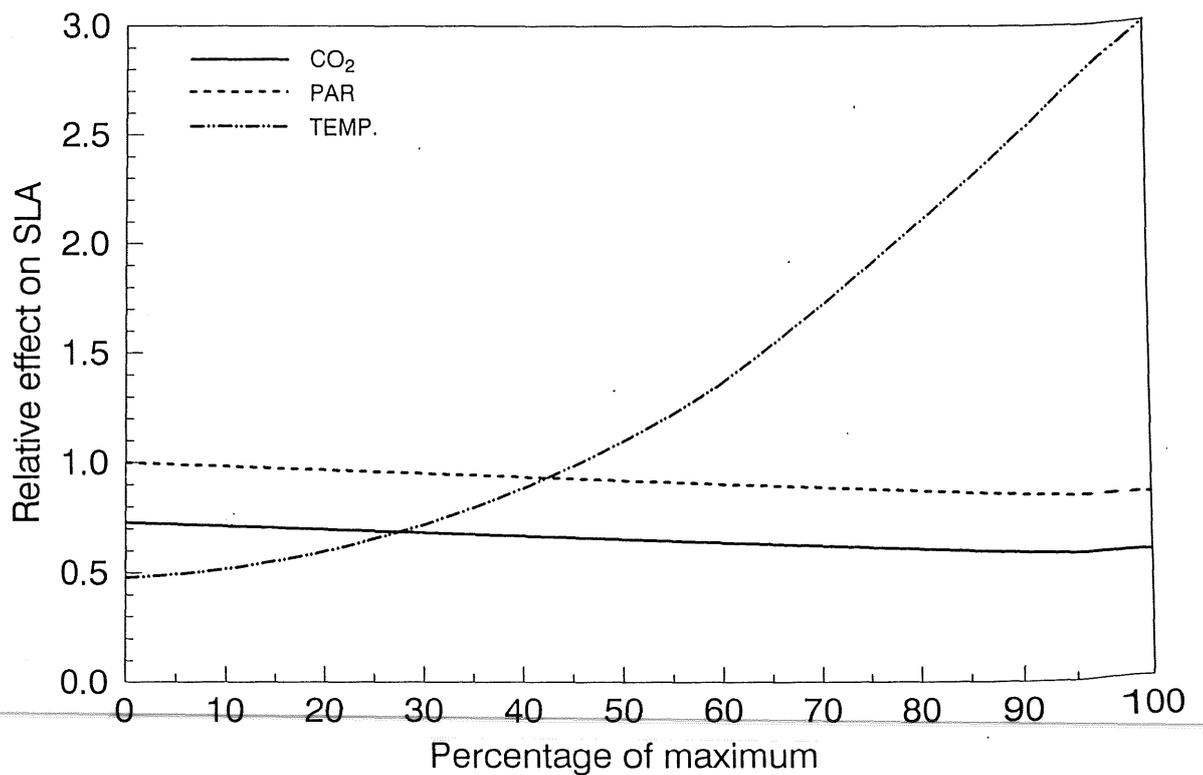


Figure 11 The relative effect of environmental conditions (PAR, temperature and CO_2 level) on specific leaf area (SLA)

The relations between physiological age and organ initiation rate, that between temperature and fruit set, that between temperature and truss splitting, and those between supply/demand ratio or temperature and relative rate of fruit abortion (Fig. 12), were all assumed to be linear.

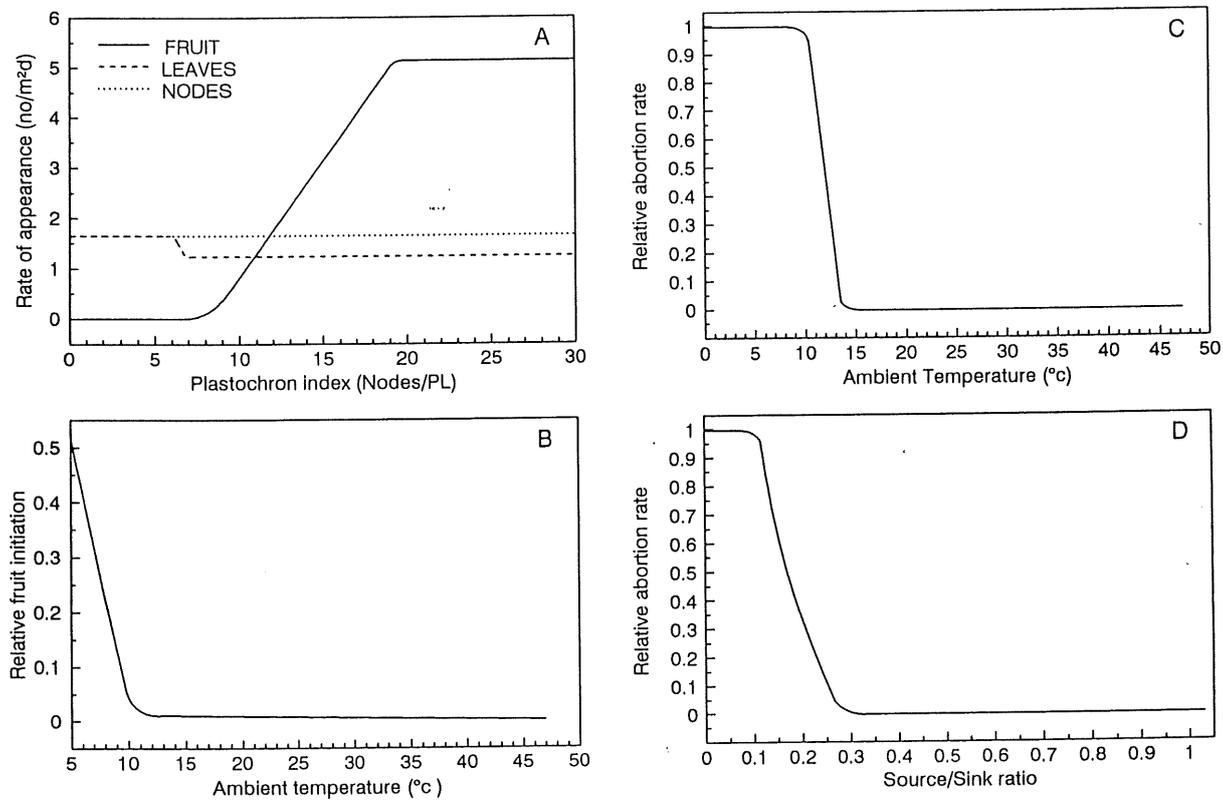


Figure 12 Physiological and environmental effects on number of fruits:

- A The effect of plastochron index on initiation of fruits, leaves and stem nodes
- B The effect of temperature on relative fruit initiation
- C The effect of temperature on relative fruit abortion rate
- D The effect of source/sink ratio on relative fruit abortion rate

Comparison of measured and simulated data

The degree of agreement between measured and simulated values varies for different crop characteristics (Fig. 13). Satisfactory agreement is obtained for total aboveground dry matter accumulation (Fig. 13A) and its distribution among the various organs, i.e. fruits, and vegetative parts. Also weight (Fig. 13B) and total number of fruits harvested (Fig. 13C) were satisfactorily predicted.

The agreement for total and live number (Figs 13F and 13G) and leaf weight (Figs 13D and 13E) is satisfactory until January, after which the simulated values for live leaves are much lower than those measured (Figs 13E and 13G). The reason is most likely that the criterion for distinguishing between live and dead leaves in the observations was not satisfactory, so that in fact, the recorded number of dead leaves is an underestimate.

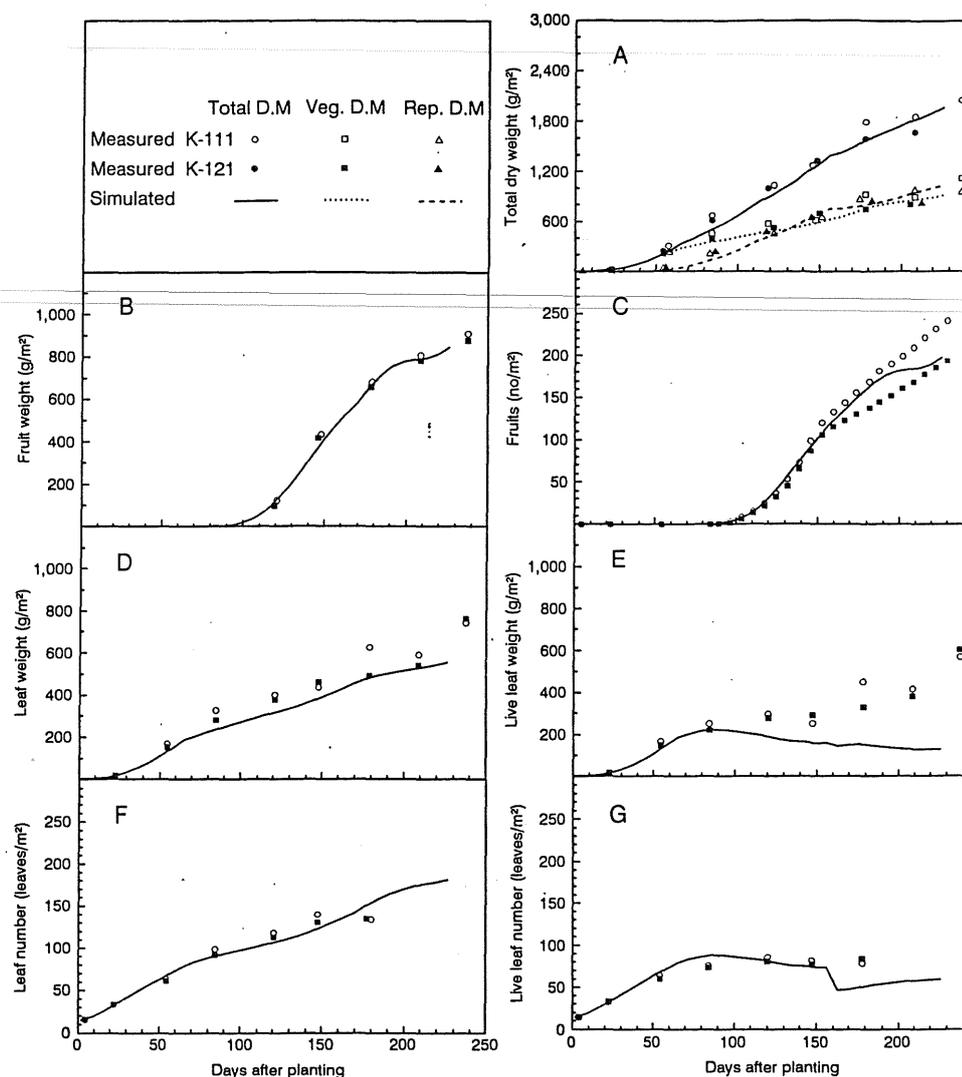


Figure 13 Comparison of measured and simulated values during the calibration phase:

- | | |
|---|--|
| A | Total dry matter accumulation, total fruit dry weight and dry matter accumulation in vegetative organs |
| B | Dry weight of harvested fruits |
| C | Number of harvested fruit |
| D | Total leaf dry weight |
| E | Live leaf dry weight |
| F | Total number of leaves |
| G | Number of live leaves |

The model satisfactorily reproduced the typical S-shaped curve for total aboveground dry matter accumulation (Fig. 13A). In the early stages of development most of the dry matter formed is invested in vegetative material (Fig. 13B), and with increasing age of the canopy, a gradual shift towards the fruits occurs (Fig. 13A). In December, growth of leaves and stems and probably also of roots, virtually ceases (Fig. 13A), coinciding with the period of maximum fruit number on the crop (Fig. 13A).

During March, after most of the fruits have been picked, dry matter accumulation in the vegetative parts resumes (Fig. 13B), albeit at a lower rate than expected for an indeterminate crop on the basis of the prevailing conditions of temperature and radiation and the green area of the canopy.

Comparison of the results of the control treatment for the varieties K-111 and K-121 shows no difference in total dry matter accumulation, but harvested fruit number (Fig. 13C) and fresh fruit yields differ.

Validation

Proper validation of the model requires comparison of model results with the results of independent experiments, not used during calibration (van Keulen, 1975). For that purpose, various experiments in Habsor were used, comprising different years, different treatments and different varieties. Various treatments: The results of the simulated validation

experiments for various treatments are very similar to those for the calibration experiment, i.e. satisfactory agreement between measured and simulated values for total dry matter accumulation and its distribution among the various crop organs, including weight and number of harvested fruits, and deviations with respect to leaf area dynamics, especially in the later part of the growing period.

Overall, simulated treatment effects are very similar to those observed. Heating during night-time causes accelerated fruit development, leading to two weeks earlier maturity and a slight reduction in fruit yield during the January/February period (Figs 14C and 14I).

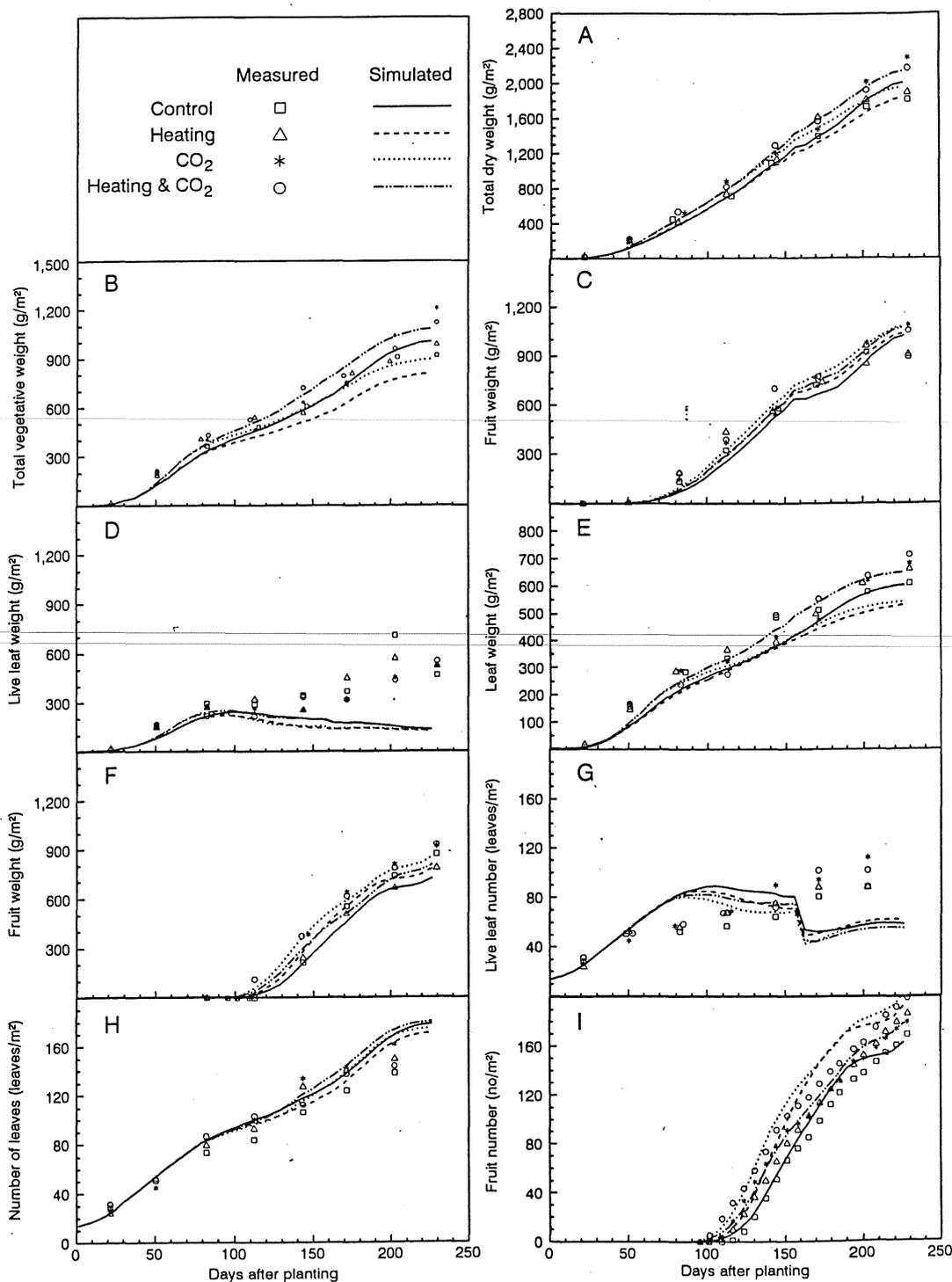


Figure 14 Comparison of measured (dots) and simulated (lines) values during the validation phase

- A Total dry matter accumulation
- B Dry matter accumulation in vegetative organs
- C Total fruit dry weight
- D Live leaf dry weight
- E Total leaf dry weight
- F Dry weight of harvested fruits
- G Number of live leaves
- H Total number of leaves
- I Number of harvested fruits

CO₂ enrichment also results in accelerated crop development, combined with a 15% increase in total dry matter production (Fig. 14A), and in the main growing season (150 days after planting), a 20% higher fruit yield (Fig. 14C), mainly as a result of higher fruit numbers (Fig. 14I). Combination of heating and CO₂ enrichment results in a synergistic effect, i.e. earliness is retained, as in each of the two treatments, but fruit yields are higher than under either of the two treatments.

The results of the simulations for the cooling treatment deviated from the measured results, for which no obvious explanation is at hand, but the high humidities associated with this treatment in the experiments may have interfered.

4.4. Discussion

Model calibration

Model application is very often hampered by the fact that appropriate parametrization requires too much effort in terms of manpower and investment, because complicated experiments under controlled conditions are necessary to establish the required functional relationships. Moreover, it has been shown, that plant behavior under variable and fluctuating field conditions is affected by adaptation mechanisms, that are not operative under controlled conditions (de Wit et al., 1978). This appeared to apply also to the present model, parametrized on the basis of experiments under controlled conditions, which satisfactorily reproduced the results of various experiments, also conducted under controlled conditions (Jones et al., 1989b), but not crop behaviour in the field situation. Therefore, an alternative approach was followed in this study, in which the shape of required basic physiological and phenological relationships (such as the temperature response of the light-saturated assimilation rate of individual leaves, or the temperature control of leaf initiation) was derived from detailed studies under controlled conditions, but the actual values of the parameters quantifying these relations were established in an iterative way on the basis of routinely collected data on morphological and physical crop characteristics (such as fruit number and dry matter accumulation) under variable field conditions.

This approach appears to be successful, and in general the selected crop characteristics were suitable for the purpose. However, the data underlying the description of leaf senescence appeared to be inaccurate, so that the model seemed to overestimate leaf senescence. However, at closer examination, it seems likely, that the morphological criterion used in the experiments to distinguish between live and senescent leaves was inaccurate.

Model validation

The principles underlying the present model, e.g. a quantitative description of the carbon balance of the whole crop, combined with a distribution pattern governed by sink/source interactions based on number and physiological age of its component parts, provide a realistic representation of the system. The parameter set derived on the basis of the results of the calibration experiments also resulted in satisfactory model behaviour in simulating completely independent validation experiments.

The model accounts for the major phenomena observed under Israeli field conditions during the traditional growing season, i.e. the successive waves of vegetative and reproductive growth, characterized by decreasing amplitudes with age of the crop, the response of the crop to variable and changing environmental conditions imposed in the various treatments and the mechanisms through which environmental conditions are operative.

Under common management practice, i.e. transplanting the seedlings at the beginning of October, the period of October/November is characterized by growth of vegetative organs, and initiation and setting of the fruits. In December and January, characterized by relatively low light levels, carbohydrate supply is a severe constraint for plant growth, and the increasing sink strength of the large number of growing fruits results in reduced carbohydrate availability for growth of the vegetative organs, including the roots. This limited carbohydrate availability also hampers fruit set. During February/March radiation gradually increases, leading to higher assimilate availability, so that vegetative growth resumes, followed after a lag period by resumption of fruit growth. However, the growth rates realized during this period are lower than those achieved in autumn, and below the values expected on the basis of environmental conditions (radiation and temperature) and green leaf area index. This is partly explained by the model, since total dry matter to be maintained is higher, and the photosynthetic capacity of the crop is lower. The latter is incorporated in the model as an age-dependent forcing function, derived from detailed simulations of daily photosynthesis (Schapendonk et al., 1990). An additional factor, not accounted for in the present model, maybe increased mutual shading of the crop, because plants reach their maximum height 120 - 150 days after planting (plastochron index about 50), after which the the youngest and most active leaves are added in downward direction (umbrella training-system). Moreover, the relatively restricted root system of the crop, a result of unfavourable growth conditions and severe competition during the winter period, may cause temporary water and/or nutrient shortages, unfavourably affecting assimilation, and resulting in susceptibility of the crop to diseases.

Heating at night-time accelerates crop development, leading to somewhat earlier harvest, with, however, hardly any increase in total fruit yield and lower total dry matter production. The main reason is that higher night-time temperatures result in higher respiration losses, in a situation where assimilate availability is already limiting. Moreover, higher temperatures lead to higher ratios of the number of vegetative to reproductive organs, and hence lower assimilate availability for the growing fruits. The consequently relatively higher assimilate availability for the vegetative parts, including the roots, however, may have a favourable effect on growth during spring.

Cooling during the hot day-time in autumn results in the model in delayed canopy development with its associated favourable effect on sink/source ratio. The lower yields recorded under the experimental conditions, may have been due to the high humidity, associated with the use of wet pads for cooling. Such high humidities may unfavourably affect fruit set and nutrient uptake, which has not been accounted for in the model.

CO₂ enrichment results in higher total dry matter production, especially during the early part of the growing period, when a relatively large proportion of the leaves operates at high light intensities, both because ambient radiation is high and mutual shading is limited. Later in the season, when growth takes place mainly in the reproductive organs, the impact of higher CO₂ concentrations is smaller as a larger proportion of the leaves operates at lower light intensities, and the crop may have adapted to elevated CO₂ concentrations (Kimball, 1983; Peet, 1985; Peet et al., 1985; Pharr et al., 1985; Zipori et al., 1986), so that the final effect on fruit yield is only modest. The adaptation mechanism is partly incorporated in the model, for instance through the effect of higher CO₂ concentrations on specific leaf area. Fruit yield under elevated CO₂ concentrations may also have been negatively affected by over-heating and high humidity, as a consequence of closure of the greenhouse during enrichment.

Under elevated CO₂ concentrations crop development is somewhat accelerated as a result of the effect of sink/source ratio on plastochron index and probably somewhat higher temperatures during closure of the greenhouse during CO₂ enrichment.

Combining CO₂ enrichment with night-time heating partly alleviates the severe constraint on assimilate availability, while retaining the advantage of accelerated canopy development. Hence, the effects on total fruit yield are additive.

5. Model application

A major advantage of a well-validated model is that it can help in analyzing the relative importance of the various factors, both genetic and environmental, that play a role in yield formation. Hence, it can be used to examine the effects of different genetic traits or management practices on crop production.

One example is the effect of supplemental heating on crop yield through extension of the growing period. As shown, that practice results in earlier harvest, albeit at the expense of total fruit yield in winter, but the associated greater vigour of the vegetative apparatus may allow maintenance of a healthy and productive crop further into spring, thus resulting in higher total fruit yields.

Another example is the synergistic effect of CO₂ enrichment and heating. Supplemental heating alone has a positive effect through earliness and extension of the growing period. However, it reinforces the positive effects of elevated CO₂ levels, and the combination is therefore favourable.

The model has also confirmed the deterioration of crop photosynthetic capacity during spring, for which no clear physiological explanation can be given. Further research is necessary to elucidate that phenomenon, which may be associated with the current canopy structure, as determined by management practices, or with inadequate root functioning. Improved insight could lead to formulation of alternative management practices or breeding goals.

The model could also be applied to establish optimum crop composition in terms of the number of vegetative and reproductive crop organs for specific production targets, e.g. fruit size or length of the growing period. This could lead to the formulation of optimum management strategies with respect to, for instance, pruning of leaves or fruits.

6. Further model development

The applicability of the model could be extended and the quality of its results improved, by incorporating additional processes and crop characteristics. For example, by combining the rate of leaf and stem node appearance with information on stem node length, it would be relatively easy to arrive at a more detailed description of canopy architecture. This in turn could form the basis for a more refined description of canopy photosynthesis as well as for incorporation of a canopy energy balance, in combination with an energy balance for the greenhouse as a whole.

Root growth is treated in the model rather rudimentary, hence a more detailed description is required that allows evaluation of the capacity of the root system to supply the required water and nutrients for optimum crop functioning.

Incorporation of effects of air humidity on crop growth and transpiration, fruit set, and possibly other relevant processes, would allow extension of its applicability to also include aspects of fruit quality.

7. Conclusions

It has been shown in this report, that a model, calibrated on the basis of results of experiments under field conditions, can be used to predict the effects of environmental conditions and management practices on tomato yield, both quantitatively and qualitatively. The procedure, in which logical response functions are introduced, and the parameters are derived through iterative procedures, based on 'standard' observations in field crops, yields satisfactory results. Several characteristics and processes have not been incorporated in the model or are treated in a very simplified way, and applicability of the model could be widened by further development.

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Appendix A:

Instructions for running the model

D. Shmuel

RUNNING THE COMPILED MODEL

For running the compiled model, the following files should be present:

TOMGRO.EXE	-	the compiled model
FILE1	-	weather and geographical data (Appendix D1)
MGT.TOM	-	crop management data, such as planting distances, etc. (Appendix D2)
CROPPARAM.TOM	-	crop characteristics, such as response curves to temperature, radiation, etc. (Appendix D3)
COMMON.TOM	-	a list of the subroutines (Appendix D4)

To run the model, type 'TOMGRO'.

You will be prompted by the question:

'Do you want a constant environment?'

If you want to test crop response to constant environmental conditions, type 'Y'. If you want the varying conditions of FILE1, type 'N'.

After environment selection, you will be prompted by:

'Enter treatment number'

Type '1' as a reply. The simulation run will then be started. When simulation is terminated, you will be prompted by the question:

'Do you want to simulate more?'

Type 'Y' or 'N', according to choice.

COMPILATION OF TOMGRO

This procedure starts from the main program and 11 subroutines, in alphabetical order. A specific subroutine can be compiled with the command:
FL /c subroutine NAME.FOR

To compile the complete model, replace 'NAME.FOR' by '*'.

The compiled subroutine(s) are linked with the command:

L [ENTER]

Appendix B:

List of subroutines and flow chart of the model

LIST OF SUBROUTINES

- | | | |
|-----|----------|---|
| 1. | TOMGRO: | Main program, controls all other subroutines. |
| 2. | DEVFAST: | Calculation of daily development rates of leaves, fruits and stems. |
| 3. | DEVSTAT: | Calculation of rates of appearance of nodes, leaves and fruits and rates of material flow between age classes. |
| 4. | DMRATE: | Calculation of dry matter partitioning and accumulation in each age class of each component. |
| 5. | GHOUSE: | Calculation of temperature and radiation regimes inside the greenhouse. Currently a 'dummy' subroutine, that can be replaced by a physical greenhouse model. |
| 6. | INITIAL: | Initialization of state variables for each age class of each component. |
| 7. | INPUT: | Defines values for each parameter within the model from the data files MGT and CROPPARM. |
| 8. | INTGRAT: | Integration routine for LAI, dry matter content and numbers for each component of the plant, i.e. leaves, fruits and stems. Technically implying integration of each state variable of each age class of each state variable. |
| 9. | IPWTH: | Input of weather data. |
| 10. | LOSRATE: | Calculation of death rates of leaves and the associated loss of dry matter, LAI, and numbers of leaves from each age class. |
| 11. | OUTPUT: | Creation and saving of output file 'OUT1'. |
| 12. | PHOTO: | Calculation of photosynthesis rates, using Acock's equation at each time interval of the fast time loop. |
| 13. | RESP: | Calculation of maintenance respiration from leaf weights, stem weights, Q10 values and temperature. |

B-2

14. **SUNRISE:** Calculation of daylength and times of sunrise and sunset from latitude and Julian calendar day number.
 15. **WCALC:** Calculation of temperature and radiation intensity at each time interval of the fast loop.
 16. **TABEX:** Interpolation function: TABEX (VAL, ARG, DUMMY, K). K values of ARG are defined for the abscissa and K values of VAL for the ordinate. DUMMY is the relevant value of the independent variable to obtain a value for the independent variable with TABEX.
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-
-
-

Appendix C:

Listing of Tomgro

```

$STORAGE:2
C*****+++***** TOMGRO V 1.0
*****
C      MAIN PROGRAM FOR THE TOMATO MODEL*
C      DEVELOPED BY E. DAYAN, J. W. JONES, H. VAN KEULEN, AND H. CHALLA *
C      DECEMBER 1990 *
C*****
$INCLUDE: 'COMMON.TOM'
      COMMON/PLT/PLTM2V
C
C      BEGIN SIMULATION
      IRUNNUM=0
10  IRUNNUM=IRUNNUM + 1
      DO 20 I = 1,25
20  HOURS(I) = I-1.
      WRITE(*,*) '  SIMULATION BEGINS.....PLEASE WAIT'
C
C      READ INPUTS
      CALL INPUT
C
C      SET INITIAL CONDITIONS
      CALL INITIAL
C
C
      DO 1000 JDAY=1,NDAYS
      PLTM2V = 22
      IF(JDAY .GT. 10) PLTM2V = 15.5
      IF(JDAY .GT. 17) PLTM2V = 11.0
      IF(JDAY .GT. 21) PLTM2V = 8.5
      IF(JDAY .GT. 36) PLTM2V = 7.0
      IF(JDAY .GT. 45) PLTM2V = 6.5
      IF(JDAY .GT. 57) PLTM2V = 6.0
      IF(JDAY .GT. 66) PLTM2V = 5.0
      IF(JDAY .GT. 84) PLTM2V = 4.0
      IF(JDAY .GT. 100) PLTM2V = 3.0
C
C*****
      PLTM2V = 1.0
C*****
      TIME=(JDAY-1)*DELT
      START = NSTART
      DATE=AMOD(TIME+START,365.)+1.0
C

```

C-2

```

C      CALL WEATHER INPUT, 1 DAY AT A TIME
      CALL IPWTH
C      ALSO COMPUTE 24-H WEATHER VARIABLES FOR FAST LOOP
      CALL WCALC

C
C      INITIALIZE VARIABLES THAT ARE ACCUMULATED IN THE COURSE OF THE DAY
      GP=0.
      MAINT=0.
      GENR=0.
      TEMFAC = 0.
      RDVLV=0.
      RDVFR=0.
      FCO2D = 0.
C      VARIABLES FOR SLA CALCULATIONS
      NCSLA = 0
      TSLA = 0.
      CSLA = 0.
C      VARIABLES FOR TEMPERATURE EFFECT ON FRUIT SET
      TTH = 0.
      TTL = 0.
      TTAB= 0.
c      WRITE(*,130)TIME,TFAST,TTAB,TTABF
C
C      FAST LOOP
      DO 100 JF=1,NFAST
C      TFAST IS CURRENT TIME (h) DURING A DAY IN THE FAST LOOP
      TFAST = (JF-1)*24./NFAST
C      CALL SUBROUTINES THAT COMPUTE RATES WITHIN A DAY, IN THE
C      FAST LOOP
C
      CALL GHOUSE
      CALL DEVFAST
      CALL PHOTO
      CALL RESP
      GPFN=(GPF-MAINTF)*GREF
c      WRITE(*,130)TIME,TFAST,GPFN,PMAX,CO2L
130  FORMAT(2X,5(1X,F8.1))
C
C      INTEGRATION OF VARIABLES WITHIN A DAY, WITHIN THE FAST LOOP
      GENR=GENR+GENRF*DFAST
      TEMFAC = TEMFAC + TEMFCF*DFAST
      RDVLV=RDVLV+RDVLVF*DFAST
      RDVFR=RDVFR+RDVFRF*DFAST
      TTH = TTH + TTHF * DFAST
      TTL = TTL + TTLF * DFAST
      TTAB= TTAB+TTABF*DFAST
C      WRITE(*,130)TIME,TFAST,TTAB,TTABF
      FCO2D = FCO2D + FCO2 * DFAST
C
      TSLA = TSLA + TSLAF * DFAST

```

```

        CSLA = CSLA + CSLAF
C
        GP=GP+GPF*DTPFAST
        MAINT=MAINT+MAINTF*DTPFAST
100  CONTINUE
C
C        WRITE (*, 650) JDAY, JF, XLAI, TAVG, SOLRAD*TRGH, PAR, GP, MAINT
C 650  FORMAT(' JDAY, JF, XLAI, TAVG, RAD, PAR, GP, MAINT' , /,
C      &2I6, 6F10.4)
C        WRITE (*, 660) TIME, GENR, TEMFAC, FCO2D, CLSDML, GENFAC
C 660  FORMAT(2X, 6(1X, F9.3))
C
C        COMPUTE AVERAGE EFFECT OF CO2 ON SLA AND LEAF EXPANSION DURING DAY
        IF(NCSLA .EQ. 0) THEN
            CSLA = 1.0
        ELSE
            CSLA = CSLA / NCSLA
        ENDIF
C
C        RESTRICT TEMPERATURE EFFECT ON SLA (TSLA) TO EXCEED 0.1
        TSLA = AMAX1(TSLA, 0.1)
C
C        CALL DMRATE
C
C        CALL DEVRATE
C
C        CALL LOSRATE
C
C        IF(JDAY.NE.1) GOTO 200
190  WRITE(*, *) ' ENTER TREATMENT NUMBER:'
        READ(*, *, ERR=190) ITRTNUM
        IF(ITRTNUM.LT.1.OR.ITRTNUM.GT.20) GOTO 190
        WRITE(*, *) ' SIMULATION CONTINUES...PLEASE WAIT'
200  CONTINUE
C
C        CALL INTGRAT
C
C        IF(((JDAY-1)/INTOUT)*INTOUT .NE. (JDAY-1)) GO TO 300
        CALL OUTPUT
C
300  CONTINUE
C        WRITE(*, 444) JDAY, TIME, LVSN(1), WLVS(1), ASTOTL, XLAI, PLSTN
C444  FORMAT(' M', I4, 6(2X, F8.2))
C        WRITE(*, 445) TIME, ASTOTL, XLAI, PLSTN, AEF
C 445  FORMAT(4X, 5(1X, F9.2))
C
1000 CONTINUE
        WRITE(*, *) ' SIMULATION ENDS'
C
        CLOSE(9)

```

C-4

```
CLOSE(10)
CLOSE(11)
WRITE(*,*) ' DO YOU WANT TO SIMULATE MORE?'
WRITE(*,*) '      Y or N? [DEFAULT "N"]'
READ(*,1200)ANS
1200 FORMAT(A1)
IF(ANS.EQ.'y'.OR.ANS.EQ.'Y')GOTO 10
CLOSE(15)
STOP
END
```

DEVFAST.FOR

\$STORAGE:2

SUBROUTINE DEVFAST

C \$INSERT COMMON.TOM

\$INCLUDE: 'COMMON.TOM'

C

C WRITE(*,*) ' AT TOP OF DEVFAST, DAY, H = ',TIME,TFAST

C

C COMPUTE FACTORS FOR DEVELOPING LEAF THICKNESS (SLA)

C AND FOR CO2 EFFECT ON DEVELOPMENT

C TEMPERATURE EFFECT

TSLAF = 1.0 + 0.045 * (24. - TMPA)

C TSLAF = 1.0 + 0.085 * (28. - TMPA)

C CO2 EFFECT ON SLA

CSLAF = 0.

FCO2 = 1.0

IF (PPFD .GE. 0.1) THEN

NCSLA = NCSLA + 1

C CSLAF = 1. + 0.51 * (CO2AVG-350.)/(950.-350.)

C CSLAF = 1.5 + 0.51 * (CO2AVG-350.)/(950.-350.)

CSLAF = 1.5 + CO2M * (CO2AVG-350.)/(950.-350.)

C

C SCO2 = RELATIVE INCREASE IN DEVELOPMENT RATE DUE TO CO2 BEING

C HIGHER THAN 350 vpm, FCO2 = SCO2*(CO2AVG-350.)

C FCO2 = 1.0 + SCO2 * (CO2AVG - 350.)*AMIN1(1,20/PLSTN)

ENDIF

C

C COMPUTE PLASTOCHRON DEVELOPMENT RATE, GENRF

TEMFCF=TABEX(GENTEM,XTEM,TMPA,6)

C

C GENRF=TEMFCF*GENFAC*CLSDML*TABEX(GENRAT,XGEN,PLSTN,6)*FCO2

C GENRF=AMIN1(AMAX1(EPS,CLSDML)/GENFAC,1)*FCO2*TEMFCF*

C &TABEX(GENRAT,XGEN,PLSTN,6)

C GENFAC ENABLES TUNING OF CLSDML; THE LOWER ITS VALUE, THE SMALLER IS

C THE EFFECT OF CLSDML.

GENRF=AMIN1(AMAX1(EPS,CLSDML)/GENFAC,1)*TEMFCF*

&TABEX(GENRAT,XGEN,PLSTN,6)

C WRITE(*,110) TIME,GENRF,CLSDML

C 110 FORMAT(4X,3(2X,F9.3))

C COMPUTE LEAF AND FRUIT DEVELOPMENT (AGEING)

RDVLVF=TABEX(RDVLVT,XLV,TMPA,9)*SPTTEL*FCO2

C

RDVFRF=TABEX(RDVFRF,XFRF,TMPA,9)*SPTTEL*FCO2

C

C COMPUTE INSTANTANEOUS EFFECT OF TEMPERATURE ON FRUIT SET

C-6

```
TTHF = 0.  
TTLF = 0.  
TTABF= 0.  
  IF (TMPA .GT. THIGH) TTHF = TMPA-THIGH  
  IF (TMPA .LT. TLOW)  TTTF = TLOW-TMPA  
  IF (TMPA .LT. TLOWAB) TTABF=TLOWAB-TMPA  
C   IF (TMPA .GT. THIGH) TTHF = AMIN1 (TMPA-THIGH, TTMX) /TTMX  
C   IF (TMPA .LT. TLOW)  TTTF = AMIN1 (TLOW-TMPA, TTMN) /TTMN  
C  
C   WRITE (*, 111) TIME, TLOWAB, TTABF  
C 111 FORMAT (4X, 3 (2X, F9.3))  
  
C  
  RETURN  
  END
```

DEVRATE.FOR

\$STORAGE:2

SUBROUTINE DEVRATE

C

\$INCLUDE: 'COMMON.TOM'

C

C ACCOUNT FOR NODE TO FIRST TRUSS

TPLA = 0.

IF (PLSTN .GE. FTRUSN) TPLA = TPL

C

C COMPUTE RATE OF LEAF AND STEM APPEARANCE (NO. /M2-DAY)

RCNL = PLM2*GENR / (1.0+TPLA)

RCST = PLM2*GENR

C

C COMPUTE RATE OF FRUIT APPEARANCE (NO. /M2-DAY)

RCNF = GENR*TABEX (FPN, XFPN, PLSTN-FRLG, 10) *PLM2

C

RCNF = RCNF * CLSDMF

C

RCNF = RCNF*AMAX1 (1.-TTH/TTMX, 0.) *AMAX1 (1.-TTL/TTMN, 0.)

C

TTL ACCOUNTS FOR TRUSS SPLITTING

RCNF = RCNF*AMAX1 (1.-TTH/TTMX, 0.) *AMAX1 (1.+TTL/TTMN, 0.)

C

WRITE (*, 110) TIME, RCNF, TTL,

1.+TTL/TTMN, AMAX1 (1.+TTL/TTMN, 0.)

C 110 FORMAT (4X, 5 (2X, F8.2))

C

TTH AND TTL ACCOUNT FOR HIGH AND LOW TEMP EFFECTS ON FRUIT

C

SET, RESPECTIVELY

C

C

COMPUTE COHORT DEVELOPMENT RATES

PUSHL = RDVLV*NL

PUSHM = RDVFR*NF

C

RETURN

END

DMRATE.FOR

\$STORAGE:2

SUBROUTINE DMRATE

\$INCLUDE: 'COMMON.TOM'

COMMON/PTL/PLTM2V

```

C
C COMPUTE SPECIFIC LEAF AREA GROWTH FACTOR BASED ON DAILY PAR
C PARSLA = (SLAMN+(SLAMX-SLAMN)*EXP(-0.0471*PAR))/SLAMX
C FROM AROUND RUN 31 TO 50 WE USED THE FOLLOWING PARSLA EQUATION:
C PARSLA = 1-(0.0005*PAR)
C PARSLA = 1-(ZBENG*PAR)
C IN EARLIER RUNS THE FOLLOWING EQUATION HAD BEEN USED:
C PARSLA = 1-(0.001*PAR)
C FROM RUN 50 ON THE FOLLOWING PARSLA:
C NOW COMPUTE OVERALL EFFECT OF ENV ON SLA, ESLA
C STDSL A IS NORMAL SLA AT 24 C, 350 CO2, LOW PAR VALUES (0.0), m2/g
C PARSLA = 1-TABEX(PART,XPART,PAR,5)
C ESLA = STDSL A * PARSLA / (TSLA * CSLA)
C ESLA = AMAX1(0.018,ESLA)
C ESLA = AMIN1(SLAMX,ESLA)
C WRITE(*,710) TIME,ESLA,TSLA,CSLA,PARSLA,PAR,ZBENG
C 710 FORMAT(4X,7(2X,F9.4))
C
C COMPUTE TOTAL DRY WEIGHT GROWTH
C TRCDRW=(GP/PLTM2V-MAINT)*GREF
C TRCDRW = AMAX1(TRCDRW,0.0)
C ACCOUNT FOR ROOT PARTITIONING, PROOT
C RCDRW=TRCDRW*
C & (1-(TABEX(PROOT,XROOT,PLSTN,6)))*
C & (AMIN1(AMAX1(EPS,CLSDML)/ZBENG,1))*TEMFAC
C WRITE(*,720) TIME,RCDRW,TRCDRW,CLSDML,TEMFAC
C 720 FORMAT(4X,5(1X,F9.3))
C COMPUTE SINK STRENGTH OF LEAVES, FRUIT
C WLVS(I) INCLUDES WT OF PETIOLES AND STEM, LFAR(I) INCLUDES AREA ONLY
C
C PTNLVS=0.
C PTNSTM = 0.
C DO 20 I=1,NL
C XBOX = I*100./NL
C RCLFA(I) = LVSN(I)*TABEX(POL,BOX,XBOX,10)*TEMFAC*FCO2D
C ACCOUNTS FOR PETIOLES AND STEM GROWTH WITH EACH INCREMENT OF
C LAI GROWTH
C FRPT = TABEX(FRPET,BOX,XBOX,10)
C FRST = TABEX(FRSTEM,BOX,XBOX,10)
C
C PNLVS(I) = (RCLFA(I) / (TABEX(ASLA,BOX,XBOX,10)*ESLA)) * (1.+FRPT)
C PTNLVS=PTNLVS+PNLVS(I)
C PNSTM(I) = PNLVS(I) / (LVSN(I)+EPS)*FRST*STMS(I)
C PTNSTM = PTNSTM + PNSTM(I)

```

```

20 CONTINUE
C
PTNFRT=0.
DO 21 I=1,NF
ZZX=AMIN1(1,AMAX1(EPS,2.0-AVWF(I)/AVFM))
XBOX = I*100./NF
PNFRT(I)=FRTN(I)*TABEX(POF,BOX,XBOX,10)*TEMFAC*FCO2D*ZZX
C   AMIN1(1,AMAX1(EPS,2.0-AVWF(I)/MAVF))
PTNFRT=PTNFRT+PNFRT(I)
21 CONTINUE
C
C COMPUTE TOTAL DEMAND (SINK STRENGTH)
PNGP=PTNLVS+PTNFRT+PTNSTM
C
C TOTAL FRUIT GROWTH RATE(TOTDMF) AND LEAF GROWTH RATE(TOTDML)
C   LIMITING GROWTH TO SINK STRENGTH
TOTDML=AMIN1(RCDRW*PTNLVS/(PNGP+EPS),PTNLVS)
TOTDMS=AMIN1(RCDRW*PTNSTM/(PNGP+EPS),PTNSTM)
TOTDMF=AMIN1(RCDRW*PTNFRT/(PNGP+EPS),PTNFRT)
C
TOPGR = TOTDMF + TOTDML + TOTDMS
EXCESS = RCDRW - TOPGR
C
C COMPUTE PROPORTION OF FRUIT DEMAND THAT IS MET TODAY
CLSDFM = 1.0
IF (PTNFRT .GT. 0.0) CLSDFM=TOTDMF/(PTNFRT+EPS)
C
C COMPUTE PROPORTION OF LEAF DEMAND THAT IS MET TODAY
CLSDML=TOTDML/(PTNLVS+EPS)
C
C COMPUTE COHORT GROWTH RATES
DO 30 I=1,NL
RCWL(I)=TOTDML*PTNLVS(I)/(PTNLVS+EPS)
RCWST(I)=TOTDMS*PTNSTM(I)/(PTNSTM+EPS)
C NOW ADJUST LEAF AREA EXPANSION TO AVAILABLE CH2O
XBOX = I*100./NL
FRPT = TABEX(FRPET,BOX,XBOX,10)
RCLFA(I)=RCWL(I)*TABEX(ASLA,BOX,XBOX,10)*ESLA/(1.+FRPT)
30 CONTINUE
C
DO 40 I=1,NF
RCWFR(I)=TOTDMF*PTNFRT(I)/(PTNFRT+EPS)
40 CONTINUE
C
C
WRITE(*,333)TRCDRW,RCDRW,PTNLVS,PTNFRT,TOTDML,TOTDMF,CLSDFM,CLSDML
C   $,EXCESS
C 333 FORMAT('TRCDRW,RCDRW,PTNLVS,PTNFRT,TOTDML,TOTDMF,CLSDFM,CLSDML,
C   &EXCESS',/,9F8.3)
C

```

C-10

```
C      WRITE(*,334) (RCWLV(I), I=1,20)
C      WRITE(*,337) (WLVS(I), I=1,20)
C      WRITE(*,335) (RCLFA(I)*100., I=1,20)
C      WRITE(*,338) (LFAR(I)*100., I=1,20)
C      WRITE(*,336) (RCWFR(I), I=1,20)
C334  FORMAT(' RCWLV',10F7.3)
C335  FORMAT(' RCLFA',10F7.3)
C336  FORMAT(' RCWFR',10F7.3)
C337  FORMAT(' LFWT.',10F7.3)
C338  FORMAT(' LFAR.',10F7.3)
      RETURN
      END
```

```

GHOUSE.FOR

C$DEBUG
$STORAGE:2
      SUBROUTINE GHOUSE
C
C  $INSERT COMMON.TOM
$INCLUDE: 'COMMON.TOM'
C
      IF(JDAY .GT. 1 .OR. TFAST .GT. 0.0001) GO TO 350
C      CHECK TO SEE IF CONTROLS ARE CONSTANT
C
C
      IENV = 0
      WRITE (*,250)
250  FORMAT(/1X,' DO YOU WANT CONSTANT ENVIRONMENT?',
+         /1X,'      Y OR N? [DEFAULT "N"] ')
      READ (*,1200) ANS
1200  FORMAT(A1)
      IF (ANS .EQ. 'n' .OR. ANS .EQ. 'N' .OR. ANS .EQ. ' ') GO TO 350
C      WHEN IENV = 1, CONSTANT GHOUSE CONDITIONS
      IENV = 1
      WRITE(*,370)
370  FORMAT(' INPUT THE DAY AND NIGHT TEMPERATURES AND THE HOURS OF '
1, ' DAYTIME TEMP, and CO2',/, ' SEPARATED BY A SPACE '
2,/, ' FOR EXAMPLE,  28.0  16.5  13.0  950.0')
      READ(*,*) TMAXGH,TMINGH,DAYTMP,CO2AVG
C
C      SET CONSTANT CONDITIONS FOR STARTING, STOPPING DAY/NIGHT TEMP CNTRL
      SUPGH = 12. - DAYTMP/2.
      SDNGH = 12. + DAYTMP/2.
C
350  CONTINUE
C
C      IF NOT CONSTANT ENV, SKIP THIS SECTION
      IF(IENV .EQ. 0) GO TO 600
C      SET HOURLY TEMP BASED ON CONSTANT DAY AND NIGHT TEMPS AS INPUT
      DO 380 II = 1,24
      XTMP = II-1
      IF (XTMP.GT.SUPGH) GO TO 385
      THR(II) = TMINGH
      GO TO 380
385  CONTINUE
      IF (XTMP.GT.SDNGH) GO TO 390
      THR(II) = TMAXGH
      GO TO 380
390  CONTINUE
      THR(II) = TMINGH
380  CONTINUE
C

```

C-12

```
450 CONTINUE
C
600 CONTINUE
C
C
C WRITE(*,*) ' AT TOP OF GHOUSE, DAY, H = ',TIME,TFAST
C COMPUTE INSTANTANEOUS OUTSIDE CONDITIONS
C   CO2L=950.
C   CO2L=TABEX(CO2LT,XCO2LT,TIME,6)
C   TMPA = TABEX(THR,HOURS,TFAST,25)
C   RADA = TABEX(RAD,HOURS,TFAST,25)
C
C COMPUTE CONDITIONS INSIDE THE GREENHOUSE FOR CURRENT TIME
C
C IF ENV. IS NOT CONTROLLED, SET INSIDE CO2 TO OUTSIDE LEVEL
C IF(IENV .NE. 1) CO2AVG = CO2L
C
C   TAVG=TMPA
C   RADCAL=RADA*TRGH
C   PAR=PARO*TRGH
C CONVERT MJ/M2 TO LY TO E/M2-H TO micro-E/M2-S
C   PPFD = RADA*23.923/PARFAC*277.78*TRGH
C TRGH IS THE TRANSMISSIVITY OF THE GREENHOUSE COVER
C
C TMPA,CO2L,PAR,AND RADCAL ARE CONDITIONS TO WHICH PLANTS IN THE
C GREENHOUSE ARE EXPOSED AT ANY POINT IN TIME
C
RETURN
END
```

INITIAL.FOR

\$STORAGE:2

 SUBROUTINE INITIAL

\$INCLUDE: 'COMMON.TOM'

C

 DTFAST = 1.0/NFAST

C

C INITIALIZE ALL COHORT VALUES TO ZERO

 DO 10 I=1,NL

 LVSNI(I)=0.0

 STMS(I)=0.0

 WLVS(I)=0.0

 WSTM(I)=0.0

 LFAR(I)=0.0

10 CONTINUE

C

 DO 20 I =1,NF

 FRTN(I)=0.0

 WFRT(I)=0.0

20 CONTINUE

C

C NOW SET INITIAL CONDITIONS BASED ON PER PLANT VALUES

C

 PLSTN=PLSTNI

 CPOOL=0.0

 LVSNI(1)=LVSNI*PLM2

 BTOTNLV=LVSNI*plm2

 STMS(1) = LVSNI(1)

 WLVS(1)=WLVSI*PLM2

 WSTM(1) = WLVS(1)*FRSTEM(1)

 LFAR(1)=LFARI*PLM2

 XLAI=LFAR(1)

 TOTWML = 0.

 ATL= 0.

 ATV=0.

 TOTWST = 0.

 WTOTF = 0.

 ASTOTL = XLAI

 WSTOTL = 0.

 FWFR10=0.

 APFFW=0

 ATT=0

C

 RETURN

 END

INPUT.FOR

C\$DEBUG

\$STORAGE:2

 SUBROUTINE INPUT

\$INCLUDE: 'COMMON.TOM'

C

 OPEN(10, FILE='CROPPARM.TOM', STATUS='OLD')

 OPEN(9, FILE='MGT.TOM', STATUS='OLD')

C

C READ CROP PARAMETERS AND TABLES

C

 READ(10, *) TABK, TLOWAB, CO2M

 READ(10, *) TPL, NL, NF, EPS, GREF, SPTEL, GENFAC

 READ(10, *) XLAIM, XMRDR, ABORMX, Q10, RMRL, RMRP, FTRUSN

 READ(10, *) WPLI, WPFI, SLAMX, SLAMN, STDSL, FRLG, AVFM

 READ(10, *) SCO2, THIGH, TLOW, TTMX, TTMN, ZBENG, TU1, TU2

C

 WRITE(*, *) TPL, NL, NF, EPS, GREF, SPTEL, GENFAC

C

 WRITE(*, *) XLAIM, XMRDR, ABORMX, Q10, RMRL, RMRP, FTRUSN

C

 READ(10, *) (BOX(I), I=1, 10)

 READ(10, *) (POL(I), I=1, 10)

 READ(10, *) (POF(I), I=1, 10)

 READ(10, *) (ASLA(I), I=1, 10)

 READ(10, *) (FRPET(I), I=1, 10)

 READ(10, *) (FRSTEM(I), I=1, 10)

 READ(10, *) (DIS(I), I=1, 10)

 READ(10, *) (DISf(I), I=1, 10)

C

 READ(10, *) (PGRED(I), I=1, 8)

 READ(10, *) (TMPG(I), I=1, 8)

C

 READ(10, *) (FPN(I), I=1, 10)

 READ(10, *) (XFPN(I), I=1, 10)

C

 READ(10, *) (GENTEM(I), I=1, 6)

 READ(10, *) (XTEM(I), I=1, 6)

C

 READ(10, *) (GENRAT(I), I=1, 6)

 READ(10, *) (XGEN(I), I=1, 6)

C

 READ(10, *) (RDVLVT(I), I=1, 9)

C

 WRITE(*, *) RDVLVT

 READ(10, *) (XLV(I), I=1, 9)

C

 READ(10, *) (RDVFRT(I), I=1, 9)

 READ(10, *) (XFRT(I), I=1, 9)

C

 READ(10, *) (PROOT(I), I=1, 6)

 READ(10, *) (XROOT(I), I=1, 6)

```
C
    READ(10,*) (DMC84T(I), I=1, 6)
    READ(10,*) (XDMC(I), I=1, 6)
C
    READ(10,*) (PART(I), I=1, 5)
    READ(10,*) (XPART(I), I=1, 5)

    READ(10,*) (AEFT(I), I=1, 6)
    READ(10,*) (XAEFT(I), I=1, 6)

C
C    NOW READ MGT FILE
    READ(9,*) NSTART, NDAYS, DELT, NFAST, INTOUT, TRGH
    READ(9,*) PLM2, ROWSPC, PLSTNI, LVSNI, WLVSJ, LFARI

    READ(9,*) (CO2LT(I), I=1, 6)
    READ(9,*) (XCO2LT(I), I=1, 6)

    READ(9,*) (DISDAT(I), I=1, 12)
    READ(9,*) (XDISDAT(I), I=1, 12)

C    WRITE(*,*) NSTART, NDAYS, DELT, NFAST, INTOUT, TRGH
C    WRITE(*,*) PLM2, ROWSPC, PLSTNI, LVSNI, WLVSJ, LFARI
C
    CLOSE(10)
    CLOSE(9)
C
    RETURN
    END
```

INTGRAT.FOR

\$STORAGE:2

SUBROUTINE INTGRAT

\$INCLUDE: 'COMMON.TOM'

```

C
C
C   ALLOW FOR CARBOHYDRATE POOL, CPOOL, ALTHOUGH NOW IS 0.0
C   CPOOL = CPOOL + (GP-RCDRW/GREF-MAINT) *DELT
C
C   INTEGRATE PLANT DEVELOPMENT (PLASTOCHRONS)
C
C   PLSTN = PLSTN + GENR*DELT
C
C   INTEGRATE LEAF PROCESSES
C
C   LVSN(NL) = LVSN(NL) + (PUSHL*LVSN(NL-1) - DENLR(NL)) *DELT
C   WLVS(NL) = WLVS(NL) + (PUSHL*WLVS(NL-1) - DEWLR(NL)) *DELT
C   LFAR(NL) = LFAR(NL) + (PUSHL*LFAR(NL-1) - DELAR(NL)) *DELT
C
C   STMS(NL) = STMS(NL) + PUSHL*STMS(NL-1) *DELT
C   WSTM(NL) = WSTM(NL) + PUSHL*WSTM(NL-1) *DELT
C
C   DO 100 I = 2, NL-1
C     II = NL - I + 1
C     LVSN(II) = LVSN(II) + PUSHL * (LVSN(II-1) - LVSN(II)) *DELT
C     &       - DENLR(II) *DELT
C     STMS(II) = STMS(II) + PUSHL * (STMS(II-1) - STMS(II)) *DELT
C     WLVS(II) = WLVS(II) + (PUSHL * (WLVS(II-1) - WLVS(II)) + RCWLV(II)) *DELT
C     &       - DEWLR(II) *DELT
C     WSTM(II) = WSTM(II) + (PUSHL * (WSTM(II-1) - WSTM(II)) + RCWST(II)) *DELT
C     LFAR(II) = LFAR(II) + (PUSHL * (LFAR(II-1) - LFAR(II)) + RCLFA(II)) *DELT
C     &       - DELAR(II) *DELT
100 CONTINUE
C     LVSN(1) = (RCNL - PUSHL * LVSN(1)) *DELT
C     &       + LVSN(1) - DENLR(1) *DELT
C     STMS(1) = STMS(1) + (RCST - PUSHL * STMS(1)) *DELT
C     WLVS(1) = (RCNL * WPLI - PUSHL * WLVS(1) + RCWLV(1)) *DELT
C     &       + WLVS(1) - DEWLR(1) *DELT
C     WSTM(1) = WSTM(1) + (RCST * WPLI * FRSTEM(1) - PUSHL * WSTM(1) + RCWST(1)) *DELT
C     FRPT = 1. + FRPET(1)
C     LFAR(1) = (RCNL * WPLI * ESLA * ASLA(1) / FRPT - PUSHL * LFAR(1) + RCLFA(1)) *DELT
C     &       + LFAR(1) - DELAR(1) *DELT
C
C   FRUIT
C   FRTN(NF) = FRTN(NF) + (PUSHM * FRTN(NF-1) - DENFR(NF)) *DELT
C   WFRT(NF) = WFRT(NF) + (PUSHM * WFRT(NF-1) - DEWFR(NF)) *DELT
C
C   DO 200 I = 2, NF-1
C     II = NF - I + 1
C     FRTN(II) = FRTN(II) + PUSHM * (FRTN(II-1) - FRTN(II)) *DELT

```

```

&          -DENFR(II)*DELT
      WFRT(II)=WFRT(II)+(PUSHM*(WFRT(II-1)-WFRT(II))+RCWFR(II))*DELT
&          -DEWFR(II)*DELT
200 CONTINUE
C      DECREASING OF ABORTION BY CO2
C      ABNF=ABNF-SPTTEL*AMAX1(0,FCO2G-1.0)
C
C      FRTN(1)=(RCNF-ABNF-PUSHM*FRTN(1))*DELT
&          +FRTN(1)-DENFR(1)*DELT
      WFRT(1)=(RCNF-ABNF)*WPFI-PUSHM*WFRT(1)+RCWFR(1))*DELT
&          +WFRT(1)-DEWFR(1)*DELT
C
C      FRTN(1)=(RCNF-PUSHM*FRTN(1))*DELT
&          +FRTN(1)-DENFR(1)*DELT
C      WFRT(1)=(RCNF)*WPFI-PUSHM*WFRT(1)+RCWFR(1))*DELT
&          +WFRT(1)-DEWFR(1)*DELT
C
C      NOW NEED TO COMPUTE XLAI, TOTAL PLANT WTS. ETC...
C      THESE ARE VARIABLES THAT ARE COMPUTED FROM STATE VAR.
C
      XLAI = 0.
      TWTLAI = 0.
      TOTNLV = 0.
      TOTWML = 0.
      TOTNST = 0.
      TOTWST = 0.
      ATV=0.
      DO 400 I = 1,NL
C      COMPUTE AVG LEAF WEIGHT
      AVWL(I)=WLVS(I)/(LVSN(I)+EPS)
C      COMPUTE XLAI
      XLAI=XLAI+LFAR(I)
C      COMPUTE TOTAL NO. OF LEAVES
      TOTNLV=TOTNLV+LVSN(I)
C      COMPUTE TOTAL WT. OF LEAVES, G/M2
      TOTWML=TOTWML+WLVS(I)
      ATL=ATL+DEWLR(I)*delt
C      COMPUTE WT. OF LEAF BLADES ONLY (EXCLUDING PETIOLE)
      XBOX = I*100./NL
C      ACCOUNT FOR PETIOLE GROWTH WITH EACH INCREMENT OF LAI GROWTH
      FRPT = TABEX(FRPET,BOX,XBOX,10)
      TWTLAI = TWTLAI + WLVS(I)/(1.+FRPT)
C      COMPUTE TOTAL NO., WT. OF STEMS
      TOTNST = TOTNST + STMS(I)
      TOTWST = TOTWST + WSTM(I)
400 CONTINUE
C      COMPUTE AVG SLA OF CANOPY, CM**2/G
      XSLA = XLAI / (TWTLAI + EPS)*10000.

```

```

C
  TOTWMF = 0.
  TOTNF = 0.
  DO 500 I = 1,NF
C   COMPUTE AVG FRUIT WT, G/FRUIT
  AVWF(I)=WFRT(I)/(FRTN(I)+EPS)
C   COMPUTE TOTAL WEIGHT OF FRUIT, G/M2
  TOTWMF = TOTWMF+WFRT(I)
C   COMPUTE TOTAL NO. OF FRUIT, NO./M2
  TOTNF = TOTNF+FRTN(I)
500  CONTINUE
C
C   NOW COMPUTE FRUIT TOTALS EXCLUDING MATURE(CLASS NF) FRUIT
  WTOTF = TOTWMF - WFRT(NF)
  TOTGF = TOTNF - FRTN(NF)
C   COMPUTE NO OF LEAVES
  BTOTNLV=BTOTNLV+RCNL*DELT
  DLN=(BTOTNLV-TOTNLV)/PLM2
c   WRITE(*,520)TIME,BTOTNLV,TOTNLV,DLN
c520  FORMAT(4X,4(1X,F8.2))
C   NOW COMPUTE LEAF TOTALS EXCLUDING MATURE(CLASS NL) LEAVES
  TOTGL = 0.
  ASTOTL = 0.
C   WEIGHT OF STILL GROWING LEAVES
  WSTOTL = TOTWML - WLVS(NL)
C   NUMBER OF STILL GROWING LEAVES
  TOTGL = TOTNLV - LVS(NL)
C   AREA OF STILL GROWING LEAVES
  ASTOTL = XLAI - LFAR(NL)
C   NUMBER OF STILL GROWING STEMS
  TOTST = TOTNST - STMS(NL)
C   WT. OF STILL GROWING STEMS
  WSTOTS = TOTWST - WSTM(NL)
C
C   NOW COMPUTE PLANT TOTALS ON A M2 BASIS
C   TOTAL DRY WEIGHT, TOTDW
  TOTDW = TOTWMF + TOTWML + TOTWST
C   NOW COMPUTE VEGETATIVE PARTS OF PLANT ONLY
  TOTVW= TOTWML +TOTWST
  ATV=TOTWML+TOTWST+ATL
  ATT=ATV+TOTWMF
c   WRITE(*,420) TIME,TOTWML,ATL,TOTVW,ATV,ATT
c420  FORMAT(4X,6(1X,F8.2))
C   TOTAL NUMBERS
TOTNU = TOTNF + TOTNLV
C   TOTAL GROWING POINTS
  NGP = TOTGL + TOTGF + TOTST
C   WRITE(*,310) TIME,TOTGF,FRTN(NF),TOTGL,LVS(NL),NGP,ABNF
C   @,RCNF,RCNL,CLSDMF,CLSDML
C 310  FORMAT(1X,11(F8.2))

```

```

C      COMPUTE FRUIT TO LEAF RATIO
      RVRW = TOTWMF/(TOTWML+EPS)
C      COMPUTE FRUIT TO TOTAL WEIGHT
      RTRW = TOTWMF/(TOTDW+EPS)
C      COMPUTE RATIO OF FRUIT NO. TO LEAF NO.
      RVRN = TOTNF/(TOTNLV+EPS)
C      COMPUTE RATIO OF FRUIT TO TOTAL NUMBER OF GROWING POINTS
      RTRN = TOTNF/(TOTNU+EPS)
C      COMPUTE AVG TOTAL WTS
      AVWMF = TOTWMF/(TOTNF+EPS)
C      COMPUTE AVG VEG LEAF WTS WHOLE PLANT, G/LF
      AVWML = TOTWML/(TOTNLV+EPS)
C      NOW COMPUTE FRESH WEIGHTS OF MATURE FRUIT, G/M2
      DMCF84 = TABEX(DMC84T,XDMC,TIME,6)
C      WRITE(*,910)TIME, FWFR10,PUSHM.WFRT(NF-1),DMCF84
C 910  FORMAT (4X, 5(2X,F8.2))
      FWFR10 = FWFR10+(PUSHM*WFRT(NF-1)*DELTA)*100./DMCF84
      APFFW= ((PUSHM*(AMAX1(WFRT(NF-1),0))*DELTA)*100./DMCF84)/
&          ((PUSHM*FRTN(NF-1)*DELTA)+EPS)
C
C      WRITE(*,910)TIME,APFFW,PUSHM,WFRT(NF-1),DMCF84,FRTN(NF-1)
C 910  FORMAT (4X, 6(2X,F8.2))
C      WRITE(*,920)TIME,ABNF
C 920  FORMAT (4X, 2(2X,F8.2))
      RETURN
      END

```

```
IPWTH.FOR

C$DEBUG
$STORAGE:2
  SUBROUTINE IPWTH
C
C  $INSERT COMMON.TOM
$INCLUDE: 'COMMON.TOM'
C  OPEN WEATHER FILE THE FIRST TIME THROUGH AND READ LINE ONE
C
  IF(JDAY.GT.1) GO TO 200
  OPEN (11,FILE = 'FILE1',STATUS = 'OLD')
  NEW = 0
  READ (11,600) XLAT,XLONG,PARFAC,PARDAT
600  FORMAT(4X,4(1X,F6.2))
      READ (11,*,END = 900) KYR,JUL,SOLRAD,TMAX,TMIN,RAIN ,
+          PARO
  IF (NSTART .GE. JUL) GO TO 300
  WRITE (*,100)
100  FORMAT(/10X,' SIMULATION DATE SPECIFIED BEFORE THE'
+ ' FIRST AVAILABLE',',/10X,'WEATHER DAY. <Ctrl-Break> AND FIX THE ',
+ 'FILE FIRST.')
  READ (*,*) ANS
200  CONTINUE
  250      READ (11,*,END = 900) KYR,JUL,SOLRAD,TMAX,TMIN,RAIN ,
+          PARO
C
300  CONTINUE
  IF(JUL .LT. NSTART .AND. NEW .EQ. 0) GO TO 250
C
  NEW = 1
C  CONVERT SOLAR RADIATION FROM MJ/M2 TO LANGLEY
C
      XLANG = SOLRAD*23.923
C 700  FORMAT(4X,I3,I4,F6.2,2F5.1,F6.1,1X,F6.2)
      CALL SUNRIS(JUL,SUP,SDN,XLAT,XLONG)
      IF (PARDAT .LE. 0) PARO = XLANG/PARFAC
C  WRITE(*,750)JUL,SOLRAD,TMAX,TMIN,RAIN,PARO,SUP,SDN
C750  FORMAT(' ',I5,5F8.1,2F8.3)
  900  CONTINUE
  RETURN
  END
```

LOSRATE.FOR

\$STORAGE:2

 SUBROUTINE LOSRATE

C

\$INCLUDE: 'COMMON.TOM'

 COMMON/PLT/PLTM2V

C

C COMPUTE FRUIT ABORTION(1ST COHORT ONLY) NO./M2-DAY

 ABNF = 0.0

 IF(TOTDMF.LT.EPS)GO TO 30

 FABOR = AMIN1(1.0,(2.0-ABORMX*CLSDML))

 FABOR = AMAX1(0.0,FABOR)

 TABOR= AMIN1(1,AMAX1(0.0,TTAB/TABK))

C

 ABNF =FABOR*RCNF/PLTM2V

 ABNF= FABOR*RCNF/PLTM2V+TABOR*RCNF/PLTM2V

30 CONTINUE

C

C COMPUTE LEAF LOSSES

 DEAR(NL) = 0.

 IF(XLAI*PLTMV2 .GT. XLAIM)

 & DEAR(NL) = XMRDR*AMIN1(LFAR(NL),(XLAI*PLTM2V-XLAIM)/PLTM2V)

 DEAR(NL) = AMAX1(0.0,DEAR(NL))

C

 DUE TO DISEASES AND PRUNING.

 DATEZ=TABEX(DISDAT,XDISDAT,TIME,12)

C

 WRITE(*,134)TIME,DATEZ

C 134 FORMAT(4X,2(2X,F8.2))

C

 DISEASES AND PRUNING STILL HAVE TO BE INCORPORATED INTO STEM

C

 DO 40 I = 1,NL-1

 XBOX = I*100./NL

 DEAR(I)=TABEX(DIS,BOX,XBOX,10)*DATEZ

40 CONTINUE

C

 DO 50 I = 1,NL

C

 NUMBER RATE LOSS, NO./M2-DAY

 DENLR(I) = LVSN(I)*DEAR(I)

C

 WEIGHT LOSS RATE, G/M2-DAY

 DEWLR(I) = DENLR(I)*AVWL(I)

C

 AREA RATE OF LOSS, M2/M2-DAY

 DELAR(I) = DEAR(I) * LFAR(I)

50 CONTINUE

C

C

 COMPUTE FRUIT LOSSES DUE TO DISEASES AND PRUNING.

 DO 140 I = 1,Nf

 XBOX = I*100./Nf

C-22

```
140 DEAF(I)=TABEX(DISF,BOX,XBOX,10)*DATEZ
    DO 150 I = 1,Nf
C    NUMBER RATE LOSS, NO./M2-DAY
    DENFR(I) = FRTN(I)*DEAF(I)
C    WEIGHT LOSS RATE, G/M2-DAY
    DEWFR(I) = DENFR(I)*AVWF(I)
150 CONTINUE
C
C    WRITE(*,133)TIME,DENFR(1),DENFR(5),DENFR(10)
C    1          ,DEWFR(1),DEWFR(5),DEWFR(10)
C 133 FORMAT(4X,7(2X,F8.2))
    RETURN
END
```

```

OUTPUT.FOR

C$DEBUG
$STORAGE:2
    SUBROUTINE OUTPUT
C  $INSERT COMMON.TOM
$INCLUDE: 'COMMON.TOM'
    IF(JDAY .GT. 1) GO TO 100
    IF(IRUNNUM.EQ.1)OPEN(UNIT = 15, FILE = 'OUT1')
    OPEN(UNIT = 16, FILE = 'OUT2')
C
    WRITE(15,400)
    WRITE(15,420)IRUNNUM
    WRITE(15,440)ITRTNUM
    WRITE(15,500)

    WRITE(16,400)
    WRITE(16,420)IRUNNUM
    WRITE(16,440)ITRTNUM
    WRITE(16,500)

100 CONTINUE
C  WRITE (*,310)TIME,BTOTNLV,TOTNLV,DLN
C 310 FORMAT(4X,4(1X,F8.2))
C
C  MODIFIED TO COMPARE WITH EHUD DAYAN'S DATA (1)
C    WRITE(15,550)DATE,PLSTN,XLAI,TOTNLV/PLM2,TOTWMLC
C    &,TOTNF,TOTWMF,FRTN(NF),WFRT(NF),XSLA
C    @,ASTOTL,GP,MAINT,TRCDRW,RCDRW,TOPGR,TOTWST
C    $,WFRT(NF)/(FRTN(NF)+EPS)
C
C  MODIFIED TO COMPARE WITH EHUD DAYAN'S DATA (2)
C  NOW BY CHANGING THE 15th VALUE 'TOPGR' TO 'FWFR10'
C
    WRITE(15,550)DATE,PLSTN,XLAI,TOTNLV/PLM2,TOTWML
    &,TOTNF,TOTWMF,FRTN(NF),WFRT(NF),XSLA
    @,ASTOTL,GP,MAINT,TRCDRW,RCDRW,FWFR10,TOTWST
    4,APFFW,TOTVW,TOTDW,DLN,CLSDML,TEMFAC,ATL,ATV,ATT

    WRITE(16,650)DATE,ATV,LVSN(5),LVSN(10),LVSN(15)
    &,LVSN(20)
    @,FRTN(1),FRTN(5),FRTN(10),FRTN(15),FRTN(20),ABNF
C
C    WRITE(*,550)DATE,PLSTN,XLAI,TOTNLV,TWTLAI
C    &,TOTNGF,TOTWMF,FRTN(NF),WFRT(NF),XSLA
C
C    WRITE(*,600)TIME,(LVSN(I),I=1,NL)
C    WRITE(*,610)(WLVS(I),I=1,NL)
C    WRITE(*,620)(LFAR(I),I=1,NL)
C    WRITE(*,630)(FRTN(I),I=1,NF)

```

```
C      WRITE(*,640)(WFRT(I),I=1,NF)
C
C600  FORMAT(' TIME,LVSN',F4.0,4X,10F6.2)
C610  FORMAT(' WLVS',10F7.2)
C620  FORMAT(' LFAR',10F6.3)
C630  FORMAT(' FRTN',10F7.2)
C640  FORMAT(' WFRT',10F7.2,/)
      650  FORMAT(12F8.2)
      400  FORMAT(' ')
      420  FORMAT(' RUN ',I2)
      440  FORMAT(' INST_ID: UF  SITE_ID: GA  EXPT_NO: 01  YEAR: 1985'
&,' TRT_NO: ',I2)
      500  FORMAT(' ',T2,'TIME',T10,'PLSTN',T18,'XLAI'
&,T26,'NO.LVS',T34,'WT.LVS',T42,'NO.FR',T50,'WT.FR'
&,T58,'MAT.NO',T68,'MAT.WT',T76,' SLA '
@,T86,'GLAI',T95,'PG',T103,'RM',T110,'GRTOT',T118,'FWFR'
#,T126,'SHOOT',T133,'APFFW',T140,'TOTVW',T148,'TOTDW'
&,T156,'DLN',T164,'CLSDML',T172,'TEMFAC',T180,'ATL'
&,T188,'ATV',T196,'ATT',/)
```

```
C
C550  FORMAT(18F8.2)
      550  FORMAT(2F8.2,F5.1,7F8.2,F5.1,4F7.2,2F10.2,9F8.2)
C
      RETURN
      END
```

PHOTO.FOR

C\$DEBUG

\$STORAGE:2

 SUBROUTINE PHOTO

C

\$INCLUDE: 'COMMON.TOM'

C

 COMMON/PLT/PLTM2V

 QE = 0.056

 XK = 0.58

 XM = 0.10

 GPF = 0.

C TAU1 = 0.07428

C TAU2 = 0.05848

C BASING PG ON THE AVG OF 4 DATES, NO DECREASE WITH TIME

C TAU1 = 0.06165

C TAU2 = 0.04854

C AVG OF TAU1 AND TAU2, LINEAR RESPONSE TO CO2 (LEAF LEVEL)

 TAU1 = 0.06638*TAU1

 TAU2 = 0.06638*TAU2

C PMAX BASED ON DATA FROM GNV TOMATO EXP.

 PMAX = TAU1 * CO2AVG

 IF(CO2AVG .GT. 350.0) PMAX = TAU1 * 350. + TAU2*(CO2AVG-350.)

C

C PGRED=REDUCE PMAX DUE TO EXTREME TEMPERATURES

C AEF=REDUCTION OF PMAX DUE TO AGE

 AEF=TABEX(AEFT,XAEFT,PLSTN,6)

 PMAX = PMAX * TABEX(PGRED,TMPG,TMPA,8)*AEF

C

 IF(PPFD .LT. 0.001) GO TO 100

C ACOCK PHOTOSYNTHESIS EQUATION

C ASTOTL = LAI OF LEAVES EXCLUDING THOSE IN THE LAST AGE CLASS

 TOP = (1.-XM)*PMAX + QE*XK*PPFD

 BOT = (1.-XM)*PMAX + QE*XK*PPFD*EXP(-XK*ASTOTL*pltm2v)

 GPF = (PMAX/XK)*ALOG(TOP/BOT)

C

C CONVERT FROM CO2 TO CH2O MOLECULAR BASIS (30/44 = 0.682)

 GPF = GPF * 0.682

C CONVERT UNITS OF GPF FROM $\mu\text{M}/\text{M}^2\text{-S}$ TO $\text{G}/\text{M}^2\text{-DAY}$

C $\mu\text{M}/\text{M}^2\text{-S} \times 0.000044 \text{ G}/\mu\text{M} \times 3600 \text{ S}/\text{H} \times 24 \text{ H}/\text{D} = 3.8016 \text{ G}/\text{M}^2\text{-DAY}$

 GPF = GPF * 3.8016

C WRITE(*,120)TIME,TFAST,CO2L,PMAX,GPF,PPFD,ASTOTL

C 120 FORMAT(2X,7(1X,F8.1))

C

C WRITE(*,111) TFAST,ASTOTL,PPFD,GPF

C111 FORMAT(' TFAST, ASTOTL, PPFD, GPF = ',4F10.3)

100 CONTINUE

C IF(JDAY .EQ. 50 .OR. JDAY .EQ. 130)

 WRITE(*,200)JDAY,TFAST,GPF

C-26

```
C 200 FORMAT(' JDAY, HOUR, GPF = ', I3, F5.0, F10.3)
      RETURN
      END
```

RESP.FOR

\$STORAGE:2

 SUBROUTINE RESP

\$INCLUDE: 'COMMON.TOM'

C

C WRITE(*,*) ' AT TOP OF RESP, DAY, H = ',TIME,TFAST

 TEFF=Q10**(0.1*TMPA-2.0)

 MAINTF=TEFF*(RMRL*(TOTWST+WSTOTL)+RMRP*WTOTF)

C

 RETURN

 END

SUNRISE.FOR

\$STORAGE:2

 SUBROUTINE SUNRIS (IJUL, XSNUP, XSNDN, XLAT, XLONG)

C-----

C

C HEMIS = SIGN OF LATITUDE, + IS N LAT, - IS S LAT
C FROM GOUDRIAAN AND VAN LAAR & JONES

C

 HEMIS = XLAT/ABS(XLAT)
 PI = 3.1416

C

C RAD = RADIANS PER DEGREE

C

 RAD = PI/180.
 DEC = -HEMIS*23.4*COS(2.*PI*(IJUL+10.)/365.)

C

C CALCULATION OF DECLINATION OF SUN

C (+10 IS TIME BETWEEN DEC 21 AND DEC 31--FOR SIDEREAL YEAR)

C

 SNDC = SIN(RAD*DEC)
 CSDC = COS(RAD*DEC)
 SNLT = SIN(RAD*XLAT)
 CSLT = COS(RAD*XLAT)
 SSIN = SNDC*SNLT
 CCOS = CSDC*CSLT
 TT = SSIN/CCOS
 AS = ASIN(TT)
 DAYL = 12.*(PI+2.*AS)/PI
 IF (XLAT .LT. 0.) DAYL = 24. - DAYL
 XSNUP = 12.- DAYL/2.
 XSNDN = 12. + DAYL/2.
 RETURN
 END

TABEX.FOR

\$STORAGE:2

\$NOFLOATCALLS

C\$DEBUG

FUNCTION TABEX (VAL, ARG, DUMMY, K)

C

C

C * TABEX IS A FORDYN TABLE LOOKUP ROUTINE. REF. LLEWELLYN,*

C * ROBERT W. 1965,FORDYN, AN INDUSTRIAL DYNAMICS SIMULATOR.*

C * PRIVATELY PRINTED, RALEIGH, NORTH CAROLINA. *

C

C

DIMENSION VAL (K) ,ARG (K)

DO 100 J = 2,K

IF (DUMMY .GT. ARG (J)) GO TO 100

GO TO 200

100 CONTINUE

J = K

200 TABEX = (DUMMY-ARG (J-1)) * (VAL (J) -VAL (J-1)) / (ARG (J) -ARG (J-1)) +VAL (J-1)

END

WALC.FOR

C\$DEBUG

\$STORAGE:2

SUBROUTINE WALC

C

C \$INSERT COMMON.TOM

C \$INCLUDE: 'COMMON.TOM'

C

C THIS SUBROUTINE CALCULATES HOURLY TEMPERATURES AND RADIATION

C

C FOR NOW, ASSUME THAT TOMORROW'S MIN AND MAX TEMPS ARE THE SAME AS TODAY

C

SDNT = SDN

SUPT = SUP

TMINT = TMIN

TMAXT = TMAX

C

IF (JDAY .GT. 1) GO TO 500

SDNY = SDN

SUPY = SUP

TMINY = TMIN

TMAXY = TMAX

500 CONTINUE

C

DO 600 IXX = 1,25

X = IXX

IF (X .LT. SUP + 2.0) GO TO 400

IF (X .GT. SDN) GO TO 300

C

C SINE CURVE

C

TAU = 3.1417 * (X-SUP-2.)/(SDN-SUP)

THR(IXX) = TMIN + ((TMAX-TMIN) * SIN(TAU))

GO TO 600

C

C AFTER SUNSET BEFORE MIDNIGHT

C

300 CONTINUE

TAU = 3.1417 * (SDN-SUP-2.)/(SDN-SUP)

TLIN = TMIN + ((TMAX-TMIN) * SIN(TAU))

HDARK = 24. - SDN + SUPT + 2.

SLOPE = (TLIN - TMINT) / HDARK

THR(IXX) = TLIN - (SLOPE * (X - SDN))

GO TO 600

C

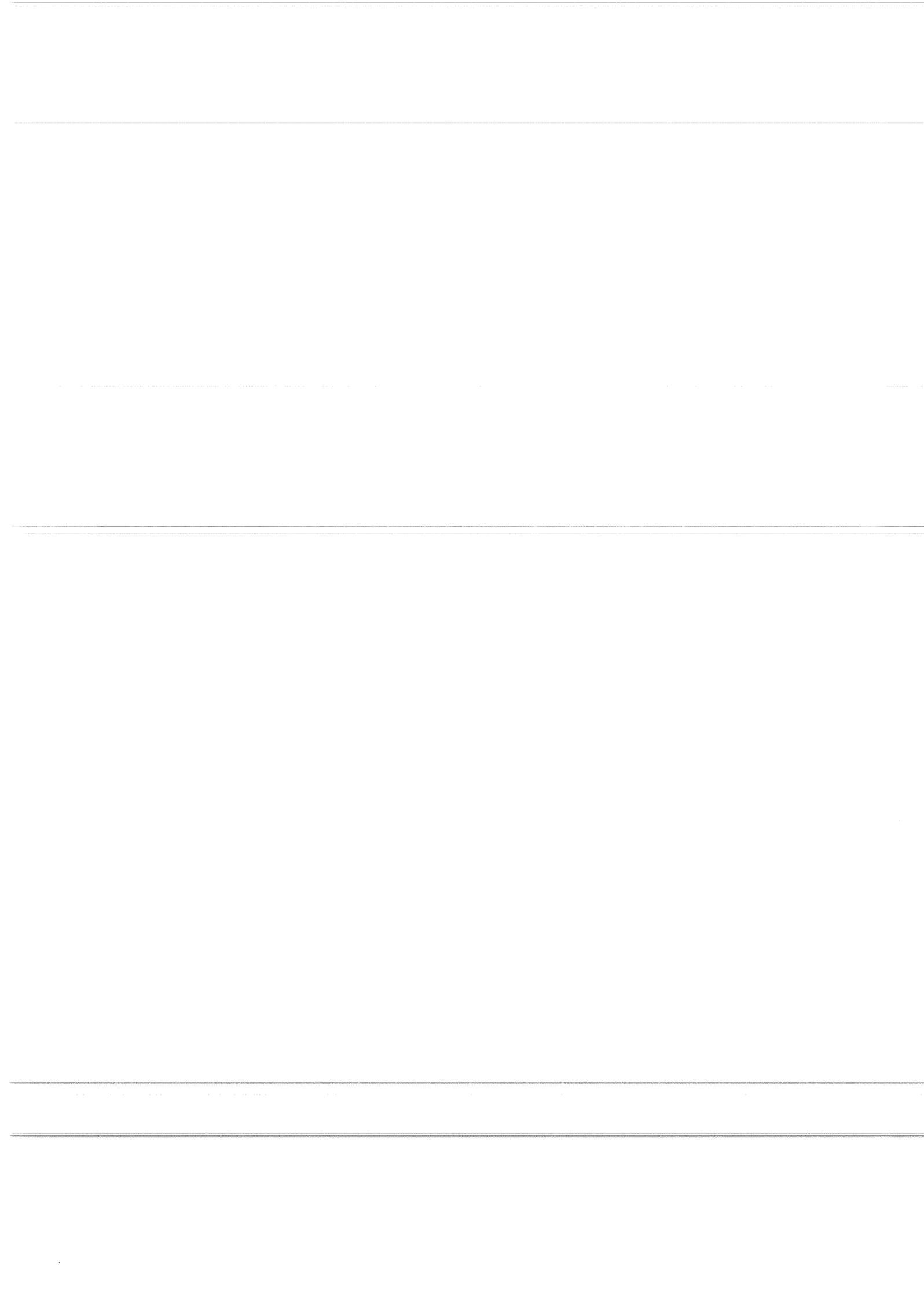
C BETWEEN MIDNIGHT AND SUNRISE + 2 HRS.

C

400 CONTINUE

TAU = 3.1417 * (SDNY-SUPY-2.)/(SDNY-SUPY)

```
        TLIN = TMINY + ((TMAXY - TMINY) * SIN(TAU))
        HDARK = 24. - SDNY + SUP + 2.
        SLOPE = (TLIN - TMIN) / HDARK
        THR(IXX) = TLIN - SLOPE * (X + 24. - SDNY)
600    CONTINUE
C
        SDNY = SDN
        SUPY = SUP
        TMINY = TMIN
        TMAXY = TMAX
C
        DL = SDN - SUP
C
C    COMPUTE HOURLY RADIATION LEVELS
        DO 900 IXX = 1,25
        X = IXX
        RAD(IXX) = 0.
        IF(X .LT. SUP .OR. X .GT. SDN) GO TO 900
        RAD(IXX) = 3.1417/(2.*DL)*SOLRAD*SIN(3.1417*(X-SUP)/DL)
C    IF(JDAY .EQ. 50 .OR. JDAY .EQ. 130) WRITE(*,*)JDAY, IXX, RAD(IXX)
C    WRITE(*,*) IXX, RAD(IXX), SOLRAD
900    CONTINUE
C
        RETURN
        END
```



Appendix D1:

Data file (file 1)

ISBO 31.20 034.40 12.07 1.00

YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
85	274	11.1	32.8	22.5	0.0	20.3
85	275	11.8	34.4	21.4	0.0	21.7
85	276	11.8	32.2	21.4	0.0	21.9
85	277	9.2	30.6	20.8	0.0	17.2
85	278	6.1	28.3	19.7	0.0	11.6
85	279	8.6	28.3	15.7	0.0	15.9
85	280	12.1	30.1	15.5	0.0	22.0
85	281	13.3	30.6	15.8	0.0	24.1
85	282	12.6	30.6	17.0	0.0	23.2
85	283	11.8	30.3	18.1	0.0	21.2
85	284	10.5	31.0	18.4	0.0	18.7
85	285	9.4	29.7	18.3	0.0	17.1
85	286	11.6	29.7	18.0	0.0	21.7
85	287	10.7	30.7	18.6	0.0	19.7
85	288	9.4	30.1	18.8	0.0	17.0
85	289	9.0	30.9	20.6	0.0	16.2
85	290	5.6	28.8	20.0	0.0	10.1
85	291	4.2	26.8	17.0	0.0	8.3
85	292	12.1	29.5	17.2	0.0	22.1
85	293	12.4	29.7	16.9	0.0	22.5
85	294	11.0	29.0	18.5	0.0	20.2
85	295	10.5	28.5	18.2	0.0	19.6
85	296	8.2	27.2	16.9	0.0	15.2
85	297	12.9	27.8	16.6	0.0	23.2
85	298	9.1	27.1	16.4	0.0	17.1
85	299	10.5	27.8	16.0	0.0	19.8
85	300	11.9	28.6	16.1	0.0	21.4
85	301	11.1	26.2	15.7	0.0	20.5
85	302	9.8	26.5	15.2	0.0	17.4
85	303	6.5	24.8	15.1	0.0	12.1
85	304	11.2	27.6	14.6	0.0	20.3
85	305	10.3	31.1	17.2	0.0	23.6
85	306	9.8	29.2	17.2	0.0	21.3
85	307	9.5	29.4	16.9	0.0	14.5
85	308	10.6	36.3	16.0	0.0	23.6
85	309	10.4	31.3	15.4	0.0	23.4

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YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
85	310	10.3	31.7	14.9	0.0	23.2
85	311	10.6	31.2	15.3	0.0	24.0
85	312	7.2	31.2	15.4	0.0	16.6
85	313	7.3	29.7	15.5	0.0	16.9
85	314	9.9	26.7	15.0	0.0	17.0
85	315	8.1	24.7	14.5	0.0	18.3
85	316	9.1	27.0	14.4	0.0	14.0
85	317	9.7	33.0	14.3	0.0	16.8
85	318	9.9	33.2	13.6	0.0	22.9
85	319	10.1	28.6	13.6	0.0	24.0
85	320	8.9	27.6	13.9	0.0	22.0
85	321	7.3	27.9	16.6	0.0	15.6
85	322	8.7	30.2	15.4	0.0	20.5
85	323	6.4	28.6	13.9	0.0	12.0
85	324	8.7	28.9	13.7	0.0	20.1
85	325	8.7	28.7	15.8	0.0	20.7
85	326	7.5	27.5	15.7	0.0	17.9
85	327	7.3	25.9	14.8	0.0	18.3
85	328	7.0	26.4	14.5	0.0	16.2
85	329	5.4	27.5	13.5	0.0	9.1
85	330	5.6	24.2	12.4	0.0	12.7
85	331	8.1	33.3	12.5	0.0	19.1
85	332	8.5	34.2	13.0	0.0	20.1
85	333	8.5	29.0	13.1	0.0	20.0
85	334	7.2	26.8	13.6	0.0	16.2
85	335	6.4	26.2	12.2	0.0	14.9
85	336	6.6	26.3	12.6	0.0	14.8
85	337	7.3	25.2	13.0	0.0	16.9
85	338	8.4	27.1	8.2	0.0	19.9
85	339	8.3	25.6	8.0	0.0	19.6
85	340	7.9	27.3	10.2	0.0	18.8
85	341	8.2	28.0	11.1	0.0	19.3
85	342	8.2	28.6	11.2	0.0	19.5
85	343	7.5	27.7	13.2	0.0	17.3
85	344	7.3	28.5	12.8	0.0	17.1
85	345	6.2	27.1	13.2	0.0	14.6
85	346	7.0	29.1	12.8	0.0	16.4
85	347	6.4	27.9	13.4	0.0	14.7
85	348	5.7	26.8	14.1	0.0	12.9
85	349	5.1	25.6	14.7	0.0	11.1
85	350	6.0	26.9	15.5	0.0	12.0
85	351	0.9	17.6	15.9	0.0	2.1
85	352	4.8	27.0	13.1	0.0	11.3
85	353	1.6	18.3	12.6	0.0	3.6
85	354	6.6	25.0	11.0	0.0	14.2
85	355	6.6	24.2	11.2	0.0	15.4

YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
85	356	6.5	24.1	11.2	0.0	14.6
85	357	7.7	24.1	8.1	0.0	16.2
85	358	7.8	23.8	8.0	0.0	16.1
85	359	7.7	25.5	9.9	0.0	16.2
85	360	3.0	23.0	10.4	0.0	7.0
85	361	6.2	28.1	10.7	0.0	10.3
85	362	7.6	28.2	11.8	0.0	14.9
85	363	7.4	28.6	11.0	0.0	15.3
85	364	7.7	28.5	10.2	0.0	16.1
85	365	7.9	29.7	10.3	0.0	19.3
86	1	6.1	26.8	12.2	0.0	13.9
86	2	5.2	24.4	12.4	0.0	11.5
86	3	7.0	27.5	12.2	0.0	16.9
86	4	8.1	29.9	11.0	0.0	19.7
86	5	8.2	28.2	11.1	0.0	20.0
86	6	6.8	28.2	11.5	0.0	15.9
86	7	8.1	29.9	12.1	0.0	19.3
86	8	8.4	25.4	12.1	0.0	19.6
86	9	8.4	26.5	13.4	0.0	19.6
86	10	8.0	25.7	10.8	0.0	18.3
86	11	8.5	24.1	10.3	0.0	19.3
86	12	7.1	23.7	11.5	0.0	16.3
86	13	8.9	27.0	11.7	0.0	20.3
86	14	9.0	24.3	10.9	0.0	20.7
86	15	8.3	22.5	10.3	0.0	18.9
86	16	9.2	25.0	9.6	0.0	20.9
86	17	9.3	26.7	8.8	0.0	20.3
86	18	9.3	25.9	8.6	0.0	21.4
86	19	8.9	25.1	8.4	0.0	20.1
86	20	8.4	24.3	8.3	0.0	18.9
86	21	8.0	23.5	8.1	0.0	17.7
86	22	7.5	22.7	7.9	0.0	16.5
86	23	8.8	21.4	7.9	0.0	19.4
86	24	8.7	25.1	7.6	0.0	20.1
86	25	8.7	25.2	8.9	0.0	18.1
86	26	9.1	27.8	9.0	0.0	22.5
86	27	9.1	24.5	9.5	0.0	20.5
86	28	10.1	23.2	9.3	0.0	21.8
86	29	8.4	21.4	9.5	0.0	18.6
86	30	8.6	23.4	10.3	0.0	19.1
86	31	7.3	26.8	10.2	0.0	16.0
86	32	11.0	25.2	8.7	0.0	24.3
86	33	10.9	23.5	8.5	0.0	23.6
86	34	4.0	22.1	12.7	0.0	9.0

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YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
86	35	5.6	25.5	13.7	0.0	12.9
86	36	7.7	25.7	11.9	0.0	16.3
86	37	9.5	24.4	11.0	0.0	20.0
86	38	7.4	25.6	10.5	0.0	16.1
86	39	2.8	19.7	12.2	0.0	6.5
86	40	10.4	21.7	8.7	0.0	21.4
86	41	11.5	27.8	8.5	0.0	23.3
86	42	11.4	27.6	8.7	0.0	23.0
86	43	11.6	30.5	9.7	0.0	24.2
86	44	11.8	26.3	10.5	0.0	24.3
86	45	7.9	23.2	10.1	0.0	16.0
86	46	5.1	19.4	10.1	0.0	10.1
86	47	10.2	28.3	10.9	0.0	21.2
86	48	7.5	27.5	9.0	0.0	15.6
86	49	11.9	25.5	9.2	0.0	24.8
86	50	12.6	27.9	9.7	0.0	26.9
86	51	12.6	28.1	10.4	0.0	26.5
86	52	12.6	27.6	11.0	0.0	26.5
86	53	10.6	26.5	12.0	0.0	22.1
86	54	13.0	24.8	12.1	0.0	26.7
86	55	12.0	23.2	12.2	0.0	25.9
86	56	13.5	26.7	10.9	0.0	28.7
86	57	13.1	27.0	10.8	0.0	28.2
86	58	11.0	23.7	11.8	0.0	23.8
86	59	10.4	24.3	14.2	0.0	21.6
86	60	11.5	22.9	10.3	0.0	24.5
86	61	12.6	23.9	10.0	0.0	27.0
86	62	8.7	25.7	12.7	0.0	18.9
86	63	10.6	24.9	12.0	0.0	22.9
86	64	12.5	24.1	11.3	0.0	26.8
86	65	13.3	24.6	11.4	0.0	28.5
86	66	12.2	23.2	11.5	0.0	26.3
86	67	13.3	26.2	11.2	0.0	28.4
86	68	11.7	24.6	13.1	0.0	24.9
86	69	11.8	23.6	11.9	0.0	25.5
86	70	13.8	24.3	11.7	0.0	29.4
86	71	13.3	24.5	12.1	0.0	28.4
86	72	14.0	27.2	12.4	0.0	29.9
86	73	13.4	25.3	12.6	0.0	28.9
86	74	10.1	23.8	11.1	0.0	22.0
86	75	14.5	24.0	11.0	0.0	31.1
86	76	13.9	26.1	11.6	0.0	30.1
86	77	13.4	24.1	11.8	0.0	29.4
86	78	13.5	23.2	10.4	0.0	29.2
86	79	13.4	23.5	10.4	0.0	29.0
86	80	13.8	24.4	10.1	0.0	31.0

YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
86	81	12.8	30.5	11.1	0.0	28.9
86	82	11.7	29.7	14.1	0.0	25.4
86	83	8.3	22.8	12.6	0.0	19.5
86	84	14.0	23.7	10.7	0.0	30.4
86	85	15.9	25.3	11.0	0.0	34.5
86	86	15.9	27.8	12.2	0.0	34.2
86	87	13.0	26.8	17.9	0.0	28.8
86	88	12.9	26.9	16.3	0.0	28.9
86	89	14.1	28.9	15.2	0.0	30.7
86	90	14.1	29.6	15.2	0.0	30.7
86	91	11.2	32.0	14.7	0.0	26.8
86	92	12.0	22.5	14.9	0.0	25.0
86	93	12.7	31.3	14.2	0.0	28.2
86	94	16.4	35.3	14.7	0.0	36.1
86	95	12.7	33.8	16.8	0.0	27.6
86	96	16.0	37.1	17.8	0.0	34.9
86	97	15.4	33.8	16.8	0.0	33.2
86	98	15.2	33.2	17.9	0.0	32.2
86	99	15.5	32.5	17.0	0.0	33.9
86	100	16.8	33.7	14.8	0.0	35.9
86	101	16.0	35.6	15.4	0.0	33.5
86	102	16.0	38.1	16.4	0.0	33.1
86	103	11.2	33.9	18.0	0.0	23.7
86	104	12.8	29.2	19.1	0.0	27.0
86	105	14.3	32.1	14.0	0.0	29.6
86	106	16.5	33.6	12.9	0.0	33.0
86	107	14.9	35.1	13.9	0.0	28.4
86	108	16.8	32.3	16.2	0.0	29.7
86	109	16.4	34.2	17.2	0.0	32.0
86	110	13.4	35.9	18.7	0.0	26.6
86	111	10.4	30.8	14.5	0.0	21.2
86	112	17.6	27.3	12.9	0.0	37.3
86	113	18.0	27.3	13.7	0.0	38.1
86	114	18.0	28.4	13.9	0.0	38.1
86	115	12.3	28.9	14.8	0.0	26.0
86	116	13.8	31.1	16.3	0.0	29.2
86	117	16.9	30.0	16.1	0.0	35.8
86	118	16.8	33.4	16.2	0.0	35.6
86	119	10.8	35.8	18.3	0.0	22.9
86	120	13.9	32.4	14.9	0.0	29.5
86	121	14.8	29.6	12.6	0.0	31.4
86	122	13.0	31.7	14.4	0.0	27.6
86	123	11.1	26.3	15.0	0.0	23.5
86	124	12.8	28.8	15.6	0.0	26.8

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YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
86	125	15.4	30.2	15.4	0.0	34.2
86	126	15.5	31.9	15.5	0.0	35.5
86	127	15.0	36.4	16.4	0.0	31.9
86	128	14.6	30.1	15.7	0.0	29.7
86	129	16.5	29.8	15.2	0.0	35.6
86	130	16.9	30.0	12.4	0.0	35.1
86	131	17.7	31.1	15.2	0.0	36.3
86	132	14.5	28.3	14.3	0.0	31.4
86	133	17.4	29.6	14.2	0.0	36.6
86	134	17.0	29.6	13.8	0.0	34.2
86	135	16.7	29.5	13.2	0.0	32.9
86	136	17.7	31.2	14.0	0.0	36.8
86	137	17.5	31.9	14.9	0.0	37.0
86	138	17.8	29.5	16.1	0.0	38.7
86	139	14.8	31.8	16.5	0.0	31.4
86	140	17.3	33.1	16.9	0.0	36.7
86	141	17.2	34.1	15.2	0.0	36.5
86	142	17.6	33.1	15.0	0.0	37.3
86	143	17.8	33.0	16.9	0.0	37.7
86	144	17.4	32.4	17.3	0.0	36.9
86	145	17.2	34.5	15.1	0.0	36.5
86	146	17.7	33.2	18.0	0.0	37.5
86	147	17.7	33.2	19.9	0.0	37.5
86	148	17.7	33.5	18.0	0.0	37.5
86	149	16.4	30.2	18.0	0.0	34.8
86	150	17.7	31.4	15.7	0.0	37.5
86	151	18.2	32.0	16.6	0.0	38.6
86	152	17.3	33.1	16.9	0.0	36.7
86	153	17.3	33.1	16.9	0.0	36.7
86	154	17.3	33.1	16.9	0.0	36.7
86	155	17.3	33.1	16.9	0.0	36.7
86	156	17.3	33.1	16.9	0.0	36.7
86	157	17.3	33.1	16.9	0.0	36.7
86	158	17.3	33.1	16.9	0.0	36.7
86	159	17.3	33.1	16.9	0.0	36.7
86	160	17.3	33.1	16.9	0.0	36.7
86	161	17.3	33.1	16.9	0.0	36.7
86	162	17.3	33.1	16.9	0.0	36.7
86	163	17.3	33.1	16.9	0.0	36.7
86	164	17.3	33.1	16.9	0.0	36.7
86	165	17.3	33.1	16.9	0.0	36.7
86	166	17.3	33.1	16.9	0.0	36.7
86	167	17.3	33.1	16.9	0.0	36.7
86	168	17.3	33.1	16.9	0.0	36.7
86	169	17.3	33.1	16.9	0.0	36.7
86	170	17.3	33.1	16.9	0.0	36.7

YEAR	JULIAN DAY	RAD. MJm ⁻² d ⁻¹	MAX. TEMP. °C	MIN. TEMP °C	RAIN mm	PAR Em ⁻² d ⁻¹
86	171	17.3	33.1	16.9	0.0	36.7
86	172	17.3	33.1	16.9	0.0	36.7
86	173	17.3	33.1	16.9	0.0	36.7
86	174	17.3	33.1	16.9	0.0	36.7
86	175	17.3	33.1	16.9	0.0	36.7
86	176	17.3	33.1	16.9	0.0	36.7
86	177	17.3	33.1	16.9	0.0	36.7
86	178	17.3	33.1	16.9	0.0	36.7
86	179	17.3	33.1	16.9	0.0	36.7
86	180	17.3	33.1	16.9	0.0	36.7
86	181	17.3	33.1	16.9	0.0	36.7
86	182	17.3	33.1	16.9	0.0	36.7
86	183	17.3	33.1	16.9	0.0	36.7
86	184	17.3	33.1	16.9	0.0	36.7
86	185	17.3	33.1	16.9	0.0	36.7
86	186	17.3	33.1	16.9	0.0	36.7
86	187	17.3	33.1	16.9	0.0	36.7
86	188	17.3	33.1	16.9	0.0	36.7
86	189	17.3	33.1	16.9	0.0	36.7
86	190	17.3	33.1	16.9	0.0	36.7
86	191	17.3	33.1	16.9	0.0	36.7
86	192	17.3	33.1	16.9	0.0	36.7
86	193	17.3	33.1	16.9	0.0	36.7
86	194	17.3	33.1	16.9	0.0	36.7
86	195	17.3	33.1	16.9	0.0	36.7
86	196	17.3	33.1	16.9	0.0	36.7
86	197	17.3	33.1	16.9	0.0	36.7
86	198	17.3	33.1	16.9	0.0	36.7
86	199	17.3	33.1	16.9	0.0	36.7
86	200	17.3	33.1	16.9	0.0	36.7
86	201	17.3	33.1	16.9	0.0	36.7
86	202	17.3	33.1	16.9	0.0	36.7
86	203	17.3	33.1	16.9	0.0	36.7
86	204	17.3	33.1	16.9	0.0	36.7
86	205	17.3	33.1	16.9	0.0	36.7
86	206	17.3	33.1	16.9	0.0	36.7
86	207	17.3	33.1	16.9	0.0	36.7
86	208	17.3	33.1	16.9	0.0	36.7
86	209	17.3	33.1	16.9	0.0	36.7
86	210	17.3	33.1	16.9	0.0	36.7
86	211	17.3	33.1	16.9	0.0	36.7

FILE1

The first line contains the location data:

XLAT - latitude (in Besor 31.2).

XLONG - longitude (in Besor 34.4).

Two accessory data items are included:

PARFAC = 12.07. This is a factor to convert short wave radiation data from cal cm^{-2} to PAR in $\mu\text{Em}^{-2}\text{s}^{-1}$

PARDAT - if this parameter has a value 1, it means that PAR data are available. If it has a value 0, PAR data should be calculated from global short-wave radiation data, SHORTRAD.

The following lines of FILE1 contain climate data in columns.

column 1 = two digits, indicating the year of observation.

column 2 = date (Julian day).

column 3 = short-wave global radiation (MJm^{-2}).

column 4 = maximum temperature ($^{\circ}\text{C}$).

column 5 = minimum temperature ($^{\circ}\text{C}$).

column 6 = rainfall data (mm).

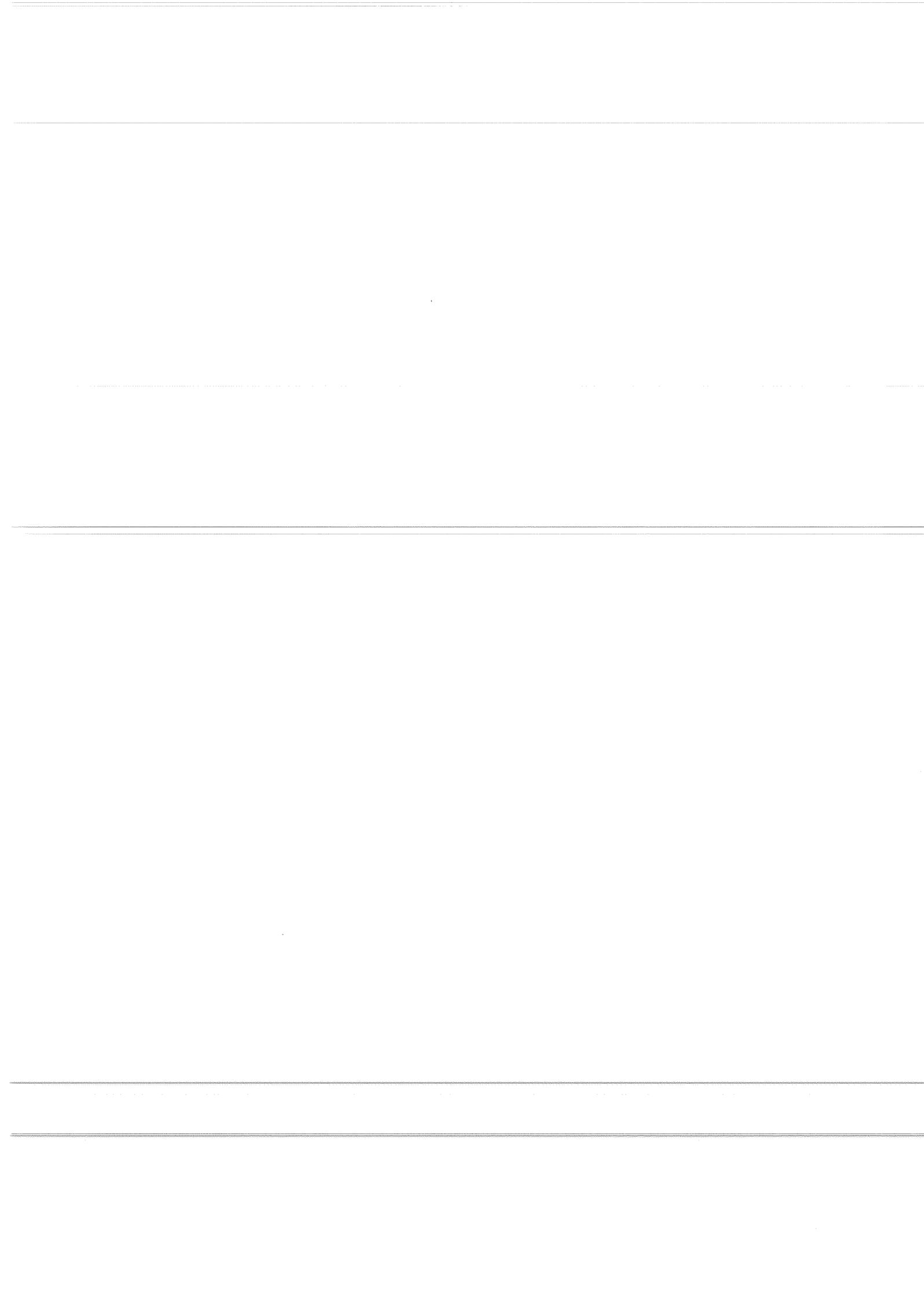
column 7 = PAR outside the greenhouse ($\text{Em}^{-2}\text{d}^{-1}$).

Appendix D2:

MGT.TOM

Data file (ASCII) for specifying crop management (starting day, output controllers and finish conditions) and initial values.

282 230 1.0 24 7 1.00	NSTART,NDAYS,DELT,
	NFAST,INTOUT,TRGH
3.0 1.0 6.0 5.0 0.5 0.002	PLM2,ROWSPC,PLSTNI,
	LVSNI,WLVSI,LFARI
350. 350. 350. 350. 350. 350.	CO2LT
0. 39. 40. 175. 176. 250.	XCO2LT
0. 0. 0. 0. 1. 1. 0. 0. 0. 0. 0. 0.	DISDAT
0. 20. 40. 160. 161. 162. 164. 300. 301. 302. 303. 304.	XDISDAT



Appendix D3:

CROPPARM

Data file (ASCII) of crop parameters and response functions.

0.3	10.5	0.21										TABK, TLOWAB, co2m
0.33	20	20	10.E-12	0.700	1.00	0.65						TPL, NL, NF, EPS, GREF,
												SPTL, GENFAC
3.0	0.100	8.3	1.4	0.015	0.010	6.0						XLAIM, XMRDR,
												ABORMX, Q10, RMRL, RMRF,
												FTRUSN
0.1	0.0	.075	.024	.075	10.0	2.5						WPLI, WPFI, SLAMX,
												SLAMN, STDSL, frlg,
												AVFM
0.00095	29.5	10.0	.15	0.1	.75	2.2	3.5					SCO2, THIGH, TLOW,
												TTMX, TTMN, ZBENG, TU1,
												TU2
10.	20.	30.	40.	50.	60.	70.	80.	90.	100.			BOX(I), I=1,10
.0007	.0016	.0031	.0032	.0032	.0032	.0032	.0032	.0032	.0032	.0007	.0007	POL(I), I=1,10
0.03	0.07	0.13	0.30	0.40	0.40	0.40	0.40	0.40	0.40	0.0		POF(I), I=1,10
1.0	1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		ASLA(I), I=1,10
.49	.49	.49	.49	.49	.49	.49	.49	.49	.49	.49		FRPET(I), I=1,10
.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43		FRSTEM(I), I=1,10
1.0	1.0	1.0	.5	.0	.0	.0	.0	.0	.0			DIS(I), I=1,10
1.0	1.0	1.0	1.0	.75	.0	.0	.0	.0	.0			DISf(I), I=1,10
0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0				PGRED(I), I=1,8
-10.	0.0	12.0	20.0	28.0	35.0	40.0	80.0					TMPG(I), I=1,8
0.01	0.01	0.01	0.2	0.25	1.5	3.1	3.1	3.1	3.1			FPN TABLE
0.0	6.0	7.0	8.0	9.0	13.0	20.0	24.0	50.0	90.0			XFPN VALUES
0.0	0.5	.95	1.0	0.2	0.0							GENTEM TABLE
0.0	6.0	21.0	28.0	50.0	80.0							XTEM VALUES, DEG C
0.55	0.55	0.55	0.55	0.55	0.05							GENRAT TABLE,
												NODES/DAY
0.0	10.0	20.0	65.0	70.0	90.0							XGEN PLSTN OR NODES
												DEV
0.0	.0035	.006	.0095	.011	.012	.012	0.001	0.0				RDVLVT TABLE,
												VEG DEV R
0.0	9.0	12.0	15.0	20.0	28.0	35.0	50.0	80.0				XLV, TEMP VALUES,
												DEG C
0.0	0.0065	.0095	.0120	.0165	.0165	.0150	0.001	0.0				RDVFRT TABLE,
												FR DEV RA
0.0	9.0	12.0	15.0	24.0	28.0	35.0	50.0	80.0				XFRT, TEMP VALUES,
												DEG
0.2	0.08	0.08	0.08	0.08	0.08							PROOT TABLE, FRACTION

D3-2

1.0 12.0 20.0 30.0 50.0 190.0
4.5 4.5 5.0 7.0 8.5 9.0
0.0 100. 130. 150. 200. 250.
0.0000 0.025 0.065 0.15 0.15
0. 15. 20. 30. 100.
1.0 1.0 1.0 0.99 0.8 0.1
0.0 20. 50. 55. 60. 200.

XROOT, PLSTN OR
VEG NOD
DMC84T TABLE,
G FW/G DW
XDMC, DAYS
PART
XPART EINSTEIN/DAY
AEFT LEAVES EFF.
XAEFT, PLSTN

Appendix D4:

COMMON.TOM

Includes all the common names of variables which are transferred to each of the subroutines.

COMMON/PARM/XLAIM, XMRDR, ABORMX, Q10, RMRL, RMRF, TPL, NL, NF, EPS
 2, GREF, GENFAC, SPTEL, FTRUSN, WPLI, WPFI, POL (10), POF (10), ASLA (10)
 3, SLA (10), FRPET (10), FRSTEM (10), DIS (10), BOX (10), HOURS (25), IRUNNUM
 4, ITRTNUM, FRLG, SCO2, THIGH, TLOW, TTMX, TTMN, disf (10)

C

COMMON/TABLE/GENTEM (6), XTEM (6), GENRAT (6), XGEN (6), RDVLVT (10)
 2, XLV (10), RDVFRT (10), XFRT (10), FPN (10), XFPN (10), PROOT (6)
 3, XROOT (6), DMC84T (6), XDMC (6), PGRED (8), TMPG (8), PART (5), XPART (5)
 4, AEFT (6), XAEFT (6), CO2LT (6), XCO2LT (6), DISDAT (12), XDISDAT (12)

C

COMMON/ENV/TMPA, CO2L, RADCAL, PPF, TAVG, CO2AVG, RADTOT, THR (25)
 2, RAD (25), SOLRAD, PARFAC, TMAX, TMIN, RAIN, PARO, PAR, SUP, SDN, DL

C

COMMON/DEV/GENRF, RDVLVF, RDVFRF, GENR, RDVLV, RDVFR, RCNL, RCNF
 2, RCST, PUSH, PUSHM, TEMFCF, TEMFAC, TTHF, TTLF, TTH, TTL

C

COMMON/CARBO/PMAX, QE, XK, XM, GPF, GP, MAINTF, MAINT

C

COMMON/GROWTH/PNLVS (50), PTNLVS, PNSTM (50), PTNSTM, PNFRT (50), PTNFRT
 2, PNGP, TOTDML, TOTDMS, TOTDMF, CLSDMF, CLSDML, RCWL (50), RCLFA (50)
 3, RCWST (50), RCWFR (50), TSLAF, TSLA, CSLAF, CSLA, PARSLA
 4, SLAMX, SLAMN, NCSLA, STDSL, XSLA, TRCDRW, RCDRW, FCO2, FCO2D, AVFM
 5, TABK, TLOWAB, TTABF, TTAB

COMMON/LOSS/ABNF, DEAR (50), DENLR (50), DEWLR (50), DELAR (50)
 2, DEAF (50), DENFR (50), DEWFR (50)

C

COMMON/MGT/NSTART, NDAYS, NFAST, INTOUT, DELT, PLM2, ROWSPC
 2, PLSTNI, LVSNI, WLVI, LFARI, DTF, TRGH

C

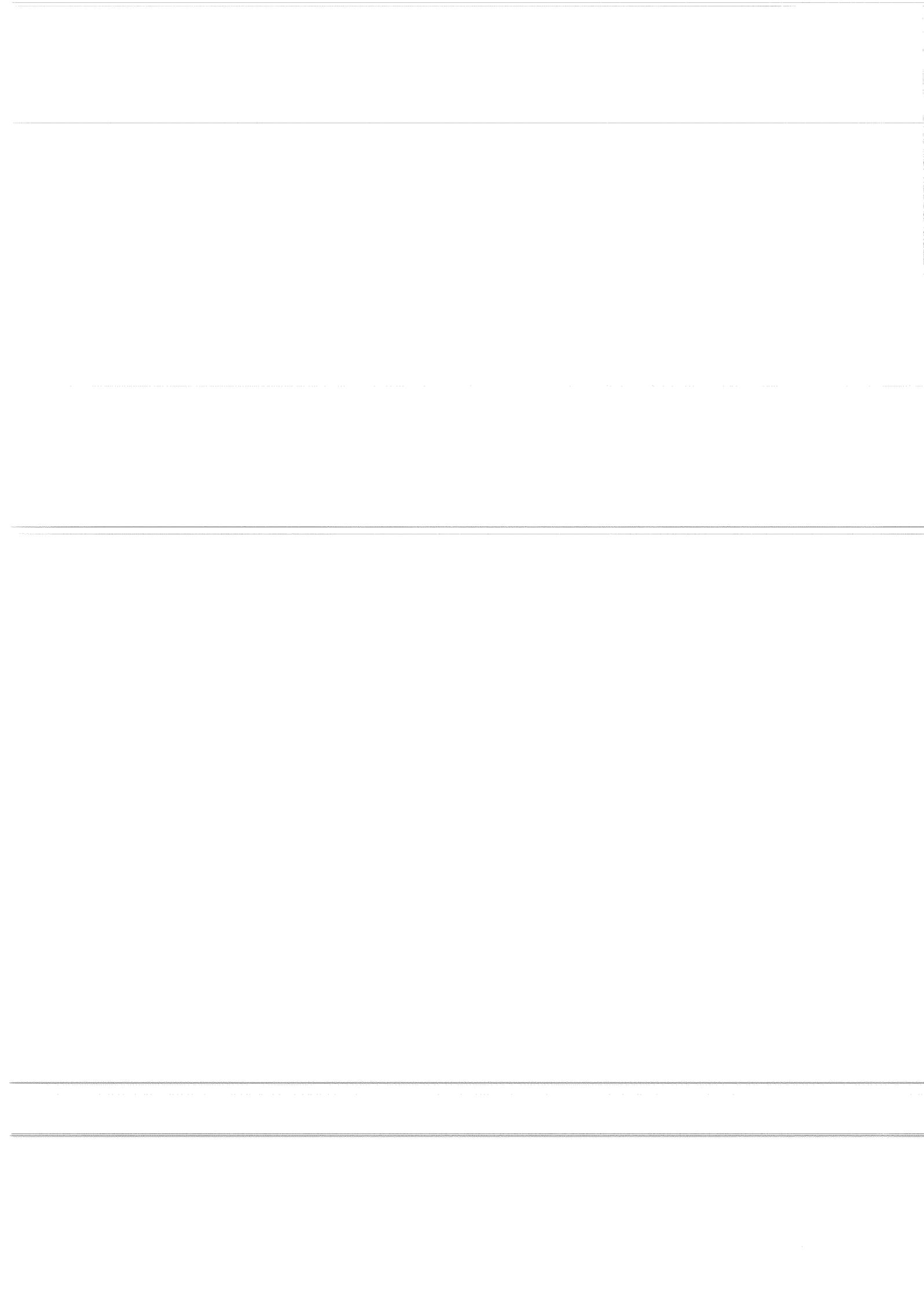
COMMON/STATE/JDAY, TIME, DATE, TFAST, CPOOL, PLSTN, LVSNI (50)
 2, WLVI (50), LFAR (50), FRTN (50), WFRT (50), STMS (50), WSTM (50), ESLA

C

COMMON/AUXVAR/XLAI, TOTNLV, TOTWML, AVWL (50), TOTNF, TOTWMF
 2, AVWF (50), WTOTF, TOTGF, TOTDW, TOTNU, NGP, RVRW, RTRW
 3, RVRN, RTRN, AVWML, FWER10, TWTLAI, TOTGL, WSTOTL, ASTOTL
 4, TOTNST, TOTWST, TOTST, WSTOT, APFFW, TOTVW, ZBENG, DLN, BTOTNLV, AEF, CLSDML
 5, ATL, ATV, TU1, TU2, ATT, co2m

C

REAL MAINT, MAINTF, LVSNI, LFARI, LVSNI, LFAR, NGP



Appendix E:

Output

Output from the model is included in two files: OUT1 and OUT2.

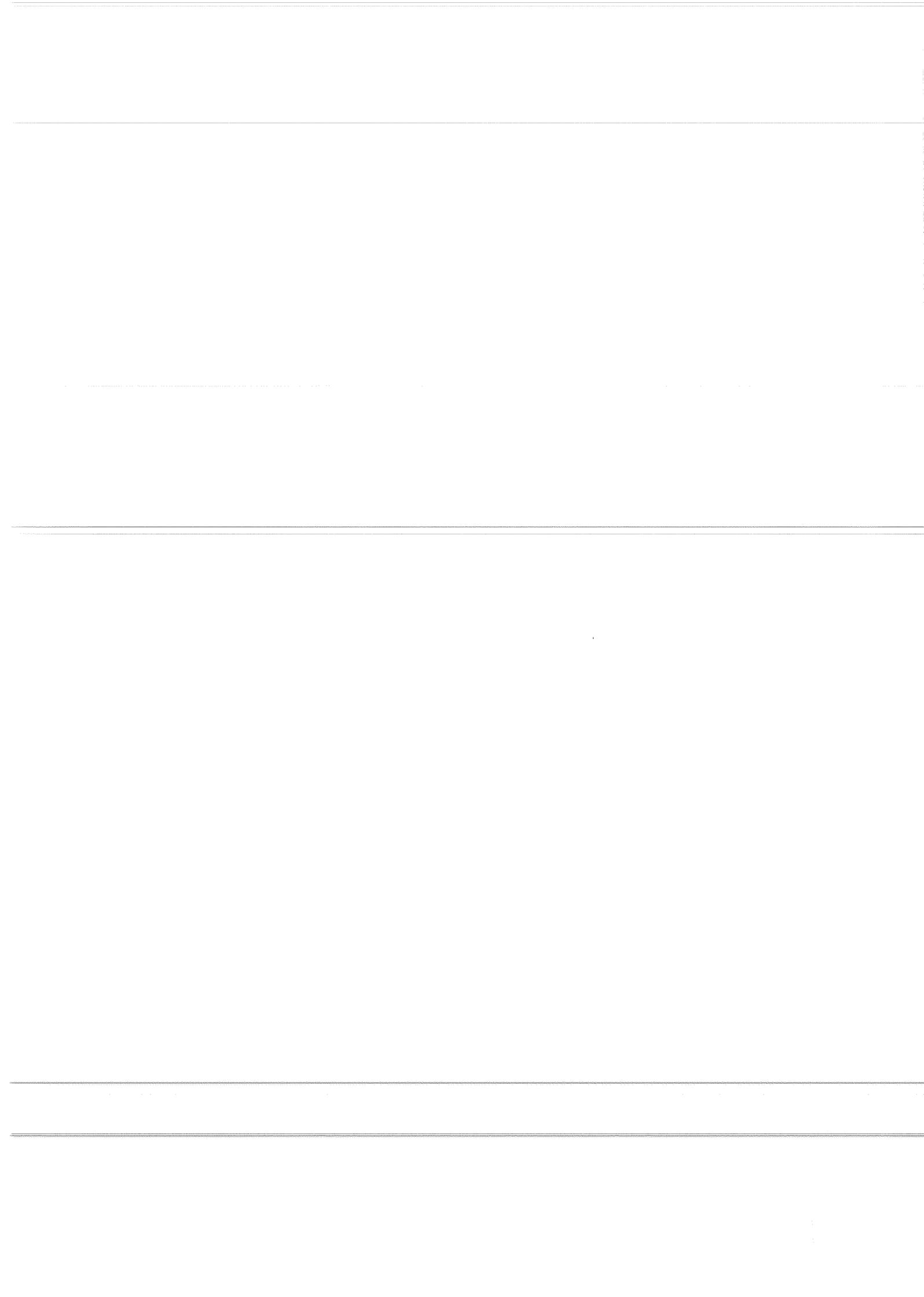
Inst ID (country): _____

Site ID (site of experiment): _____

EXPT No. (number of experiment): _____

TRT No. (number of treatment): _____

TIME (Julian day): _____



Appendix F:

Drawing graphs with the graph1 Program

A BASIC program, Graph1, enables graphic presentation of the simulation results.

Running a compiled graphic program

The files required for running the compiled graphic program are:

- A. GRAPH1.EXE - A compiled BASIC program.
- B. SELPGM.BAT - A file on which the model indicates end of job with the word "TOMGRO".
- C. \$\$ODS.DAT - This file includes:
 1. The file with the simulation's results (available options are OUT1 or OUT2).
 2. Names of 20 files, containing experimentally measured data to compare with the simulation's results.
 3. A screen option.
- D. GLABEL.DAT - A file with headlines for the drawings.
- E. OUT1 or OUT2 - A file containing the simulation results.
- F. CFIELD.DAT - A file containing experimentally measured data.

F1: GLABEL.DAT

Calculated and measured data which may be presented by the "Graph1" procedure.

This is an example of the printout of file GLABEL.DAT, which directs the GRAPH1 program to each variable and labels the vertical axis. On the first line of each number is the description and on the second line the label that is displayed on the vertical axis of the graph on the screen.

```
-----
1  PLSTN:          Nodes per plant
   PLSTN          [Nodes/plant]
2  XLAI:          LAI (2+10)
   XLAI          [m**2(leaves)/m**2(ground)]
3  TOTNL/PLM2:   live leaves/plant
   TOTNL/PLM2   [No (leaves)/plant]
4  TOTWML:       Total leaf weight
   TOTWML       [g(leaves)/m**2]
5  TOTNF:        Total fruit number
   TOTNF        [No (fruit)/m**2]
6  TOTWMF:       Total fruit weight
   TOTWMF       [g(fruit)/m**2]
7  FRTN (NF):    Picked fruit number
   FRTN (NF)    [No (fruit)/m**2]
8  WFRT (NF):    Picked fruit weight
   WFRT (NF)    [g(dry fruit)/m**2]
```

F-2

9	XSLA:	Overall specific leaf area
	XSLA	[m**2(leaf)/g]
10	ASTOL:	LAI growing leaves
	ASTOL	[m**2(leaves)/m**2(ground)]
11	GP:	Gross photosynthesis rate
	GP	[g(CH2O)/m**2/day]
12	MAINT:	Maintenance respiration rate
	MAINT	[g(CH2O)/m**2/day]
13	TCDRW:	Net photosynthesis rate
	TCDRW	[g(CH2O)/m**2/day]
14	RCDRW:	Rate of aboveground dry matter accumulation
	RCDRW	[g(CH2O)/m**2/day]
15	FWFR10:	Fresh weight of picked fruit
	FRFR10	[g/m**2/day]
16	TOTWST:	Stem weight
	TOTWST	[g/m**2]
17	APFFW:	Average fresh weight per fruit
	APFFW	[g/fruit]
18	TOTVM:	Total live vegetative dry weight (s+l+t)
	TOTVM	[g/m**2]
19	TOTDW:	Total live aboveground dry weight (s+l+t+f)
	TOTDW	[g/m**2]
20	DLV:	Total number of dead leaves
	DLV	(No/plant)& available field data for comparison
21	CLSDML:	Supply/Demand
	CLSDML	[Supply/Demand]
22	TEMFAC:	Effect of temperature
	TEMFAC	[Effect of temperature]
23	ATL:	Accumulated dead leaf weight (dl)
	ATL	[g(leaves)/m**2]
24	ATV:	Cumulative vegetative aboveground dry weight (s+l+dl+t)
	ATOTVW	[g/m**2]
25	ATT:	Total cumulative aboveground dry weight (s+l+dl+t+f)
	ATT	[g/m**2]

F2: OUT1 or OUT2 (see appendix E)

F3: CFIELD.CAL

Line 1 - location ID and date.

Line 2 - 14 numbers, one for each column in the file. The number is the corresponding variable number in file GLABEL.DAT.

Line 3 - and on, columns with field information (in column 1: Julian date).

INST ID:IS; SITE ID:BS; EXPT. 01, 1985.

J. DAY	4	16	23	18	25	8	6	3	20	1	15	7	17
286	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.00	0.00	5.87	0.00	0.00	0.00
304	18.31	4.19	0.00	22.50	22.50	0.00	0.00	11.00	0.00	13.67	0.00	0.00	0.00
336	169.63	67.32	0.00	236.95	275.60	0.00	38.65	21.33	0.00	27.44	0.00	0.00	0.00
1	253.63	136.64	72.45	390.28	677.05	0.00	214.32	25.33	7.67	43.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	74.70	0.89	88.38
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	290.72	3.47	85.20
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	700.78	8.46	80.95
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1291.63	15.13	88.71
34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2120.57	24.39	89.45
37	299.26	170.72	102.37	469.98	1042.40	107.72	470.05	28.67	10.83	51.67	0.00	0.00	0.00
41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3086.79	36.13	82.95
48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4403.84	53.11	78.32
55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5942.23	73.09	77.03
62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7727.83	98.42	70.53
64	254.27	189.78	182.70	444.05	1281.56	428.04	654.81	27.33	19.33	61.22	0.00	0.00	0.00
69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9062.05	119.85	62.08
76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9774.91	132.53	55.86
83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10351.90	143.40	52.94
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10975.81	155.28	52.89
95	452.60	303.36	174.83	755.96	1794.92	677.71	863.93	26.33	18.50	58.78	0.00	0.00	0.00
98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11675.30	168.23	53.79
104	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12412.35	181.12	57.25
111	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12827.45	189.23	51.58
118	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13256.94	198.42	46.76
125	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13745.67	208.66	48.33
125	418.23	304.00	174.83	722.23	1853.06	808.65	956.01	0.00	0.00	0.00	0.00	0.00	0.00
132	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14341.42	220.58	50.42
139	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14850.45	231.13	48.62
146	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15284.79	240.84	44.47
154	570.87	351.41	174.83	922.28	2054.29	910.81	957.18	0.00	0.00	0.00	0.00	0.00	0.00

Appendix G: TOMGRO model dictionary

Units

°C	Degrees Centigrade
d	Day
DM	Dry matter
E	Einstein
g	gram
FW	fresh weight
h (H)	Hour
J	Joule
M	Mega
m (M)	Meter
mm	Millimeter
no	Number
s	Second
sub	Subroutine
vpm	Part per million (volume)
-	Unitless

Acronym	Description	units	Subroutine(s) where it appears
AABNF	Cumulative number of aborted fruits	no m ⁻²	LOSRATE OUTPUT
ABNF	Fruit abortion rate	no m ⁻² d ⁻¹	LOSRATE INTGRAT
ABORMX	Auxiliary variable for calculating fruit abortion rate as a function of supply/demand ratio for dry matter	-	CROPPARM LOSRATE
AEF	Age effect on PMAX	-	PHOTO CROPPARM
AEFT	Function describing the effect of age on PMAX	-	PHOTO CROPPARM
AFRWT	Average fruit weight	g	OUTPUT
ANS	Auxiliary variable, indicating wait for answer	-	IPWTH
APFFW	Average fresh weight of picked fruits	g	INTGRAT OUTPUT
ARG(K)	Auxiliary variable in sub-TABEX		TABEX
ASLA (1-NL)	Table describing the effect of age on SLA	-	INPUT DMRATE INTGRAT CROPPARM
ASTOLTL	LAI of 'growing leaves' (XLAI), excluding leaves in the last age class	m ² (leaf) m ⁻² (ground)	INITIAL INTGRAT PHOTO OUTPUT
ATL	Accumulated weight of dead leaves	g m ⁻²	INITIAL NTGRAT OUTPUT
ATV	Total dry matter production of aboveground vegetative plant parts (including dead leaves)	g m ⁻²	INITIAL INTGRAT OUTPUT
ATT	Total dry matter production of aboveground plant parts	g m ⁻²	INTGRAT OUTPUT
AVWL(NL)	Average weight per leaf in leaf class NL	g	LOSRATE INTGRAT
AVWF(NF)	Average weight per fruit in fruit class NF	g	INTGRAT
AVWMF (1-NF)	Average weight per fruit (including ripe fruits)	g	INTGRAT
AVWML (1-NL)	Average weight per leaf on the plant	g	INTGRAT
AVFM	Average weight per mature fruit	g	DMRATE CROPPARM

Acronym	Description	units	Subroutine(s) where it appears
BOT	Auxiliary variable representing denominator in Acock's equation		PHOTO
BOX (1-10)	Box (l) = 10,20,100 representing age classes, used as abscissa for some tables.	-	CROPPARM DMRATE INTGRAT LOSRATE
BTOTNLV	Total number of leaves initiated	no m ⁻²	INITIAL INTGRAT OUTPUT
CLSDMF	Proportion of fruit sink demand that is satisfied	-	DMRATE DEVSTATE
CLSDML	Proportion of leaf sink demand that is satisfied	-	DMRATE LOSRATE
CO2AVG	Daily average CO ₂ level	μmol mol ⁻¹	GHOUSE DEVFAST PHOTO
CO2L	Current CO ₂ level within the greenhouse	μmol mol ⁻¹	GHOUSE
CO2LT	Average daily CO ₂ level in the greenhouse as a function of day number	μmol mol ⁻¹	GHOUSE MGT
CO2M	Factor to calculate effect of CO ₂ on specific leaf area	-	DEVFAST CROPPARM
CPOOL	Pool of carbohydrates for daily growth (gross assimilation minus total respiration)	g m ⁻² d ⁻¹	INITIAL INTGRAT
CSLA	Integrated daily effect of CO ₂ level on SLA	-	TOMGRO DMRATE
CLSAF	Partial instantaneous effect of CO ₂ level on SLA	-	TOMGRO DEVFAST
DATE	Day number in Julian calendar	-	TOMGRO OUTPUT
DATEZ	Day number of pruning	-	LOSRATE
DAYL	Astronomic daylength	h	SUNRISE
DAYTMP	Length of daytime period	h	GHOUSE
DEAF (1-NF)	Fraction of fruit loss per age class due to pruning	-	LOSRATE
DEAR (1-NL)	Fraction of leaf loss per age class due to disease or pruning	-	LOSRATE
DELAR (1-NL)	Death rate of leaf area per age class	m ² m ⁻² d ⁻¹	LOSRATE INTGRAT
DELT	Time step of simulation within the main loop	d	TOMGRO INTGRAT MGT
DENFR (1-NF)	Rate of loss of fruit number per age class due to pruning	no m ⁻² d ⁻¹	LOSRATE INTGRAT

Acronym	Description	units	Subroutine(s) where it appears
DEWLR (1-NL)	Total death rate of leaf weight per age class	$\text{g m}^{-2} \text{d}^{-1}$	LOSRATE INTGRAT
DEWFR (1-NF)	Total death rate of fruit weight per age class	$\text{g m}^{-2} \text{d}^{-1}$	CROPPARM LOSRATE
DIS (1-NL)	Fraction of leaf death per age class due to disease or pruning	-	CROPPARM LOSRATE
DISF (1-NF)	Fraction of fruit death per age class due to disease or pruning	-	CROPPARM LOSRATE
DISDAT	Auxiliary variable assuming value 1 at the time of pruning or disease incidence	-	LOSRATE MGT
DL	Photoperiodic daylength	h	WCACL
DLA	Cumulative area of dead leaves	m^2 (leaves) m^{-2} (ground)	INTGRAT
DLN	Cumulative number of dead leaves	no m^{-2}	INTGRAT
DLW	Cumulative weight of dead leaves	g m^{-2}	INTGRAT
DMC84T	Observed fruit dry matter content as a function of daynumber for 1984	$\text{g(DM) g}^{-1}(\text{FW})$	CROPPARM INTGRAT
DMCF84	Fraction dry matter in fruits picked on a given day, obtained from DMC84T	-	INTGRAT
DFAST	Time step of simulation within the fast loop	d	INITIAL TOMGRO
DUMMY	Auxiliary variable in sub TABEX, used to replace 'X' value for which the corresponding 'Y' value is calculated	-	TABEX
EPS	Auxiliary variable, very small number ($10\text{E}-12$), to avoid zero division	-	TOMGRO CROPPARM DMRATE LOSRATE INTGRAT OUTPUT
ESLA	SLA as determined by environmental conditions (CO_2 , PAR and temperature)	$\text{m}^2 \text{g}^{-1}$	DMRATE INTGRAT
EXCESS	Difference between actual rate of DM accumulation (RCDRW) and potential rate of DM accumulation (TOPGR); EXCESS > 1 if carbohydrate availability exceeds demand	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE
FABOR	Fraction of fruit aborted in first fruit age class	-	LOSRATE
FCO2	Partial relative increase in development rate at CO_2 levels exceeding $350 \mu\text{mol mol}^{-1}$	-	TOMGRO DMRATE

Acronym	Description	units	Subroutine(s) where it appears
FCO2D	Daily relative increase in development rate at CO ₂ levels exceeding 350 μmol mol ⁻¹	-	TOMGRO DMRATE
FILE1	File containing weather data, including daily minimum and maximum temperature, rain and global and photosynthetically active radiation, normally referring to outside conditions	-	IPWTH
FPN	Number of new fruits per node as function of PLSTN	no node ⁻¹	CROPPARM DEV RATE
FLRG	Lag period between the time that a truss appears and a fruit appears on that truss	no (nodes) plant ⁻¹	INPUT DEV RATE CROPPARM
FRPET	Table containing petiole weight as fraction of leaf weight, function of leaf age class	-	INPUT INTGRAT CROPPARM
FPRT	Actual fraction of petiole weight	-	DMRATE INTGRAT
FRST (1-NL)	Fraction stem in total dry matter demand, defined in FRSTEM as function of leaf age class	-	DMRATE
FRSTEM	Table defining fraction stem in total dry matter demand as function of leaf age class	-	CROPPARM DMRATE INTGRAT
FRTN(I)	Number of fruits per fruit age class	no m ⁻²	INITIAL INTGRAT OUTPUT
FRTN(NF)	Number of harvested fruits	no m ⁻²	INITIAL INTGRAT OUTPUT
FTRUSN	Node number on the plant that bears the first truss	-	CROPPARM DEV RATE
FWFR10	Fresh weight of harvested fruits	g m ⁻²	INTGRAT
GENFAC	Factor accounting for the effect of supply/demand ratio on initiation of new nodes	-	CROPPARM INPUT DEVFAST
GENR	Daily integrated rate of node initiation per plant	no d ⁻¹	TOMGRO DEV RATE INTGRAT
GENRAT	Daily node initiation rate per plant as a function of plastochron index	no d ⁻¹	DEVFAST CROPPARM

Acronym	Description	units	Subroutine(s) where it appears
GENRF	Instantaneous rate of node initiation per plant, function of temperature, CO ₂ level and genetic properties	no d ⁻¹	TOMGRO DEVFAST
GENTEM	Function describing the effect of temperature on node initiation rate	-	DEVFAST CROPPARM
GP	Daily rate of gross photosynthesis	g(CH ₂ O) m ⁻² d ⁻¹	TOMGRO DMRATE INTGRAT OUTPUT
GPF	Instantaneous rate of gross photosynthesis	g(CH ₂ O) m ⁻² d ⁻¹	PHOTO TOMGRO
GR	Conversion factor from μmol (CO ₂) m ⁻² s ⁻¹ to g(CH ₂ O) m ⁻² d ⁻¹	μmol (CO ₂) m ⁻² s ⁻¹ g(CH ₂ O) m ⁻² d ⁻¹	TOMGRO
GRES	Growth efficiency, accounting for growth respiration	g(DM) g ⁻¹ (CH ₂ O)	CROPPARM DMRATE INTGRAT
HDARK	Length of the dark period, auxiliary variable for calculation of average night-time temperature	h	WCALC
HOURS	Number of hours within a day (24)	-	TOMGRO
IDPR	Program identification	-	TOMGRO OUTPUT
IENV	Identifier for constant environment	-	GHOUSE
INID	Identification of location (UF/Israel)	-	OUT1
INTOUT	Interval for output	d	MGT
IRUNNUM	Counter for number of simulation runs	-	TOMGRO OUTPUT
ITRTNUM	Treatment number	-	TOMGRO OUTPUT
JDAY	Counter for number of main loop iterations, used as indicator for number of days to be simulated	-	TOMGRO OUTPUT
JUL	Day number in Julian calendar	-	IPWTH FILE1
KYR	Identification of year (last two digits)	-	IPWTH FILE1
K	Auxiliary variable (see TABEX)	-	TABEX
LFAR (1-NL)	Leaf area index per age class	m ² (leaf) m ⁻² (ground)	INITIAL LOSRATE INTGRAT
LFARI	Initial leaf area per plant	m ²	MGT INITIAL

Acronym	Description	units	Subroutine(s) where it appears
LVSN (1-NL)	Number of leaves per age class	no m ⁻²	INITIAL DMRATE INTGRAT
LVSNI	Initial number of leaves per plant	no	MGT INITIAL INTGRAT OUTPUT
MAINT	Integrated daily maintenance respiration rate	g(CH ₂ O) m ⁻² d ⁻¹	TOMGRO DMRATE
MAINTF	Instantaneous maintenance respiration rate	g(CH ₂ O) m ⁻² d ⁻¹	TOMGRO RESP
NCSLA	Counter for number of periods with radiation level (PAR) above 0.1, used in calculation of effect of CO ₂ on SLA	-	TOMGRO DEVFAST
NDAYS	Number of days to be simulated	d	TOMGRO
NEW	Auxiliary value to mark the onset of a new simulated day.	-	MGT IPWTH
NF	Number of fruit age classes distinguished	-	INPUT INITIAL DEVSTATE CROPPARM DMRATE
NFAST	Number of time steps within the fast loop during one day	-	MGT INITIAL
NGP	Total number of growing points including leaves, fruit and stems	no m ⁻²	INTGRAT
NL	Number of leaf age classes distinguished	-	INPUT INITIAL DEVSTATE CROPPARM DMRATE LOSRATE
NSTART	Starting day (number of Julian calendar day)	-	INPUT INITIAL CROPPARM TOMGRO
PARPAR	Intensity of photosynthetically active radiation	μE m ⁻² d ⁻¹	DMRATE GHOUSE FILE1
PART	Function to account for the effect of PAR (XPART) on SLA of growing leaves	-	CROPPARM
PARFAC	conversion factor from global short wave radiation to PAR	μE m ⁻² s ⁻¹ /cal cm ⁻² d ⁻¹	DMRATE IPWTH FILE1

Acronym	Description	units	Subroutine(s) where it appears
PARDAT	Auxiliary variable, 1 indicates availability of PAR data, 0 absence	-	IPWTH FILE1
PARO	Level of PAR outside greenhouse, either from measurement (FILE1) or calculated from global short wave radiation (SOLRAD)	$\mu\text{Em}^{-2}\text{s}^{-1}$	IPWTH GHOUSE FILE1
PGRED	Function accounting for the reduction in P _{MAX} under extreme temperatures	-	INPUT CROPPARM PHOTO
PLM2	Plant density	no m^{-2}	MGT DEV RATE OUTPUT
PLSTN	Plastochron index	nodes plant ⁻¹	INITIAL DEVFAST OUTPUT
PLSTNI	Initial plastochron index	nodes plant ⁻¹	DMRATE MGT INITIAL
PLTM2V	Plant density in Gainesville experiment 1985	no m^{-2}	TOMGRO DMRATE LOSRATE OUTPUT PHOTO
P _{MAX}	Light-saturated leaf photosynthetic rate	$\mu\text{mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$	PHOTO RESP
P _{NFRT} (1-NF)	Potential sink capacity per fruit age class	$\text{g m}^{-2}\text{ d}^{-1}$	DMRATE
P _{NGP}	Total potential sink capacity of all growing points, i.e stems, leaves and fruits	$\text{g m}^{-2}\text{ d}^{-1}$	DMRATE
P _{NLVS} (1-NL)	Potential sink capacity per leaf age class	$\text{g m}^{-2}\text{ d}^{-1}$	DMRATE
P _{NSTM} (1-NF)	Potential sink capacity per stem age class	$\text{g m}^{-2}\text{ d}^{-1}$	DMRATE
P _{OF} (1-NF)	Relative potential sink capacity per fruit age class	-	CROPPARM DMRATE
P _{OL} (1-NL)	Potential leaf area expansion rate	$\text{m}^2\text{ m}^{-2}\text{ d}^{-1}$	CROPPARM DMRATE
P _{PPFD}	PAR radiation intensity inside the greenhouse, as derived from RADA	$\mu\text{E m}^{-2}\text{ s}^{-1}$	GHOUSE PHOTO
P _{ROOT}	Fraction of photosynthate allocated to growth of the root system, function of physiological age	-	CROPPARM DMRATE

Acronym	Description	units	Subroutine(s) where it appears
PTNFRT	Total potential sink capacity of all fruit age classes	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE
PTNLVS	Total potential sink capacity of all leaf age classes	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE
PUSHL	Auxiliary variable, governing transition between leaf age classes	-	DEVRATE INTGRAT
PUSHM	Auxiliary variable, governing transition between fruit age classes	-	DEVRATE INTGRAT
QE	Quantum efficiency of photosynthetic process	$\text{mol CO}_2 \text{ mol}^{-1}$ (photons)	PHOTO
Q10	Effect of temperature on maintenance respiration	-	RESP CROPPARM
RAD	PI/180	radians	GHOUSE SUNRISE
RAD (1-25)	Table containing hourly values of global radiation intensity calculated from SOLRAD, assuming a sinusoidal pattern	$\text{MJ m}^{-2} \text{d}^{-1}$	WCALC GHOUSE
RADA (1-25)	Instantaneous global radiation intensity outside greenhouse (equivalent to RAD(1-25))	$\text{MJ m}^{-2} \text{d}^{-1}$	GHOUSE
RADCAL	Global radiation intensity inside the greenhouse, calculated from RADA(I) by multiplication with transmission coefficient	$\text{MJ m}^{-2} \text{d}^{-1}$	GHOUSE
RAIN	Daily rain	mm	IPWTH FILE1
RCDRW	Rate of change in aboveground dry matter	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE INTGRAT
RCLFA (1-NL)	Potential rate of leaf area expansion per leaf age class	$\text{m}^2(\text{leaf}) \text{ m}^{-2}(\text{ground}) \text{d}^{-1}$	DMRATE INTGRAT
RCNF	Rate of fruit appearance	$\text{no m}^{-2} \text{d}^{-1}$	LOSRATE INTGRAT DEVRATE
RCNL	Rate of leaf appearance	$\text{no m}^{-2} \text{d}^{-1}$	DEVRATE INTGRAT
RCST	Rate of stem node appearance	$\text{no m}^{-2} \text{d}^{-1}$	DEVRATE INTGRAT
RCWFR (1-NF)	Rate of fruit growth per age class	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE INTGRAT
RCWLV (1-NL)	Rate of leaf growth per age class	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE INTGRAT

Acronym	Description	units	Subroutine(s) where it appears
RCWSTDM (1-NL)	Rate of stem node growth per age class	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE INTGRAT
RDVFR	Integrated effect of temperature and CO_2 level on fruit development rate	-	TOMGRO DEV RATE
RDVFRF	Instantaneous effect of temperature and CO_2 level on fruit development rate	-	DEVFAST
RDVFRT	Fruit development rate as a function of temperature	-	CROPPARM DEVFAST
RDVLV	Integrated effect of temperature and CO_2 level on leaf development rate	-	TOMGRO DEV RATE
RDVLVF	Instantaneous effect of temperature and CO_2 level on leaf development rate	-	DEVFAST
RDVLVTA	Vegetative development rate as a function of temperature	-	CROPPARM DEVFAST
RMRF	Maintenance requirements of fruits	$\text{g}(\text{CH}_2\text{O})$ $\text{g}^{-1}(\text{tissue}) \text{d}^{-1}$	CROPPARM RESP
RMRL	Relative maintenance requirements of vegetative material	$\text{g}(\text{CH}_2\text{O})$ $\text{g}^{-1}(\text{tissue}) \text{d}^{-1}$	CROPPARM RESP
ROWSPC	Row spacing	m	MGT
RTRN	Ratio of total number of fruits to total number of apices	-	INTGRAT
RTRW	Ratio of fruit dry weight to total plant dry weight	-	INTGRAT
RVRN	Ratio of total fruit number to total leaf number	-	INTGRAT
RVRW	Ratio of total fruit weight to total leaf weight	-	INTGRAT
SCO2	Relative increase in development rate as a function of CO_2 level	-	INPUT CROPPARM DEVFAST
SDN	Time of sunset on give day	h	IPWTH WCALC
SDNGH	Computed time of sunset	h	GHOUSE
SDNT	Time of sunset on a given day	h	IPWTH WCALC
SDNY	Time of sunset for day J	h	IPWTH WCALC
SLA	Specific leaf area per leaf age class	$\text{m}^2 \text{g}^{-1}$	DMRATE INTGRAT
SLAMN (1-NL)	Minimum value of SLA per leaf age class	$\text{m}^2 \text{g}^{-1}$	INPUT CROPPARM DMRATE

Acronym	Description	units	Subroutine(s) where it appears
SOLRAD	Daily total global radiation	MJ m ⁻² d ⁻¹	DMRATE IPWTH FILE1
SPTL	Auxiliary value for adaptation of units	-	CROPPARM DEVFAST
START	Starting day of simulation (number of Julian calendar day)	-	TOMGRO
STDSLA	'Standard' value of SLA at 24 C, 350 μmol mol ⁻¹ CO ₂ and low PAR	m ² g ⁻¹	INPUT CROPPARM DMRATE
STMS (1-NL)	Number of stem internodes per age class	no m ⁻²	INITIAL DMRATE INTGRAT
SUP	Time of sunrise for current day J	h	IPWTH WCALC
SUPGH	Time of sunrise used for constant conditions	h	GHOUSE
SUPT	Time of sunrise for day J+1	h	IPWTH WCALC
SUPY	Time of sunrise for day J-1	h	IPWTH WCALC
TABEX	Subroutine for interpolation TABEX (VAL, ARG, DUMMY, K) VAL: Set of fixed dependent Y-variables in which interpolation takes place ARG: Set of fixed independent X-variables DUMMY: Value of dependent variable for which corresponding Y-value must be determined K: Number of arguments		TABEX
TABK	Factor accounting for the effect of low temperature on fruit abortion.	-	LOSRATE CROPPARM
TABOR	Effect of temperature on fruit abortion	-	LOSRATE
TAU	Auxiliary variable for calculation of temperature distribution over the day	-	WCALC
TAU1	Factor accounting for the effect of CO ₂ level on P _{MAX}	μmol(CO ₂) m ⁻² s ⁻¹ μmol mol ⁻¹ (CO ₂)	PHOTO
TAU2	Factor accounting for the effect of CO ₂ level on P _{MAX}	μmol(CO ₂) m ⁻² s ⁻¹ μmol mol ⁻¹ (CO ₂)	PHOTO
TAVG	Air temperature at current time		GHOUSE
TEFF	Effect of temperature on maintenance respiration	°C -	RESP

Acronym	Description	units	Subroutine(s) where it appears
TEMFAC	Correction factor for apex initiation rate, potential leaf expansion rate and potential fruit growth rate as a function of temperature	-	TOMGRO DEVFAST DMRATE
TEMFCF	Factor accounting for the instantaneous effect of temperature on apex initiation rate, potential leaf expansion rate and potential fruit growth rate		DEVFAST
TFAST	Current time during fast loop	d	TOMGRO GHOUSE
THIGH	Temperature threshold above which fruit set decreases	°C	INPUT CROPPARM DEVFAST
THR (1-25)	Air temperature at each whole hour during the day	°C	GHOUSE WCALC
TIME	Number of days since the beginning of simulation	d	TOMGRO
TLIN	Auxiliary variable for calculation of temperature during night-time		WCALC
TLOW	Temperature threshold below which splitting of trusses occurs and more fruits are initiated per new leaf	°C	INPUT CROPPARM DEVFAST
TLOWAB	Temperature threshold below which fruits are aborted	°C	DEVFAST CROPPARM
TMAX	Daily maximum temperature on current day J	°C	WCALC
TMAXGH	Constant daytime temperature in greenhouse (when option of constant environment is selected)	°C	GHOUSE
TMAXT	Maximum temperature on day J+1	°C	WCALC
TMAXY	Maximum temperature on day J-1	°C	WCALC
TMIN	Daily minimum temperature on current day J	°C	IPWTH FILE1
TMINGH	Constant night-time temperature in greenhouse (when option of constant environment is selected)	°C	GHOUSE
TMINT	Minimum temperature on day J+1	°C	WCALC
TMINY	Minimum temperature on day J-1	°C	WCALC
TMPG(8)	Fixed set of independent abscissa values (temperature) in function PGRED	°C	INPUT CROPPARM PHOTO

Acronym	Description	units	Subroutine(s) where it appears
TMPA	Air temperature at current time	°C	GHOUSE DEVFAST PHOTO PHOTO
TOP	Auxiliary value, nominator in Acock's equation (See BOT)	-	PHOTO
TOPGR	Actual growth rate of total aboveground plant biomass	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE
TOTDMF	Total rate of dry matter accumulation in fruits	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE LOSRATE OUTPUT
TOTDML	Total rate of dry matter accumulation in leaves	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE
TOTDMS	Total rate of dry matter accumulation in stems	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE OUTPUT
TOTDW	Total aboveground dry weight	g m^{-2}	INTGRAT
TOTGF	Total number of growing fruits	no m^{-2}	INTGRAT
TOTGL	Total number of growing leaves	no m^{-2}	INTGRAT
TOTNF	Total number of fruits in the field (summation of FRTN(1-NF))	no m^{-2}	INTGRAT
TOTNLV	Total number of leaves in the field (summation of LVS(1-NL))	no m^{-2}	INTGRAT OUTPUT
TOTNST	Total number of main stems in the field (summation of STMS (1-NL))	no m^{-2}	INTGRAT
TOTNU	Total number of leaf and fruit growing points	no m^{-2}	INTGRAT
TOTST	Total number of growing main stems	no m^{-2}	INTGRAT
TOTWMF	Total dry weight of fruits in the field	g m^{-2}	INITIAL INTGRAT OUTPUT
TOTWML	Total dry weight of leaves in the field	g m^{-2}	INITIAL INTGRAT OUTPUT
TOTWST	Total dry weight of main stems in the field	g m^{-2}	INITIAL INTGRAT RESP
TOTVW	Total dry weight of aboveground vegetative plant parts	g m^{-2}	INTGRAT OUTPUT
TPL	Number of trusses per leaf after initiation of first truss	-	CROPPARM OUTPUT
TPLA	Number of trusses per node Initially zero, after initiation of the first truss equal to TPL	-	DEV RATE
TRCDRW	Total rate of dry matter accumulation, including roots and shoots	$\text{g m}^{-2} \text{d}^{-1}$	DMRATE

Acronym	Description	units	Subroutine(s) where it appears
TRGH	Transmissivity of the greenhouse cover	-	INPUT MGT GHOUSE
TSLA	Factor accounting for integrated daily effect of temperature on SLA	-	TOMGRO DMRATE
TSLAF	Factor accounting for instantaneous effect of temperature on SLA	-	TOMGRO DEVFAST
TTAB	Integrated thermal time below threshold temperature (TLOWAB) for fruit abortion	°Cd	LOSRATE
TTH	Daily integrated thermal time above threshold temperature (THIGH) for fruit abortion	°Cd	TOMGRO DEVRATE
TTABF	Negative deviation of average temperature from lower threshold for fruit abortion	°C	DEVFAST TOMGRO
TTHF (1-25)	Positive deviation of average temperature from upper threshold for unrestricted fruit set	°C	TOMGRO DEVFAST
TTL	Daily integrated thermal time below threshold temperature (TLOW) for truss splitting	°Cd	TOMGRO DEVRATE
TTLF	Negative deviation of average temperature from lower threshold (TLOW) for truss splitting	°C	TOMGRO DEVFAST
TTMN	Cumulative thermal time below TLOW necessary for complete truss splitting	°Cd	INPUT CROPPARM DEVFAST DEVRATE
TTMX	Cumulative thermal time above THIGH necessary for complete inhibition of fruit set	°Cd	INPUT CROPPARM DEVFAST DEVRATE
TWTLAI	Total dry weight of leaf blades plus petioles	g m ⁻²	INTGRAT OUTPUT
TU1	Auxiliary variable used for adaptation - of Gainesville TAU1 to conditions in Israel		PHOTO CROPPARM
TU2	Auxiliary variable used for adaptation - of Gainesville TAU2 to conditions in Israel		PHOTO CROPPARM
VAL (K)	See TABEX		TABEX

Acronym	Description	units	Subroutine(s) where it appears
WLVS (1-NL)	Dry weight of leaves per age class	g m^{-2}	OUTPUT INITIAL INTGRAT
WLVSI	Initial weight of leaves	g plant^{-1}	INITIAL MGT
WPFI	Initial weight per initiated fruit	g	CROPPARM INTGRAT
WPLI	Initial weight per initiated leaf	g	CROPPARM INTGRAT
WSTM (1-NL)	Dry weight of stems per age class	g m^{-2}	INITIAL INTGRAT
WSTOTL	Total dry weight of growing leaves	g m^{-2}	INITIAL INTGRAT RESP
WSTOTS	Total dry weight of growing stems	g m^{-2}	INTGRAT
WTOTF	Total dry weight of growing fruits	g m^{-2}	INITIAL INTGRAT RESP
XBOX	Age class number expressed as percentage	%	DMRATE INTGRAT LOSRATE
XCO2LT	Time scale (independent variable) in function CO2LT	d	MGT
XDMC	Day number within the growing season, used as independent variable in function DMC84T	-	CROPPARM INTGRAT
XDISDAT	Day number within the growing season, used as independent variable for DISDAT	-	LOSRATE INPUT MGT
XFPN	Number of nodes per plant (PLSTN), used as independent variable in function FPN	no plant^{-1}	DEV RATE
XFRT	Air temperature, used as independent variable in function RDVFRT	$^{\circ}\text{C}$	CROPPARM DEV RATE
XGEN	Plastochron index, used as independent variable in function GENRAT	$\frac{\text{nodes}}{\text{plant}^{-1}}$	CROPPARM DEVFAST
XK	Extinction coefficient for light within canopy	-	PHOTO
XLAI	Total LAI, summation of all LFAR age classes	$\text{m}^2(\text{leaf})$ $\text{m}^2(\text{ground})$	INITIAL INTGRAT OUTPUT
XLAIM	LAI above which death of leaves due to shading starts	$\text{m}^2(\text{leaf})$ $\text{m}^2(\text{ground})$	CROPPARM LOSRATE
XLANG	Short wave radiation expressed in langley (cal cm^{-2})	langley d^{-1}	IPWTH

Acronym	Description	units	Subroutine(s) where it appears
XLAT	Geographical latitude of location	deg	IPWTH
XLONG	Geographical longitude of location	deg	IPWTH
XLV	Air temperature, used as independent variable in function RDVFRT	°C	CROPPARM DEVFAST
XM	Leaf light transmission coefficient	-	PHOTO
XMRDR	Fraction of leaves dying due to shading	-	CROPPARM LOSRATE
XSNUP	Time of sunrise	h	SUNRISE
XSMDN	Time of sunset	h	SUNRISE
XROOT	Plastochron index, used as independent variable in function PROOT	nodes plant ⁻¹	CROPPARM DMRATE
XSLA	Average specific leaf area	m ² g ⁻¹	INTGRAT OUTPUT
XTEM	Air temperature, used as independent variable in function GENTEM	°C	CROPPARM DEVFAST
XTMP	Time in case of constant environment	h	GHOUSE
simulations			
XAEFT	Plastochron index (PLSTN), used as independent variable in function AEFT	nodes plant ⁻¹	CROPPARM PHOTO
XPARTX	Photon flux density, used as independent variable in function PART	E d ⁻¹	CROPPARM DMRATE
ZBENG	Factor accounting for the effect of supply/demand ratio on root growth	-	CROPPARM DMRATE