

Simulation of photosynthesis and dry matter production of greenhouse crops

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Summary

This report describes two explanatory simulation models of photosynthesis and dry matter production of greenhouse crops. One model, ASKAM, was developed for estimating crop net CO₂ uptake for short time intervals during the day. The other model, SUKAM, was developed for estimation of dry matter production over the growing period. The latter model is based on the model SUCROS87 for field crops (Spitters *et al.*, 1989).

Sensitivity analysis was performed with both models. Effects were studied of changing parts of the models on model output. An additional subroutine for light absorption was developed that 1) takes account of the modified angular distribution of incoming diffuse light in the greenhouse, and that 2) implicitly assumes a more horizontal leaf angle distribution than the commonly assumed spherical leaf angle distribution.

Of the parameters and variables tested, a significant influence on crop photosynthesis was found of:

- a change of greenhouse light transmissivity,
- the orientation of the dark greenhouse in wintertime,
- the leaf light use efficiency, and
- a Leaf Area Index less than 3.

Significant changes in crop photosynthesis were calculated to result from:

- an increase in the reflection coefficient of the ground from 0 to 0.5,
- an increase in the CO₂ concentration from 350 to 600 µl l⁻¹, and
- a doubling of the boundary layer resistance from 100 to 200 s m⁻¹, at clear days.

The solar elevation was calculated to have a significant effect on crop photosynthesis, mostly via differential light transmission of the greenhouse cover.

A temperature increase of 5 °C was simulated to have a significant effect on dry matter production via increase of the maintenance costs. Maintenance costs did have a large effect on dry matter production at days with short daylength.

The construction parts of the greenhouse cover cast a pattern of sunlit and shaded patches on the canopy. This enhances the unevenness of radiation distribution in the canopy, and could significantly depress crop photosynthesis on clear days in a greenhouse with a heavy construction.

When measured fraction diffuse in global radiation was used for simulations instead of simulated fraction diffuse, daily crop photosynthesis was little changed, but instantaneous crop photosynthesis could be significantly altered.

When assuming all the light diffuse, significant overestimations of crop photosynthesis were obtained. In summertime this effect was almost completely the result of differential light absorption and distribution in the canopy; in other parts of the year it was largely the result of increased transmission by the greenhouse cover.

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1 Introduction

Models for photosynthesis and growth of crops are becoming increasingly important in protected cultivation. They can aid the grower with climate control, with planning cultural practices and with making decisions on long term investments. Models can assist researchers in studying the complex greenhouse-crop system and in gaining insight in the importance of various processes. Thereby they can help in, e.g., analysing and designing growing experiments, and in studying alternative cropping practices.

With these aims two simulation models were developed. The first model, ASKAM ('CO₂-assimilatie kasgewasmodel'), was designed for calculating crop CO₂ uptake during short time intervals during the day. ASKAM can, for example, be used for analysing measurements of crop photosynthesis and respiration. ASKAM can also serve as a submodel in a larger model that calculates the CO₂ balance of the greenhouse air, e.g., for optimization of the CO₂ concentration.

The second model, SUKAM ('SUCROS-gebaseerd kasgewasmodel'), is meant for a global estimation of the dry matter production during the year. SUKAM can be used to compare crop performances in different years, and for studying the effects of changing the values of various parameters on long term production. As SUKAM does not need detailed environmental and crop data, it can be used as a submodel in a model on a higher integration level, e.g. a bio-economic model.

Model SUKAM is based on the model SUCROS87 that has been designed specifically for field crops (Spitters et al., 1989). Model ASKAM uses the procedures for calculating light extinction as applied in SUCROS87. Both models are mechanistic simulation models, i.e., they quantify processes that underlie crop photosynthesis and crop production, and thereby explain how the rate of the given overall process is reached. The models are composed of several submodels, which can be validated separately. The models can be modified very easily in order to describe a different situation. The models can be adapted by changing parameter values, or can be changed more drastically by replacing one submodel by another. For example, the submodel for transmissivity of a Venlo-type glasshouse can be replaced by another submodel that describes a different greenhouse cover, or the submodel for distribution of light in a horizontally homogeneous canopy can be replaced by a submodel for light distribution in a row canopy.

The following Chapter (Ch. 2) describes the models ASKAM and SUKAM. In Chapter 3 some additional theory is described, and in Chapter 4 the set-up is described of the simulation environment for sensitivity analyses and model investigations. In Chapter 5 a sensitivity analysis is performed to show the relative importance of various parameters and processes. Lastly, in Chapter 6 results are shown of the effects of changing the model description of various processes on total model output. In Appendices II and III listings of the two models are given. The subroutines used by both model ASKAM and model SUKAM are given in a separate appendix (Appendix IV). The descriptions and dimensions of variables and parameters are given in Appendix IX.

Present programming of the simulation models was done largely following recommendations by Van

Kraalingen & Rappoldt (1989). Input/output of the models was kept simple. For more sophisticated I/O, one could for instance use the Fortran modules as developed by Rappoldt & Van Kraalingen (1990).

The source code of the models is available on a diskette upon request.

2 Description of the models

A summary of the characteristics of the two models is given in Table 1. Both models are carbon balance models: they calculate the CO₂ uptake by the canopy, how much of the assimilates is respired for maintenance of the crop and for conversion into dry matter, and, in model SUKAM, how much leaf, stem, root and fruit dry matter is formed.

ASKAM calculates instantaneous gross and net photosynthesis based on short term (e.g. half-hourly) data on radiation, temperature and CO₂ concentration.

SUKAM calculates the daily rate of gross photosynthesis and dry matter production from daily radiation, temperature and CO₂ concentration, much the same as SUCROS87. Instantaneous rates of radiation during the day are generated from daily totals of radiation.

The present structure of the models (see Appendices II & III) does not need to be fixed, e.g. in model SUKAM even the core part for calculating photosynthesis can be changed when hourly data are available instead of daily ones. In that case model SUKAM can abandon the special procedures for generating diurnal courses of climate variables from daily values.

Present versions of the models only incorporate the effects of light, CO₂ concentration and temperature on photosynthesis and dry matter production. Therefore, photosynthesis and dry matter production can be called potential as no factors with negative effects on production are taken into account, like high vapour pressure deficit of the air, water stress, or diseases.

2.1 General structure of the models

The general structure of the models is depicted in Figure 1. Both reading of the climate variables from a data file and calculation of the various processes are repeated for each time-step.

The time step in model ASKAM can be equal to any short-term interval within the day, and may depend on the time resolution of the data. The time step in model SUKAM is equal to one day.

Table 1. Summary of the main characteristics of the models ASKAM and SUKAM

	ASKAM	SUKAM
climate data input	short time scale (e.g. 30 min.)	daily or daily averaged data
respiration	calculation of CO ₂ release by respiration	calculation of costs of assimilates needed for respiration
net photosynthesis	gross photosynthesis minus CO ₂ release by respiration	not calculated
dry matter production	not calculated	calculated from available assimilates after maintenance costs have been subtracted

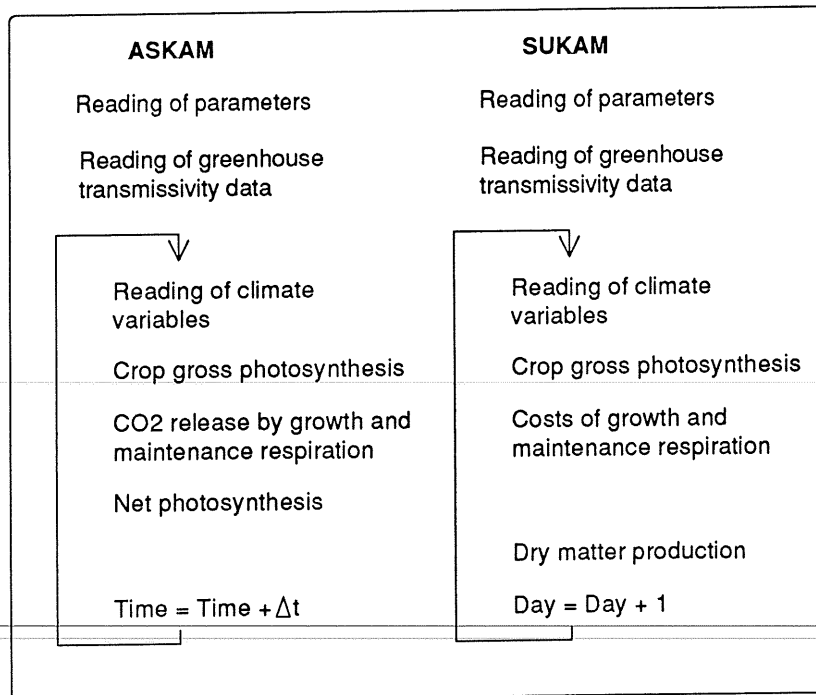


Figure 1. Diagram of the structure of the models ASKAM and SUKAM

2.2 Radiation

Crop photosynthesis is calculated in both models from the flux of PAR (Photosynthetically Active Radiation, 400-700 nm; W m^{-2}) that arrives at the top of the canopy. In the following the term 'light' is used interchangeably with PAR. In present model versions, global radiation is input to the models and from this the flux of PAR is calculated.

The transmissivity of the greenhouse cover can be very different for diffuse and direct light (Bot, 1983), and crop photosynthesis can be significantly overestimated when all the light is assumed to be diffuse (Spitters, 1986). Therefore, the fluxes of direct and diffuse light have to be estimated.

2.2.1 Diffuse and direct global radiation outside the greenhouse

The calculation steps are shown in Figures 2 and 3, for ASKAM and SUKAM, respectively. The fraction diffuse in instantaneous global radiation is made dependent on the ratio of measured (ASKAM) or estimated (SUKAM) global radiation to radiation outside the atmosphere (extra-terrestrial radiation), according to a regression equation:

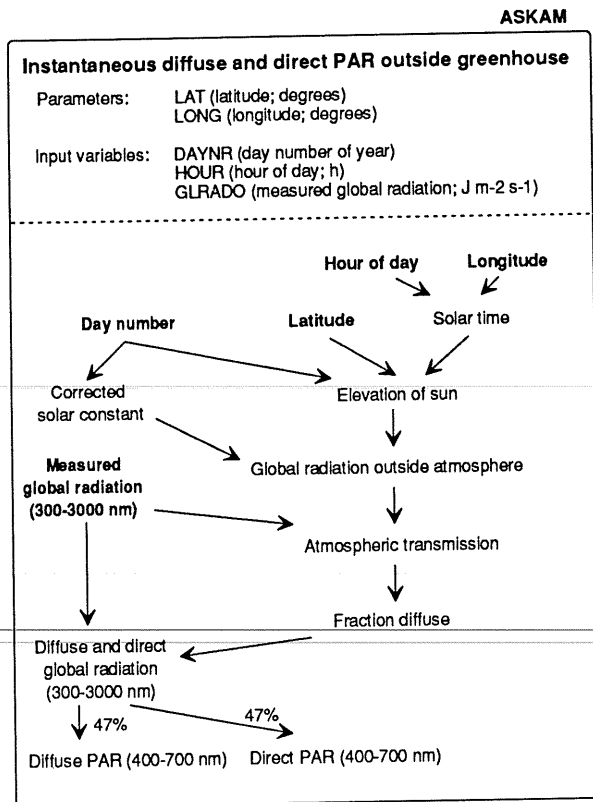


Figure 2. Diagram showing steps in the calculation of the fluxes diffuse and direct PAR outside the greenhouse in model ASKAM. Parameters and variables shown in bold-face are input in the calculation of this subprocess.

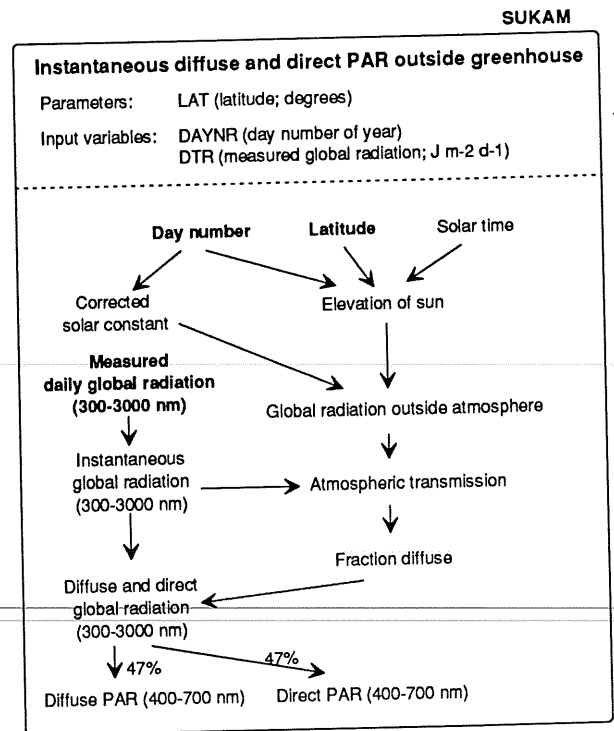


Figure 3. Diagram showing steps in the calculation of the fluxes diffuse and direct PAR outside the greenhouse in model SUKAM. Parameters and variables shown in bold-face are input in the calculation of this subprocess.

$$F_{dif} = f(I/I_{ex}, \sin \beta) \quad (1)$$

where

- F_{dif} = the fraction diffuse,
 function f = the regression relation,
 I = measured or estimated global radiation,
 I_{ex} = calculated global radiation outside the atmosphere (extra-terrestrial),
 $\sin \beta$ = the sine of solar elevation

(Spitters *et al.*, 1986) (Fig. 4; see function FRACDF, Appendix IV).

The ratio I/I_{ex} is called the atmospheric transmission or the clearness index. The relation is based on the notion that when less radiation is received at the surface of the earth compared with what could have been measured when no atmosphere was present, radiation is more scattered and intercepted by air, ozone, water vapour, clouds and aerosols, and consequently is more diffused. Regression models

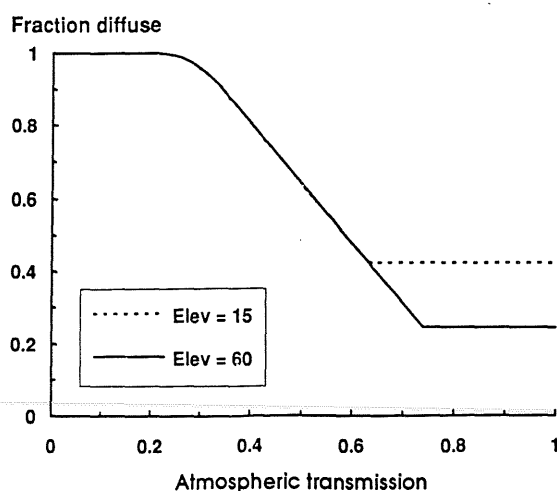


Figure 4. The relation between fraction diffuse in hourly global radiation and atmospheric transmission (I/I_{ex}) at De Bilt, at two solar elevations

relating the fraction diffuse with atmospheric transmission are often called 'Liu & Jordan-type' models.

In both models the same regression equation is used, using measured instantaneous global radiation in ASKAM, and instantaneous radiation estimated from daily radiation in SUKAM (Spitters *et al.*, 1986, Appendix I).

The regression equation as given in the appendix of Spitters *et al.* (1986) was changed for the calculation of the lowest fraction diffuse (J. Goudriaan, pers. comm., 1989). In the original formulas the lower limit of the fraction diffuse depends on the sine of solar elevation in such a way that the lowest limit was minimal at 50° solar elevation and increased at higher solar elevations. However, measurements show that for clear skies the fraction diffuse decreases with higher solar elevation (Iqbal, 1983). The 'extinction coefficient' 0.1 in the negative-exponential lower limit corresponds to a rather clean atmosphere.

Model ASKAM

In ASKAM the fraction diffuse is estimated in the measured flux instantaneous global radiation.

The regression equation is based on hourly radiation data. When radiation data of shorter time intervals are used, theoretically another regression equation should be used. However, Gijzen *et al.* (in prep.) found that the regression equation on hourly basis differed only slightly from the equation for the fraction diffuse in radiation data at 10 minute intervals. The significant scattering of measured fraction diffuse around the regression line that is apparent for hourly time intervals, was found to be even larger for 10 minute intervals. Considering the large scatter, the relation for hourly values is assumed to be, at present, accurate enough for time intervals shorter than 1 hour. In Chapter 6.5 the effects of the variability in fraction diffuse on light intensity in the greenhouse and on crop photosynthesis are further investigated.

Model SUKAM

In SUKAM the diurnal courses of atmospheric transmission and global radiation are generated from the daily total of global radiation (Spitters *et al.*, 1986). Here, long year average radiation data of De

Bilt (the Netherlands, latitude 52°) are used, applying a special procedure for introducing variation in the average data (see Ch. 4.2.2 and Appendix I).

The diurnal course of the atmospheric transmission is described according to a linear relation

$$I/I_{ex} = a + b \sin \beta \quad (2)$$

where a and b are empirical regression coefficients. Spitters *et al.* (1986) found that model results were rather insensitive to the choice of the value of quotient b/a (i.e. 0.4 for De Bilt).

Note that the calculation of the fraction diffuse from estimated instantaneous global radiation in model SUKAM is different from the procedure used by Spitters *et al.* (1986) and in SUCROS87 (Spitters *et al.*, 1989). These authors estimated the fraction diffuse from the daily total of global radiation. In the improved procedure the hourly fraction diffuse is calculated from the instantaneous global radiation as generated from the daily total (J. Goudriaan, pers. comm., 1989). In this way the higher fractions diffuse that normally occur at the beginning and the end of the day are accounted for.

2.2.2 Diffuse and direct PAR outside the greenhouse

The next calculation step is the estimation of diffuse and direct PAR from diffuse and direct global radiation.

From measurements at Uccle, near Brussels (Anonymous, 1981a,b), it was calculated that daily radiation in the 400-700 nm range was on average 47% in daily totals of global radiation. Variation was from 40% for clear days to 60% for very cloudy days. Monthly percentage PAR varied from 41% in November and December to 49% in July. Presently, a percentage PAR of 47% is adopted.

Theoretical analysis showed that for photosynthesis calculations the fraction diffuse in the PAR-region can be taken equal to the fraction diffuse in total global radiation (Spitters *et al.*, 1986). Therefore, both diffuse and direct global radiation are multiplied by 0.47 to obtain diffuse and direct PAR.

2.2.3 Light climate inside the greenhouse

The fluxes diffuse and direct PAR (W m^{-2}) inside the greenhouse are calculated by multiplication of the fluxes diffuse and direct PAR outside the greenhouse by their respective transmissivities of the greenhouse cover (Fig. 5). The position of the sun at the sky is determined by the elevation (height of the sun above the horizon) and the azimuth (angle of the sun beam with the north-south direction; east negative). The orientation (azimuth) of the greenhouse is the angle of the direction of the ridge-gutter system with the north-south direction.

Here, the transmissivity of the greenhouse cover for diffuse global radiation and tables of transmissivity for direct global radiation were obtained from the model of Bot (1983). Parameters of a Venlo glasshouse at the Glasshouse Crops Research Station at Naaldwijk (PTG) were given as input to Bot's model, and transmissivities of direct radiation, T_{rdir} , were calculated for various positions of the sun at the sky. The transmissivity of diffuse radiation, T_{rdif} , was calculated by

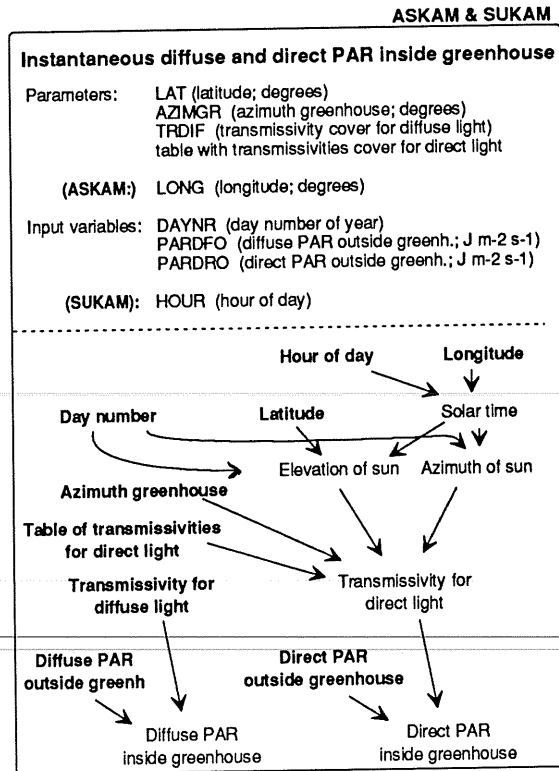


Figure 5. Diagram showing the steps in the calculation of the fluxes diffuse and direct PAR inside the greenhouse. Parameters and variables shown in bold-face are input in the calculation of this subprocess.

averaging the transmissivity of direct radiation over the whole sky hemisphere. Transmissivity of PAR is assumed equal to that of global radiation.

In the models two tables (one for the construction, one for the cladding material) with direct light transmissivities for various solar positions (azimuth and elevation) are used (SUBROUTINE TRANSM, Appendix IV). For any exact sun position, the transmissivity for direct light is found by interpolating actual elevation and actual difference between sun and greenhouse azimuth, in the table linking elevation of the sun and difference of sun and greenhouse azimuth with transmissivity.

2.2.4 Light absorption by the canopy

The distribution and absorption by leaves of direct and diffuse PAR within the canopy are calculated according to Spitters (1986) (SUBROUTINE ASSIMR, App. IV). The general equation to calculate the light intensity at a point P in the canopy, I_c , is

$$I_c = I_o(1 - \rho) \exp(-K L_c) \quad (3)$$

where

- I_o = the light intensity above the canopy,
- ρ = the reflection by the canopy,
- K = the extinction coefficient,
- L_c = the leaf area above point P.

This equation is used for both diffuse and direct PAR. The extinction coefficient for diffuse PAR,

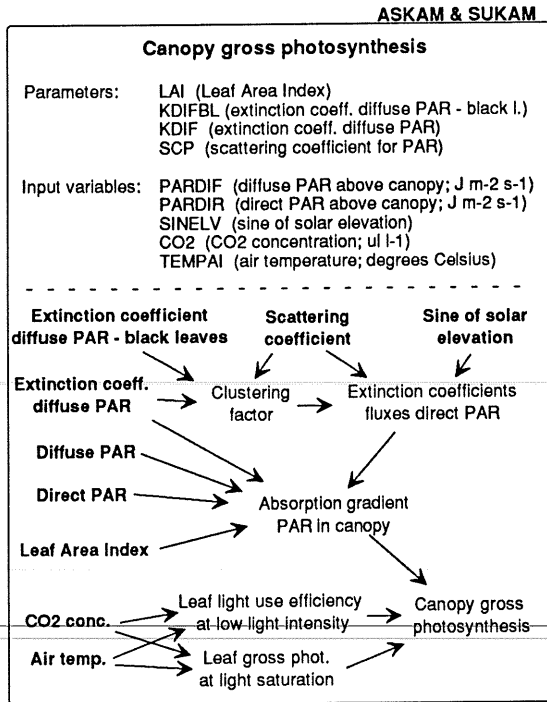


Figure 6. Diagram showing the steps in the calculation of canopy gross photosynthesis. Parameters and variables shown in bold-face are input in the calculation of this subprocess.

K_{dif} is constant, whereas that for direct PAR, K_{dir} , depends on solar elevation.

The extinction of PAR is determined by the orientation of the leaves, the positions they take relative to each other, and the scattering coefficient. The scattering coefficient for PAR, σ , is equal to the sum of the fractions of incident PAR that are transmitted and reflected by the leaf (Goudriaan, 1977). With more erect leaves and with higher values of σ , the extinction of PAR is less and reflection by the canopy larger. With more horizontal leaves and lower σ 's the situation is reversed.

The extinction of light is also changed when leaves take preferential positions to each other (e.g. by clustering, or by avoidance of self-shading (negative clustering)).

Extinction of diffuse PAR

Reflection, multiple scattering and absorption of diffuse PAR are computed from the parameters (Fig.6):

- extinction coefficient of diffuse light for scattering leaves, K_{dif} ,
- extinction coefficient of diffuse light for non-scattering leaves, K_{difbl} ,
- scattering coefficient for PAR, σ .

The measured (or estimated) value of K_{dif} is compared with the theoretical value of K_{dif} . The theoretical value of K_{dif} is equal to (Spitters, 1986)

$$K_{dif} = K_{difbl} \sqrt{1 - \sigma} \quad (4)$$

A clustering factor accounts for the difference between the measured and the theoretical K_{dif} (Spitters, 1986). This factor adjusts the extinction profiles of both diffuse and direct PAR.

The value of K_{dif} has been found to vary from 0.4 to 0.7 for monocotyledonous crops and from 0.65 to 1.1 for dicotyledonous crops (Monteith, 1969). σ of an average thin leaf is 0.15 (Jones, 1983), as was also found for cucumber, sweet pepper and tomato (unpublished results). With K_{difbl} equal to 0.8 and σ equal to 0.15, the theoretical value of K_{dif} is 0.74.

In SUBROUTINE ASSIMR it is assumed that leaves have no preferential orientation, i.e. have the so-called spherical or isotropic leaf angle distribution. The diffuse light extinction in the canopy is not exactly exponential, but is approximated using a single extinction coefficient (Goudriaan, 1977). In SUBROUTINE ASSIMR K_{difbl} is equal to 0.8. This value gives the best fit for the extinction profile as calculated numerically assuming a spherical leaf angle distribution and a uniform intensity distribution of the diffuse light in all directions of the sky hemisphere, the so-called Uniform OverCast sky (Goudriaan, 1977).

This value of K_{difbl} changes when another leaf angle distribution is assumed, or when the sky radiance distribution of diffuse light changes. The value of K_{difbl} is also affected by light interception by the greenhouse cover. In Chapter 6.1 it is calculated how K_{difbl} changes when a more horizontal leaf angle distribution is assumed (e.g. for tomato and cucumber), and when the effect of the greenhouse cover on the angular distribution of diffuse light is accounted for.

Extinction of direct PAR

The extinction and absorption of direct PAR are computed from

- the average projection of leaves into the direction of the sun, O , and
- the sine of solar elevation, $\sin \beta$,

where the projection of a leaf into the direction of the solar beam is equal to the cosine of the angle of incidence of the beam on the leaf.

The extinction coefficient for direct light is calculated for non-scattering leaves, as

$$K_{dirbl} = \frac{O}{\sin \beta} \quad (5)$$

(De Wit, 1965). With a spherical leaf orientation O is 0.5 for every sun position.

The variation in orientation of leaves causes differences in amount of direct radiation that is absorbed by different sunlit leaves, and must be known for calculation of photosynthesis. In SUBROUTINE ASSIMR the range of projections of leaves into the direction of the solar beam is taken into account. Absorbed direct PAR and leaf gross photosynthesis are calculated for three projections, within the range of variation, using Gaussian integration (Goudriaan, 1988). The range of projections is unity for the spherical leaf angle distribution.

For leaf angle distributions other than spherical, the average projection O and the range of projections will be different. In Chapter 6.1 this is further investigated for a more horizontal leaf angle distribution than the spherical one.

2.2.5 Reflection by the ground surface

In greenhouses the ground surface can have a high reflection coefficient due to the use of ground covering materials like white plastic sheets. Radiation reflected back into the canopy can significantly increase the total amount of absorbed radiation, and hence also canopy photosynthesis.

In SUBROUTINE ASSIMR analytical solutions are used (developed by J. Goudriaan) for describing the effect of ground reflectance on the extinction of radiation in the canopy, including the effect on (increased) canopy reflectance.

For comparison, in Appendix VII a listing is given of SUBROUTINE ASSIM. This subroutine does not the algorithms for calculating the effect of ground reflectance. This subroutine is essentially the same as SUBROUTINE ASS from SUCROS87.

2.3 Leaf and canopy photosynthesis

2.3.1 Leaf photosynthesis

Leaf gross photosynthesis at any layer in the canopy is calculated from the intensity of absorbed PAR (SUBROUTINE LPHCUR, Appendix IV). An asymptotic negative-exponential function is used to describe the response of leaf gross photosynthesis to absorbed PAR (Spitters, 1986)

$$P_g = P_{gm} \left\{ 1 - \exp \left(\frac{-\epsilon PAR_{abs}}{P_{gm}} \right) \right\} \quad (6)$$

where

P_g	= the rate of leaf gross photosynthesis (per m ² leaf area), and
PAR_{abs}	= the absorbed PAR (per m ² leaf area) at that leaf layer,
ϵ	= the leaf initial light use efficiency (mg CO ₂ J ⁻¹ absorbed), and
P_{gm}	= the rate of leaf gross photosynthesis at light saturation (mg CO ₂ m ⁻² leaf s ⁻¹).

The intermediate variables ϵ and P_{gm} determine the shape of this light response curve. ϵ is the initial slope of the response, and P_{gm} the saturation value. P_{gm} and ϵ are both affected by leaf temperature and CO₂ concentration and their values are calculated as partly described by Goudriaan *et al.* (1985). A C₃-species is assumed.

Leaf initial light use efficiency ϵ

The leaf initial light use efficiency is increased at higher CO₂ concentrations due to suppression of photorespiration. This is modelled according to Goudriaan *et al.* (1985):

$$\varepsilon = \varepsilon_o \frac{C_a - \Gamma_*}{C_a + 2\Gamma_*} \quad (7)$$

where

C_a = the CO₂ concentration in ambient air (μl l⁻¹) and
 Γ_* = the CO₂ compensation point in absence of dark respiration (μl l⁻¹).

A higher temperature increases photorespiration, and consequently increases Γ_* . Via Γ_* , ε is decreased at higher temperatures. The temperature dependency of Γ_* is described according to Brooks & Farquhar (1985):

$$\Gamma_* = 42.7 + 1.68 (T_l - 25) + 0.012 (T_l - 25)^2 \quad (8)$$

at O₂ concentration 210 ml l⁻¹, and where T_l is leaf temperature (°C).

Leaf maximal rate of gross photosynthesis P_{gm}

The light saturated rate of gross photosynthesis P_{gm} is simulated to be dependent on the CO₂-limited rate of net photosynthesis $P_{n,c}$ (mg CO₂ m⁻² s⁻¹) and on the maximal endogeneous photosynthetic capacity, i.e. the rate of photosynthesis at high light and high CO₂, P_{mm} (mg CO₂ m⁻² s⁻¹) (J. Goudriaan, pers. communication, 1989)). The dependency of P_{gm} on the CO₂ concentration is described by a Blackman-curve,

$$P_{gm} = \min\{P_{n,c}, P_{mm}\} \quad (9)$$

where R_d is the rate of dark respiration of the leaf (mg CO₂ m⁻² leaf s⁻¹).

At the first part P_{gm} is linearly dependent on $P_{n,c}$, and at the second part (the plateau) it is determined by the endogeneous capacity. R_d of a sun leaf is at 20 °C about equal to 0.05 mg CO₂ m⁻² s⁻¹.

$P_{n,c}$ is simulated to be dependent on resistances in the pathway of CO₂ in ambient air to CO₂ bound to RuBP by Rubisco, in which boundary layer resistance (R_b , s m⁻¹), stomatal resistance (R_s , s m⁻¹), and the carboxylation resistance (R_c , s m⁻¹) are placed in series

$$P_{n,c} = \frac{1.8 (C_a - \Gamma_*)}{1.37 R_b + 1.6 R_s + R_c} \quad (10)$$

where constant 1.8 converts μl l⁻¹ to mg CO₂ m⁻³. Constants 1.37 and 1.6 are factors for conversion of resistance to H₂O diffusion to resistance to CO₂ diffusion (von Caemmerer & Farquhar, 1981).

Note that the carboxylation resistance is a chemical resistance. Also a resistance for diffusion of CO₂ from the substomatal cavities to the chloroplast stroma should be included in the chain, but as its value is probably small in comparison with R_c and its value is not well known, it is left out.

The maximal endogeneous capacity P_{mm} is temperature dependent. It is described by an optimum curve with zero values at 5 and at 40 °C, and with a maximum of 2.5 mg CO₂ m⁻² s⁻¹ at 30 °C. This maximum at 30 °C was chosen such as to make P_{mm} at 25 °C equal to 2 mg CO₂ m⁻² s⁻¹; this value is comparable with the rate of leaf photosynthesis, at high light and high CO₂, as calculated with the biochemical model described by Farquhar & von Caemmerer (1982). Parameters assumed for this calculations were those of a leaf of a 'high light grown' plant (Farquhar & von Caemmerer, 1982, p. 579). Such a leaf was presumed to have maximal leaf photosynthetic rates comparable to those of fast growing greenhouse crops, grown under optimal conditions.

The value of stomatal resistance (to H₂O) was set at 50 s m⁻¹. This value is about equal to values of minimum resistance found in tomato by Hicklenton & Jolliffe (1980), Paez *et al.* (1984) and Nederhoff & De Graaf (1993), in cucumber by Bakker (1991) and Nederhoff & De Graaf (1993), and in sweet pepper by Nederhoff *et al.* (1992). The boundary layer resistance (to H₂O) is assumed to be 100 s m⁻¹, as was found by Stanghellini (1985) using artificial leaves in a tomato canopy during the night.

Leaf photosynthetic response

The simulated responses of leaf gross photosynthesis to absorbed PAR, CO₂ concentration and leaf temperature are shown in Figures 7A, B and C. The present model needs to be validated with measurements on leaf photosynthesis. The simulated CO₂ response (Fig. 7B) shows a somewhat pronounced bend in the curve at 550 µl l⁻¹. Measured responses could be more smooth. The temperature response is modelled quite schematically. This results in rather sharp bends in simulated temperature response curves. Some published temperature responses (Berry & Bjorkman, 1980) indicate that optimum curves generally are broader.

The values of ϵ and P_{gm} at 25 °C and 350 vpm CO₂ were calculated to be 0.012 mg CO₂ per J PAR absorbed and 1.27 mg CO₂ m⁻² leaf s⁻¹, respectively. In SUBROUTINE ASSIMR it is presumed that all leaves in the canopy have the same photosynthetic characteristics. In literature many authors have reported that the initial light use efficiency does hardly vary between different C₃-species, and hardly varied when leaves grew at different light intensities (Ehleringer & Pearcy, 1983). Thus, ϵ should vary little between leaves of different age and at different places in the canopy. P_{gm} is quite variable, depending on, among others, acclimation to light intensity and temperature, and on leaf age. Leaves lower in the canopy generally have a lower P_{gm} . The intensities of absorbed PAR for leaves lower in the canopy are close to the initial parts of the photosynthesis light-response curves. Thus, assuming the same P_{gm} for these leaves as for leaves in the upper part of the canopy does not cause large calculation inaccuracies.

2.3.2 Crop gross photosynthesis

The instantaneous rate of crop gross photosynthesis is obtained by integrating leaf photosynthesis at various leaf layers over the total canopy, using Gaussian integration (Goudriaan, 1986). Some simulated crop responses to PAR, CO₂ concentration and temperature are shown in Figure 8.

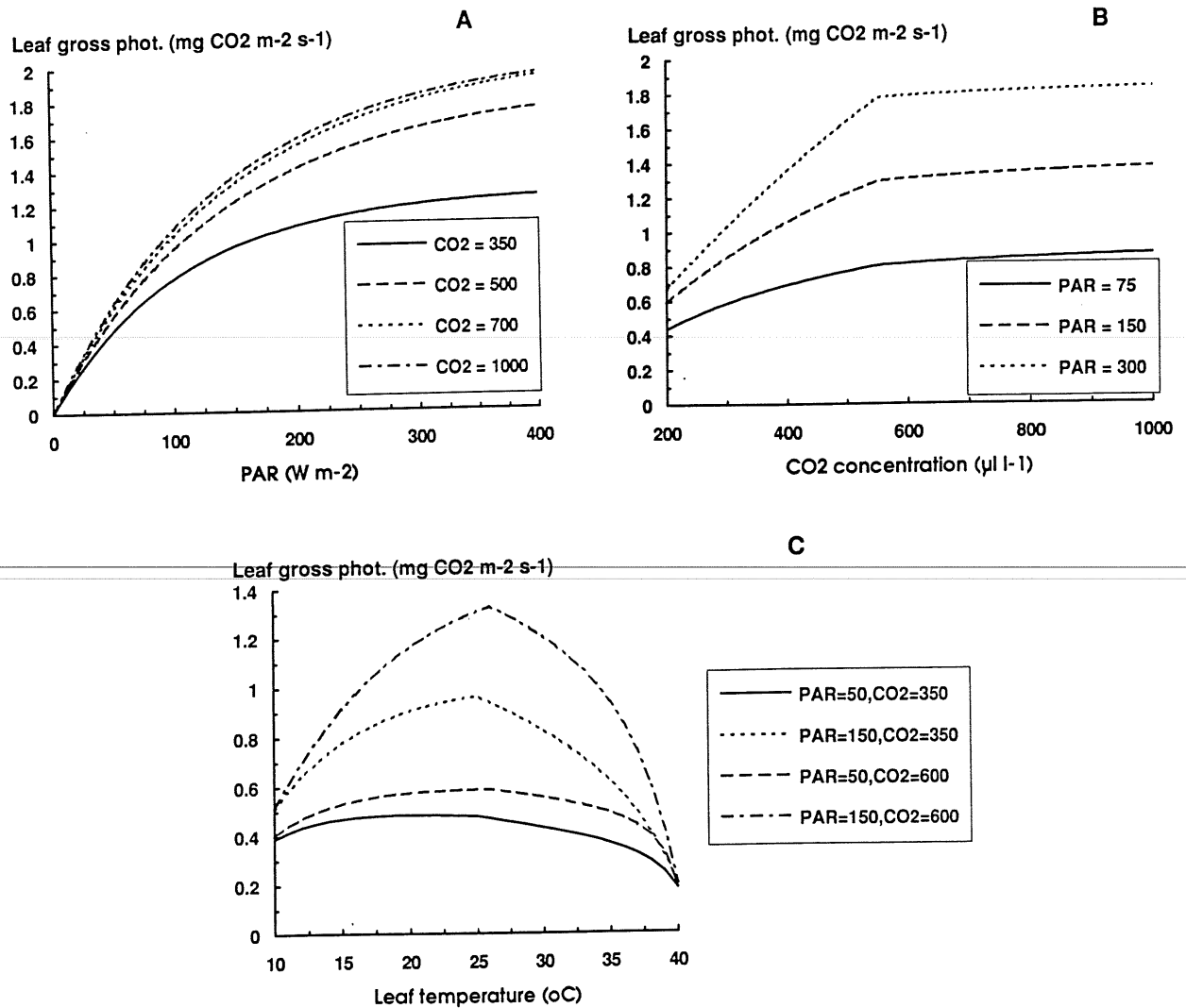


Figure 7. Simulated responses of leaf gross photosynthesis (mg CO₂ m⁻² s⁻¹) to A) absorbed PAR (W m⁻²) at different CO₂ concentrations (μl l⁻¹) and at 25 °C, to B) CO₂ concentration (μl l⁻¹) at different PAR intensities (W m⁻²) and at 25 °C, and to C) leaf temperature (°C).

In model ASKAM the instantaneous photosynthesis is calculated from short term climatic data (PAR, CO₂ concentration and air temperature).

In model SUKAM instantaneous crop photosynthesis is computed based on instantaneous values, derived from daily values, of light intensity, CO₂ concentration and temperature. The instantaneous light intensity is calculated as described by Spitters *et al.* (1989, see also Ch. 2.2.1). In Chapter 6.9 the effects of different diurnal patterns of temperature and CO₂ concentration on daily photosynthesis are calculated.

In SUKAM the daily rate of photosynthesis is obtained from integrating instantaneous gross photosynthesis at five selected times of the day, using 5-point Gaussian integration (see Chapter 6.9).

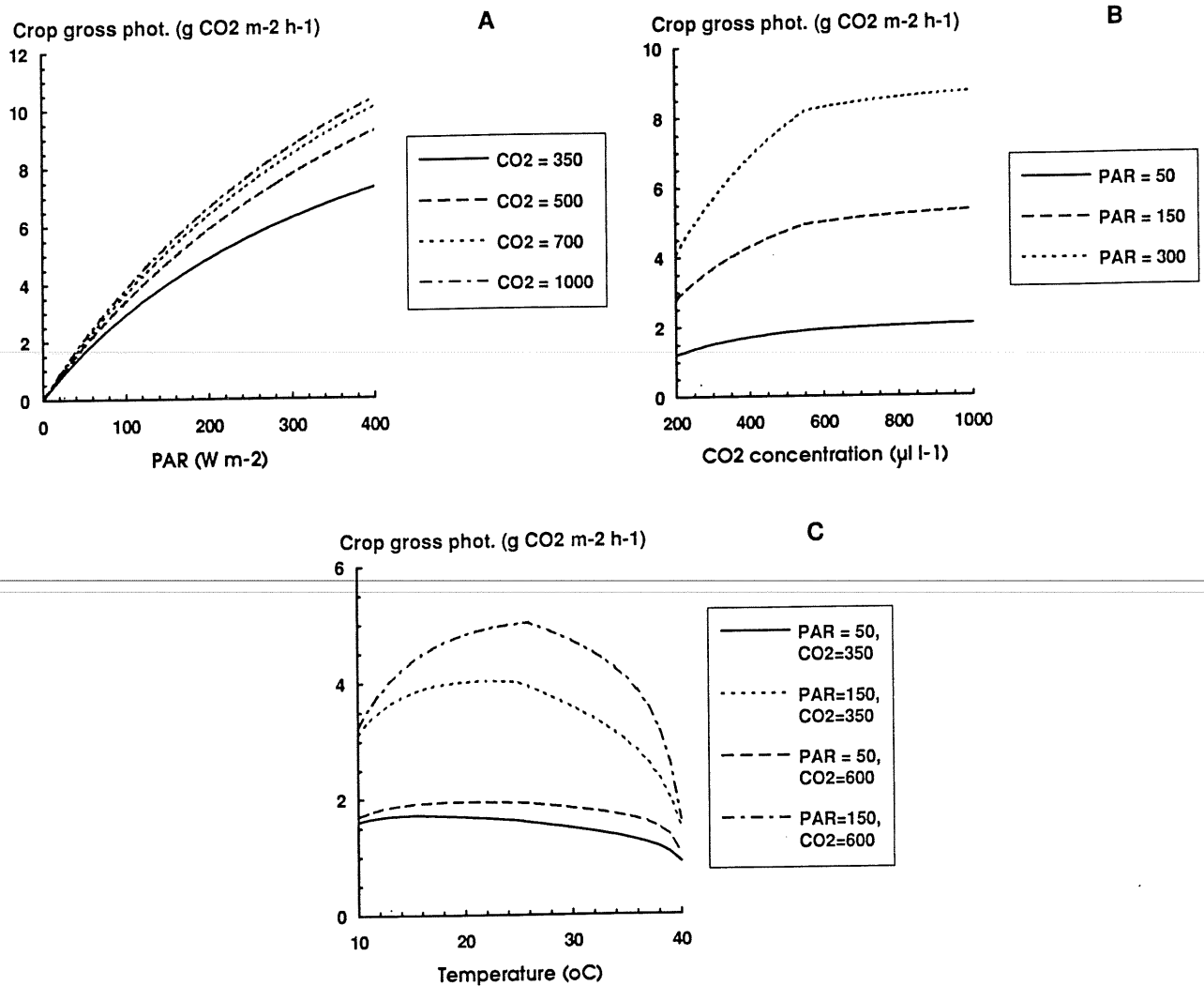


Figure 8. Simulated responses of crop gross photosynthesis with LAI at 3, fraction diffuse 0.5, solar elevation 45° and zero ground reflectivity. A spherical leaf angle distribution was assumed with $\sigma = 0.15$, $K_{dif} = 0.74$ and $K_{difbl} = 0.8$. A. Response to incident PAR, at 25 °C. B. Response to CO₂ concentration, at 25 °C. C. Response to temperature.

2.4 Respiration, net photosynthesis and dry matter production

In the models two respiration processes are considered: growth respiration and maintenance respiration (Fig. 9).

2.4.1 Maintenance respiration

Energy is needed for maintenance of the plant. Carbohydrates are combusted to deliver this energy.

Maintenance costs (expressed in carbohydrates, CH₂O) are calculated by multiplying the dry weights (in g dry matter, DM) of the plant parts with their respective maintenance coefficients,

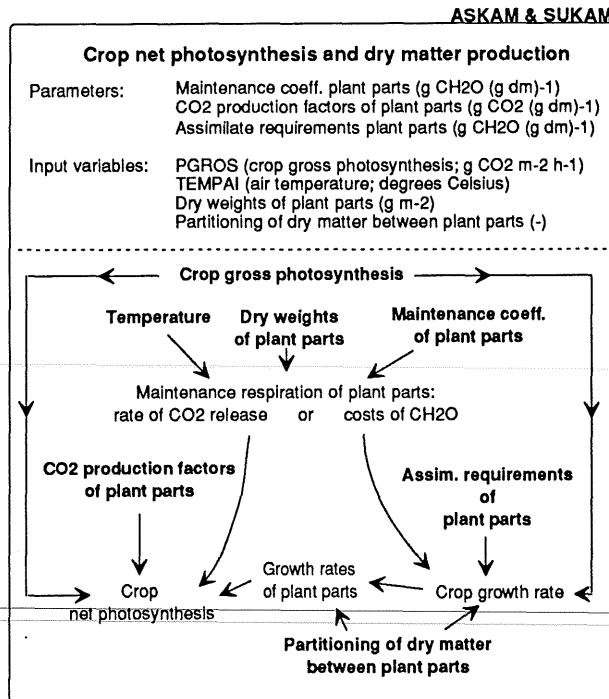


Figure 9. Diagram showing steps in the calculation of crop net photosynthesis and dry matter production. Parameters and variables shown in bold-face are input in the calculation of this subprocess.

according to Spitters *et al.* (1989)

$$R_{m,pp} = R_{m25,pp} W_{pp} 2^{\frac{T-25}{10}} \quad (11)$$

where

- $R_{m,pp}$ = maintenance cost of plant part (g CH₂O m⁻² d⁻¹),
 $R_{m25,pp}$ = maintenance costs of plant part at 25 °C (g CH₂O g⁻¹ DM d⁻¹),
 W_{pp} = weight of plant part (g DM m⁻²), and
 T = temperature (°C).

Plants are divided into four parts: leaves, stems, roots and storage organs. It is assumed that the rate of maintenance respiration doubles for every 10 degrees temperature rise, i.e. a Q₁₀ of 2 was assumed.

To calculate the rate of CO₂ release from maintenance respiration, the weight of CH₂O needed for maintenance is converted into weight of CO₂ released (i.e. multiplication by 1.44, the molar weight of CO₂ divided by the molar weight of CH₂O).

The maintenance coefficients are assumed to be constant. However, there are indications that for many crops maintenance respiration per unit of biomass is reduced in the course of the growing season (e.g. Bunce, 1989). A better approach would take account of the metabolic activity of the crop.

2.4.2 CO₂ release by growth respiration

From the assimilates that remain after subtraction of the costs for maintenance, the amount of newly formed dry matter is calculated (see Ch. 2.4.4), and also the concomitant CO₂ release is calculated for estimation of crop net photosynthesis (see Ch. 2.4.3). CO₂ is released during synthesis and breakdown processes, and also as a result of energy delivery for uptake of nutrients and transport of material within the plant.

The CO₂ release associated with the conversion of assimilates to dry matter can be calculated for specific plant parts from their chemical composition according to Penning de Vries *et al.* (1974), Vertregt & Penning de Vries (1987) and Spitters *et al.* (1989)

$$C_{p,pp} = C_{pf,pp} \Delta W_{pp} \quad (12)$$

where

$C_{p,pp}$ = the CO₂ release associated with growth of the plant part (g CO₂ m⁻² h⁻¹)

$C_{pf,pp}$ = the CO₂ production factor of the plant part
(g CO₂ per g plant part dry matter formed),

ΔW_{pp} = the growth rate of the plant part (g DM m⁻² h⁻¹).

In the procedure of Vertregt & Penning de Vries the assimilate requirements (ASRQ-value, g assimilates needed per g of plant part being formed) and CO₂ production factors are calculated from the carbon content and mineral content. The calculations are valid only for vegetative material containing less than 13% minerals and for storage organs containing less than 6% minerals. However, leaves of cucumber, tomato and sweet pepper, and fruits of tomato can yield after heating at 550 °C high amounts of ash that is formed from the minerals (with cucumber leaves 20-50% of dry weight) (Challa, 1976; Schapendonk, 1984; unpublished results). Uncertainties arise in the calculations of assimilate requirements and CO₂ production factors, as the amount of C contained in the ash, and the mineral composition of the ash is not known. For example, cucumber leaves can contain high amounts of Ca-carbonate (CaCO₃). With ashing this carbonate is not transformed, consequently the mineral content of the ash will be 40%, instead of the 67% taken as an approximation in the procedure of Vertregt & Penning de Vries (1987). Thus, assuming a carbon content of dry matter, C_{dm} , of 0.4 g g⁻¹, and an ash yield of the dry matter of 0.22 g g⁻¹, and using the slightly modified Eqn 11 of Vertregt & Penning de Vries

$$ASRQ_{lv} = 5.39 * C_{dm} + 1.19 * ash * m_a - 1.191 \quad (13)$$

where

$ASRQ_{lv}$ = the assimilate requirement for leaf growth (g CH₂O per g leaf DM),

m_a = the mineral content of the ash,

$ASRQ_{lv}$ would be 1.14 assuming minerals are 67% of the ash, and 1.07 assuming minerals are 40% of the ash.

2.4.3 Net photosynthesis

For estimation of net photosynthesis (model ASKAM), the CO₂ fluxes associated with the respiration processes have to be considered. The rate of CO₂ release by the total crop due to growth and maintenance respiration must be subtracted from the rate of gross photosynthesis to obtain the net rate of CO₂ uptake by the total crop, P_{nc} (g CO₂ m⁻² h⁻¹):

$$P_{nc} = P_{gc} - R_g - 44/30 R_m \quad (14)$$

where

P_{gc}	= crop gross photosynthesis,
R_g	= the rate of CO ₂ release by growth respiration (g CO ₂ m ⁻² h ⁻¹),
44/30	= the conversion of CH ₂ O to CO ₂ (ratio of molar weights).

The rate of CO₂ release by respiration at daytime could be estimated by calculating maintenance and growth respiration separately, or by estimation from measured nighttime crop respiration.

Diurnal pattern of growth respiration

The daily total of CO₂ release by growth respiration of the whole crop can be calculated from the daily rate of crop dry matter production, the partitioning of the dry matter increment over the plant parts and the CO₂ production factors of the plant parts. However, the estimation of the diurnal course of rate of growth respiration of the crop is difficult.

One would expect that the rate of growth respiration is higher during daytime when the crop is producing carbohydrates and temperatures are higher, and also is higher during periods of the year with higher photosynthetic activity. However, it is still unclear how day and night patterns are. In the present version of ASKAM it is assumed that the rate of growth respiration at daytime is the same as that at nighttime.

Gijzen *et al.* (1990) assumed that the measured nighttime respiration continued at about the same rate at daytime. Thus, 'measured' gross photosynthesis was assumed to be equal to measured net photosynthesis + measured nighttime respiration. Respiration was found by interpolating in average nighttime rates measured in the night(s) before and the night(s) after.

A calculation example

In some recent experiments with cucumber and tomato at the Glasshouse Crops Research Station (J.G. Vegter & E.M. Nederhoff) average crop growth rate in spring was measured to be about 10 g DM m⁻² d⁻¹. The CO₂ production factor was estimated at 0.4 g CO₂ per g of crop dry weight increment. This yields a daily average CO₂ release by growth respiration of 4 g CO₂ m⁻² d⁻¹. Crop dry weights were on average about 400 g DM m⁻². Thus, when assuming an overall maintenance coefficient for the crop of 0.015 g CH₂O per g d.m., CO₂ release by maintenance respiration was $0.015 \times 400 \times 44/30 = 8.8$ gram CO₂ m⁻² d⁻¹ (at 25 °C).

2.4.4 Dry matter production

In SUKAM the daily maintenance costs (in CH₂O) are subtracted from the daily total of photosynthates. The crop growth rate is obtained by dividing the resulting amount of carbohydrates by the assimilate requirements of 1 gram of new crop dry matter

$$\Delta W_{cr} = \frac{\frac{30}{44} P_{gc} - R_m}{ASRQ_{cr}} \quad (15)$$

where

- ΔW_{cr} = the rate of crop growth (g DM m⁻² d⁻¹),
- $ASRQ_{cr}$ = the assimilate requirement of 1 g of crop dry matter,
- $30/44$ = the conversion of CO₂ to CH₂O

The value of $ASRQ_{cr}$ is determined by the assimilate requirements of the plant parts weighted by the partitioning of the crop dry weight increment over leaves, stems, roots and fruits (Spitters *et al.*, 1989). A typical value of $ASRQ_{cr}$ is 1.45.

In present version of SUKAM only the production stage is simulated. It is assumed that in this stage approximately constant fractions of the assimilates are diverted to plant parts, including the fruits.

3 Some additional theory

In the sensitivity analysis and the evaluation of the effect of changing model parts, two topics are dealt with that will be briefly discussed here: 1) the angular distribution of diffuse light, and 2) use of a simple expression for the absorption of PAR by the canopy.

3.1 Angular distribution of diffuse radiation

Commonly, in models of the radiation climate it is assumed that the diffuse radiance of the sky is uniform over the sky hemisphere. This is the so-called Uniform OverCast sky (UOC). The radiance can also be assumed to change with the angle with the horizon. In the latter case, often a function is used that describes the so-called Standard OverCast sky (SOC):

$$I = I_z \frac{1 + b \cos \beta}{1 + b} \quad (16)$$

where

β = the angle with the horizon, and
 I_z = the intensity at the zenith.

For coefficient b a value commonly used is 2, as found by Moon & Spencer (1942), who measured luminance of the sky (i.e. brightness as experienced by the human eye). When measuring radiance, Stevens & Unsworth (1980) found b to vary from 0.5 to 2.5, with mean 1.25, and Rosen & Hooper (1989) measured values of b in the range 1.5 to 2.8. In present calculations a value of 2 is assumed for b (cf. Fig. 31).

The angular distribution of diffuse light affects both the diffuse light transmissivity of the greenhouse and the penetration of diffuse light in the canopy. These aspects are further dealt with in Chapters 4.2.4 and 6.1.

3.2 PAR absorption by the canopy

In several simulation runs changes in crop photosynthesis or dry matter production due to parameter changes were compared with changes in absorbed radiation. The fractional absorption was approximated by (after Russell *et al.*, 1986)

$$\alpha = 1 - \rho - \tau + \rho_{gr} \tau \quad (17)$$

where

α = the fractional absorption
 ρ = the reflectivity of the canopy-ground system,
 τ = the fractional transmission expressed as $\tau = \exp(-K \cdot LAI)$, and
 ρ_{gr} = the reflectivity of the ground.

The reflectivity of the canopy-ground system was calculated as (Russell *et al.*, 1986, based on Goudriaan, 1977):

$$\rho = \rho' - (\rho' - \rho_{gr}) \tau^2 \quad (18)$$

where ρ' is the reflectivity of a crop with τ close to zero (i.e. at high LAI). For σ equal to 0.15, ρ' is equal to 0.04.

4 Parameter values and data in the simulation runs

The effects of changing values of parameters and intermediate variables or parts of the models ASKAM and SUKAM on model output were investigated by one or several of the following ways:

- 1) comparing two simulation runs: one reference run and another run with a changed parameter or intermediate value; absolute differences between model outputs were compared,
- 2) as 1), but the output of the new run was expressed as a percentage of that of the reference run, and
- 3) the sensitivity of model output to changes in values of parameters or intermediate variables was expressed as a partial sensitivity

$$\frac{dY/Y}{dP/P}$$

where dY/Y is the fractional change in model output, and dP/P is the fractional change in parameter value.

4.1 Model parameters and intermediate variables

Values of intermediate variables were calculated in the models, but some were also used as inputs, i.e.

- the leaf initial efficiency of light utilization, ϵ ,
- the rate of leaf gross photosynthesis at light saturation, P_{gm} , and
- and the canopy extinction coefficient for diffuse light, K_{dif} .

The values of main parameters and intermediate variables as adopted in the simulation runs are given in Table 2 (See also App. X). These values are the reference values, and one or two were changed in the simulation runs for sensitivity analysis.

Maintenance costs were assumed to be proportional to LAI, with LAI at 3 used as a reference. Thus, crop maintenance costs with LAI at 2 were assumed to be $2/3 * 0.25 \text{ g CH}_2\text{O m}^{-2} \text{ d}^{-1}$ (at 25 °C), and with LAI at 4 assumed to be at $4/3 * 0.25 \text{ g CH}_2\text{O m}^{-2} \text{ d}^{-1}$.

The magnitudes of the variations in parameters and intermediate variables were chosen such as was thought to occur commonly in greenhouse practice. Although some values become somewhat unrealistically in the winter season, e.g. a LAI at 3, primarily the degree of change was of interest.

Table 2. The reference values of the parameters and intermediate variables used in the simulation runs. The greenhouse concerned was a Venlo-type multispans glasshouse. The crop was assumed to have average parameter values of leaf photosynthesis, conversion of assimilates to dry matter and maintenance costs.

Description	Value
Transmissivity greenhouse diffuse light	65%
Transmissivity greenhouse direct light	variable
Greenhouse azimuth	north-south
Reflection coefficient of ground surface	0.0
Extinction coefficient diffuse light - black leaves	0.8
Extinction coefficient diffuse light	0.74
Leaf Area Index	3.0
Temperature	20 °C (ASKAM), or 16 °C to 23 °C (SUKAM)
CO ₂ concentration	350 µl l ⁻¹
ϵ at 25 °C and 350 µl l ⁻¹ CO ₂	0.012 mg CO ₂ J ⁻¹ absorbed
P _{gm} at 25 °C and 350 µl l ⁻¹ CO ₂	1.27 mg CO ₂ m ⁻² s ⁻¹
Crop maintenance costs at LAI = 3 and 25 °C	0.25 g CH ₂ O m ⁻² h ⁻¹
Assimilate requirement total crop dry matter	1.45 g CH ₂ O g ⁻¹ DM

4.2 Radiation data

Three sets of radiation data were used to study the effects of changing parameters and specific parts of the models on model output. These sets were:

- 1) a cloudy and a sunny day, both on 15 February and 15 June, with artificially generated radiation levels, and
- 2) the 30-year average (1951-1980) of daily global radiation as measured at De Bilt (the Netherlands, latitude 52°) (Buishand *et al.*, 1982),
- 3) the hourly diffuse and direct global radiation of selected months from the 1971-1980 weather records at De Bilt, called the SEL-year (Breuer & Van de Braak, 1989).

4.2.1 Artificial days

Artificial radiation patterns were created on 15 February and 15 June, and were used for sensitivity analysis with model ASKAM.

Daily radiation levels were chosen at these days, such that the values for the atmospheric transmissions (I/I_{ex}) were 0.22 and 0.8 for the cloudy and clear days, respectively (Table 3). With I/I_{ex} at 0.22 the calculated daily fraction diffuse is just 1, and at 0.8 a totally clear day is obtained. Diurnal courses for instantaneous diffuse and direct radiation were generated as described above. Total, diffuse and direct PAR outside the greenhouse as generated from the daily total of global radiation, for clear days at 15 February and 15 June, are shown in Figure 10.

Table 3. Daily global radiation of cloudy and clear days as assumed for 15 February and 15 June, for De Bilt, and calculated atmospheric transmissions and fractions diffuse, as used for sensitivity analysis with model ASKAM.

	15 February		15 June	
	Cloudy	Clear	Cloudy	Clear
Atmospheric transmission	0.22	0.8	0.22	0.8
Global radiation (MJ m^{-2})	2.9	10.6	8.9	33.4
Daily fraction diffuse	1.0	0.39	1.0	0.72

4.2.2 30-year average radiation data

The 30-year average radiation data were used for sensitivity analysis with model SUKAM. The diurnal courses of diffuse and direct radiation were generated from daily radiation as described by Spitters *et al.* (1986). A daily course of greenhouse air temperature was generated, taking a constant value at nighttime (16°C), and a sinusoidal course from sunrise to sunset, with maximum temperature at noon 23°C .

An artificial variation had to be introduced in the radiation data to avoid overestimation of the fraction diffuse. The fraction diffuse is estimated with a regression equation (Eqn 1, FUNCTION FRACDF) that was obtained by relating individual hourly records of global radiation with the fraction diffuse. However, when averaging global radiation over longer periods, the associated fraction diffuse is decreased. This results from the fact that hours with higher radiation levels have a lower fraction diffuse but a higher weight in the average fraction diffuse. Thus, use of Eqn 1 with parameters as in FRACDF, with average data from the 30-year average radiation records, would give too high fractions diffuse. By introducing an artificial variation in the data, the fraction diffuse can be calculated correctly again.

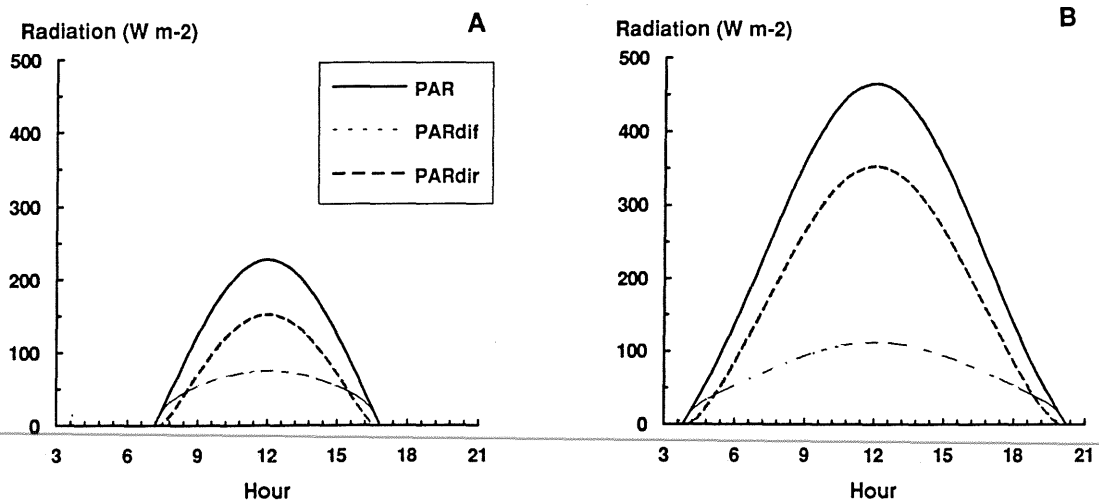


Figure 10. Simulated diurnal course of total PAR, diffuse and direct PAR at clear days at 15 February (A) and 15 June (B)

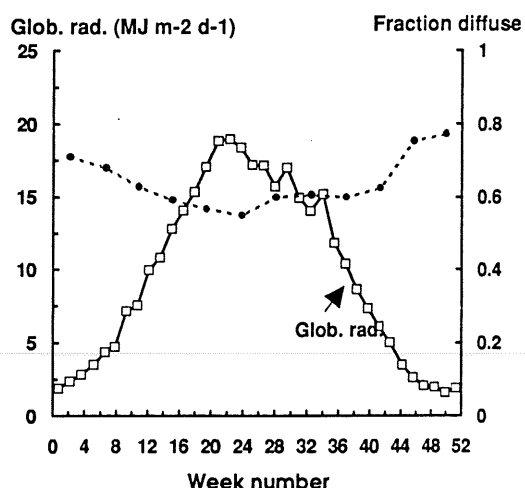


Figure 11. Decade values of 30-year (1951-1980) average daily global radiation, and associated monthly average fraction diffuse, at De Bilt (the Netherlands).

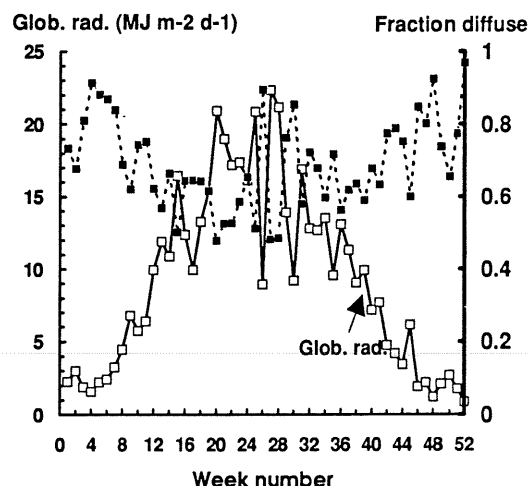


Figure 12. Weekly averaged daily global radiation outside the greenhouse and the weekly average of the fraction diffuse in the SEL-year

A second reason for introduction of variation was that daily radiation inside the greenhouse and daily crop photosynthesis are not linearly related with total global daily radiation outside the greenhouse.

The description of the procedure by which the magnitude of variation, necessary to correctly estimate the fraction diffuse, was found, and its application, is given in Appendix I.

In output of runs with SUKAM, the effects of parameter changes were also expressed as the yearly total of dry matter production as a percentage of that of the reference run. For this purpose a hypothetical growing season was assumed from week 5 onwards (29 January, Day number 29) up to and including week 44 (4 November, Day number 308).

The yearly course of the 30-year average of global radiation outside the greenhouse and the fraction diffuse are shown in Figure 11. Cumulative global radiation in weeks 5 to 44 is 3.3 GJ m⁻², and over the whole year 3.5 GJ m⁻².

4.2.3 The SEL-year

The SEL-year contains data on selected months (Jan. 1971, Feb. 1973, etc.) that are fairly representative with respect to their average radiation level and the magnitude of variation in radiation level for the radiation climate in the Netherlands. These radiation data are therefore particularly suited for calculation of processes for which buffering is important (e.g. heat).

Although in present calculations only instantaneous assimilation rates were considered, the short time step of the data (hours) and the preservation of natural variation of, among others radiation, make them suitable for sensitivity analysis of crop photosynthesis.

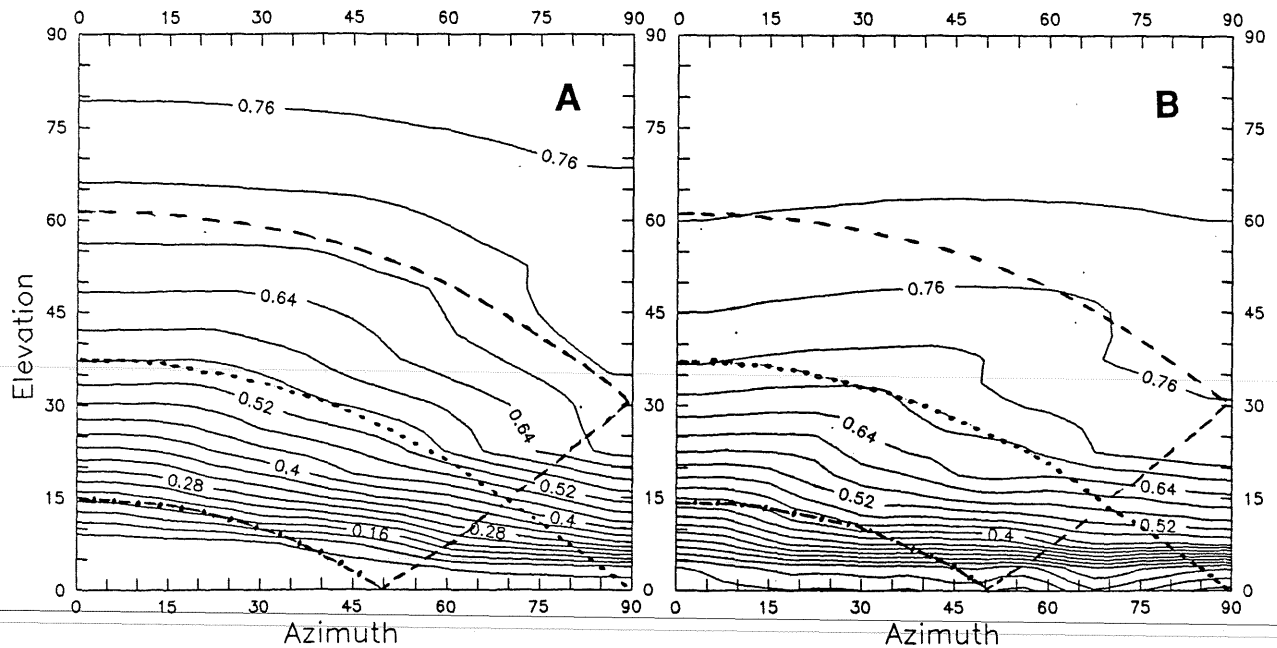


Figure 13. The direct light transmissivity (continuous lines) of the dark (A) and the light (B) greenhouse as dependent on difference between beam and greenhouse azimuth and elevation of the beam. Also shown are the path's of the sun at the winter solstice (21 Dec., dot-dash lines), equinoxes (21 Mar. and 23 Sep., dotted lines), and the summer solstice (21 June, dashed lines; azimuth $> 90^\circ$ is mirrored around 90°), at N-S orientation of the greenhouses.

The yearly course of the intensity of weekly averaged daily global radiation outside the greenhouse and weekly average of the fraction diffuse of the SEL-year are shown in Figure 12. Global radiation total of the whole year amounts to 3.4 GJ m^{-2} .

4.2.4 The dark and the light greenhouse

In several simulations two greenhouses were compared: a so-called 'dark' greenhouse, and a so-called 'light' greenhouse. The dark one was the standard greenhouse (see Table 2) and its parameters were derived from a Venlo-type glasshouse at the PTG at Naaldwijk (data from E.M. Nederhoff). The parameters of a light greenhouse, also a Venlo-type glasshouse, were derived from a glasshouse recently built for a grower (data from G. Houter, PTG). The light greenhouse had a light construction, large glasspanes and clean glass.

The dependency of direct light transmissivity on azimuth and elevation is shown for both greenhouses in Figure 13. Also shown are the paths of the sun at the solstices and the equinoxes for north-south orientations of the greenhouses.

Under a SOC T_{rdif} was calculated to be higher than under a UOC. With the dark greenhouse T_{rdif} was calculated, with Bot's model, to be 0.65 under a SOC, and to be 0.62 under a UOC, i.e. a decrease of 4.1%; with the light greenhouse T_{rdif} was 0.75 under a SOC, and 0.73 under a UOC, a decrease of 2.8%. In all simulations T_{rdif} was assumed to be 0.65 and 0.75 with the dark and the light greenhouse, respectively.

5 Sensitivity analysis

In both models several parameters have effects on the light interception and absorption by the canopy. In some cases then the simulated change in canopy photosynthesis due to parameter change was compared with the change in the absorption of diffuse PAR by the canopy.

5.1 Gross and net photosynthesis - model ASKAM

With model ASKAM the partial sensitivity $((dY/Y)/(dP/P))$ of instantaneous crop gross photosynthesis, P_{gc} , was calculated for several parameters (Fig. 16). In addition, diurnal and daily photosynthesis were calculated for clear and cloudy days at 15 February and 15 June.

Reference run

Diurnal transmission of direct radiation of the dark greenhouse at the clear days was very different for 15 February and 15 June (Fig. 14). With the north-south orientation, the direct light transmission was very dependent on solar elevation lower than 18° at 15 February, and lower than 22° at 15 June.

The simulated diurnal courses of P_{gc} at clear days at 15 February and 15 June, with and without greenhouse cover are shown in Figure 15.

Daily photosynthesis at the cloudy day at 15 June was 30% higher than at the clear day at 15 February (Table 4), although total global radiation outside the greenhouse was 19% less (but inside the greenhouse 14% higher).

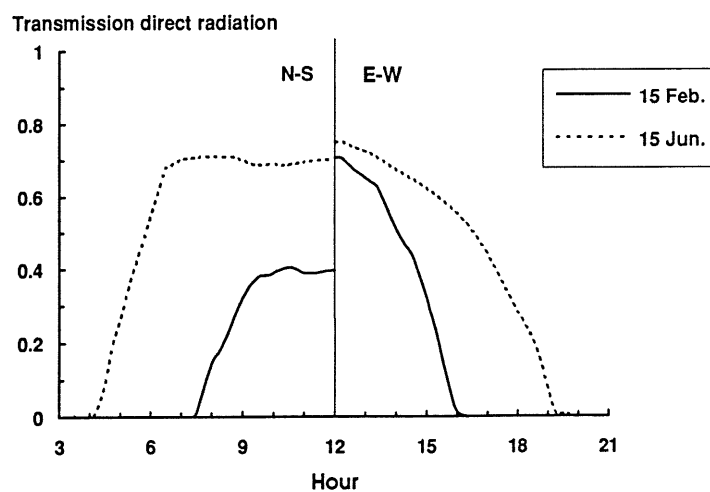


Figure 14. The diurnal direct light transmission of the dark greenhouse at 15 February and 15 June, at orientations N-S and E-W

Table 4. The effect of changing values of parameters and intermediate variables on daily gross photosynthesis (P_{gcd} , $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), also expressed as a percentage of the reference run, at cloudy and clear days at 15 February and 15 June. Radiation characteristics are given in Table 3.

	15 February				15 June			
	Cloudy		Clear		Cloudy		Clear	
Daily PAR inside greenhouse (MJ m^{-2})	0.9		2.4		2.7		10.6	
	P_{gcd}	%	P_{gcd}	%	P_{gcd}	%	P_{gcd}	%
Reference run	9.0	100.	20.0	100	25.9	100	60.3	100
LAI = 2	7.7	85.6	17.6	88.0	22.1	85.0	50.2	83.2
$K_{dif} = 0.6$	8.5	94.4	20.9	104.8	24.7	95.2	63.9	105.9
$\sigma = 0.2$	8.9	98.3	19.7	98.4	25.5	98.4	60.0	99.5
$R_b = 200$	8.9	98.3	18.9	94.6	25.2	97.2	54.6	90.5
$\rho_{gr} = 0.5$	9.5	105.4	20.8	103.9	27.4	105.5	65.5	108.5
$\epsilon + 10\%$	9.9	109.2	21.5	107.5	28.2	108.9	63.5	105.3
$P_{gm} + 10\%$	9.1	100.7	20.4	102.3	26.2	101.2	62.9	103.0

Leaf Area Index

The partial sensitivity of P_{gc} to LAI was calculated to be significant, and to decrease with increasing LAI (Fig. 16). With LAI at 2, a 10% change in LAI caused a 5% change in P_{gc} . The effect on crop photosynthesis of a decrease of LAI from 3 to 2 was quite large (Fig. 17). The daily totals of crop photosynthesis were decreased by 12 to 17% (Table 4).

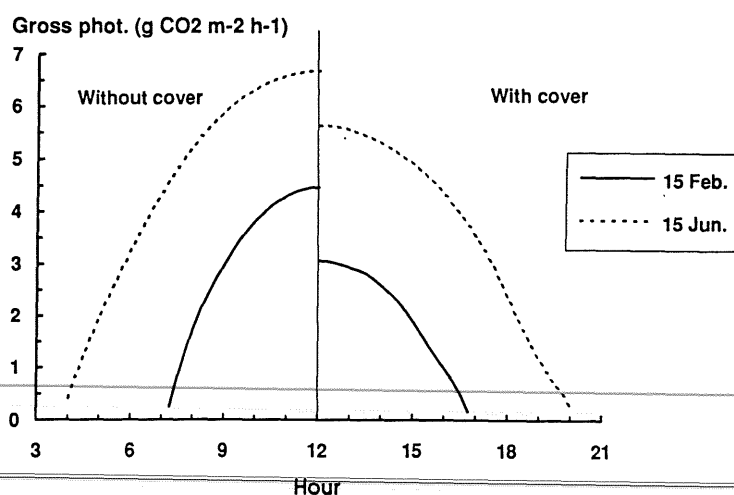


Figure 15. Simulated canopy gross photosynthesis ($\text{g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$) at clear days at 15 February and 15 June, with and without greenhouse cover (dark greenhouse)

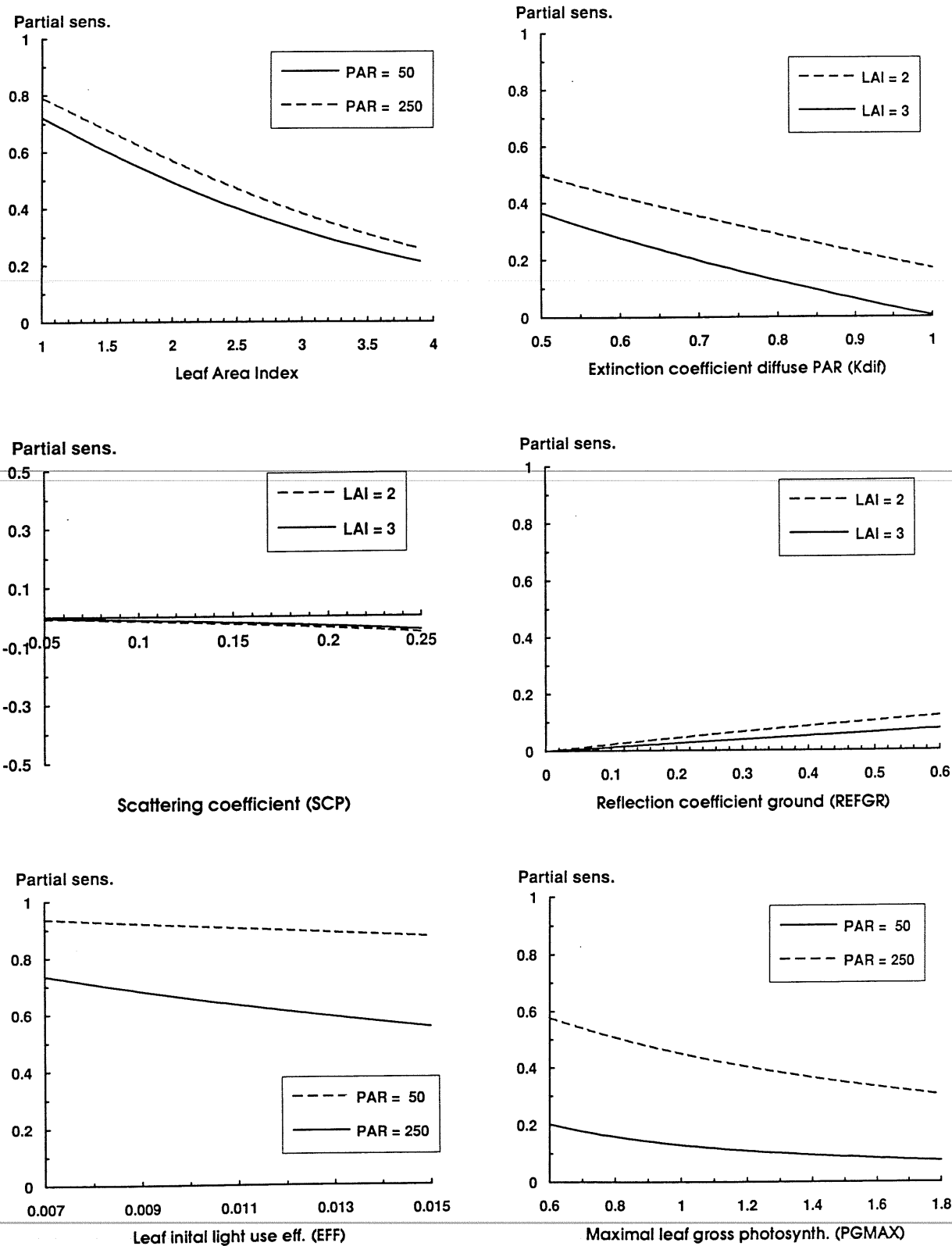


Figure 16. Partial sensitivities of canopy gross photosynthesis (P_{gc}) for several parameters, at given ranges of these parameters. Standard values of parameters are given in Table 2. When not indicated otherwise, PAR was at 150 W m^{-2} , CO_2 concentration at $350 \mu\text{l l}^{-1}$ and temperature at 25°C .

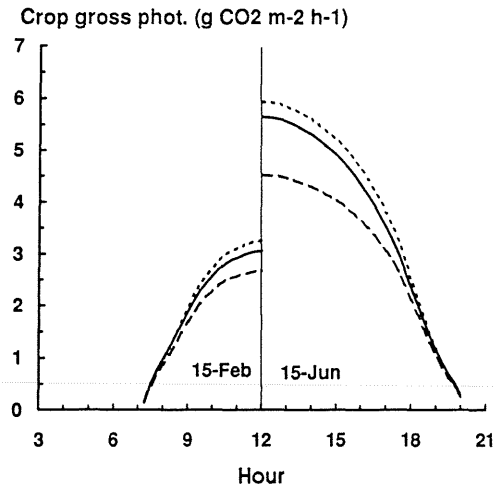


Figure 17. Effects of changing LAI and K_{dif} on diurnal canopy gross photosynthesis at clear days at 15 February and 15 June. Solid line: LAI = 3, K_{dif} = 0.74; dashed line: LAI = 2, K_{dif} = 0.74; dotted line: LAI = 3, K_{dif} = 0.6.

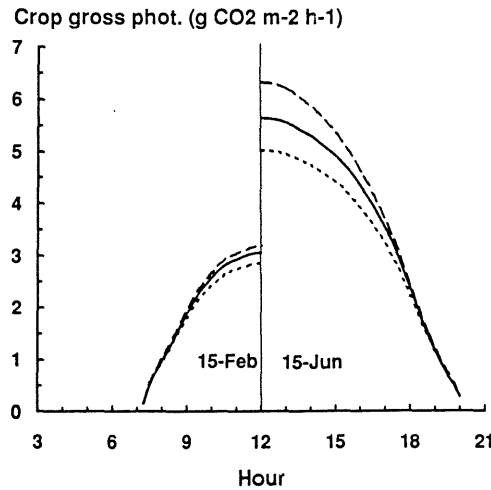


Figure 18. The effect of increasing the reflection coefficient of the ground, ρ_{gr} , and increasing the boundary layer resistance, R_b , from 100 to 200 $s\ m^{-1}$ on diurnal canopy gross photosynthesis at clear days at 15 February and 15 June. Solid line: ρ_{gr} = 0., R_b = 100 $s\ m^{-1}$ (reference run); dashed line: ρ_{gr} = 0.5; dotted line: R_b = 200 $s\ m^{-1}$.

Extinction coefficient

The partial sensitivity of P_{gc} to K_{dif} was not so large and became only significant at low LAI (Fig. 16). The decrease in the extinction coefficient from 0.74 to 0.6 caused a decrease in the fractional absorption of diffuse light from 0.85 to 0.80 and a concomitant increase in diffuse light loss to the ground from 10.5% to 16%. However, photosynthesis was enhanced at clear days (Fig. 17, Table 4). The decreased extinction coefficient also caused a more equal light distribution in the canopy, and at the clear day this effect was larger than the loss of light to the ground. At the cloudy days the decrease in K_{dif} caused a decrease in daily photosynthesis of about 5% (Table 4), comparable to the

changes in absorbed PAR.

Scattering coefficient

The partial sensitivity of P_{gc} to the scattering coefficient for PAR, σ , was small (Fig. 16). Changing σ within the range of values that is characteristic for PAR did have little effect on crop photosynthesis (Table 4). An increase in σ from 0.15 to 0.2 decreased daily photosynthesis at the cloudy days by 1.5%. At the clear days this decrease in photosynthesis was diminished by a better light distribution in the canopy.

Reflection coefficient of the ground

P_{gc} was little sensitive to variation in reflection coefficient ρ_{gr} ; at a lower LAI the sensitivity was increased (Fig. 16). Increase of ρ_{gr} from 0 to 0.5 increased daily P_{gc} significantly, by about 4-8% (Table 4). Instantaneous crop gross photosynthesis could even be increased by more than 10% at noon at the clear days (Fig. 18).

Boundary layer and stomatal conductance

Changes in the boundary layer resistance and the stomatal resistance have comparable effects on leaf CO_2 assimilation. Both resistances are placed in series with the carboxylation resistance to form the total resistance in the pathway of CO_2 from ambient air to CO_2 fixed by the Rubisco enzyme.

The simulated effect of doubling the boundary layer resistance, R_b , was significant at moderate to high light intensities. It reached significant levels at the clear day at 15 June (Fig. 18, Table 4). The effect increased with increasing light level, as with increasing light level the CO_2 diffusion to the site of carboxylation becomes more limiting for leaf photosynthesis.

This results indicate that increases in stomatal resistance could easily have comparable effects on crop photosynthesis. For example, it seems likely that an increase could occur in R_s from 50 to 100 s m^{-1} or to higher values at high light intensities and unfavourable conditions.

Note that the sensitivity of the model output to changes of one of these two resistances is much influenced by the value of the other resistance, and of the carboxylation resistance.

Leaf light use efficiency and maximal rate of photosynthesis

The partial sensitivity of P_{gc} to the leaf efficiency of light utilization, ϵ , was high (Fig. 16). Even at a relatively high light intensity (PAR at 250 W m^{-2}) the sensitivity is significant. A 10% increase of ϵ increased P_{gc} significantly on the clear days at 15 February and at 15 June (Fig. 19, Table 4). The effect decreased with increasing light levels. Note that an increase in CO_2 concentration from 350 to 600 $\mu\text{l l}^{-1}$ (at 25°C) was calculated to increase ϵ by 15%.

The partial sensitivity of P_{gc} to the maximal rate of leaf photosynthesis becomes significant at high light levels (Fig. 16). At the clear day at 15 June an increase of P_{gm} of 10% increased daily crop

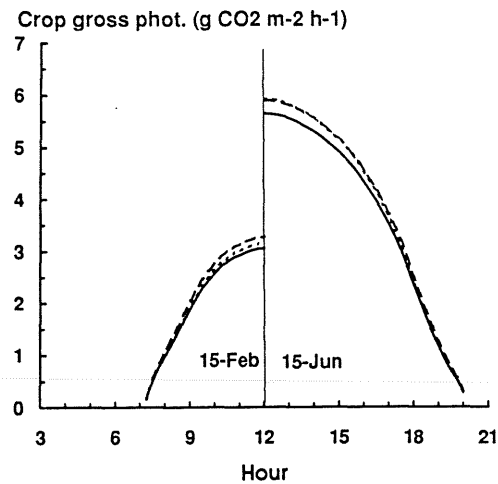


Figure 19. The effect of increasing the leaf efficiency of light utilization (ϵ) or the light saturated rate of leaf gross photosynthesis (P_{gm}) with 10% on canopy gross photosynthesis at clear days at 15 February and 15 June. Solid line: $\epsilon = 0.0128 \text{ mg CO}_2 \text{ J}^{-1}$, $P_{gm} = 1.1 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (reference run); dashed line: $\epsilon = 0.0141 \text{ mg CO}_2 \text{ J}^{-1}$, $P_{gm} = 1.1 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$; dotted line: $\epsilon = 0.0128 \text{ mg CO}_2 \text{ J}^{-1}$, $P_{gm} = 1.32 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$.

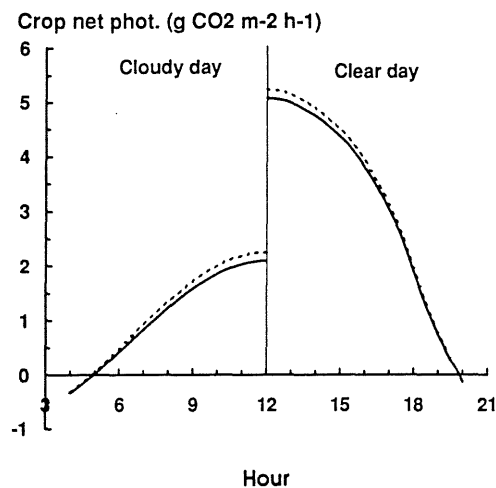


Figure 20. Crop net photosynthesis simulated with a sinusoidal course of respiration during daytime (from 0.4 to 0.56 to $0.4 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$; solid line), and crop net photosynthesis simulated with a constant rate of respiration ($0.4 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$; dotted line) at clear days at 15 February and 15 June

photosynthesis only by 3%, but note that P_{gm} can vary substantially. For example, an increase in CO_2 concentration from 350 to 600 $\mu\text{l l}^{-1}$ (at 25 °C) was calculated to increase P_{gm} by 64%.

At present, the parameters in the leaf photosynthesis submodel assume more or less 'high light'-adapted leaves. It is to be expected that for the low light levels as are prevailing mid-February, the value of P_{gm} would be lower, possibly to the extent that a given increase of P_{gm} has the same effect in this period as at 15 June.

Respiration

For validation of simulations of canopy gross photosynthesis with net photosynthesis data, estimations have to be made about the rate of crop respiration during daytime. Different patterns of crop respiration during daytime will result in different patterns of crop net CO_2 uptake. For this reason the effect of changing the simulated pattern of respiration on net photosynthesis was investigated.

Two respiration patterns were compared: the first one assumed a constant respiration pattern at daytime, i.e. $0.4 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$, the second one assumed that at sunrise and sunset respiration was $0.4 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ and followed a sinusoidal course during the day, with the maximum at noon 40% higher, i.e. at $0.56 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$. (A 40% increase would follow from a 5°C temperature rise, if total respiration would have a Q_{10} of 2.). The increase in respiration caused simulated instantaneous net photosynthesis at noon to decrease with 3% at the clear day 15 June, and with 7% at the cloudy day at 15 June (Fig. 20). However, respiratory pattern will probably be different at cloudy and clear days. It is expected that daytime respiration at cloudy days would be lower than at clear days, due to lower temperatures and lower metabolic activity of the crop.

This calculations indicate that an unknown respiration pattern will cause some inaccuracy in validating photosynthesis models.

5.2 Photosynthesis and dry matter production - model SUKAM

Reference run

The yearly course of daily photosynthesis and dry matter production for the 30-year average radiation data closely followed the course of the radiation, as all parameters were kept constant during the year (Fig. 21). As already mentioned, a steady state growth of the crop was assumed, with constant partitioning of dry matter to plant parts. The simulated cumulative canopy gross

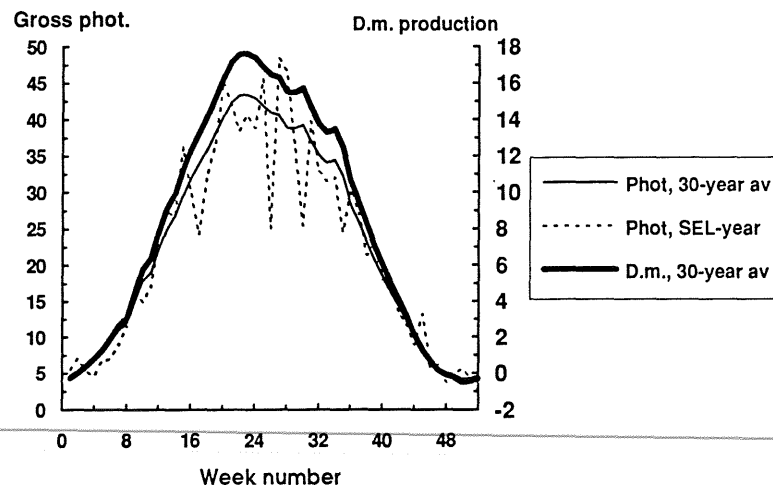


Figure 21. The rates of daily crop gross photosynthesis ($\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) and dry matter production ($\text{g DM m}^{-2} \text{ d}^{-1}$) as calculated for the 30-year average radiation data of De Bilt, the Netherlands, with model SUKAM

photosynthesis for the reference set of parameter values was $7.8 \text{ kg CO}_2 \text{ m}^{-2}$ for weeks 5 to 44 (8.3 kg for the whole year).

Simulated cumulative dry matter production in weeks 5-44 was 3.0 kg m^{-2} and cumulative maintenance costs were $1.1 \text{ kg CH}_2\text{O m}^{-2}$ (i.e. 20% of the photosynthates). With the dark greenhouse, the level at which all photosynthates were consumed by maintenance respiration (the 'crop light compensation point'), was at $2.1 \text{ MJ m}^{-2} \text{ d}^{-1}$ global radiation outside the greenhouse and $0.52 \text{ MJ PAR m}^{-2} \text{ d}^{-1}$ inside (at Day number 10 and Day number 329). Crop gross photosynthesis at these days was $5.2 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. With the light greenhouse average daily crop photosynthesis always remained above this crop light compensation point.

Note that an increase of cumulative photosynthesis of 10% will result in an increase of cumulative dry matter production with 12.4%, with larger maintenance costs increasing the effect of change in the rate of photosynthesis on change in dry matter production.

Dark versus light greenhouse

Light transmission and crop photosynthesis of the light greenhouse were compared with those of the standard dark greenhouse.

PAR

The simulated level of PAR in the light greenhouse was, with the north-south orientation, 15 to 25% higher than in the dark greenhouse, the highest increase being attained in winter time (Fig. 22); with the east-west orientation light gain varied less between summer and wintertime (15 to 20%). In summertime the light gain at the north-south orientation was somewhat less than at the east-west orientation (15% versus 17%). The increase in total, diffuse + direct, light intensity inside the greenhouse cumulated over weeks 5 to 44 was slightly higher than the increase in diffuse light transmissivity, i.e. an increase of 17% versus an increase in 15% in T_{rdif} , at both orientations.

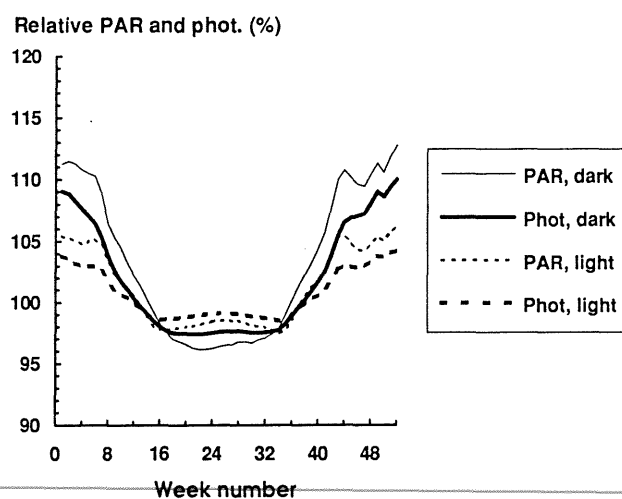


Figure 22. The effect of the increased light transmissivity of the light greenhouse compared with the dark greenhouse on the relative level of PAR in the greenhouse and on relative daily crop gross photosynthesis, at N-S and E-W orientation

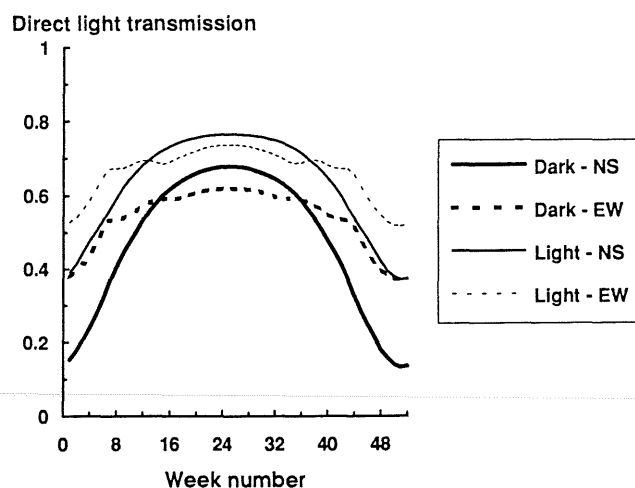


Figure 23. The yearly course of daily average direct light transmission of the greenhouse covers of the light and the dark greenhouse, at north-south and east-west orientation.

Daily direct light transmission varied considerably during the year (Fig. 23). The largest variation was with the north-south oriented dark greenhouse (from 0.15 to 0.67; the smallest variation was with the east-west oriented light greenhouse (0.52 to 0.73). Total, diffuse + direct, light transmission varied less during the year than the direct beam transmission, as the differential transmissions for diffuse and direct light were weighted by the fractions diffuse and direct radiation, and the fraction diffuse decreased with daylength and daily average solar elevation (not shown).

The year-round higher transmission of PAR of the light greenhouse was almost completely the result of less shading by the construction parts. With the dark greenhouse the light interception of the relatively heavy construction of the cover became higher at lower solar elevations in winter time. In this period it was higher for a N-S dark greenhouse than for an E-W greenhouse (not shown). As with the dark greenhouse, the construction parts of the light greenhouse intercepted more radiation with lower solar elevations, but there was no difference between N-S and E-W orientations (not shown).

Photosynthesis

The gain in crop photosynthesis followed the same yearly pattern as did the gain in light intensity, but the gain was less. At the higher light levels in summertime photosynthesis responded less to increased levels of PAR, than at the lower light levels in wintertime (Fig. 22). Photosynthesis cumulated over weeks 4 to 55 was increased by 12% and 12.5%, at the N-S and the E-W orientation, respectively.

Dry matter production

The cumulative dry matter production in weeks 5 to 44 in the light greenhouse was increased by 15% compared with the dark greenhouse, both at the N-S orientation (Fig. 24), and at the E-W orientation (not shown). Thus, cumulative dry matter production was simulated to increase to the same extent as the diffuse light transmissivity of the greenhouse, and little less than the increase in light intensity accumulated over the year. These simulation results were in accordance with the rule of thumb 'one percent more light is one percent more production'.

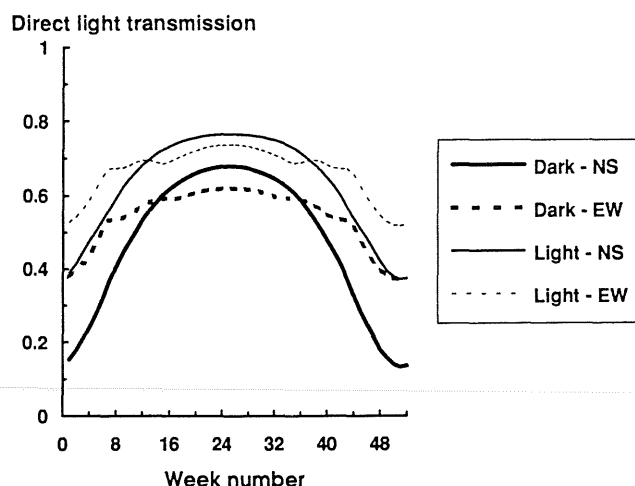


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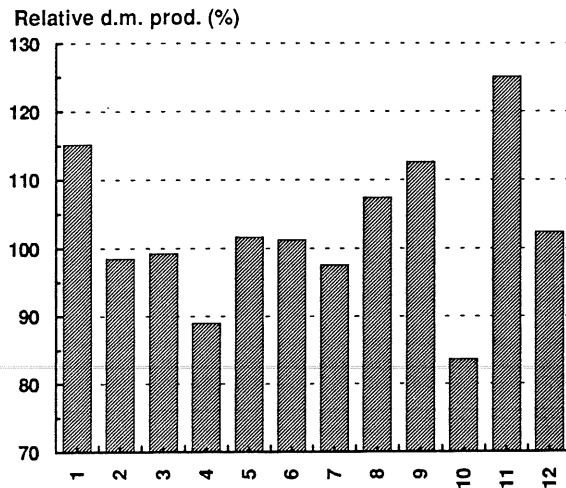


Figure 24. The effect of changing parameter values on total crop dry matter production, accumulated over weeks 5 to 44, expressed as a percentage of the reference run.

- Runs:
- 1 - Light versus dark greenhouse
 - 2 - Dark greenh., E-W versus N-S orientation.
 - 3 - Light greenh., E-W versus N-S orientation
 - 4 - LAI at 2 versus LAI at 3
 - 5 - LAI at 4 versus LAI at 3
 - 6 - LAI at 3: K_{dif} at 0.6 versus K_{dif} at 0.74
 - 7 - LAI at 2: K_{dif} at 0.6 versus K_{dif} at 0.74
 - 8 - LAI at 3: ρ_{gr} at 0.5 versus ρ_{gr} at 0.0
 - 9 - LAI at 2: ρ_{gr} at 0.5 versus ρ_{gr} at 0.0
 - 10 - Temperature increased with 5 °C
 - 11 - CO₂ concentration: 600 versus 350 $\mu\text{l l}^{-1}$
 - 12 - Maintenance costs decreased by 10%

Greenhouse orientation

In summertime the simulated levels of PAR and crop photosynthesis in the E-W dark greenhouse were, compared with the N-S greenhouse, somewhat decreased relatively, but significantly increased in wintertime (Fig. 25). With the light greenhouse the effect of orientation was smaller. For the dark greenhouse the differential effect of orientation at summertime and at wintertime was due to both differential light interception by the construction parts and differential light reflection by glasspanes, but for the light greenhouse for the major part due to differential light reflection by the panes.

Total dry matter production in weeks 5 to 44 of the E-W dark greenhouse was only 1.5% lower than in the N-S dark greenhouse (Fig. 24). With the light greenhouse the effect of orientation was even smaller, less than 1% (Fig. 24). Thus the strong positive effects in wintertime were more than offset by the negative effects in summertime, due to the larger weight of this latter period in the yearly total.

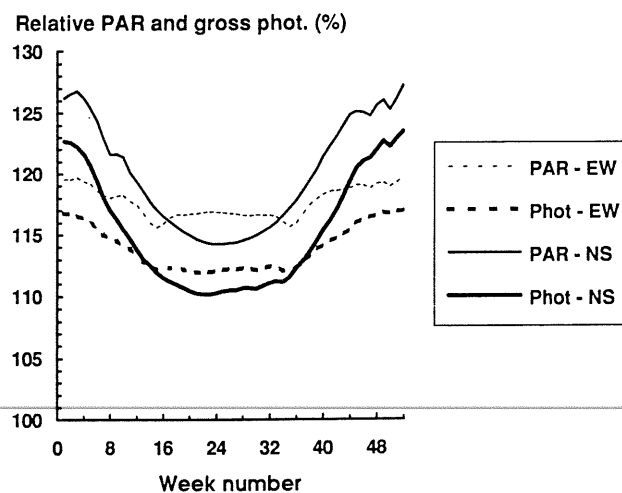


Figure 25. The effect of changing the greenhouse orientation from north-south to east-west on daily PAR inside the greenhouse and on the rate of daily crop gross photosynthesis, in the dark greenhouse and the light greenhouse

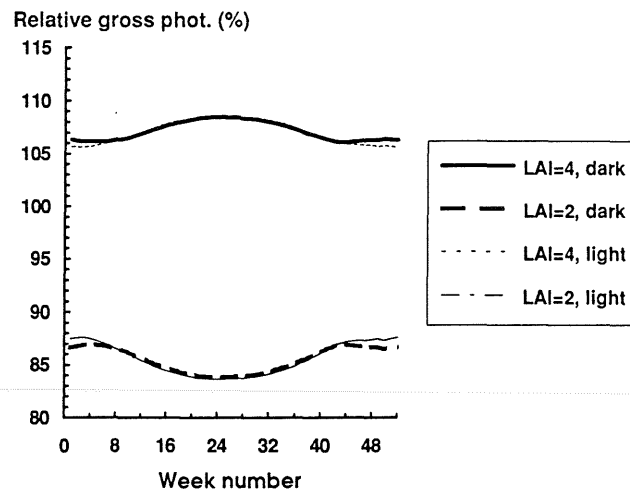


Figure 26. The effect of changing the LAI from 3 to 2 or from 3 to 4 on daily crop gross photosynthesis, in the dark greenhouse and in the light greenhouse

Leaf Area Index

The simulated effect on photosynthesis of changing the LAI from 3 to 2 was relatively large; the effect of changing the LAI from 3 to 4 was smaller, but still significant (Fig. 26). Effects were the same for the dark and the light greenhouse. The relative changes in daily crop gross photosynthesis were comparable with the relative changes in diffuse light absorption as calculated with Eqn 17, i.e. changing LAI from 3 to 2 decreased absorption of diffuse light by 13% (fractional interception decreased from 0.89 to 0.77), and changing LAI from 3 to 4 decreased absorption of diffuse light by 6.5 % (fractional interception decreased from 0.89 to 0.95).

Decreasing the LAI from 3 to 2 decreased cumulative dry matter production by 11%, increasing LAI from 3 to 4 increased dry matter production by 2% (Fig. 24). Note that the maintenance costs were made to change proportionally with LAI.

Ground reflectivity

The effect of a ground reflectivity (ρ_{gr}) of 50% on crop photosynthesis at LAI is 3 was significant (5-7% increase, Fig. 27). With LAI at 2 the effect was much larger (10-12% increase), as more light reached the ground and reflected back into the canopy. These figures corresponded with the changes in fractional absorption as calculated with Eqn 17. Absorption of diffuse light was increased by 5 and 12%, with LAI at 3 and 2, respectively.

A ground reflectivity of 50% increased cumulative dry matter production with 7 and 13% with LAI at 3 and at 2, respectively (Fig. 24). With ρ_{gr} at 20%, the estimated reflectivity of a clean concrete floor, cumulative dry matter production was calculated to increase by 3 and 5.5%, with LAI at 3 and 2, respectively.

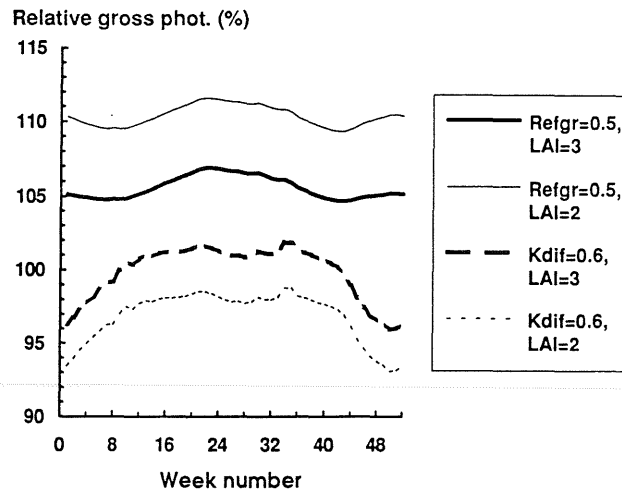


Figure 27. The effect of changing the ground reflectivity from 0. to 50%, or decreasing the diffuse extinction coefficient from 0.74 to 0.6, on daily crop gross photosynthesis, with LAI at 2 or at 3

Extinction coefficient

A decrease of diffuse extinction coefficient K_{dif} from 0.74 to 0.6 decreased crop photosynthesis in wintertime, due to increased light loss to the ground (Fig. 27). The diffuse light absorption by a crop with LAI at 3 was decreased by 6%. At the high radiation levels in summertime, this decrease was compensated for by a better (more equal) light distribution in the canopy. With LAI at 2 relative photosynthesis followed the same pattern. Here, the increased light loss to the ground was more important than a better light distribution. Diffuse light absorption with LAI at 2 was decreased by 10%.

The cumulative dry matter productions were little affected. With LAI at 3 it was increased by 1%, with LAI at 2 it was decreased by 2.5% (Fig. 24).

CO₂ concentration and temperature

CO₂ had a large effect on crop photosynthesis: by raising the CO₂ concentration from 350 to 600 $\mu\text{l l}^{-1}$, crop photosynthesis increased from 15% in wintertime to 23% in summertime (Fig. 28). By comparison, with the leaf photosynthesis model it was calculated that, at 20 °C, ϵ increased by 12%, and P_{gm} by 41%.

Temperature had little effect on daily crop gross photosynthesis: increasing the temperature by 5 °C (the night temperature from 16 to 21 °C, the maximal day temperature from 23 to 28 °C) decreased crop photosynthesis by 4% (Fig. 28). By coincidence, little seasonal effect was simulated as ϵ and P_{gm} changed by about the same extent. With a temperature decrease of 16 to 21 °C, ϵ decreased by 6%, and with a temperature decrease from 23 to 28 °C, P_{gm} decreased by 6.5%.

The CO₂ increase enhanced total dry matter production with 25%, and the temperature increase

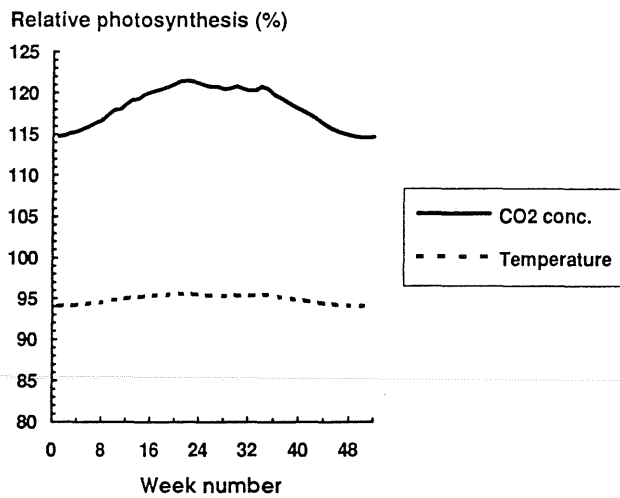


Figure 28. The effects of raising the CO_2 concentration of the greenhouse air from 350 to 600 $\mu\text{l l}^{-1}$, or the temperature of the greenhouse air with 5 $^{\circ}\text{C}$ on daily crop photosynthesis

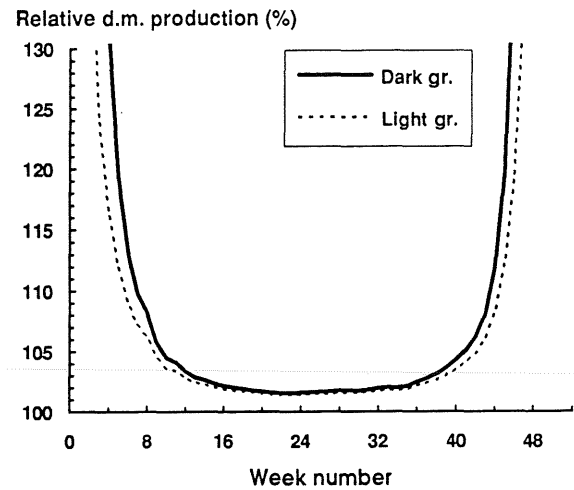


Figure 29. The effect of decreasing the maintenance costs with 10% on dry matter production, with the dark and the light greenhouse

decreased dry matter production by 16% (Fig. 24). Due to the temperature rise the maintenance costs were increased with 40%; the increase in maintenance costs alone caused dry matter production to decrease by 11%.

Maintenance costs

A decrease of the maintenance costs by 10% resulted in an increase of the rate of crop dry matter production of 0.25 g DM $\text{m}^{-2} \text{d}^{-1}$. The relative increase in crop dry matter production was small in the summer period (Fig. 29). In the winter period dry matter production was enhanced very significantly because the amount of assimilates that were consumed by maintenance respiration constitute a large fraction of the total available assimilates in this period. The effect of a higher light transmissivity of the greenhouse (the light greenhouse compared with the dark greenhouse) on the amount of net assimilates available for dry matter production was quite large in wintertime.

The cumulative dry matter production was only little affected by the decrease in maintenance costs of 10%; both with the dark (Fig. 24) and the light greenhouse (not shown) it was increased by about 2%.

6 Effect of changing submodels

6.1 Changing the leaf angle distribution and the sky diffuse radiance distribution

In SUBROUTINE ASSIMR the leaf angle distribution is assumed by default to be spherical and the angular distribution of diffuse light to be uniform. Here two different versions of SUBROUTINE ASSIMR are presented and tested:

- SUBROUTINE NUMEX: the extinction of diffuse light is calculated numerically; both the leaf angle distribution and angular distribution of diffuse sky radiance are input to the subroutine,
- SUBROUTINE ASSIMN: (N stands for near-planophile leaf angle distribution) the effect of the greenhouse cover on angular distribution of diffuse light and the effect of a more horizontal leaf angle distribution than the spherical one are approximated with simple formulae.

Leaf angle distribution

Crops like cucumber (E.M. Nederhoff, PTG, unpublished results) and tomato (Tchamitchian, 1990) appear to have a rather horizontal leaf angle distribution in the early stage of crop growth. These leaf angle distributions are similar to the one that was called the planophile leaf angle distribution by De Wit (1965). In later stages of growth of tomato and cucumber the average leaf angle becomes somewhat steeper; with tomato leaf angles around 45° were dominating (Tchamitchian, 1990). Also for sweet pepper the leaf angle distribution was found to be concentrated around 45° (Shell *et al.*,

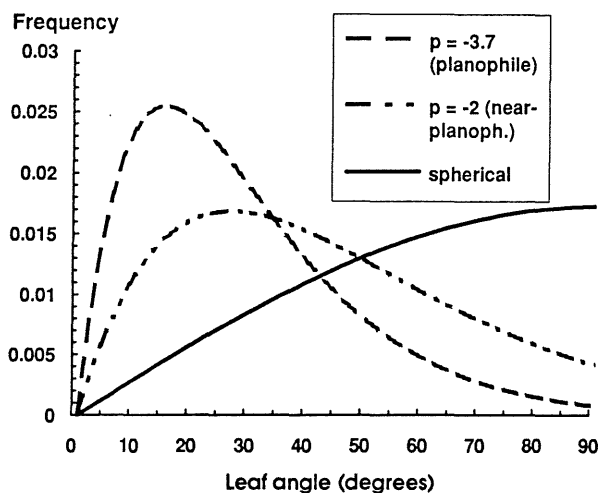


Figure 30. Frequency distribution of leaf angles described according to $\sin\lambda \exp(p\lambda)$ (Goudriaan, 1989). With $p = 0$ a spherical leaf angle distribution is obtained, with $p = -3.7$ a planophile distribution, and with $p = -2$ a distribution that is considered representative for tomato, cucumber and sweet pepper.

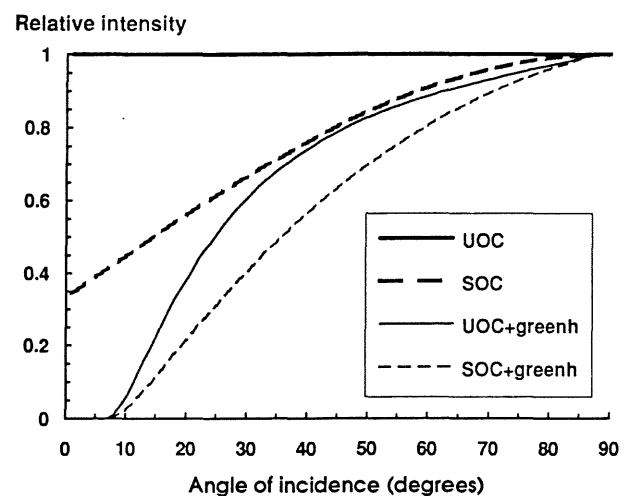


Figure 31. Relative intensity of diffuse sky radiance as dependent on elevation of beam (angle with horizontal) for a UOC, and a SOC (with $b=2$), and for both types of sky with interference of the cover of the dark greenhouse

1974). In Figure 30 the planophile and the spherical leaf angle distribution are depicted, and also the distribution that is considered here a representative approximation for cucumber, tomato and sweet pepper, called here the near-planophile leaf angle distribution. Goudriaan (1988) showed that distribution of the frequencies of leaf angles in 3 classes (0-30°, 30-60° and 60-90°) provides sufficient detail to describe extinction of radiation in the canopy.

Angular distribution of diffuse radiation

Superimposed on the angular distribution of diffuse radiance outside the greenhouse (see Ch. 3.1) is the pattern that is caused by the greenhouse cover. With a decreasing elevation, single beams are intercepted more by construction parts and are differentially reflected by glasspanes. This effect is shown for the dark greenhouse in Figure 31.

6.1.1 Profile of diffuse light in the canopy

The profile of diffuse light intensity in the canopy is the result of multiple extinctions of beams coming from all directions. With a spherical leaf angle distribution, the intensity of beams with lower elevation is decreasing with canopy depth more rapidly than that of beams coming from higher elevations (Goudriaan, 1988). This means that when the intensity of sky radiance at the zenith increases relatively to that at the horizon, the total intensity of diffuse radiation in the canopy is decreasing more slowly with depth.

The profile of the extinction of diffuse light in the canopy is not exactly exponential (except for horizontal leaves), but can suitably be described by an exponential function with an extinction coefficient (Goudriaan, 1977). The best fit of K_{dif} can be found by fitting the exponential function with the numerically calculated one, using the least squares method. For a spherical leaf angle distribution and under a UOC, a K_{difbl} for black non-scattering leaves of 0.78 was found (0.80 as calculated by Goudriaan, 1977, who used a slightly different calculation procedure). The effects on K_{difbl} of a SOC, of the interference by the greenhouse cover, and of other leaf angle distributions are shown in Table 5. It was calculated that by interference of the greenhouse cover K_{difbl} decreased, whereas it increased for a more horizontal leaf angle distribution.

6.1.2 SUBROUTINE NUMEX

In this subroutine (see Appendix VII) the extinction of diffuse light is calculated numerically instead of by an exponential function. The extinction of diffuse light is obtained by calculating the extinction of individual beams from every direction of the hemisphere. The average projection of the leaves and the range of projections of sunlit leaves are calculated based on the frequency distribution of leaf angles, according to Goudriaan (1988). This subroutine is flexible and can take account of different leaf angle distributions, sky diffuse radiance distributions and any greenhouse cover effect on 'apparent' sky diffuse radiance.

Table 5. The value of the extinction coefficient of diffuse light for black non-scattering leaves, K_{difbl} , as dependent on the radiance distribution of the sky (UOC or SOC), on the presence of the greenhouse cover and on the leaf angle distribution. The SOC was described according to $(1 + 2 \cos \beta)/(1+2)$. The leaf angle distribution was described according to $\sin(\lambda) \exp(p\lambda)$, with λ leaf angle with horizontal. With $p = 0$, a spherical leaf angle distribution was obtained, with $p = -3.7$ the planophile leaf angle distribution, and with $p = -2$ a leaf angle distribution that was considered representative for cucumber, tomato and sweet pepper, and is called near-planophile. Also K_{difbl} in a canopy with all leaf angles condensed in class 30-60° is given.

		spherical	near planophile ($p = -2$)	planophile ($p = -3.7$)	30-60 degrees
without cover	UOC	0.78	0.90	0.91	0.82
	SOC	0.72	0.85	0.88	0.77
dark greenhouse	UOC	0.72	0.85	0.87	0.77
	SOC	0.68	0.82	0.85	0.74
light greenhouse	UOC	0.74	0.86	0.88	0.78
	SOC	0.69	0.83	0.86	0.75

6.1.3 SUBROUTINE ASSIMN

In this subroutine (see Appendix V) it is implicitly assumed that the crop has a near-planophile leaf angle distribution. Also a 'greenhouse cover effect' is implicitly assumed in the value of K_{difbl} . The calculation of O , the average projection of leaves into the direction of the direct light, and the calculation of the variation of projections of sunlit leaves into the direction of the direct light are based on approximations of detailed calculations according to Goudriaan (1988).

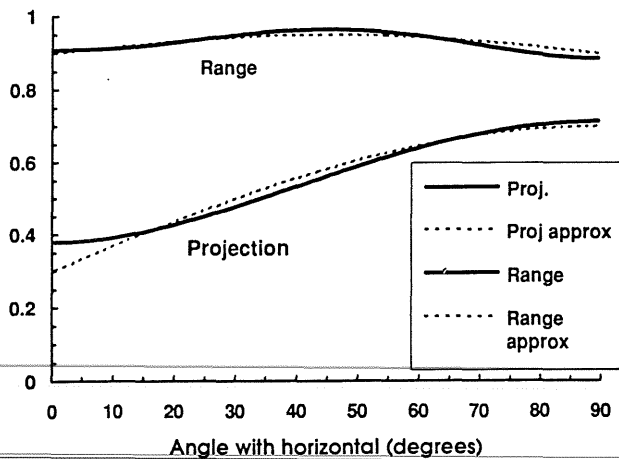


Figure 32. The effect of solar elevation on average projection (O_{np}) and the range of projections of leaves with the near-planophile leaf angle distribution. Shown are curves from detailed calculations according to Goudriaan (1988), and from approximations.

A value of 0.85 of K_{difbl} is adopted to account for the effects of leaf angle distribution and greenhouse cover (Table 5). The average projection of the leaves depends on the solar elevation, and was approximated by (Fig. 32):

$$O_{np} = 0.3 + (0.7-0.3) \sin \beta \quad (19)$$

Also the range of projections depends on the solar elevation, and was approximated by (Fig. 32)

$$r = 0.9 + 0.05 \sin (2 \beta) \quad (20)$$

6.1.4 Effects of leaf angle distribution and sky radiance distribution on photosynthesis

Leaf angle distribution

The effect of leaf angle distribution on photosynthesis was calculated with SUBROUTINE NUMEX. It was simulated that a crop with the near-planophile leaf angle distribution had a significantly higher rate of crop photosynthesis under diffuse light conditions than a crop with a spherical leaf angle distribution (about 5% higher) (Fig. 33, Table 6). Under direct light conditions the enhancement of crop photosynthesis calculated at diffuse light conditions was decreased, the more so with increasing solar elevations and higher direct light intensities. Photosynthesis of a canopy with horizontal leaves was somewhat higher.

Angular distribution of diffuse light

The influence of the angular distribution of diffuse light on crop photosynthesis was calculated to be very small. Under a SOC (with $b = 2$) photosynthesis was decreased compared with a UOC; with a spherical leaf angle distribution daily photosynthesis was about 1% lower, with the near-planophile leaf angle distribution it was less than 0.2% lower (results not shown). (With horizontal leaves the diffuse radiance distribution does not have effect as in that case the extinction coefficient for a light beam is always 1, for any elevation). Under direct light conditions (the diffuse part of the radiation still having a SOC distribution), differences were even less.

Table 6. The effects of leaf angle distribution on daily gross photosynthesis as calculated with SUBROUTINE NUMEX. Results of spherical leaf angle distribution-calculations are taken as a reference. A UOC distribution of diffuse light was assumed.

Day	spherical	spherical	near-plan.	horizontal	30-60°
15 Febr. - cloudy	8.86 ⁺	100	105.8	106.7	101.8
15 Febr. - clear	20.39 ⁺	100	103.0	107.7	101.9
15 June - cloudy	25.73 ⁺	100	104.8	105.9	101.7
15 June - clear	63.98 ⁺	100	99.7	101.5	99

⁺) Daily gross photosynthesis expressed as g CO₂ m⁻² d⁻¹

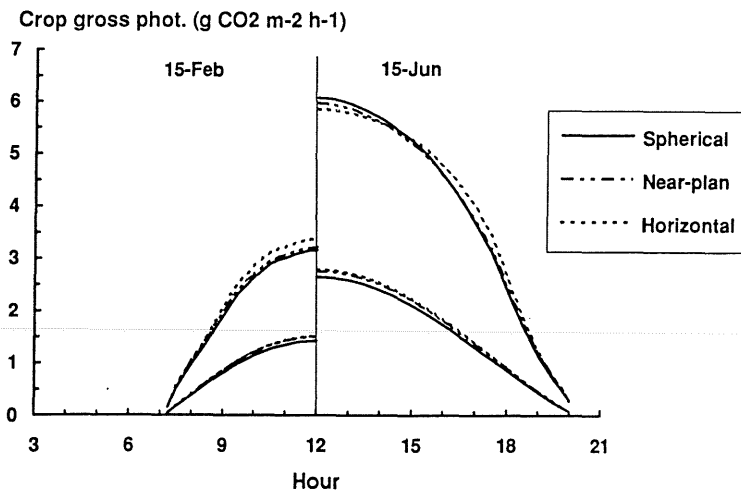


Figure 33. The effect of leaf angle distribution on diurnal canopy gross photosynthesis on cloudy days (3 bottom lines at each side of vertical line) and clear days (3 upper lines) at 15 February and 15 June

Thus, the effect of the diffuse radiance distribution on crop photosynthesis was smaller than on the diffuse transmissivities of the greenhouses (4.1 and 2.8% higher diffuse transmissivities under SOC for the dark and light greenhouse, respectively). Note that in all the above calculations T_{rdif} was assumed to be 0.65, irrespective of the sky diffuse radiance distribution.

A still more detailed calculation of diffuse light interception than that calculated by SUBROUTINE NUMEX was tested. In this procedure, for any single beam of the diffuse light, first the transmission by the greenhouse cover was calculated, and after that the penetration in the canopy. Compared with results of SUBROUTINE NUMEX, daily photosynthesis at cloudy days decreased by 1.5% for a spherical leaf angle distribution, and decreased with less than 1% for the near-planophile and the horizontal leaf angle distributions.

6.1.5 Accuracy of the simplified computations

The results of calculations of SUBROUTINE ASSIMR and SUBROUTINE ASSIMN were compared with the detailed calculations of SUBROUTINE NUMEX. For completeness, also the results are shown of SUBROUTINE ASSIM. This subroutine is similar to ASSIMR, but does not contain the calculations of the effect of ground reflectance. The inclusion of the reflectance calculations has led to slightly different results between the two subroutines for a zero ground reflectivity (about 0.5% difference).

Daily crop photosynthesis at diffuse light conditions as calculated with ASSIMR was larger than that calculated by NUMEX (Table 7). With direct light, the differences became smaller, as the calculation of direct light extinction was the same in the two subroutines. The differences between SUBROUTINE NUMEX and SUBROUTINE ASSIMN were on average smaller. With normal radiation conditions during a growing season, in which clear and cloudy days are alternating, average crop growth calculated with SUBROUTINE ASSIMN would differ very little with a growth rate based on more detailed calculations of light interception.

Table 7. Daily crop gross photosynthesis as calculated with SUBROUTINEs ASSIMR, ASSIMN and ASSIM as a percentage of daily crop gross photosynthesis as calculated with SUBROUTINE NUMEX. ASSIMR and ASSIM were compared with NUMEX assuming a spherical leaf angle distribution and a UOC, ASSIMN was compared with NUMEX assuming a near-planophile leaf angle distribution and a SOC ($b = 2$). Results of ASSIMN are also expressed as a percentage of those of ASSIM.

Day	ASSIMR (spherical)	ASSIM (spherical)	ASSIMN (near-pl.)	ASSIMN versus ASSIM
15 Febr. - cloudy	102.3	102.7	98.4	101.1
15 Febr. - clear	101.3	101.7	100.0	101.4
15 June - cloudy	102.4	102.9	99.0	100.9
15 June - clear	100.4	101.1	101.5	100.2

The differences between results of ASSIMN and ASSIM were small (Table 7), which was partly a result of the overestimation by SUBROUTINE ASSIM, compared with the numerical calculations.

6.2 Sunlit and shaded areas in the greenhouse

Under conditions at which direct light constitutes at least a significant fraction of the total light flux, a pattern of sunlit and shaded patches is thrown on top of the crop, due to the shadows cast by the construction elements. Strictly, crop photosynthesis should be computed separately for the sunlit and shaded areas. In all simulations in this report, the transmissivity for direct light was averaged over the total crop. Thus, crop photosynthesis was calculated according to

```
PARDIF = PARDFO * TRDIF
TRDIR = TRCON * TRGLAS
PARDIR = PARDRO * TRDIR
CALL ASSIMR( PARDIF, PARDIR, .... , PGROS )
```

where

PARDIR = intensity of direct light average over the whole crop area.

In the alternative procedure crop photosynthesis was calculated as

```
PARDIF = PARDFO * TRDIF
PARDIR = PARDRO * TRGLAS
CALL ASSIMR( PARDIF, PARDIR, .... , PHOT1 )
CALL ASSIMR( PARDIF, 0. , .... , PHOT2 )
PGROS = TRCON * PHOT1 + (1. - TRCON) * PHOT2
```

where

PARDIR = the intensity of direct light in sunlit patches (on a horizontal plane above the canopy),

PHOT1 = the rate of crop photosynthesis for the sunlit canopy, and

PHOT2 = the rate of crop photosynthesis for the shaded canopy.

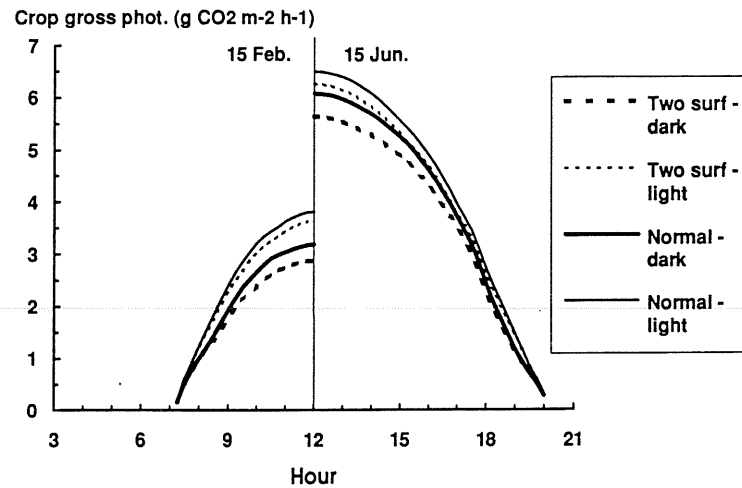


Figure 34. The effect of introducing calculation of crop photosynthesis both for sunlit and shaded crop area, as caused by the greenhouse construction, at clear days at 15 February and 15 June, for a dark and a light greenhouse

Total canopy photosynthesis was then obtained by weighing over the sunlit and shaded surfaces (per ground area).

Introduction of the alternative calculation resulted in significantly lower rates of crop photosynthesis at clear days for both greenhouses (Fig. 34). Daily photosynthesis as calculated with model SUKAM and with the 30-year average radiation data for De Bilt, was decreased by 3% for most of the year, in January and December by 1%.

In reality, the unevenness of the total light intensity between sunlit and shaded crop area as assumed now, is probably less. Leaves that are shaded by a construction part are receiving some of the secondary diffuse radiation that is generated from direct light scattered by sunlit leaves. This will be more the case in shades cast by thin structural members like the bars between window panes. Further quantification is needed of the effect of shading by the greenhouse cover.

6.3 Equation of time

The normal algorithms to calculate the sun position have a slight inaccuracy due to the fact that the length of a solar day is not exactly 24 hours but varies during the year. This is caused by the facts that 1) the orbit of the sun is not a circle but an ellipse, and 2) the axis of the earth is tilted (Iqbal, 1983). The discrepancy between solar time calculated with the normal equations and true solar time (at 12 hour solar time the sun is exactly in the south) is called the equation of time, E_t :

$$t_{s,t} = t_s + E_t \quad (21)$$

where

$t_{s,t}$ = the true solar time, and
 t_s = the solar time calculated with the normal procedure.

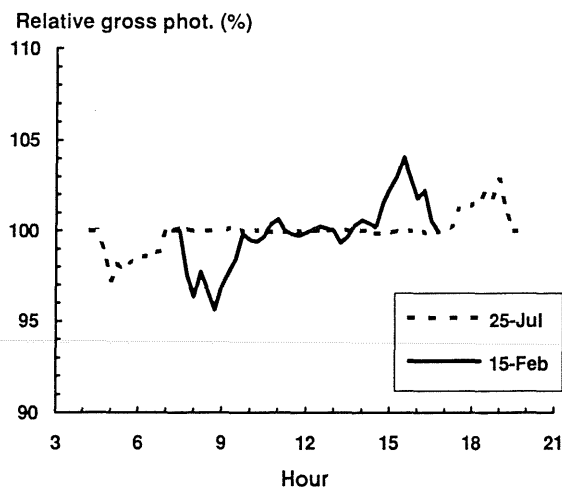


Figure 35 . The effect on relative canopy gross photosynthesis of a more accurate calculation of the position of the sun (i.e. introduction of calculation of the equation of time), at clear days at 15 February and 25 July

E_t has a minimum of -14 at 19 February and a maximum of +16 minutes at 27 October.

The effect of introducing the equation of time into the calculations was investigated for 15 February and 25 July, with model ASKAM. At these dates E_t is -14 and -6 minutes, respectively. Gross photosynthesis calculated taking account of E_t differed with gross photosynthesis calculated with the normal procedure by 4 and 2% at maximum, at 15 February and 25 July, respectively (Fig. 35). The differences were most pronounced early morning and late afternoon, at times when transmissions of the construction and the glass were changing fast with solar azimuth and elevation, and direct radiation still had a significant contribution in total radiation. At these times of the day solar azimuths of the two calculation methods differed 3 and 1 degrees for 15 February and 25 July, respectively, and solar elevations 2 and 1 degrees.

It is concluded that for most purposes the calculation of E_t does not need to be introduced, as differences of more than a few percent are only arising at clear days in February and October-November, and over- and underestimations in morning and afternoon cancel each other in many cases. Moreover, for greenhouses with a less heavy constructed cover differences will be less.

6.4 Daily versus hourly radiation data

In SUBROUTINE TOTASG of model SUKAM the diurnal course of global radiation is derived from the average trend of atmospheric transmission during the day. Using the average trend means that much of the variation in global radiation between different hours is lost. The effect of this was investigated by calculating daily photosynthesis using either daily radiation totals or hourly radiation, both from the SEL-year. Thus, daily radiation totals calculated from the hourly values of the SEL-year, were used to generate the diurnal course of global radiation as is done in SUBROUTINE TOTASG.

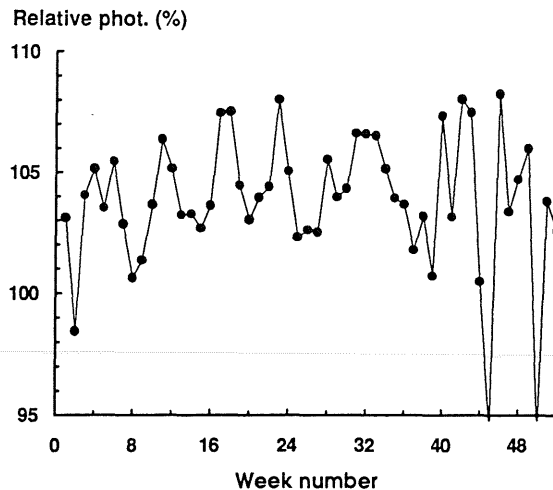


Figure 36. Weekly averages of crop photosynthesis calculated using daily totals of global radiation, expressed as a percentage of weekly average of crop photosynthesis calculated using hourly global radiation data. Radiation data from the SEL-year.

Daily crop photosynthesis based on daily radiation data, was expressed as a percentage of the hourly-based crop photosynthesis, and varied mostly between 99 and 112% (not shown). The weekly averaged crop photosynthesis was on average 2-7% larger than weekly averaged photosynthesis based on hourly radiation totals (Fig. 36). Over the whole year crop photosynthesis was increased by 3.8%.

The overestimation obtained appeared to be the result of the increased fraction diffuse that was simulated. The yearly total of diffuse radiation was increased by 8% by, when using daily radiation totals instead of hourly radiation. In this way, the use of the 'smoothed' diurnal trends of global radiation was leading to a consistent slight overestimation of crop photosynthesis (see also the problem of using average radiation data, Ch. 4.2.2). This same phenomenon was noted by Spitters (1986), who calculated that introduction of variation around the diurnal sine decreased daily crop photosynthesis with 1-3%, for a field crop with LAI at 5.

An improvement of the calculations based on daily radiation totals could be obtained by using a relation of the fraction diffuse versus atmospheric transmission, obtained by fitting hourly measured fraction diffuse against hourly atmospheric transmission derived from the daily global radiation total.

6.5 Simulated versus measured fraction diffuse

By using the regression equation relating the fraction diffuse to the atmospheric transmission (Eqn 1, FUNCTION FRACDF), the variation in the fraction diffuse around the mean is lost. This variation is in many climates quite large (c.f. Fig. 37). The standard deviation for hourly De Bilt-data is about 0.1 (De Jong, 1980). The effect of using the simulated fraction diffuse instead of the measured fraction diffuse on crop photosynthesis, was calculated with the SEL-year and with model ASKAM.

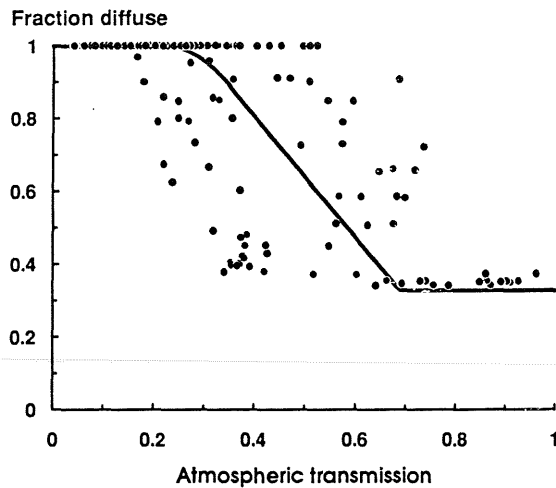


Figure 37. The relation between measured fraction diffuse in global radiation and atmospheric transmission (I/I_{ex}) (dots), for hourly global radiation in the SEL-year. Data from March and April, and for solar elevations between 20 and 30 degrees. Also is depicted the regression equation for the relation fraction diffuse and atmospheric transmission (see also Fig. 4).

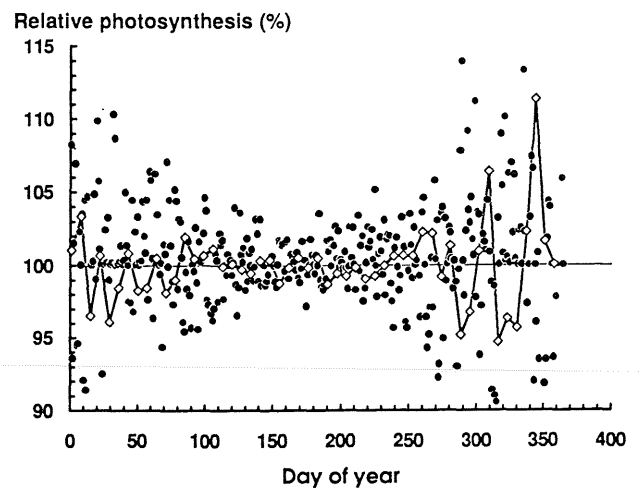


Figure 38. Crop photosynthesis calculated using hourly simulated fraction diffuse expressed as a percentage of crop photosynthesis calculated using measured fraction diffuse. Daily (symbols) and weekly averaged (drawn line) relative crop photosynthesis rates are shown.

Daily photosynthesis calculated with the simulated fraction diffuse differed mostly less than 3% from daily photosynthesis calculated with the measured fraction diffuse (Fig. 38). Yearly totals differed less than 0.1%. Thus, the regression equation could be applied satisfactorily to the SEL-year.

6.5.1 Dependency of PAR in greenhouse and of photosynthesis on fraction diffuse

Instantaneous rates of crop photosynthesis calculated with simulated hourly diffuse radiation differed on many occasions more than 10% from crop photosynthesis calculated using measured fraction diffuse. The differences in crop photosynthesis appeared for the major part to be due to the significant effect of the fraction diffuse on greenhouse light transmission.

This is illustrated for a specific situation, namely 15 February, at 9.00 hour solar time, and for a N-S oriented greenhouse. Total PAR was 50 W m^{-2} (about average for De Bilt at this time and day), and solar elevation 15° . At this day and hour of the day the greenhouse light transmission was very much dependent on the fraction diffuse, both with the dark and the light greenhouse (Fig. 39). The transmissivities for direct radiation were for this sun position 0.32 and 0.55, for the dark and the light greenhouse, respectively. This is very much lower than the transmissivities for diffuse radiation, i.e. 0.65 and 0.75, respectively.

The decrease in the rate of crop photosynthesis with decrease in fraction diffuse was for the dark greenhouse completely, and for the light greenhouse almost completely the result of the decrease in PAR intensity inside the greenhouse. For this particular case, a change of the fraction diffuse of 0.1

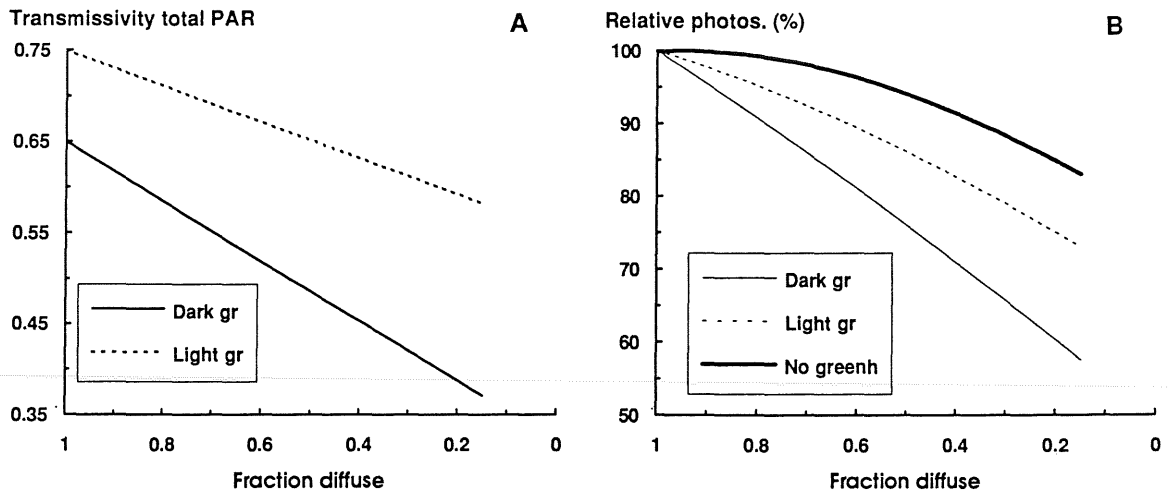


Figure 39. The effect of the fraction diffuse in PAR (outside the greenhouse) at 15 February at 9.00 hour, with PAR at 50 W m^{-2} , and with N-S orientation of the greenhouse, on (A) greenhouse transmissivity of total PAR, and (B) crop relative photosynthesis

(equal to the standard deviation) resulted in a change of PAR intensity of 5%, and in a change of crop photosynthesis of 5%, with the dark greenhouse, and in changes of 2.5 and 3%, respectively, with the light greenhouse.

The decrease in crop photosynthesis and change in PAR intensity in the greenhouse were also calculated for other cases. In this procedure, the fraction diffuse, F_{dif} , was decreased from 0.8 to 0.4, and one quarter of the resultant change in PAR and photosynthesis was expressed as a percentage of PAR and photosynthesis at $F_{dif} = 0.6$ (0.6 was assumed as a mean fraction diffuse for Dutch conditions)

$$PAR_{rel} = \frac{0.25(PAR_{0.8} - PAR_{0.4})}{PAR_{0.6}} * 100 \quad \text{and} \quad Phot_{rel} = \frac{0.25(Phot_{0.8} - Phot_{0.4})}{Phot_{0.6}} * 100 \quad (22)$$

where PAR_{rel} and $Phot_{rel}$ are the percentages change, and where subscripts 0.4, 0.6 and 0.8 refer to PAR intensities in the greenhouse and crop photosynthesis at $F_{dif} = 0.4$, 0.6 and 0.8, respectively. PAR_{rel} and $Phot_{rel}$ calculated in this way were thought to give an idea of the percentage change as a result of variation in the fraction diffuse by 0.1 (i.e. one standard deviation).

Significant changes in PAR and crop photosynthesis were calculated to occur frequently in early spring (and obviously also in autumn), when solar elevations are on average low (Table 8). Also in late spring and summer significant variations occur at beginning and end of days. The change in photosynthesis was always equal to or higher than the change in PAR intensity. Where PAR_{rel} was negative, T_{rdir} was higher than T_{rdif} .

Table 8. The effect of changing the fraction diffuse in global radiation outside the greenhouse with 0.1 (equal to the standard deviation) on the percentage change in PAR intensity inside the greenhouse (PAR_{rel}) and percentage change in crop photosynthesis ($Phot_{rel}$). See text for calculation method. Calculations with model ASKAM; other conditions according to Table 2.

		$PAR_{rel}(\%)$					$Phot_{rel}(\%)$				
		Solar elevation (degrees)					Solar elevation (degrees)				
		15	25	35	45	55	15	25	35	45	55
no	15 Feb	-	-				2.1	1.9			
greenhouse	15 Apr.	-	-	-			2.4	2.2	2.2		
	15 June	-	-	-	-	-	2.4	2.1	2.2	2.3	2.3
dark	15 Feb	5.7	4.4				5.6	4.4			
greenhouse	15 Apr.	1.9	0.1	0.3	0.4		2.8	1.4	1.7	2.0	
	15 June	3.6	-5	-1.	-1.	-6	4.1	1.0	0.9	1.2	1.6
light	15 Feb	2.6	2.2				3.3	2.9			
greenhouse	15 Apr	1.8	0.2	0.2	0.		2.9	1.7	1.8	1.9	
	15 June	2.3	0	0.3	0.1	0.4	3.2	1.6	1.5	1.8	1.9

6.5.2 Probabilities of over or under-estimation of PAR inside greenhouse

A further investigation of the importance of the variation of the fraction diffuse around the mean for the estimation of the PAR intensity in the greenhouse, was done by comparing the transmissivities for both direct and diffuse light. The decrease in transmission for total, diffuse + direct, PAR, as dependent on the fraction diffuse can be calculated as

$$\Delta PAR = \Delta F_{dif} \frac{T_{rdif} - T_{rdir}}{T_{rdif}} \quad (23)$$

where the ratio $(T_{rdif} - T_{rdir}) / T_{rdif}$ is called here the relative transmissivity difference ΔT_r . Thus, for $\Delta T_r = 0.5$ and $\Delta F_{dif} = 0.1$, PAR intensity would change with 5%.

The frequency distribution of hours in three classes of ΔT_r was calculated for the dark and the light greenhouse at latitudes 52, 40, and 60° (Table 9). For the dark greenhouse a significant percentage of the hours was associated with a rather high variation in PAR intensity as a result of change in fraction diffuse. With the light greenhouse this percentage was much lower. The orientation of the greenhouse changed little the frequency distribution of hours in the three classes of ΔT_r , nor did it change the average elevation for these hours. A higher latitude significantly enhanced the occurrence of large values of ΔT_r . At latitude 60° this is not apparent in Table 9, as (a significantly higher

Table 9. The frequency distribution (percentage) of hours with given relative transmissivity difference of direct and diffuse radiation, ΔT_r , and associated solar elevations, with the dark and the light greenhouse, at latitudes 52, 40, and 60°. Only hours with solar elevation larger than 10 degrees were considered.

Latit.	Greenhouse	Azimuth (degrees)	Percentage of hours			Average solar elevation (degrees)		
			Relat. transm. diff. (ΔT_r)			Relat. transm. diff. (ΔT_r)		
			>0.50	0.50 - 0.25	< 0.25	>0.50	0.50- 0.25	<0.25
52	Dark	0	16*	17	67	14	19	37
	Dark	45	13	25	62	14	18	39
	Dark	90	19	21	61	14	21	39
	Light	0	-	20	80	-	14	34
	Light	45	2	17	81	11	14	34
	Light	90	3	19	78	12	15	35
40	Dark	0	3	24	73	13	20	42
	Light	0	-	7	93	-	12	37
60	Dark	0	13	20	67	14	18	34
	Light	0	2	18	80	11	14	32

*) I.e. for 16% of the hours the relative transmissivity difference is larger than 0.5

number of) hours with solar elevations below 10° were not considered.

Note that in a normal probability distribution of events, 70% of the events is within standard deviation σ_{sd} of the mean, and 95% within $2\sigma_{sd}$ of the mean. Thus, if the measured fraction diffuse is distributed normally around the average trend of fraction diffuse versus atmospheric transmission, then about 30% of the actual fractions diffuse would be more than σ_{sd} away from the average trend.

With the dark greenhouse at latitude 52°, about one-third of the hours had relative transmissivity difference larger than 0.25. From the normal probability distribution it follows that for these hours, a 30-percent probability existed that the actual intensity of PAR in the greenhouse differed more than 2.5% ($= 0.1 * 0.25$) from the simulated level of PAR (for solar elevation above 10°). Likewise, with the dark greenhouse but at azimuth 45° and at latitude 52°, for 13% of the hours a 30-percent probability existed that the real PAR differed more than 5% from the simulated PAR. Obviously, this assumes that at low solar elevation the variation in the fraction diffuse was not smaller due to confinement by the upper limit of 100% diffuse.

6.6 Daily values for direct light transmissivity

It was tested whether single daily factors for direct light transmissivity could be used for calculating daily and diurnal photosynthesis with satisfactory accuracy. In the normal procedure (method 1, see Ch. 2.2.3) repeated interpolation is done during the day in an azimuth-elevation table with direct light transmissivities; this would not be necessary then. The effects of two simplifications were tested:

- method 2: daily averaged direct light transmissivities, and
- method 3: approximation of the diurnal course of direct light transmissivity by a sinusoidal course.

6.6.1 Daily averaged direct light transmissivity

In method 2 a constant direct light transmissivity during the day was assumed. The yearly course of daily averaged direct light transmissivities was calculated for latitude 52°, assuming for each day a sinusoidal course of direct radiation, and dividing inside daily direct radiation total by outside daily direct radiation total

$$T_{rd,av} = \frac{\int_{t=t_{sr}}^{t=t_{ss}} T_{rdir} * PARDRO dt}{\int_{t=t_{sr}}^{t=t_{ss}} PARDRO dt} \quad (24)$$

where

- | | |
|------------|---|
| t_{sr} | = sunrise, |
| t_{ss} | = sunset, and |
| T_{rdir} | = the instantaneous direct light transmissivity calculated by interpolation in the azimuth-elevation table (SUBROUTINE TRANSM). |

Daily average direct light transmissivities were calculated both for N-S and E-W orientations. Results were put into tables. In the simulations instantaneous direct light transmissivity for any given day and azimuth of the greenhouse was found by interpolating for the day in the tables for the N-S and the E-W greenhouses, and, consecutively, interpolating for the azimuth between N-S and the E-W daily transmissivity. Radiation data of the SEL-year were used.

In the photosynthesis calculations the approximation appeared to work best for N-S oriented greenhouses, and least for the E-W orientation. With the dark greenhouse, the differences between daily photosynthesis calculated with method 1 and method 2 were mostly less than 1% with the N-S orientation, but were maximally 3% with azimuth 45°, and, maximally 4% with the E-W orientation (Fig.40). With the light greenhouse differences were smaller; with worst-case E-W orientation, differences were maximal 1.5%. Differences between weekly average photosynthesis varied in all cases less than 1%. Differences between photosynthesis based on method 1 and method 2 were most pronounced when direct light transmission varied much in the middle hours of the day, i.e. with E-W oriented greenhouses (see Fig. 14). This is evident from comparison of the diurnal rates of

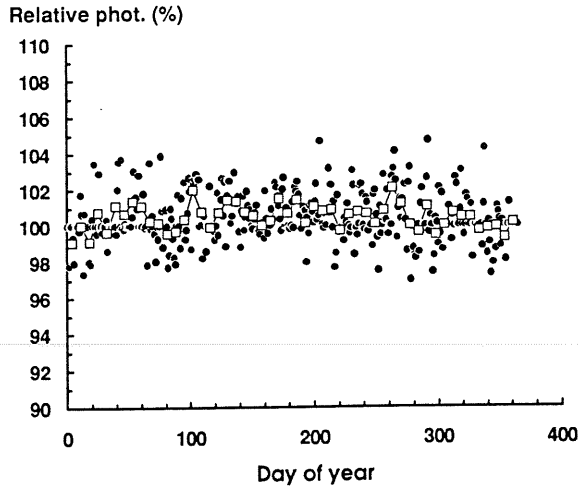


Figure 40. Daily (dots) and weekly (line) canopy gross photosynthesis calculated assuming direct light transmissivity to be constant during the day, expressed as a percentage of daily canopy gross photosynthesis calculated with the normal procedure to find instantaneous direct light transmissivity, for the E-W dark greenhouse. Radiation data of the SEL-year.

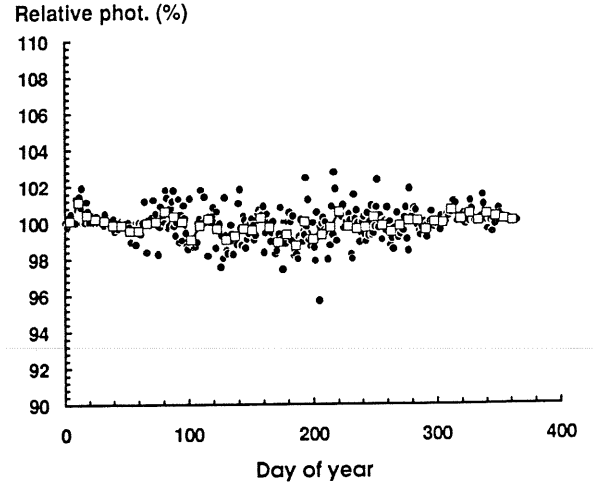


Figure 41. Daily (dots) and weekly (line) canopy gross photosynthesis calculated assuming a sinusoidal course of diurnal direct light transmissivity, expressed as a percentage of daily canopy gross photosynthesis calculated with the normal procedure to find instantaneous direct light transmissivity, for N-S oriented dark greenhouse. Radiation data of the SEL-year.

photosynthesis. At a clear day at 15 June, rates of crop photosynthesis calculated with $T_{rd,av}$ varied, as a percentage of method 1, from about 140% in the morning and afternoon hours, to 92% at noon, in the E-W dark greenhouse, and from 118 to 98% in the E-W light greenhouse (not shown).

6.6.2 Sinusoidal course of diurnal direct light transmissivity

In method 3, diurnal direct light transmissivity $T_{rd,sin}$ was approximated by a sinusoidal course

$$T_{rd,sin} = \frac{T_{rd,m} \sin \beta}{\sin \beta_{\max}} \quad (25)$$

where

β_{\max} = the maximal solar elevation of the day, and
 $T_{rd,m}$ = the direct light transmissivity for maximal solar elevation.

$T_{rd,m}$ at any day was found from

$$T_{rd,m} = \frac{\int_{t=t_{sr}}^{t=t_{ss}} T_{rdir} PARDRO dt}{\int_{t=t_{sr}}^{t=t_{ss}} (\sin \beta / \sin \beta_{max}) PARDRO dt} \quad (26)$$

In the photosynthesis calculations method 3 worked best for E-W oriented greenhouses, and worst for the N-S orientation. Differences in daily photosynthesis between method 3 and the normal procedure (method 1) were for the N-S dark greenhouse mostly less than 2% (Fig. 41). Average deviation for the dark greenhouse with azimuth 45 degrees was similar. Deviation were mostly less than 0.5% and 1.5% for the E-W dark greenhouse and the N-S light greenhouse, respectively.

Instantaneous crop photosynthesis as a percentage of photosynthesis calculated according to method 1, varied, at a clear day at 15 June, with both the dark and the light N-S greenhouse, from 83% at morning and afternoon hours, to 105% at noon. This deviation was caused by the fact that a rather constant direct light transmission during a large middle fraction of the day (cf. Fig. 14) could not be fitted very well by a sinusoidal pattern.

Conclusively, when one is interested in instantaneous crop photosynthesis, e.g. with model ASKAM, use of daily averaged $T_{rd,av}$ (method 2) or a sinusoidal pattern of direct light transmissivity (method 3) does not give, in most cases, results that are accurate enough. For simulation of dry matter production aimed at longer time intervals (days, weeks) (e.g. with model SUKAM) these calculation methods are sufficiently accurate.

6.7 Diurnal courses of temperature and CO₂ concentration

With SUKAM instantaneous crop photosynthesis is calculated based not only on total daily radiation, but also on daily average values of temperature and CO₂ concentration. The effect on crop photosynthesis was investigated of different diurnal patterns of these two climate variables.

Temperature

Two simulation runs with model SUKAM and with the 30-year average radiation data were compared: in one run temperature was kept constant at 20 °C, and in another run day temperature was allowed to follow a sinusoidal course with maximal temperature at 25 °C at noon, and with 20 °C at sunrise and sunset. Crop gross photosynthesis was simulated to be very little affected by the change in diurnal pattern, and, by the concomitantly small increase in average temperature level (Fig. 42).

Changes in diurnal temperature patterns will also have effects, although small, on maintenance costs and dry matter production, as the maintenance respiration is theoretically varying exponentially with temperature and the arithmetic mean of varying respiration will not be equal to respiration calculated with the average of the varying temperature. Note that the average level of temperature was simulated to have significant effect on dry matter production (Ch. 5.2).

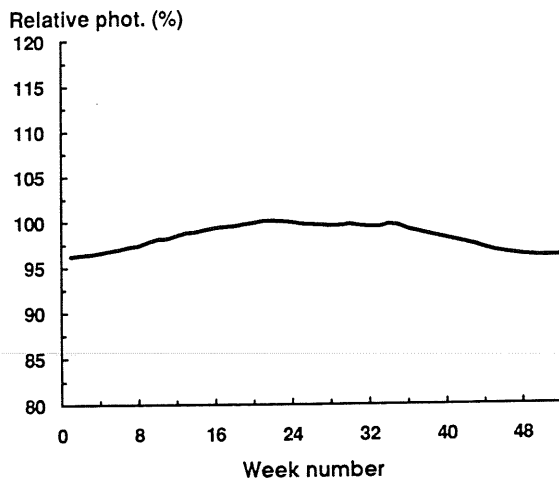


Figure 42. Effect of changing the diurnal pattern of temperature from a constant level (at 20 °C) to a sinusoidal course during the daylight period (with 25 °C at noon, and 20 °C at sunrise and sunset) on daily crop gross photosynthesis. Radiation data were 30-year averages of De Bilt.

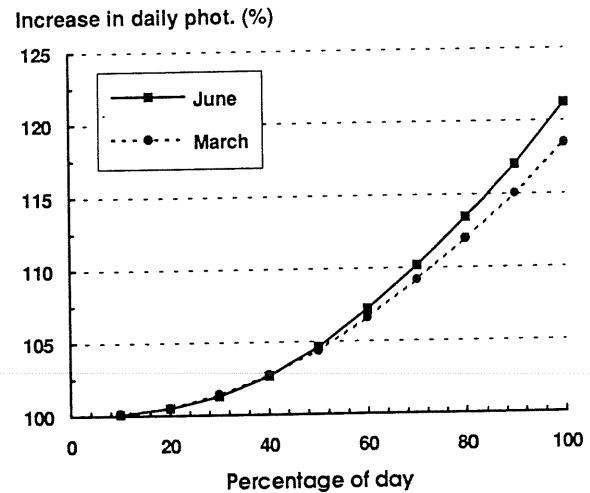


Figure 43. The effect of the length of the period (expressed as a percentage of the day) during which CO_2 concentration is at $600 \mu\text{l l}^{-1}$, on the daily total of crop photosynthesis, expressed as a percentage of daily crop photosynthesis at continuously $350 \mu\text{l l}^{-1}$. The period of increased CO_2 has various lengths from sunrise and sunset onwards to noon. The effect was simulated as the average of 4 weeks in March or 4 weeks in June, using the 30-year average radiation data of De Bilt.

CO₂ concentration

The diurnal course of CO_2 concentration was varied by varying the length of the period of CO_2 enrichment (to a level of $600 \mu\text{l l}^{-1}$), that extended from the beginning and end of the daylight period onwards to noon. For example, with enrichment during 20% of the day, CO_2 concentration was $600 \mu\text{l l}^{-1}$ during the earliest 10% of the day in the morning, and the latest 10% of the day in the afternoon.

Simulated daily crop photosynthesis was little increased for enrichment periods up to the first 30% of the daylight period, but was with longer periods increased more, about 3% for any additional 10% of the day (Fig. 43). The lines in this figure could in practice rise more steeply, as prolonged delay of opening, or earlier closing, of the windows to enable continued enrichment, will increase temperature, and will consequently increase the response to enhanced CO_2 levels. These results show that the diurnal course of CO_2 concentration must be known rather accurately.

6.8 Assuming all the light diffuse

The assumption that all the light is diffuse is a simplification often done in crop growth models. The magnitude of the error introduced by this simplification was investigated with SUKAM and the 30-year average radiation data of De Bilt.

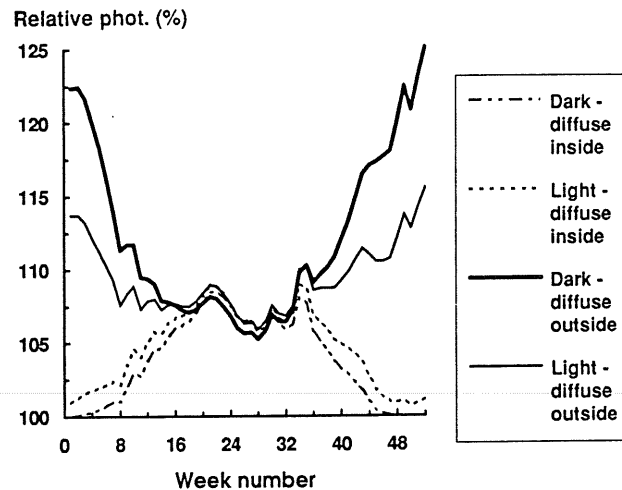


Figure 44. The effect on relative daily crop photosynthesis of the assumptions that all the light inside or outside the greenhouse was diffuse, with the dark and the light greenhouse. Simulation runs with model SUKAM and the 30-year average radiation data of De Bilt.

By assuming all the light inside the greenhouse to be diffuse but not the light outside, a significant overestimation of daily crop photosynthesis was obtained for a large part of the year (Fig. 44). The effect was reduced in wintertime as less direct light had entered the greenhouse. Without greenhouse cover crop photosynthesis was increased with 8-10% (not shown). Cumulative dry matter productions were increased by 7 and 8%, with the dark and the light greenhouse, respectively.

By assuming all the light outside the greenhouse to be diffuse, overestimation of daily crop gross photosynthesis was significant in summertime (Fig. 44); and it was large in the rest of the year, when direct light transmissivities were more unfavourable compared with diffuse light transmissivity. In the summer period it did not matter whether light outside or inside was assumed to be diffuse, as transmissivities of direct and diffuse light were about equal. Cumulative dry matter productions were increased by 11 and 10%, for the dark and the light greenhouse, respectively.

6.9 3-point versus 5-point Gaussian integration

With 3-point Gaussian integration (G.I.) an accurate integration can be obtained of instantaneous crop photosynthesis over the day and of photosynthesis at different leaf layers over the total canopy (Goudriaan, 1986). 3-point G.I. can be used for functions that can be described by up to fifth-order polynomials. 5-point G.I. is used with the calculation of crop photosynthesis in SUBROUTINE TOTASG (App. III), as it appeared that the fast changing greenhouse direct light transmission in morning and afternoon could result in diurnal patterns of crop photosynthesis that must be described by a higher than fifth-order function. The deviations in daily crop photosynthesis using 3-point G.I. compared with using 5-point G.I. was, with the 30-year average radiation data, for most of the year negligible, but increased to 1% in the winter period. Thus, although at present 5-point G.I. is applied in SUBROUTINE TOTASG, 3-point G.I. could also be applied without serious consequences.

Likewise, with numerical calculation of diffuse light extinction (SUBROUTINE NUMEX), the 5-point G.I. was somewhat more accurate than 3-point G.I.. At the cloudy day at 15 February, 3-point G.I. yielded 0.7 and 1.9 % lower daily photosynthesis than 5-point G.I., with the spherical and the near-planophile leaf angle distribution, respectively.

7 Discussion

The models described and tested here are mechanistic, so that they potentially describe many crop-greenhouse systems. Present structures of the models is easily modified. For applications currently aimed at and for other ones, different versions of the models could be made that are composed from of a different set of subroutines, or versions could be made in which subroutines are substituted by a single line of coding, or by a parameter.

A likely type of combination model would be one with which dry matter production during the course of the growing season can be simulated and where also the effects of a specific CO₂ enrichment or artificial lighting regime can be calculated. In that case model SUKAM could be used, but then SUBROUTINE TOTASG may need to be modified, replacing current "Gaussian integration do-loop" over the day by an "hour do-loop" in which radiation, CO₂ and temperature are either read from a data file or are calculated assuming a specific diurnal pattern.

In the simulations it was implicitly assumed that conditions were optimal for photosynthesis. However, this is, also for greenhouse conditions, not always the case. Conditions can be unfavourable for crop photosynthesis, notably in summertime. Therefore, not so much the absolute levels are to be considered, as are the sensitivities of the model output to parameter changes.

The angular distribution of diffuse light is changed by interference by the greenhouse cover. This affects the extinction for diffuse light. However, crop photosynthesis appeared to be hardly affected by this change. Crop photosynthesis was affected more by change of leaf angle distribution. Subroutine ASSIMN was developed, which takes into account both the changed angular distribution of diffuse light in the greenhouse, and a so-called near-planophile leaf angle distribution.

In model SUKAM use of daily averages of the CO₂ concentration when CO₂ enrichment is applied, will be in many cases not so accurate. Some description of the diurnal pattern of the CO₂ concentration is necessary then.

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Appendix I. Generation of an artificial variation in the 30-year average radiation data.

An artificial variation was generated by replacing each average day by two days: one day with less radiation than the average level ('cloudy day'), and one day with more radiation than the average level ('clear day'). Consequently, crop photosynthesis was calculated twice for each day number of the year.

The appropriate differences in radiation levels was empirically found by increasing the difference in radiation level between the two days from low to high. Thereby the calculated average fraction diffuse was made to decrease, until the average fraction diffuse was equal to the long year average measured fraction diffuse. The difference in radiation level that was found was expressed as 'delta' atmospheric transmission:

$$ATMTR1 = ATMTR - \Delta ATMTR \quad (27)$$

$$ATMTR2 = ATMTR + \Delta ATMTR \quad (28)$$

where

- ATMTR1 = the atmospheric transmission of the cloudy day,
- ATMTR2 = the atmospheric transmission of the clear day, and
- ATMTR = the atmospheric transmission based on the average level of global radiation.

For the De Bilt data $\Delta ATMTR$ was found to be approximately constant for the whole year, and to be equal to 0.19.

The overestimation obtained when not introducing this artificial variation varied from 8% in summer to 20% in winter (Fig. 45).

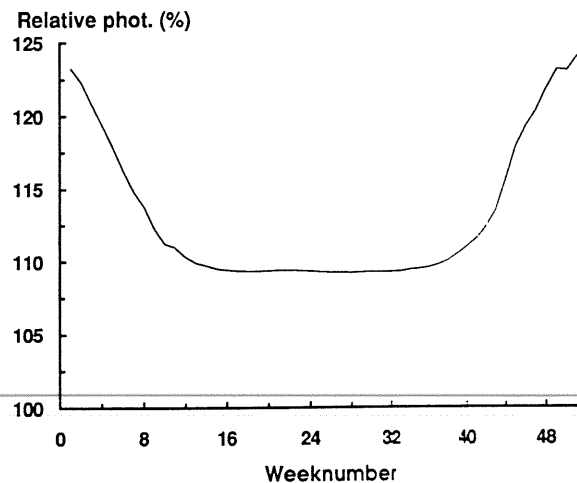
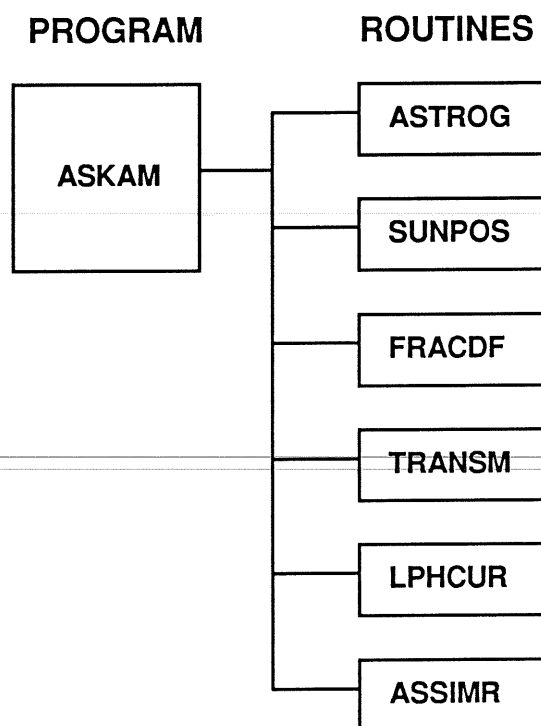


Figure 45. The effect of omission of variation in the 30-year average (1951-1980) radiation data of De Bilt on daily crop photosynthesis. Simulation with model SUKAM.

Appendix II. Listing of model ASKAM



Routine	Calculation of:
ASSIMR	canopy gross photosynthesis
ASTROG	daylenght, solar constant, intermediate variables
FRACDF	fraction diffuse in global radiation outside greenhouse
LPHCUR	leaf initial light use efficiency and maximal rate of gross photosynthesis
SUNPOS	solar position
TRANSM	greenhouse light transmission

```

*****
*
* 28-11-1991
*
*          ASKAM - CO2-ASSimilatie KAsgewasModel
*
*-----
*   Program for calculation of gross and net photosynthesis
*           of greenhouse crops
*
* Necessary input files:
*   - ASKAM.PAR : greenhouse, crop and experim. parameters and data
*   - greenhouse transmissivity file (file with special layout)
*****
PROGRAM ASKAM
IMPLICIT REAL(A-Z)

INTEGER ITASK

CHARACTER*40 LABEL, FMTEXP, FMTPHO
CHARACTER*40 FILTRN, FILPHO
INTEGER IUNOUT, IUNEXP, IUPHOT, IUTRAN

INTEGER SKPEOF, SKPIOS
INTEGER IOSPHO

*   Unit numbers for file I/O
PARAMETER( IUNEXP = 10, IUPHOT = 12, IUTRAN = 14 )
PARAMETER( IUNOUT = 7 )

*-----
*   Initialization section
*-----
ITASK = 1

PI = 3.1415926
*   Factor for conversion radians to degrees and vice versa
RADN = PI/180.

*---- experimental data
OPEN (UNIT = IUNEXP, FILE = 'ASKAM.PAR', STATUS = 'OLD')
*   first skip comments and read format for reading datafile
CALL SKIPCM( IUNEXP, '*', SKPEOF, SKPIOS )
READ( IUNEXP, '(A)' ) FMTEXP

*   Latitude of site [degrees]
READ( IUNEXP, FMTEXP ) LABEL, LAT
*   Longitude of site [degrees]
READ( IUNEXP, FMTEXP ) LABEL, LONG
*   Fraction PAR in global radiation
READ( IUNEXP, FMTEXP ) LABEL, FRACPAR
*   Azimuth of greenhouse [degrees]
READ( IUNEXP, FMTEXP ) LABEL, AZIMGR
*   Reflection coefficient ground surface
READ( IUNEXP, FMTEXP ) LABEL, REFGR
*   Leaf Area Index
READ( IUNEXP, FMTEXP ) LABEL, LAI
*   Extinction coefficient diffuse light for non-scattering leaves
READ( IUNEXP, FMTEXP ) LABEL, KDIFBL
*   Extinction coefficient diffuse light
READ( IUNEXP, FMTEXP ) LABEL, KDIF
*   Scattering coefficient leaves
READ( IUNEXP, FMTEXP ) LABEL, SCP
*   Reference temperature for maintenance respiration [oC]
READ( IUNEXP, FMTEXP ) LABEL, REFTMP
*   Q10 maintenance respiration
READ( IUNEXP, FMTEXP ) LABEL, Q10MN
*   Maintenance costs [g CH2O m-2 d-1]
READ( IUNEXP, FMTEXP ) LABEL, MN25D
*   CO2 production factor total crop dry weight increment

```



```

*      [g CO2 g-1 DM]
      READ( IUNEXP,FMTEXP ) LABEL, CO2PFT
*      Crop growth rate [g DM m-2 d-1]
      READ( IUNEXP,FMTEXP ) LABEL, GTW
*      File with transmissivity data
      CALL SKIPCM( IUNEXP, '*', SKPEOF, SKPIOS )
      READ( IUNEXP,'(A)') FILTRN

*      Time correction for M.E.T.
      TIMCOR = - (1. - LONG/15.)

*----- Initialization transmissivity greenhouse: reading datafile,
*                                     filling tables
      CALL TRANSM( ITASK, IUTRAN, FILTRN, AZIMGR, AZIMS,
&                  ELEVN, TRDIF, TRCON, TRGLAS )

*----- Ask for input file

      WRITE (*,'(A,$)') ' Which file with photosynthesis data : '
      READ (*,'(A)') FILPHO

      OPEN( UNIT = IUPHOT, FILE = FILPHO, STATUS = 'OLD')

*-----initialization outputfile

      OPEN( UNIT = IUNOUT, FILE = 'ASKAM.CSV', STATUS='NEW' )

      WRITE (IUNOUT, '(A)') ' File created by ASKAM.FOR'
      WRITE (IUNOUT, '(A,F8.3)') ' LAI : ', LAI
      WRITE (IUNOUT, '(A,F8.3)') ' KDIFBL : ', KDIFBL
      WRITE (IUNOUT, '(A,F8.3)') ' KDIF : ', KDIF
      WRITE (IUNOUT, '(A,F8.3)') ' SCP : ', SCP
      WRITE (IUNOUT, '(A,F8.3)') ' AZIMGR : ', AZIMGR
      WRITE (IUNOUT, '(A,F8.3)') ' REFG : ', REFG
      WRITE (IUNOUT, 910)
910  FORMAT( ' HOUR, GLRADO, PAR, TEMP, CO2AIR, PHOTMEAS, PHOTSIM ')

      ITASK = 2

*----- Conversions of degrees to radians
      LAT = LAT * RADN
      AZIMGR = AZIMGR * RADN

*      Flag
      IOSPHO = 0
*--- Loop: steps determined by data file
100  IF( IOSPHO .EQ. 0) THEN

*--- Reading climate data and measured photosynthesis from data file
      READ( IUPHOT, *, IOSTAT = IOSPHO)
&      DAYNR, HOUR, GLRADO, TEMP, CO2AIR, PHOTMS

*--- day length and daily radiation
*      characteristics from day of year and latitude
      CALL ASTROG( DAYNR,LAT,
&                  SOLARC,SINLD,COSLD,DECL,DAYL,DSINBE )

*--- solar time, derived from M.E.T.
      SOLHR = HOUR + TIMCOR

*--- solar position
      CALL SUNPOS( LAT,SINLD,COSLD,DECL,SOLHR,
&                  ELEVN, AZIMS, SINELV )

*--- total PAR outside greenhouse
      PAROUT = FRACPAR * GLRADO

      IF( ELEVN .GT. 0.001) THEN

```

```

*--- diffuse PAR (PARDFO) and direct PAR (PARDRO) outside greenhouse
      FRDIF = FRACDF( SOLARC, GLRADO, SINELV )
      PARDFO = FRDIF * PAROUT
      PARDRO = PAROUT - PARDFO

*--- light climate inside the greenhouse, multiplication with
*      greenhouse light transmissivities

*--- transmission greenhouse
      CALL TRANSM( ITASK, IUTRAN, FILTRN, AZIMGR, AZIMS,
&                ELEVN, TRDIF, TRCON, TRGLAS )

      PARDIF = PARDFO * TRDIF
      PARDIR = PARDRO * TRCON * TRGLAS
      PAR = PARDIF + PARDIR

*--- Determine EFF and PGMAX value of leaf photosynthesis light
*      response curve from temperature and CO2 concentration
*      Leaf temperature is assumed equal to air temperature

      TLEAF = TEMPPI
      CALL LPHCUR( TLEAF, CO2AIR, EFF, PGMAX )

*--- instantaneous crop gross photosynthesis [g CO2 m-2 ground h-1]
      CALL ASSIMR( REFGR, SCP, PGMAX, EFF, KDIFBL, KDIF, LAI,
&                SINELV, PARDIR, PARDIF, PGROSH )
*      conversion to g CO2 m-2 h-1
      PGROSH = 3.6 * PGROSH

      ELSE

      FRDIF = 1.
      PARDFO = FRDIF * PAROUT
      PARDRO = PAROUT - PARDFO
      PARDIF = 0.
      PARDIR = 0.
      PAR = 0.
      PGROSH = 0.

      ENDIF

*--- CO2 release by maintenance respiration [g CO2 m-2 h-1]
      MNRESP = MN25D * Q10MN ** (.1*(TEMPPI - REFTMP))
&            / 24. * 44./30.

*--- CO2 release by growth respiration [g CO2 m-2 h-1]
      GRRESP = GTW * CO2PFT / 24.

*--- Net photosynthesis
      PNET = PGROSH - MNRESP - GRRESP

*=====
*      Output
*=====

      WRITE( IUNOUT, 920 ) HOUR, GLRADO, PAR, TEMPPI, CO2AIR,
&                        PHOTMS, PNET
920      FORMAT( 7(F8.3, ',') )

      GOTO 100

      ENDIF

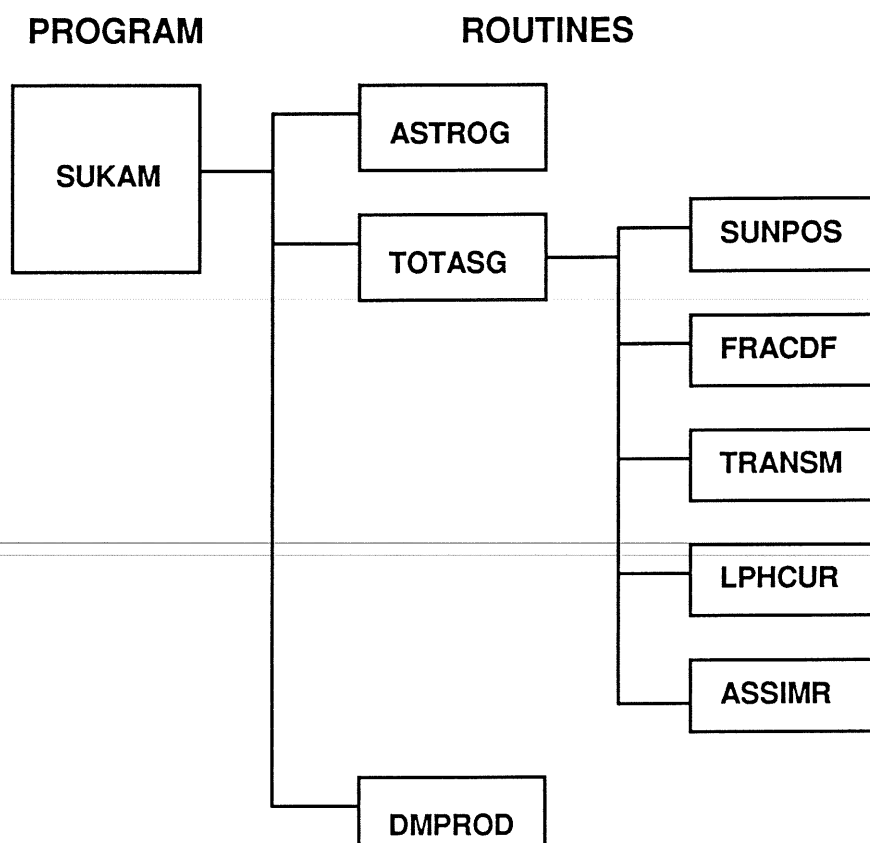
      CLOSE( IUNOUT )

      STOP ' Output to ASKAM.CSV '

      END

```

Appendix III. Listing of model SUKAM



Routine	Calculation of:
ASTROG	daylength, solar constant, intermediate variables
TOTASG	daily gross photosynthesis
DMPROD	dry matter production of leaves, stems, roots, fruits, and of whole crop
ASSIMR	canopy gross photosynthesis
FRACDF	fraction diffuse in global radiation outside greenhouse
LPHCUR	leaf initial light use efficiency and maximal rate of gross photosynthesis
SUNPOS	solar position
TRANSM	greenhouse light transmission

III-2

```

*****
*
*                               SUKAM.FOR
*
*
* Simulation of dry matter production of greenhouse crops.
* SUKAM has been based on SUCROS87 (Spitters et al., 1989)
*
* Simulation is based on daily values of global radiation
* outside greenhouse and CO2 concentration and temperature
* inside greenhouse
*
* This program uses task-variables for control of initialization,
* rate calculations and integration as described by
* Van Kraalingen & Rappoldt (1989);
* and Van Kraalingen & Penning de Vries (1990).
*
* Necessary inputfiles:
* - TIMER.DAT
* - RADIAT.DAT
* - SUKAM.PAR
* - file with greenhouse transmissivity data
*****

PROGRAM SUKAM
IMPLICIT REAL(A-Z)
LOGICAL TERMNL, OUTPUT
INTEGER I, ITASK

INTEGER IDTRTB
DIMENSION DTRTB (732)

* File I/O
CHARACTER*40 LABEL, FMTEXP, FMTWEA, FMTTIM, FILTRN
INTEGER IUNEXP, IUWEAT, IUTRAN, IUTIME
INTEGER IUOUT
INTEGER IOSSKP, EOFSKIP
INTEGER IOSWEA

* Unit numbers for file I/O
PARAMETER( IUNEXP = 10, IUWEAT = 12, IUTRAN = 14, IUTIME = 16 )
PARAMETER( IUOUT = 7 )

* -----
* Initialization section
* -----

ITASK = 1
TERMNL = .FALSE.

PI = 3.1415926
* Factor for conversion radians to degrees and vice versa
RADN = PI/180.

*---- read data

*---- experimental data
OPEN (UNIT = IUNEXP, FILE = 'SUKAM.PAR', STATUS = 'OLD')
* first skip comments and read format for reading datafile
CALL SKIPCM( IUNEXP, '*', EOFSKIP, IOSSKIP )
READ( IUNEXP, '(A)' ) FMTEXP

READ( IUNEXP, FMTEXP ) LABEL, LAT
READ( IUNEXP, FMTEXP ) LABEL, FRACPAR
READ( IUNEXP, FMTEXP ) LABEL, AZIMGR
READ( IUNEXP, FMTEXP ) LABEL, REFG
READ( IUNEXP, FMTEXP ) LABEL, TEMPAT
READ( IUNEXP, FMTEXP ) LABEL, CO2AIR
READ( IUNEXP, FMTEXP ) LABEL, LAI
READ( IUNEXP, FMTEXP ) LABEL, KDIFBL

```

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```

READ ( IUNEXP,FMTEXP ) LABEL, KDIF
READ ( IUNEXP,FMTEXP ) LABEL, SCP
READ ( IUNEXP,FMTEXP ) LABEL, MAINLV
READ ( IUNEXP,FMTEXP ) LABEL, MAINST
READ ( IUNEXP,FMTEXP ) LABEL, MAINRT
READ ( IUNEXP,FMTEXP ) LABEL, MAINSO
READ ( IUNEXP,FMTEXP ) LABEL, ASRQLV
READ ( IUNEXP,FMTEXP ) LABEL, ASRQST
READ ( IUNEXP,FMTEXP ) LABEL, ASRQRT
READ ( IUNEXP,FMTEXP ) LABEL, ASRQSO
READ ( IUNEXP,FMTEXP ) LABEL, REFTMP
READ ( IUNEXP,FMTEXP ) LABEL, Q10MN
READ ( IUNEXP,FMTEXP ) LABEL, FLV
READ ( IUNEXP,FMTEXP ) LABEL, FST
READ ( IUNEXP,FMTEXP ) LABEL, FRT
READ ( IUNEXP,FMTEXP ) LABEL, FSO
READ ( IUNEXP,FMTEXP ) LABEL, WLVI
READ ( IUNEXP,FMTEXP ) LABEL, WSTI
READ ( IUNEXP,FMTEXP ) LABEL, WRTI
READ ( IUNEXP,FMTEXP ) LABEL, WSOI
CLOSE ( IUNEXP )

*---- Weather data
OPEN( UNIT = IUWEAT, FILE = 'RADIAT.DAT', STATUS = 'OLD' )

*      read conversion factor for obtaining J m-2 d-1
CALL SKIPCM( IUWEAT, '*', EOFSKP, IOSSKP )
READ( IUWEAT, * ) GRADCF

*      read format for reading datafile
I = 1
IOSWEA = 0
READ( IUWEAT, '(A)' )
READ( IUWEAT, '(A)' ) FMTWEA
5  IF (IOSWEA.EQ. 0) THEN
    READ( IUWEAT,FMTWEA, IOSTAT=IOSWEA ) DTRTB(I), DTRTB(I+1)
    I = I + 2
    GOTO 5
ENDIF
IDTRTB = I - 3
CLOSE( IUWEAT )

*---- Simulation run data
OPEN( UNIT = IUTIME, FILE = 'TIMER.DAT', STATUS = 'OLD' )
*      first read format for reading datafile
CALL SKIPCM( IUTIME, '*', EOFSKP, IOSSKP )
READ (IUTIME,'(A)') FMTTIM
READ( IUTIME, FMTTIM ) LABEL, STDAY
READ( IUTIME, FMTTIM ) LABEL, FINDAY
READ( IUTIME, FMTTIM ) LABEL, DELT
READ( IUTIME, FMTTIM ) LABEL, PRDEL
CLOSE( IUTIME )

*-----initialization outputfile

OPEN( IUOUT, FILE='SUKAM.CSV', STATUS='UNKNOWN' )

WRITE (IUOUT, '(A)') ' File created by SUKAM.FOR'
WRITE (IUOUT, '(A,F8.3)') ' LAI : ', LAI
WRITE (IUOUT, '(A,F8.3)') ' KDIF : ', KDIF
WRITE (IUOUT, '(A,F8.3)') ' AZIMGR : ', AZIMGR
WRITE (IUOUT, 910)
910  FORMAT( ' DAYNR, DTR, DPARDF, DPARDR, ',
&      ' DTGA, GTW, WLV, WST, WSO, TWT' )

*---- Conversions from degrees to radians
LAT = LAT * RADN
AZIMGR = AZIMGR * RADN

```

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```

*      initialization timer
      CALL DAYTIM( ITASK, TERMNL, DELT, PRDEL, STDAY, FINDAY,
&                DAYNR, OUTPUT )

*      Reading transmissivity data

      WRITE (*,'(A,$)') ' Which file with transmissivity data : '
      READ (*,'(A)') FILTRN

*      Initialization photosynthesis calculations by reading
*      transmissivity data
      CALL TOTASG( ITASK, DAYNR,
& IUTRAN, FILTRN,
& LAT, DECL, SOLARC, DAYL, SINLD, COSLD, DSINBE,
& DTR, FRACPAR, CO2AIR, TEMPAL,
& SCP, KDIFBL, KDIF, LAI, AZIMGR, REFGR,
& DTGA, DPARDF, DPARDR )

*      initialization dry weights
      CALL DMPROD( ITASK, DAYNR, DELT,
&                WLVI, WSTI, WRTI, WSOI,
&                FLV, FST, FRT, FSO,
&                ASRQLV, ASRQST, ASRQRT, ASRQSO,
&                Q10MN, REFTMP,
&                MAINLV, MAINST, MAINRT, MAINSO,
&                TEMPAL, DTGA,
&                GLV, GST, GRT, GSO, GTW,
&                WLVI, WST, WRT, WSO, TWT )

* -----
*      Dynamic simulation section
* -----

*      run loop while TERMNL is not .TRUE.
10      IF (.NOT. TERMNL) THEN

*      =====
*      integration section
*      =====

      ITASK = 3

*---- dry matter
      CALL DMPROD( ITASK, DAYNR, DELT,
&                WLVI, WSTI, WRTI, WSOI,
&                FLV, FST, FRT, FSO,
&                ASRQLV, ASRQST, ASRQRT, ASRQSO,
&                Q10MN, REFTMP,
&                MAINLV, MAINST, MAINRT, MAINSO,
&                TEMPAL, DTGA,
&                GLV, GST, GRT, GSO, GTW,
&                WLVI, WST, WRT, WSO, TWT )

*      =====
*      section calculation of driving variables
*      =====

      ITASK = 2

*---- day length and daily radiation
*      characteristics from day of year and latitude
      CALL ASTROG( DAYNR, LAT,
&                SOLARC, SINLD, COSLD, DECL, DAYL, DSINBE )

*---- daily total of global radiation, conversion to J m-2 d-1
      DTR = LINTNM( 'DTR', DTRTB, IDTRTB, DAYNR ) * GRADCF

*      =====

```

III-5

```

*      section calculation of rates
*      =====

*----- Gross photosynthesis [g CO2 m-2 day-1]
      CALL TOTASG( ITASK, DAYNR,
&      IUTRAN, FILTRN,
&      LAT, DECL, SOLARC, DAYL, SINLD, COSLD, DSINBE,
&      DTR, FRACPAR, CO2AIR, TEMPAL,
&      SCP, KDIFBL, KDIF, LAI, AZIMGR, REFGR,
&      DTGA, DPARDF, DPARDR )

*----- rate of dry matter production [g DM m-2]
      CALL DMPROD( ITASK, DAYNR, DELT,
&      WLVI, WSTI, WRTI, WSOI,
&      FLV, FST, FRT, FSO,
&      ASRQLV, ASRQST, ASRQRT, ASRQSO,
&      Q10MN, REFTMP,
&      MAINLV, MAINST, MAINRT, MAINSO,
&      TEMPAL, DTGA,
&      GLV, GST, GRT, GSO, GTW,
&      WLV, WST, WRT, WSO, TWT )

*----- output
      IF( OUTPUT ) THEN
*      conversions for output; now radiation in MJ m-2
          ODPDIF = DPARDF * 1.E-6
          ODPDIR = DPARDR * 1.E-6
          ODTR = DTR * 1.E-6

          WRITE( IUOUT, 920 ) DAYNR, ODTR, ODPDIF, ODPDIR,
&      DTGA, GTW, WLV, WST, WSO, TWT
920      FORMAT( F6.0, ',', ' ', 3(F6.2, ',', ' '), 12(F7.1, ',', ' ') )
          ENDIF

*----- time update, check for FINDAY and for OUTPUT for next simulation step
      CALL DAYTIM( ITASK, TERMNL, DELT, PRDEL, STDAY, FINDAY,
&      DAYNR, OUTPUT )

      GOTO 10
      ENDIF

* -----
*      Terminal section
* -----

*      conversions for output; now radiation in MJ m-2
          ODPDIF = DPARDF * 1.E-6
          ODPDIR = DPARDR * 1.E-6
          ODTR = DTR * 1.E-6

          WRITE( IUOUT, 920 ) DAYNR, ODTR, ODPDIF, ODPDIR,
&      DTGA, GTW, WLV, WST, WSO, TWT

*-----closing file

          CLOSE( IUOUT, STATUS='KEEP' )

          STOP ' Output to SUKAM.CSV '

      END

```

III-6

```

*****
* timer subroutine for simulation with DELT as whole number of days
*****
      SUBROUTINE DAYTIM( ITASK, TERMNL, DELT, PRDEL, STDAY, FINDAY,
&          DAYNR, OUTPUT )
      IMPLICIT REAL(A-Z)
      INTEGER ITASK
      LOGICAL TERMNL, OUTPUT
      INTEGER IDAY

      SAVE

*--- Initialization
      IF (ITASK .EQ. 1) THEN
          IF (ABS (AMOD (DELT,1.) ) .GT. .0001) THEN
              WRITE (*, '(A) ')
              & ' Error DAYTIM - DELT not whole number '
              STOP
          ENDIF

          IDAY = NINT( STDAY )
          DAYNR = FLOAT( IDAY )

          OUTPUT = .TRUE.

      ELSE

*--- Update timer and turn output flag (OUTPUT) on or off; check for
* finishing time

          IDAY = IDAY + NINT (DELT)
          DAYNR = FLOAT(IDAY)

          IF (DAYNR .GE. FINDAY) THEN
              TERMNL = .TRUE.
              ITASK = 4
          ENDIF

          IF ( AMOD (DAYNR,PRDEL) .LT. .001) THEN
              OUTPUT = .TRUE.
          ELSE
              IF (TERMNL) THEN
                  OUTPUT = .TRUE.
              ELSE
                  OUTPUT = .FALSE.
              ENDIF
          ENDIF

      ENDIF

      RETURN
      END
*****
* SUBPROGRAM: TOTASG
*
* Purpose: This subroutine calculates daily total gross
*          assimilation (DTGA)
* Description:
*          daily total gross assimilation is calculated by performing
*          a Gaussian integration
*          over time. At five different times of the day,
*          radiation is computed and used to compute assimilation
*          whereafter integration takes place.
*
* Origin: TOTASS by D. van Kraalingen
*          Modified by Jan Goudriaan 5-Febr-1988
*          Modified by Jan Goudriaan and Kees Spitters 7 December 1989
*
* Control variables: ITASK

```


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```

* Init variables: ITASK
* Timer variables: DAYNR
*
* Input:
*   ITASK   : (I4)   control variable for initialization
*               (ITASK=1) and rate calculation (ITASK=2)           [-]
*   DAYNR   : (R4)   day number (Jan 1st = 1)                     [-]
*   IUTRAN  : (I4)   unit number file transmissivity data        [-]
*   FILTRN  : (CH40) name of file with transmissivity data       [-]
*   LAT     : (R4)   latitude                                     [radians]
*   DECL    : (R4)   declination of sun                          [radians]
*   SOLARC  : (R4)   solar constant                               [J m-2 s-1]
*   DAYL    : (R4)   astronomical daylength (base = 0 degrees)   [h]
*   SINLD   : (R4)   seasonal offset of sine of solar height     [-]
*   COSLD   : (R4)   amplitude of sine of solar height           [-]
*   DSINBE  : (R4)   daily total of effective solar height       [s]
*   DTR     : (R4)   daily total of global radiation              [J m-2 d-1]
*   FRACPAR : (R4)   fraction PAR in global radiation             [-]
*   CO2AIR  : (R4)   CO2 concentration greenhouse air            [mul 1-1]
*   TEMPAT  : (R4)   temperature of greenhouse air               [oC]
*   SCP     : (R4)   scattering coefficient of leaves for PAR     [-]
*   KDIFBL  : (R4)   extinction coefficient for diffuse light -
*                   non-scattering leaves
*   KDIF    : (R4)   extinction coefficient for diffuse light     [-]
*   LAI     : (R4)   Leaf area index                             [m2 m-2]
*   AZIMGR  : (R4)   azimuth greenhouse                          [radians]
*   REFGR   : (R4)   reflection of ground surface                [-]
*
* Output:
*   DTGA    : (R4)   daily total gross assimilation              [g CO2 m-2 d-1]
*   DPARDF  : (R4)   Daily diffuse PAR inside greenhouse         [J m-2 d-1]
*   DPARDR  : (R4)   Daily direct PAR inside greenhouse          [J m-2 d-1]
*
* FATAL ERROR CHECKS: none
*
* WARNINGS: none
*
* SUBPROGRAMS CALLED:
*   ASSIMR, FRACDF, LPHCUR, SUNPOS, TRANSM
*
*****

      SUBROUTINE TOTASG( ITASK, DAYNR,
&   IUTRAN, FILTRN,
&   LAT, DECL, SOLARC, DAYL, SINLD, COSLD, DSINBE,
&   DTR, FRACPAR, CO2AIR, TEMPAT,
&   SCP, KDIFBL, KDIF, LAI, AZIMGR, REFGR,
&   DTGA, DPARDF, DPARDR )

      IMPLICIT REAL(A-Z)
      INTEGER ITASK

      INTEGER IUTRAN
      CHARACTER*40 FILTRN

      REAL XGAUS5(5), WGAUS5(5)

      INTEGER I, IGAUSS

      DATA IGAUSS /5/
      DATA XGAUS5 /0.04691,0.23077,0.50000,0.76923,0.95309/
      DATA WGAUS5 /0.11846,0.23931,0.28444,0.23931,0.11846/

      IF( ITASK .EQ. 1 ) THEN

*****
* Initialization
*****

```

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```

*---- transmissivity greenhouse
      CALL TRANSM( ITASK, IUTRAN, FILTRN, AZIMGR, AZIMS,
&                ELEVN, TRDIF, TRCON, TRGLAS )

      ELSEIF (ITASK .EQ. 2) THEN

*=====
*      Rate calculation
*=====

*---- Determine EFF and PGMAX value of leaf photosynthesis
*      light-response curve
*      from temperature and CO2 concentration
*      Leaf temperature is assumed equal to air temperature

      TLEAF = TEMPAT
      CALL LPHCUR( TLEAF, CO2AIR, EFF, PGMAX )

*      assimilation set to zero

      DPARDF = 0.
      DPARDR = 0.
      DTGA = 0.
      DO 10 I=1, IGAUSS

*---- Solar time
      SOLHR = 12.0+DAYL*0.5*XGAUS5(I)

*---- solar position
      CALL SUNPOS( LAT, SINLD, COSLD, DECL, SOLHR,
&                ELEVN, AZIMS, SINELV )

*---- global radiation outside greenhouse
      GLRADO = DTR*SINELV*(1.+0.4*SINELV)/DSINBE

      FRDIF = FRACDF( SOLARC, GLRADO, SINELV )
      PAROUT = FRACPAR * GLRADO

*---- diffuse PAR (PARDFO) and direct PAR (PARDRO) outside greenhouse
      PARDFO = FRDIF * PAROUT
      PARDRO = PAROUT - PARDFO

*---- light climate inside the greenhouse, multiplication with
*      greenhouse light transmissivities

*---- transmission greenhouse
      CALL TRANSM( ITASK, IUTRAN, FILTRN, AZIMGR, AZIMS,
&                ELEVN, TRDIF, TRCON, TRGLAS )

      PARDIF = PARDFO * TRDIF
      PARDIR = PARDRO * TRCON * TRGLAS

*      integration PAR inside greenhouse to a daily total
      DPARDF = DPARDF+PARDIF*WGAUS5(I)*3600.
      DPARDR = DPARDR+PARDIR*WGAUS5(I)*3600.

*---- instantaneous canopy assimilation [g CO2 m-2 ground h-1]
      CALL ASSIMR( REFGR, SCP, PGMAX, EFF, KDIFBL, KDIF, LAI, SINELV,
&                PARDIR, PARDIF, PGROS )
*      conversion of mg CO2 m-2 s-1 to g m-2 h-1
      PGROSH = PGROS * 3.6

*      integration of assimilation rate to a daily total (DTGA)
      DTGA = DTGA + PGROSH*WGAUS5(I)

10      CONTINUE

*---- Daily total of gross assimilation [g CO2 m-2 ground d-1]

```

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```

      DTGA = DTGA*DAYL

*--- Daily total of PAR direct and PAR diffuse inside
* greenhouse [J m-2 d-1]
      DPARDF = DPARDF * DAYL
      DPARDR = DPARDR * DAYL

      ENDIF

      RETURN
      END
*****
* SUBPROGRAM: DMPROD
*
* Purpose:
*   calculation of dry matter production of leaves, stems, roots and
*   fruits of greenhouse crop from daily total of gross assimilation
* Description:
*   Maintenance respiration is subtracted from daily gross
*   photosynthesis, and resulting net assimilates are converted to
*   dry matter. Coefficients for dry matter partitioning are used
*   to calculate dry matter production of individual organs
*
* Origin: SUCROS87 by Spitters et al. (1989)
*
* Control variables: ITASK, TERMNL
* Init variables: ITASK
* Timer variables: DAYNR, DELT
*
* Input:
*   ITASK      : (I4)  control variable for initialization (ITASK=1),
*                   rate calculation (2) and integration (3)      [-]
*   DAYNR      : (R4)  day number (Jan 1st = 1)                  [-]
*   DELT       : (R4)  time step                                  [d]
*   WLVI       : (R4)  initial leaf dry weight of crop           [g m-2]
*   WSTI       : (R4)  initial stem dry weight of crop           [g m-2]
*   WRTI       : (R4)  initial root dry weight of crop           [g m-2]
*   WSOI       : (R4)  initial dry weight of storage organs      [g m-2]
*   FLV        : (R4)  dry matter partitioning to leaves         [-]
*   FST        : (R4)  dry matter partitioning to stems          [-]
*   FRT        : (R4)  dry matter partitioning to roots          [-]
*   FSO        : (R4)  dry matter partitioning to storage organs [-]
*   ASRQLV     : (R4)  assimilate requirement leaves             [g CH2O g dm-1]
*   ASRQST     : (R4)  assimilate requirement stems              [g CH2O g dm-1]
*   ASRQRT     : (R4)  assimilate requirement roots              [g CH2O g dm-1]
*   ASRQSO     : (R4)  assimilate requirement storage org.       [g CH2O g dm-1]
*   MAINLV     : (R4)  maintenance costs leaves                 [g CH2O g dm-1 d-1]
*   MAINST     : (R4)  maintenance costs stems                  [g CH2O g dm-1 d-1]
*   MAINRT     : (R4)  maintenance costs roots                  [g CH2O g dm-1 d-1]
*   MAINSO     : (R4)  maintenance costs storage org.           [g CH2O g dm-1 d-1]
*   Q10MN      : (R4)  Q10 maintenance respiration              [-]
*   REFTMP     : (R4)  reference temperature maint. resp.       [oC]
*   TEMPAT     : (R4)  temperature greenhouse air               [oC]
*   DTGA       : (R4)  daily total gross assimilation            [g CO2 m2 d-1]
*
* Output:
*   GLV        : (R4)  rate of DM increase of leaves            [g m-2 d-1]
*   GST        : (R4)  rate of DM increase of stems             [g m-2 d-1]
*   GRT        : (R4)  rate of DM increase of roots             [g m-2 d-1]
*   GSO        : (R4)  rate of DM increase of stor. org.        [g m-2 d-1]
*   GTW        : (R4)  rate of DM increase of crop              [g m-2 d-1]
*   WLW        : (R4)  dry weight of leaves                     [g DM m-2]
*   WST        : (R4)  dry weight of stems                      [g DM m-2]
*   WRT        : (R4)  dry weight of roots                      [g DM m-2]
*   WSO        : (R4)  dry weight of storage organs             [g DM m-2]
*   TWT        : (R4)  dry weight of crop                      [g DM m-2]
*
* SUBPROGRAMS CALLED: none

```

```

*****
      SUBROUTINE DMPROD( ITASK, DAYNR, DELT,
&          WLVI, WSTI, WRTI, WSOI,
&          FLV, FST, FRT, FSO,
&          ASRQLV, ASRQST, ASRQRT, ASRQSO,
&          Q10MN, REFTMP,
&          MAINLV, MAINST, MAINRT, MAINSO,
&          TEMPAL, DTGA,
&          GLV, GST, GRT, GSO, GTW,
&          WLVI, WSTI, WRTI, WSOI, TWT )
      IMPLICIT REAL(A-Z)
      INTEGER ITASK, ITOLD

      DATA ITOLD /4/

*      The task that the subprogram should do (ITASK) is compared with
*      the task done during the previous call (ITOLD)
*      Only certain combinations are allowed:
*
*      New task          Old task
*      -----          -
*      initialization    terminal
*      integration       rate calculation
*      rate calculation  initialization, integration
*      terminal          any task
*
*      Note: integration after initialization is strictly correct,
*      but will not result in any calculations

      IF( ITOLD.EQ.1 .AND. ITASK.EQ.3 ) THEN
          ITOLD = ITASK
          RETURN
      ENDIF

      IF( ITASK .EQ. 1 ) THEN

*=====
*      initialization
*=====

          WLVI = WLVI
          WSTI = WSTI
          WRTI = WRTI
          WSOI = WSOI
          TWT = WLVI + WSTI + WRTI + WSOI

          ELSEIF( ITASK .EQ. 2 ) THEN

*=====
*      rate calculation section
*=====

*----- Daily assimilates, conversion of CO2 to sugars [g CH2O m-2 day-1]
          DTASS = DTGA * 30./44.

*----- Maintenance respiration [g CH2O m-2 day-1]
          MAINTS = WLVI*MAINLV + WSTI*MAINST + WSOI*MAINSO + WRTI*MAINRT
          TEFF = Q10MN**((TEMPAL-REFTMP)/10.)
          MAINT = AMIN1( DTASS, MAINTS*TEFF )

*----- Assimilate requirements for dry matter conversion
*      [g CH2O/g dry matter]
          ASRQ = FLV*ASRQLV + FST*ASRQST + FSO*ASRQSO + FRT*ASRQRT

*----- Rate of growth [g DM m-2 day-1]
          GTW = (DTASS - MAINT) / ASRQ
          GLV = GTW * FLV
          GST = GTW * FST

```

```
GSO = GTW * FSO
GRT = GTW * FRT
```

```
ELSEIF (ITASK .EQ. 3) THEN
```

```
*=====
*           integration section
*=====
```

```
*---- Dry weights of leaves stems, storage organs, roots
*      and total biomass (g DM m-2) as integrals of growth rates.
*      Note that no biomass is removed.
```

```
WLV  = WLV + GLV * DELT
WST  = WST + GST * DELT
WRT  = WRT + GRT * DELT
WSO  = WSO + GSO * DELT
TWT  = WLV + WST + WRT + WSO
```

```
ENDIF
```

```
ITOLD = ITASK
```

```
RETURN
END
```

Appendix IV. Listing of routines that are common to both ASKAM and SUKAM

Routine	Calculation of
ASSIMR	canopy gross photosynthesis
ASTROG	daylength, solar constant, intermediate variables
FRACDF	fraction diffuse in global radiation outside greenhouse
LPHCUR	leaf initial light use eff. and maximal rate of gross photosynthesis
SUNPOS	solar position
TRANSM	greenhouse light transmission
Additional routines	
AZINT	interpolation routine
LINTNM	interpolation routine
SKIPCM	routine for reading data file

IV-2

```

*****
* SUBPROGRAM: ASSIMR
*
* Purpose:
* Calculation of instantaneous crop CO2 assimilation
* (PGROS, mg CO2 m-2 s-1)
*
* Description:
* A closed canopy and a spherical leaf angle distribution
* are assumed. Exponential extinction of diffuse, direct, and
* secondary diffuse radiation is assumed. Multiple scattering of
* light is taken into account. Ground reflection is taken into account.
* Based on subroutine ASS from SUCROS87.
*
* Input:
* REFGR : (R4) reflection of ground surface [-]
* SCP : (R4) scattering coefficient for PAR [-]
* PGMAX : (R4) leaf gross assim. at light satur. [mg CO2 m-2 s-1]
* EFF : (R4) initial light use efficiency [mg CO2 J-1]
* KDIFBL : (R4) extinction coefficient diffuse light -
* non-scattering leaves [-]
* KDIF : (R4) extinction coefficient diffuse light [-]
* LAI : (R4) Leaf Area Index [-]
* SINELV : (R4) sine of solar elevation [-]
* PARDIR : (R4) flux direct PAR [J m-2 s-1]
* PARDIF : (R4) flux diffuse PAR [J m-2 s-1]
*
* Output:
* PGROS : (R4) canopy instantaneous gross assim. [mg CO2 m-2 s-1]
*
* COMMENT:
* Analytical solutions of effect ground reflectance developed by
* J. Goudriaan
*****
      SUBROUTINE ASSIMR( REFGR, SCP, PGMAX, EFF, KDIFBL, KDIF, LAI,
& SINELV, PARDIR, PARDIF, PGROS )
      IMPLICIT REAL (A-Z)
      INTEGER L,I2
      DIMENSION XGAUS3(3), WGAUS3(3)

      DATA XGAUS3 /0.112702, 0.5, 0.887298/
      DATA WGAUS3 /0.277778,0.444444,0.277778/

*--- Prevent math overflow; name change to prevent change of
* variable value
      SINEL = AMAX1( 0.02, SINELV )

*--- Canopy reflection coefficient
      REFL = (1. - SQRT(1.-SCP)) / (1. + SQRT(1.-SCP))
      REFPD = REFL * 2. / (1 + 2.*SINEL)

*--- Extinct.coeff. for direct component (KDIRBL) and
* total direct flux (KDIRT) and cluster factor
      CLUSTF = KDIF / (KDIFBL * SQRT(1.-SCP))
      KDIRBL = (0.5/SINEL) * CLUSTF
      KDIRT= KDIRBL * SQRT(1.-SCP)

*-----
*---- Section calculating effect of ground reflectance of radiation;
*-----
* transmissivity T, effective transmissivity TE and effective
* reflectivity RE for incoming diffuse (1), incoming direct and
* its diffused components together (2) and reflected diffuse
* radiation from the ground surface (3) reckoned in upward direction
      T1 = EXP(-KDIF*LAI)
      T2 = EXP(-KDIRT*LAI)
      T3 = T1
      CORR1 = (REFL-REFGR) / (REFGR-1./REFL) *T1*T1

```


IV-3

```

CORR2 = -REFPD*REFPD*T2*T2
CORR3 = -REFL*REFL*T3*T3
RE1 = (REFL+CORR1/REFL)/(1.+CORR1)
RE2 = (REFPD+CORR2/REFPD)/(1.+CORR2)
RE3 = (REFL+CORR3/REFL)/(1.+CORR3)
TE1 = T1*(REFL*REFL-1.)/(REFL*REFGR-1.)/(1+CORR1)
TE2 = T2*(1.-REFPD*REFPD)/(1.+CORR2)
TE3 = T3*(1.-REFL*REFL)/(1.+CORR3)

*--- Reflected diffused flux at ground surface originating from
* direct radiation, including secondary reflection
PHIU = REFGR*PARDIR*TE2/(1.-RE3*REFGR)
*-----

* selection of canopy depths (LAIC from top)
PGROS = 0.
DO 200 L = 1,3
    LAIC = LAI * XGAUS3(L)

*--- absorbed fluxes per unit leaf area: diffuse flux, total direct
* flux, direct component of direct flux.

    PARLDF=(1.-REFL)*KDIF*(PARDIF*(EXP(-KDIF*LAIC)+CORR1*
& EXP(KDIF*LAIC)/REFL)/(1.+CORR1) + PHIU*(EXP(KDIF*(LAIC-LAI))
& + CORR3*EXP(KDIF*(LAI-LAIC))/REFL)/(1.+CORR3) )
    PARLT = (1.-REFPD)*PARDIR*KDIRT*(EXP(-KDIRT*LAIC)+CORR2*
& EXP(KDIRT*LAIC)/REFPD)/(1.+CORR2)
    PARLDR = (1.-SCP)*PARDIR*KDIRBL*EXP(-KDIRBL*LAIC)

*--- absorbed fluxes (J/m2 leaf/s) for shaded and sunlit leaves
    PARLSH = PARLDF + (PARLT - PARLDR)
*--- direct par absorbed by leaves perpendicular on direct beam
    PARLPP = PARDIR * (1.-SCP)/SINEL

*--- fraction sunlit leaf area
    FSLLA = CLUSTF*EXP(-KDIRBL*LAIC)

*--- assimilation of shaded leaf area (mg CO2 m-2 leaf s-1)
    ASSSH = PGMAX * (1.-EXP(-EFF*PARLSH/PGMAX))
*--- assimilation of sunlit leaf area (mg CO2 m-2 leaf s-1)
    ASSSL=0.
    DO 210 I2=1,3
        PARLSL = PARLSH + PARLPP * XGAUS3(I2)
        ASSSL = ASSSL + PGMAX * (1. - EXP(-PARLSL * EFF / PGMAX))
& * WGAUS3(I2)
210 CONTINUE

    PGROS = PGROS + ((1.-FSLLA)*ASSSH + FSLLA*ASSSL)*WGAUS3(L)

200 CONTINUE

*--- total gross assimilation (mg CO2 m-2 soil s-1)
PGROS = PGROS * LAI

RETURN
END
*****
* SUBPROGRAM: LPHCUR
*
*
* Purpose:
* Determination of EFF- and PGMAX- values in negative exponential
* light - response curve of leaf gross photosynthesis
*
* Description: descriptive formulae are used to calculated initial slope
* and light-saturation value of negative-exponential light
* response curve. Formulae are developed partly based on theory
* of Farquhar, von Caemmerer and Berry (1980)
*

```

IV-4

```

* Origin: J. Goudriaan, "Kollegediktaat", and Goudriaan et al., 1985
*
* Input:
*   TLEAF      : (R4)  leaf temperature           [oC]
*   CO2AIR     : (R4)  CO2 concentration         [mul 1-1]
*
* Output:
*   EFF        : (R4)  leaf initial light use efficiency [mg CO2 J-1]
*   PGMAX      : (R4)  leaf gross assim. at light satur. [mg CO2 m-2 s-1]
*
* SUBPROGRAMS CALLED:
*   LINTNM
*
* COMMENT:
*   Parameters:
*   EFF0 : Potential light use efficiency in absence of
*          oxygen (mg CO2 J-1)
*   RB   : boundary layer resistance to H2O diffusion (s m-1)
*   RS   : stomatal resistance to H2O diffusion (s m-1)
*   RD20 : dark respiration at 20 oC (mg CO2 m-2 s-1)
*   Q10RD : Q10 of dark respiration
*   Table of temperature dependence of inverse of carboxylation
*          resistance (m s-1)
*   Table of temperature dependence of maximal endogenous photosynthetic
*          capacity (mg CO2 m-2 s-1)
*****
SUBROUTINE LPHCUR( TLEAF, CO2AIR, EFF, PGMAX )
  IMPLICIT REAL(A-Z)

  DIMENSION PMMT(10), GCT(10)
  PARAMETER (EFF0=0.017, RS=50., RB=100., RD20=0.05, Q10RD=2.0)

  *--- Table for temperature dependence of inverse of carboxylation
  * resistance (m s-1)
  DATA GCT/0.,0., 5.,0., 25.,.004, 40.,0., 100.,0./

  *--- Table for temperature dependence of maximal endogenous
  * photosynthetic capacity (mg CO2 m-2 s-1)
  DATA PMMT/0.,0., 5.,0., 30.,2.5, 40.,0., 100.,0./

  *--- Conductance GC is a function of temperature (m s-1)
  GC = LINTNM( 'GCT', GCT, 10, TLEAF )
  * RC is the carboxylation resistance to CO2 assimilation
  IF( GC .LT. 0.00001) THEN
    RC = 3.0E+30
  ELSE
    RC = 1. / GC
  ENDIF

  *--- Endogenous photosynthetic capacity PMM (mg CO2 m-2 s-1)
  * is a function of temperature
  PMM = LINTNM( 'PMMT', PMMT, 10, TLEAF )

  *--- CO2 compensation point increases with temperature
  * dependance according to Brooks & Farquhar, 1985
  GAMMA = 42.7 + 1.68 * (TLEAF - 25) + 0.012 * (TLEAF-25)**2

  *--- Reduction of light use efficiency by photorespiration;
  * affected by CO2 concentration
  CO2 = MAX( CO2AIR, GAMMA )
  EFF = EFF0 * (CO2-GAMMA) / (CO2+2.*GAMMA)

  *--- PNC is maximum as determined by CO2 diffusion
  * 1.830 mg CO2 per m3 per mul 1-1
  *--- Stomatal resistance and boundary layer resistance to CO2 are
  * 1.6 and 1.37 times larger than to water vapour, respectively
  PNC = (CO2-GAMMA) * 1.830 / (1.37*RB + 1.6*RS + RC)

  *--- PNMAX shows saturation with PNC

```

IV-5

```

      IF (PMM .LT. 0.00001) THEN
        PNMAX = 0.0
      ELSE
        PNMAX = AMIN1( PNC,PMM )
      ENDIF

*--- Dark respiration (mg CO2 m-2 s-1)
      RD = RD20 * Q10RD**(0.1*(TLEAF-20.))

*--- PGMAX (mg CO2 m-2 leaf s-1) is determined by
* maximal net assimilation PNMAX and RD
      PGMAX = PNMAX + RD

      RETURN
      END
*****
* SUBPROGRAM: ASTROG
*
* Purpose:
* This subroutine calculates astronomic daylength,
* and diurnal radiation characteristics such as daily
* integral of sine of solar elevation, solar constant
*
* Description: Daylength, solar constant are calculated
* for a given day. Also some intermediate variables are calculated
* that are needed for
* - calculation of solar position (declination, SINLD,
* COSLD) and for
* - generating diurnal course of radiation (SINLD, COSLD, DSINBE)
*
* Origin: ASTRO by D. van Kraalingen
* Modified by Jan Goudriaan 4 Febr 1988
* Modified by Jan Goudriaan and Kees Spitters 7 december 1989
*
* Timer variables: DAYNR
*
* Input:
* DAYNR      : (R4) Day number (Jan 1st = 1)          [-]
* LAT        : (R4) Latitude                          [radians]
*
* Output:
*
* SOLARC      : (R4) corrected solar constant          [J m-2 s-1]
* SINLD       : (R4) Seasonal offset of sine of solar elevation  [-]
* COSLD       : (R4) Amplitude of sine of solar elevation      [-]
* DECL        : (R4) Declination of sun                  [radians]
* DAYL        : (R4) Astronomical daylength (base = 0 degrees) [h]
* DSINBE      : (R4) Daily total of effective solar elevation   [s]
*
* FATAL ERROR CHECKS:
*
* LAT > 67 degrees, LAT < -67 degrees
*
* SUBPROGRAMS CALLED: none
*****
      SUBROUTINE ASTROG( DAYNR,LAT,
& SOLARC,SINLD,COSLD,DECL,DAYL,DSINBE )

      IMPLICIT REAL (A-Z)

*-----PI and conversion factor from degrees to radians
      PARAMETER( PI=3.141592654, RADN=0.017453292 )

*-----check on input range of parameters
      IF( LAT.GT. 67.*RADN ) STOP 'ERROR IN ASTROG: LAT > 67'
      IF( LAT.LT. -67.*RADN ) STOP 'ERROR IN ASTROG: LAT < -67'

*-----declination of the sun as function of daynumber (DAYNR)

```

IV-6

```

DECL = -ASIN( SIN(23.45*RADN)*COS(2.*PI*(DAYNR+10.)/365.) )

*-----SINLD, COSLD and AOB are intermediate variables
      SINLD = SIN(LAT) * SIN(DECL)
      COSLD = COS(LAT) * COS(DECL)
      AOB = SINLD/COSLD

*-----daylength (h)
      DAYL = 12.0*(1.+2.*ASIN(AOB)/PI)

      DSINBE= 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
&          12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT(1.-AOB*AOB)/PI)

*-----corrected solar constant (J m-2 s-1)
      SOLARC = 1370. * (1.+0.033*COS(2.*PI*DAYNR/365.))

      RETURN
      END
*****
* SUBPROGRAM: SUNPOS
*
* Purpose: Calculation of position of sun at given day of year,
*          time of day and latitude
*
* Description: Calculates solar elevation (height above horizon) and
*              solar azimuth (difference of direction of sun with north-south).
*              Azimuth: east negative sign, west positive sign
*
* Input:
*   LAT      : (R4) latitude of location                [radians]
*   SINLD    : (R4) seasonal offset of sine of solar height [-]
*   COSLD    : (R4) amplitude of sine of solar height    [-]
*   DECL     : (R4) declination                          [radians]
*   SOLHR    : (R4) time of the day (solar time)         [h]
* Output:
*   ELEVN    : (R4) elevation of sun                    [radians]
*   AZIMS    : (R4) azimuth of sun (east negative)       [radians]
*   SINELV   : (R4) sine of solar elevation              [-]
*
* SUBPROGRAMS CALLED: none
*
*****
      SUBROUTINE SUNPOS( LAT,SINLD,COSLD,DECL,SOLHR,
&          ELEVN,AZIMS,SINELV )
      IMPLICIT REAL(A-Z)

      PI = 3.1415926

*--- Sine of solar elevation (inclination)
      SINELV = SINLD+COSLD*COS(2*PI*(SOLHR+12.)/24.)
      ELEVN = ASIN( SINELV )

*--- Solar azimuth
*   function from Campbell, 1981; Encyclop. of Physiol. Plant Ecol.,
*   vol. 12A
*   Cosine function is used because ACOS-function gives angles
*   higher than 90 degrees when solar azimuth is passing East-West line
      COSAZ = - (SIN(DECL) - SIN(LAT)*SINELV) /
&          (COS(LAT)*COS(ELEVN))

*   Place upper limit and under limit to COSAZ as this variable can
*   be more than 1 or less than -1 because of calculation inaccuracy
      IF( COSAZ .LT. -1.0 ) THEN
          COSAZ = -1.0
      ELSEIF( COSAZ .GT. 1.0 ) THEN
          COSAZ = 1.0
      ENDIF
      AZIMS = ACOS( COSAZ )

```

IV-7

```

*--- East has negative sign, West has positive sign
      IF( SOLHR.LE.12. ) THEN
          AZIMS = -AZIMS
      ENDIF

*--- Limit set to SINELV
      IF( SINELV.LT. 0. ) THEN
          SINELV = 0.
      ENDIF

      RETURN
      END

*****
* SUBPROGRAM: FRACDF
*
* Modifications:
*   - Feb-1990 calculation fraction diffuse at high
*               atmospheric transmissions
*               (J. Goudriaan, pers. comm.)
* Purpose:
*   Calculation of fraction diffuse in hourly global radiation for
*   De Bilt (The Netherlands)
* Description: Fraction diffuse is calculated from relation of
*   hourly values of atmospheric transmission versus hourly values
*   of fraction diffuse
*
* Origin: De Jong (1980), ref. in appendix of Spitters et al. (1986)
*
* Input:
*   SOLARC      : (R4) solar constant [J m-2 s-1]
*   GLRADO      : (R4) global radiation outside greenhouse [J m-2 s-1]
*   SINELV      : (R4) sine of solar elevation [-]
*
* Output:
*   FRACDF      : (R4) fraction diffuse radiation [-]
*
* SUBPROGRAMS CALLED: no
*
* Comment: relation was obtained from 1961-1977 De Bilt data
*****
      REAL FUNCTION FRACDF( SOLARC, GLRADO, SINELV )
      IMPLICIT REAL (A-Z)

      SO = SOLARC * SINELV
      ATMTR = GLRADO/SO

      FRACDF = 1.47 - 1.66 * ATMTR
      IF (ATMTR.LE. 0.35 .AND. ATMTR.GT. 0.22) THEN
          FRACDF = 1. - 6.4 * (ATMTR-0.22)**2
      ELSEIF (ATMTR.LE. 0.22) THEN
          FRACDF = 1.
      ENDIF
      FRACDF = AMAX1( FRACDF, 0.15+0.85*(1.-EXP(-0.1/SINELV)) )

      RETURN
      END

*****
* SUBPROGRAM: TRANSM
*
* Purpose: Calculation of transmissivity of
*   greenhouse cover for diffuse and direct global radiation and PAR.
* Description:
*   Uses output from detailed model of Bot (1983).
*   Calculates transmissivity of greenhouse for direct radiation by
*   interpolation in table. Transmissivity for diffuse radiation is
*   constant factor.
*
* Control variables: ITASK

```

```

* Init variables: ITASK
*
* Input:
* ITASK      : (I4)  control variable for initialization
*              (ITASK=1) and transmission calc. (ITASK=2)  [-]
* IUTRAN     : (I4)  unit nr. for file reading            [-]
* FILNAM     : (CH*) name of input file                   [-]
* AZIMS      : (R4)  azimuth of sun                      [radians]
* AZIMGR     : (R4)  azimuth greenhouse                  [radians]
* ELEVN      : (R4)  elevation of sun                    [radians]
* Output:
* TRDIF      : (R4)  transmissivity of greenhouse for diffuse light
*              [-]
* TRCON      : (R4)  transmission of the construction for direct radiation
*              [-]
* TRGLAS     : (R4)  transmission of the glass for direct radiation
*              [-]
*
* FATAL ERROR CHECKS:
*   when premature end of input file found
*
* SUBPROGRAMS CALLED: AZINT
*
* FILE USAGE:
*   unit      file name      description
*   =====
* IUTRAN      FILNAM         input file with table of transmissivities
*
* Read variables:
*   name      unit      description
*   =====
* TRDIF      IUTRAN      transmissivity diffuse radiation
* FMT        IUTRAN      format for reading transmissivities
*              direct radiation
* AZ         IUTRAN      2-dim. table azimuth values
* EL         IUTRAN      1-dim. table elevation layers
* TBCON      IUTRAN      2-dim. table transmissivities construction
* TBGLAS     IUTRAN      2-dim. table transmissivities glass
*
* Write variables: none
*
* COMMENT:
*   - when ITASK = 1 (initialization) data of transmissivities are
*     read from data file;
*   - when ITASK = 2 interpolation in tables takes places to find
*     transmissivity of direct radiation for given solar position;
*   - transmissivities are grouped according to azimuth values with
*     the same elevation (elevation layer)
*****
      SUBROUTINE TRANSM( ITASK, IUTRAN, FILNAM,
&      AZIMGR, AZIMS, ELEVN, TRDIF, TRCON, TRGLAS )
      IMPLICIT REAL(A-Z)
      INTEGER ITASK
      INTEGER EOFSKP, IOSSKP
      INTEGER IUTRAN
      CHARACTER*(*) FILNAM
      CHARACTER*40 LABEL, FMT

      INTEGER NLayer, NENTR, IA, IE
      INTEGER I, IXMAX, IXMIN
      DIMENSION NENTR(20), EL (20)
      DIMENSION AZ(20,20), TBCON(20,20), TBGLAS(20,20)

      IF (ITASK .EQ. 1) THEN
        OPEN( UNIT = IUTRAN, FILE = FILNAM, STATUS = 'OLD' )

        CALL SKIPCM( IUTRAN, '*', EOFSKP, IOSSKP )
        IF (EOFSKP .EQ. -1) THEN

```



```

        WRITE (*,'(A,A,A)')
&        ' TRANSM reading file ', FILNAM,
&        ' End Of File found when searching TRANSM DIFFUSE '
        STOP
    ENDIF

*--- Diffuse light transmissivity
    READ( IUTRAN, * ) TRDIF

    CALL SKIPCM( IUTRAN, '*', EOFSKP, IOSSKP )
    IF( EOFSKP .EQ. -1 ) THEN
        WRITE (*,'(A,A,A)')
&        ' TRANSM reading file ', FILNAM,
&        ' End Of File found when searching NR OF LAYERS '
        STOP
    ENDIF

*--- Number of elevation layers
    READ (IUTRAN, '(I6)') NLAYR

    CALL SKIPCM( IUTRAN, '*', EOFSKP, IOSSKP )
    IF( EOFSKP .EQ. -1 ) THEN
        WRITE (*,'(A,A,A)')
&        ' TRANSM reading file ', FILNAM,
&        ' End Of File found when searching FORMAT '
        STOP
    ENDIF

*--- Format for reading azimuth and transmissivity tables
    READ (IUTRAN, '(A)') FMT

    CALL SKIPCM( IUTRAN, '*', EOFSKP, IOSSKP )
    IF( EOFSKP .EQ. -1 ) THEN
        WRITE (*,'(A,A,/,A,A)')
&        ' TRANSM reading file ', FILNAM,
&        ' End Of File found when searching beginning of',
&        ' direct transmissivity data '
        STOP
    ENDIF

    DO 50 IE=1,NLAYR
*--- Elevation of elevation layer (degrees)
        READ( IUTRAN,*, END=51 ) EL (IE)
*--- Number of entries in elevation layer
        READ (IUTRAN,'(I8)', END=51) NENTR(IE)
*--- Azimuth values corresponding with transmissivity data
        READ (IUTRAN, FMT, END=51) (AZ(IA,IE), IA=1,NENTR(IE))
*--- Transmissivity construction
        READ (IUTRAN, FMT, END=51) (TBCON(IA,IE), IA=1,NENTR(IE))
*--- Transmissivity glass
        READ (IUTRAN, FMT, END=51) (TBGLAS(IA,IE), IA=1,NENTR(IE))
50    CONTINUE
        GOTO 52
51    CONTINUE

        WRITE (*,'(A,A,/,A,A,/,A,I5,/,A,I5)')
&        ' TRANSM reading file ', FILNAM,
&        ' End Of File found when reading',
&        ' direct transmissivity data',
&        ' Total number of elevation layers is : ', NLAYR,
&        ' Currently reading layer nr : ', IE
        STOP

52    CONTINUE

        CLOSE( IUTRAN )

    ELSEIF( ITASK .EQ. 2 ) THEN

```


IV-10

```

RADN = 0.017453292

*--- Conversion of radians to degrees
A1 = (AZIMS - AZIMGR) / RADN
A1 = AMOD( A1, 180. )
E = ELEVN / RADN

*--- If necessary, mirroring of azimuth
IF (A1.GE.90..AND.A1.LE.180.) A=180.-A1
IF (A1.LT.0..AND.A1.GT.-90.) A=-A1
IF (A1.LE.-90..AND.A1.GE.-180.) A=180.+A1
IF (A1.GE.0. .AND. A1.LT.90.) A = A1

*--- Search for layer number
DO 5 I=1,NLAYER
  IF(E.LT.EL(I)) GOTO 10
5  CONTINUE
  IXMIN = NLAYER
  IXMAX = NLAYER
  GOTO 20

10  IXMIN = MAX0(I-1,1)
  IXMAX = I

*--- Interpolation in azimuth
20  TC1 = AZINT( A,TBCON(1,IXMIN),AZ(1,IXMIN),NENTR(IXMIN) )
  TG1 = AZINT( A,TBGLAS(1,IXMIN),AZ(1,IXMIN),NENTR(IXMIN) )

  IF(IXMIN.EQ.IXMAX) THEN
    TRCON = TC1
    TRGLAS = TG1
  ELSE
*--- Interpolation in azimuth
    TC2 = AZINT( A,TBCON(1,IXMAX),AZ(1,IXMAX),NENTR(IXMAX) )
    TG2 = AZINT( A,TBGLAS(1,IXMAX),AZ(1,IXMAX),NENTR(IXMAX) )
*--- Interpolation in elevation
    TRCON = TC1+(TC2-TC1)*(E-EL(IXMIN))/(EL(IXMAX)-EL(IXMIN))
    TRGLAS = TG1+(TG2-TG1)*(E-EL(IXMIN))/(EL(IXMAX)-EL(IXMIN))
  END IF

  ENDIF

  RETURN
  END
*****
* SUBPROGRAM: AZINT
*
* Purpose:
*   Interpolation in azimuth-table.
* Description: Interpolates in azimuth tables derived from
*   subroutine for interpolating in transmissivity values of greenhouse.
*   Corresponding value in table is output of function.
*
* Input:
*   AZIMUTH      : (R4)  azimuth of beam                      [degrees]
*   AZIMTB       : (R4)  azimuth table (length 20)             [-]
*   TRTB         : (R4)  transmissivity table (length 20)       [-]
*   NAZFIL       : (I4)  number of places in table that are filled [-]
*
* Output:
*   AZINT        : (R4)  transmissivity found in table          [-]
*
* SUBPROGRAMS CALLED: none
*****
REAL FUNCTION AZINT( AZIMUTH, TRTB, AZIMTB, NAZFIL )
IMPLICIT REAL(A-Z)
INTEGER I, NAZFIL

```

```

      DIMENSION AZIMTB(20),TRTB(20)

      DO 30 I=1, NAZFIL
        IF( AZIMUTH.LT.AZIMTB(I) ) GOTO 10
30    CONTINUE
      AZINT = TRTB( NAZFIL )
      RETURN

10    IF(I.EQ.1) THEN
      AZINT = TRTB( 1 )
    ELSE
      AZINT = TRTB(I-1)+(TRTB(I)-TRTB(I-1)) *
&      (AZIMUTH-AZIMTB(I-1))/(AZIMTB(I)-AZIMTB(I-1))
    END IF
    RETURN
  END
*****
* SUBPROGRAM: LINTNM
*
* Origin: LINT from D. van Kraalingen
*
* Purpose: This function is a linear interpolation function.
*
* Description:
*   The function does not extrapolate : in case of X below or
*   above the region defined by TABLE, the first
*   respectively the last Y-value is returned and a message
*   is generated. This function is adapted from function LINT
*   (D. van Kraalingen): name of calling routine is output when
*   error occurs
*
* Input:
*   TBNAME : (CH*) Name of table in which to interpolate      [-]
*   TABLE : (R4)  A one-dimensional array with paired
*   data: x,y,x,y, etc.                                         [-]
*   ILTAB  : (R4)  The number of elements of the array TABLE [-]
*   X      : (R4)  The value at which interpolation should take place [-]
*
* Output:
*   LINTNM : (R4)  function name, result of the interpolation   [-]
*
* FATAL ERROR CHECKS:
*   condition
*   -----
*   TABLE(I) < TABLE(I-2) , for I odd
*   ILTAB odd
*
* Read variables: none
*
* Write variables: tables values and name of calling routine
*   are written to screen when an error occurs
*
*****
      REAL FUNCTION LINTNM( TBNAME, TABLE, ILTAB, X )
      IMPLICIT REAL (A-Z)
      INTEGER I, IUP, ILTAB
      DIMENSION TABLE( ILTAB )
      CHARACTER*(*) TBNAME

*---  check on odd ILTAB
      IF( MOD(ILTAB,2).NE.0 ) THEN
        WRITE (*, '(A,I4/,A,/,A,A) ')
$      ' ERROR in function LINTNM: ILTAB=', ILTAB,
$      ' ILTAB must be even !',
&      ' Called by table ', TBNAME
        STOP
      END IF

      IUP = 0

```

```

DO 10 I=3,ILTAB,2
*--- check on ascending order of X-values in function
      IF( TABLE(I).LE.TABLE(I-2) ) THEN
          WRITE (*,'(A,I4/,A,I4,A/,A/,A,A)')
$          ' X-coordinates not in ascending order at element',I,
$          ' LINTNM-function contains',ILTAB,' points',
$          ' Run deleted!',
&          ' Called by table ',TBNAME
          STOP
      END IF
      IF( IUP.EQ.0.AND.TABLE(I).GE.X ) IUP = I
10 CONTINUE

      IF( X.LT.TABLE(1) ) THEN
          WRITE (*,'(A/A,I4,A/A,G12.4,/,A,A)')
$          ' Interpolation below defined region!!',
$          ' LINTNM-function contains ',ILTAB,' points,',
$          ' Interpolation at X=',X,
&          ' Called by table ',TBNAME
          LINTNM = TABLE( 2 )
          GOTO 40
      END IF

      IF( X.GT.TABLE(ILTAB-1) ) THEN
          WRITE (*,'(A/A,I4,A/A,G12.4,/,A,A)')
$          ' Interpolation above defined region!!',
$          ' LINTNM-function contains ',ILTAB,' points,',
$          ' Interpolation at X=',X,
&          ' Called by table ',TBNAME
          LINTNM = TABLE( ILTAB )
          GO TO 40
      END IF

*--- normal interpolation
      SLOPE = (TABLE(IUP+1)-TABLE(IUP-1))/(TABLE(IUP)-TABLE(IUP-2))
      LINTNM = TABLE(IUP-1)+(X-TABLE(IUP-2))*SLOPE

40 RETURN
END

*****
* SUBPROGRAM: SKIPCM
*
* Purpose:
*   Move pointer in input file beyond comment lines
* Description:
*   Reads in file and skips lines with comment character at first column.
*   Does backspace when no more comment line is found
*
* Input:
*   IUNIT          : (I4)      unit number of data file      [-]
*   CSTR           : (CH1)     comment string                 [-]
*
* Output:
*   EOFSKP         : (I4)      flag for end of file condition  [-]
*   IOSSKP         : (I4)      flaf for error in file reading  [-]
*
* SUBPROGRAMS CALLED: none
*
* FILE USAGE:  unit IUNIT
*
* Read variables:
*   Unit          Name
*   ==           ==
*   IUNIT         CHAR1
*
* Write variables: none
*
*****

```

```
SUBROUTINE SKIPCM( IUNIT, CSTR, EOFSKP, IOSSKP )
IMPLICIT REAL (A-Z)
INTEGER IUNIT, EOFSKP, IOSSKP
CHARACTER*1 CSTR, CHAR1

EOFSKP = 0

DO 10 I = 1, 100000
  READ( IUNIT, '(A1)', END = 20, IOSTAT = IOSSKP ) CHAR1
  IF (CHAR1 .NE. CSTR) THEN
    BACKSPACE( IUNIT )
    RETURN
  ENDIF
10  CONTINUE
20  CONTINUE

EOFSKP = -1

RETURN
END
```


Appendix V. Listing of subroutine ASSIMN

```

*****
* SUBPROGRAM: ASSIMN
*
* Purpose:
* Calculation of instantaneous crop CO2 assimilation
*                                     (PGROS, mg CO2 m-2 ground s-1)
*
* Description:
* A closed canopy and a near-planophile leaf angle distribution are
* assumed.
* Exponential extinction is calculated of diffuse, direct, and
* secondary diffuse radiation. Multiple scattering of
* light, and ground reflection are taken into account.
* Based on subroutine ASS from SUCROS87 and on subroutine ASSIMR
*
* Input:
* REFGR  : (R4) reflection of ground surface          [-]
* SCP    : (R4) scattering coefficient for PAR         [-]
* PGMAX  : (R4) leaf gross assim. at light satur.      [mg CO2 m-2 s-1]
* EFF    : (R4) initial light use efficiency           [mg CO2 J-1]
* KDIFBL : (R4) extinction coefficient diffuse light -
*           non-scattering leaves                      [-]
* KDIF   : (R4) extinction coefficient diffuse light    [-]
* LAI    : (R4) Leaf Area Index                       [-]
* SINELV : (R4) sine of solar elevation                [-]
* PARDIR : (R4) flux direct PAR                        [J m-2 s-1]
* PARDIF : (R4) flux diffuse PAR                      [J m-2 s-1]
*
* Output:
* PGROS  : (R4) canopy instantaneous gross assim.     [mg CO2 m-2 s-1]
*
* SUBPROGRAMS CALLED: none
*
* COMMENT:
* - Analytical solutions of effect soil reflectance developed by
*   J. Goudriaan.
* - Average projection of leaves into direction of sun and
*   range of projections are calculated as approximations of more
*   detailed calculations. The near-planophile leaf angle distribution
*   is described by  $\sin(\lambda) \cdot \exp(p \cdot \lambda)$ , where  $\lambda$  is leaf
*   angle with horizon, and  $p = -2$ . This leaf angle distribution is
*   considered representative for cucumber, tomato and sweet pepper.
*
*****

      SUBROUTINE ASSIMN( REFGR, SCP, PGMAX, EFF, KDIFBL, KDIF, LAI,
&      ELEVN, PARDIR, PARDIF, PGROS )
      IMPLICIT REAL (A-Z)
      INTEGER L,I2
      DIMENSION XGAUS3(3), WGAUS3(3)

      DATA XGAUS3 /0.112702, 0.5, 0.887298/
      DATA WGAUS3 /0.277778,0.444444,0.277778/

*--- Prevent math overflow
      SINELV = AMAX1( 0.02, SIN(ELEVN) )

*--- Direct light: average projection and range of projections
      OAV = 0.3 + (0.7 - 0.3) * SINELV
      RNG = 0.9 + 0.05 * SIN( 2. * ELEVN )

*--- canopy reflection coefficient (REFL)
      REFL = (1. - SQRT(1.-SCP)) / (1. + SQRT(1.-SCP))
      REFPD = REFL * 2. * OAV / (OAV + SINELV)

```

```

*--- Extinct.coeff. for direct component (KDIRBL) and
* total direct flux (KDIRT); and cluster factor
  CLUSTF = KDIF / (KDIFBL * SQRT(1.-SCP))
  KDIRBL = (OAV/SINELV) * CLUSTF
  KDIRT= KDIRBL * SQRT(1.-SCP)

*-----
* Section calculating effect of ground reflectance of radiation;
*-----
* transmissivity T, effective transmissivity TE and effective
* reflectivity RE for incoming diffuse (1), incoming direct and
* its diffused components together (2) and reflected diffuse
* radiation from the ground surface (3) reckoned in upward direction
  T1 = EXP(-KDIF*LAI)
  T2 = EXP(-KDIRT*LAI)
  T3 = T1
  CORR1 = (REFL-REFGR) / (REFGR-1./REFL) * T1 * T1
  CORR2 = -REFPD * REFPD * T2 * T2
  CORR3 = -REFL * REFL * T3 * T3
  RE1 = (REFL + CORR1 / REFL) / (1. + CORR1)
  RE2 = (REFPD + CORR2 / REFPD) / (1. + CORR2)
  RE3 = (REFL + CORR3 / REFL) / (1. + CORR3)
  TE1 = T1 * (REFL * REFL - 1.) / (REFL * REFGR - 1.) / (1 + CORR1)
  TE2 = T2 * (1. - REFPD * REFPD) / (1. + CORR2)
  TE3 = T3 * (1. - REFL * REFL) / (1. + CORR3)

*--- reflected diffused flux at ground surface originating from
* direct radiation, including secondary reflection
  PHIU = REFGR * PARDIR * TE2 / (1. - RE3 * REFGR)
*-----

* selection of canopy depths (LAIC from top)
  PGROS = 0.
  DO 200 L = 1, 3
    LAIC = LAI * XGAUS3(L)

*--- absorbed fluxes per unit leaf area: diffuse flux, total direct
* flux, direct component of direct flux.

  PARLDF = (1. - REFL) * KDIF * (PARDIF * (EXP(-KDIF*LAIC) + CORR1 *
& EXP(KDIF*LAIC) / REFL) / (1. + CORR1) + PHIU * (EXP(KDIF*(LAIC-LAI))
& + CORR3 * EXP(KDIF*(LAI-LAIC)) / REFL) / (1. + CORR3) )
  PARLT = (1. - REFPD) * PARDIR * KDIRT * (EXP(-KDIRT*LAIC) + CORR2 *
& EXP(KDIRT*LAIC) / REFPD) / (1. + CORR2)
  PARLDR = (1. - SCP) * PARDIR * KDIRBL * EXP(-KDIRBL*LAIC)

*--- absorbed fluxes (J m-2 leaf s-1) for shaded and sunlit leaves
  PARLSH = PARLDF + (PARLT - PARLDR)
*--- direct par absorbed by leaves perpendicular on direct beam
  PARLPP = PARDIR * (1. - SCP) / SINELV

*--- fraction sunlit leaf area
  FSLLA = CLUSTF * EXP(-KDIRBL*LAIC)

*--- assimilation of shaded leaf area (mg CO2 m-2 leaf s-1)
  ASSSH = PGMAX * (1. - EXP(-EFF*PARLSH/PGMAX))
*--- assimilation of sunlit leaf area (mg CO2 m-2 leaf s-1)
  ASSSL = 0.
  DO 210 I2 = 1, 3
    PARLSL = PARLSH + PARLPP * (OAV + RNG * (XGAUS3(I2) - 0.5))
    ASSSL = ASSSL + PGMAX * (1. - EXP(-PARLSL * EFF / PGMAX))
    & * WGAUS3(I2)
210 CONTINUE

  PGROS = PGROS + ((1. - FSLLA) * ASSSH + FSLLA * ASSSL) * WGAUS3(L)

200 CONTINUE

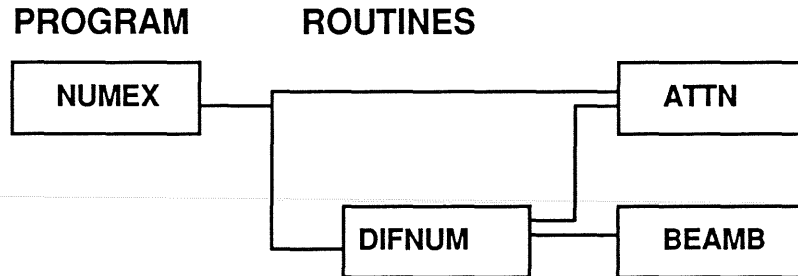
```

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```
*--- total gross assimilation (mg CO2 m-2 soil s-1)
PGROS = PGROS * LAI

RETURN
END
```


Appendix VI. Listing of subroutine NUMEX and its auxilliary routines



Routine	Calculation of
NUMEX	instantaneous canopy gross photosynthesis with numerical calculation of diffuse light extinction
DIFNUM	numerical calculation of diffuse light extinction
ATTN	reflection of single beam, average projection of leaves into direction of beam, and range of projections
BEAMB	relative radiance of sky at given elevation

```

*****
* SUBPROGRAM: NUMEX
*
* Purpose:
*   calculates instantaneous canopy assimilation (mg CO2 m-2 s-1)
*
* Description: instantaneous canopy photosynthesis is calculated from
*   absorbed diffuse and direct PAR at various depths in canopy.
*   Diffuse light extinction is calculated numerically. A UOC or
*   a SOC can be assumed.
*
* Input:
*   SCP      : (R4) scattering coefficient for PAR          [-]
*   PGMAX    : (R4) leaf gross assim. at light satur.      [mg CO2 m-2 s-1]
*   EFF      : (R4) initial light use efficiency            [mg CO2 J-1]
*   LAI      : (R4) Leaf Area Index                          [-]
*   IATTN    : (I4) index for leaf angle distribution        [-]
*   SINELV   : (R4) sine of solar elevation                 [-]
*   PARDIR   : (R4) flux direct PAR                          [J m-2 s-1]
*   PARDIF   : (R4) flux diffuse PAR                         [J m-2 s-1]
*
* Output:
*   PGROS    : (R4) canopy instantaneous gross assim.      [mg CO2 m-2 s-1]
*
* SUBPROGRAMS CALLED: ATTN, DIFNUM
*
*****

      SUBROUTINE NUMEX( SCP, PGMAX, EFF, LAI, IATTN, BDIF,
&                     ELEVN, PARDIR, PARDIF, PGROS )
      IMPLICIT REAL (A-Z)
      INTEGER L,I2
      INTEGER IATTN
      DIMENSION XGAUS5(5), WGAUS5(5)
      DIMENSION XGAUS3(3), WGAUS3(3)

      DATA XGAUS5 /0.046910,0.230765,0.500000,0.769235,0.953090/
      DATA WGAUS5 /0.118463,0.239314,0.284445,0.239314,0.118463/
      DATA XGAUS3 /0.1127, 0.5000, 0.8873/
      DATA WGAUS3 /0.2778, 0.4444, 0.2778/

*--- Prevent math overflows at low solar elevations; limit
*   solar elevation set at 3 degrees
      SINELV = AMAX1( 0.05, SIN(ELEVN) )

      SQP = SQRT( 1.-SCP )
      CALL ATTN( IATTN, SQP, ELEVN, OAV, RNG, REFPD )

*--- extinct.coeff. for direct component (KDIRBL) and
*   total direct flux (KDIRT)
      KDIRBL = OAV/SINELV
      KDIRT = KDIRBL * SQRT(1.-SCP)

*--- selection of canopy depths (LAIC from top)
      PGROS = 0.
      DO 200 L = 1, 5
          LAIC = LAI * XGAUS5(L)

*--- absorbed radiation fluxes per unit leaf area (J m-2 s-1):
*   diffuse flux, total direct flux, direct component of direct flux
      CALL DIFNUM( LAIC, IATTN, SQP, BDIF, DIFABS )
      PARLDF = PARDIF * DIFABS
      PARLT = (1.-REFPD) * PARDIR * KDIRT * EXP( -KDIRT*LAIC )
      PARLDR = (1.-SCP) * PARDIR * KDIRBL * EXP( -KDIRBL*LAIC )

*--- absorbed fluxes (J m-2 leaf s-1) for shaded and sunlit leaves
      PARLSH = PARLDF + (PARLT - PARLDR)

```

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```

*--- direct PAR absorbed by leaves perpendicular on direct beam
      PARLPP = PARDIR * (1.-SCP)/SINELV

*--- fraction sunlit leaf area
      FSLLA = EXP(-KDIRBL*LAIC)

*--- assimilation of shaded leaf area (mg CO2 m-2 leaf s-1)
      ASSSH = PGMAX * (1.-EXP(-EFF*PARLSH/PGMAX))
*--- assimilation of sunlit leaf area (mg CO2 m-2 leaf s-1)
      ASSSL=0.
      DO 210 I2=1,3
        OX = OAV + RNG * (XGAUS3(I2) - 0.5)
        PARLSL = PARLSH + PARLPP * OX
        ASSSL = ASSSL + PGMAX * (1. - EXP(-PARLSL * EFF / PGMAX))
      &      * WGAUS3(I2)
210    CONTINUE

      PGROS = PGROS + ((1.-FSLLA)*ASSSH + FSLLA*ASSSL)*WGAUS5(L)
200 CONTINUE

*--- Instantaneous canopy gross assimilation (mg CO2 m-2 s-1)
      PGROS = PGROS * LAI

      RETURN
      END
*****
* SUBPROGRAM: DIFNUM
*
* Purpose:
*   calculation of absorbed diffuse radiation at given canopy depth,
*   using numerical integration
*
* Input:
*   PLAI   : (R4)  partial LAI                                [-]
*   IATTN  : (I4)  number for leaf angle distribution          [-]
*   SQP    : (R4)  scattering factor                            [-]
*   BDIF   : (R4)  parameter for angular distr, diffuse radiance [-]
*
* Output:
*   DIFABS : (R4)  fraction absorbed diffuse radiation          [-]
*
* SUBPROGRAMS CALLED: none
*
* COMMENT:
*   coordinates according to Gijzen & Goudriaan (1990);
*   vertical axis is z-axis
*****
      SUBROUTINE DIFNUM( PLAI, IATTN, SQP, BDIF, DIFABS )
      IMPLICIT REAL(A-Z)
      INTEGER NA,NB, IATTN

      DIMENSION XGAUS5(5),WGAUS5(5)

*-----Gauss weights for five point Gaussian integration
      DATA XGAUS5 /0.0469101,0.2307653,0.5000000,0.7692347,0.9530900/
      DATA WGAUS5 /0.1184634,0.2393143,0.2844445,0.2393143,0.1184634/

      PI = 3.1415926

      TAB = 0.
      DO 20 NA=1,5
        SA1 = 0.
        B1 = XGAUS5(NA) * .5 * PI
        DO 10 NB=1,5
          B2 = XGAUS5(NB) * .5 * PI
          SINELV = COS(B1)*COS(B2)
          ELEVN = ASIN( SINELV )
          CALL ATTN( IATTN, SQP, ELEVN, OAV, RNG, REFPD)
          IABR = OAV * EXP(-OAV*PLAI/SINELV*SQP)*COS(B2)

```

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```

&          * (1.-REFPD) * BEAMB( BDIF, SINELV )
      SA1 = SA1 + IABR*WGAUS5(NB)
10      CONTINUE
*---  Integration over 180 degrees in yz-plane
      SA2 = SA1 * PI
      TAB = TAB+SA2 * WGAUS5(NA)
20      CONTINUE
*---  Integration over 180 degrees in xz-plane
      DIFABS = TAB * PI * SQP

      RETURN
      END
*****
* SUBPROGRAM: ATTN
*
* Purpose:
*   calculation of reflection of a radiation beam, average projection
*   of leaves into direction of beam, and range of angles of incidence
*   of beam on leaves. According to Goudriaan (1988)
*
* Input:
*   IATTN      : (I4) number indication leaf angle distribution      [-]
*   SQP        : (R4) scattering factor                             [-]
*   ELEVN      : (R4) elevation of beam                             [-]
*
* Output:
*   OAV        : (R4) average projection of leaves into direction of beam [-]
*   RNG        : (R4) range of projections                           [-]
*   REFPD      : (R4) reflection of beam                             [-]
*
* SUBPROGRAMS CALLED: none
*
* COMMENT:
*   Leaf angle distribution is described according to
*    $\sin(\lambda) * \exp(p * \lambda)$  (Goudriaan, 1988)
*   IATTN = 1 --> spherical leaf angle distribution
*   IATTN = 2 --> horizontal leaf angle distribution
*   IATTN = 3 --> near-planophile leaf angle distribution (p=-2.)
*   IATTN = 4 --> planophile leaf angle distribution (p=-3.7)
*****
      SUBROUTINE ATTN( IATTN, SQP, ELEVN, OAV, RNG, REFPD )
      IMPLICIT REAL(A-Z)

      INTEGER IATTN

*---  Reflection by canopy with horizontal leaves
      REFH = (1. - SQP) / (1. + SQP)

      SINELV = SIN( ELEVN )

      IF( IATTN .EQ. 1 ) THEN
*---  Spherical
          OAV = 0.5
          RNG = 1.
      ELSEIF( IATTN .EQ. 2 ) THEN
*---  Horizontal
          OAV = SINELV
          RNG = 0.
      ELSEIF( IATTN .EQ. 3 ) THEN
*---  Near planophile: p = -2.
          OAV = 0.3 + (0.7 - 0.3) * SINELV
          RNG = 0.9 + 0.05 * SIN( 2. * ELEVN )
      ELSEIF( IATTN .EQ. 4 ) THEN
*---  Planophile: p = -3.7
          F1 = 0.615
          F2 = 0.318
          F3 = 0.067
          O15 = AMAX1(0.26, 0.93*SINELV )

```

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```

      O45 = AMAX1(0.47, 0.68*SINELV)
      O75 = 1.0 - 0.268*O15 - 0.732*O45
      OAV = F1*O15 + F2*O45 + F3*O75
      T2DS=F1*0.06 + F2*0.25 + F3*0.467
&      +SINELV * SINELV * (F1*0.81 + F2*0.25 + F3*0.4)
      RNG = SQRT( 12.0 * AMAX1(0., T2DS - OAV * OAV ))
      ENDIF

*--- Reflection
      REFPD = 2. * OAV /(OAV + SINELV) * REFH

      RETURN
      END
*****
* SUBPROGRAM: BEAMB
*
* Purpose:
*   Calculation of relative radiance of sky at point with
*   sine of elevation SINELV
*
* Input:
*   B      : (R4)   radiance distribution           [-]
*   SINELV : (R4)   sine of solar elevation         [-]
*
* Output:
*   BEAMB  : (R4)   relative radiance                [-]
*
*****
      REAL FUNCTION BEAMB( B, SINELV )
      IMPLICIT REAL(A-Z)

      PI = 3.1415926

*--- If B = 0 then Uniform OverCast sky
      c = 1. - B / (3. * (1.+B) )
      BEAMB = 1./c * (1. + B * SINELV)/ (1 .+ B) / PI

      RETURN
      END

```


Appendix VII. Listing of subroutine ASSIM

```

*****
* SUBPROGRAM: ASSIM
*
* Origin: SUBROUTINE ASS from SUCROS87 (Spitters et al., 1989)
* Purpose:
*   calculates instantaneous canopy assimilation (mg CO2 m-2 s-1)
*
* Description:
*   Instantaneous canopy photosynthesis is calculated from
*   absorbed diffuse and direct PAR at various depth's in canopy.
*   A spherical leaf angle distribution is assumed.
*   Photosynthesis is calculated for sunlit and shaded leaves.
*   A negative-exponential photosynthesis-light response curve is assumed.
*
* Input:
*   SCP      : (R4) scattering coefficient for PAR          [-]
*   PGMAX    : (R4) leaf gross assim. at light satur.      [mg CO2 m-2 s-1]
*   EFF      : (R4) initial light use efficiency           [mg CO2 J-1]
*   KDIFBL   : (R4) extinction coefficient diffuse light -
*               non-scattering leaves                      [-]
*   KDIF     : (R4) extinction coefficient diffuse light    [-]
*   LAI      : (R4) Leaf Area Index                        [-]
*   SINELV   : (R4) sine of solar elevation                [-]
*   PARDIR   : (R4) flux direct PAR                        [J m-2 s-1]
*   PARDIF   : (R4) flux diffuse PAR                       [J m-2 s-1]
*
* Output:
*   PGROS    : (R4) canopy instantaneous gross assim.     [mg CO2 m-2 s-1]
*
* SUBPROGRAMS CALLED: none
*
*****
      SUBROUTINE ASSIM( SCP,PGMAX,EFF,KDIFBL,KDIF,LAI,
& SINELV,PARDIR,PARDIF, PGROS )
      IMPLICIT REAL (A-Z)
      INTEGER L,I2, IGAUSS
      DIMENSION XGAUSS(3), WGAUSS(3)

      DATA IGAUSS /3/
      DATA XGAUSS /0.1127, 0.5000, 0.8873/
      DATA WGAUSS /0.2778, 0.4444, 0.2778/

*--- Prevent math overflows at low solar elevations; limit solar
* elevation set at 3 degrees
      SINEL = AMAX1( 0.05, SINELV )

*--- canopy reflection coefficient (REFL)
      REFL = (1. - SQRT(1.-SCP)) / (1. + SQRT(1.-SCP))
      REFPD = REFL * 2. / (1. + 2.*SINEL)

*--- extinct.coeff. for direct component (KDIRBL) and
* total direct flux (KDIRT); cluster factor as ratio between
* empirical and theoretical value of KDIF
      CLUSTF = KDIF / (0.8*SQRT(1.-SCP))
      KDIRBL = (0.5/SINEL) * CLUSTF
      KDIRT = KDIRBL * SQRT(1.-SCP)

*--- selection of canopy depths (LAIC from top)
      PGROS = 0.
      DO 200 L = 1, IGAUSS
        LAIC = LAI * XGAUSS(L)

*--- absorbed radiation fluxes per unit leaf area (J m-2 s-1):
* diffuse flux, total direct flux, direct component of direct flux
      PARLDF = (1.-REFL) * PARDIF * KDIF * EXP(-KDIF * LAIC)
      PARLT  = (1.-REFPD) * PARDIR * KDIRT * EXP(-KDIRT*LAIC)

```


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```

      PARLDR = (1.-SCP) * PARDIR * KDIRBL * EXP(-KDIRBL * LAIC)

*--- absorbed fluxes (J m-2 leaf s-1) for shaded and sunlit leaves
      PARLSH = PARLDF + (PARLT - PARLDR)
*--- direct par absorbed by leaves perpendicular on direct beam
      PARLPP = PARDIR * (1.-SCP)/SINEL

*--- fraction sunlit leaf area
      FSLLA = CLUSTF*EXP(-KDIRBL*LAIC)

*--- assimilation of shaded leaf area (mg CO2 m-2 leaf s-1)
      ASSSH = PGMAX * (1.-EXP(-EFF*PARLSH/PGMAX))
*--- assimilation of sunlit leaf area (mg CO2 m-2 leaf s-1)
      ASSSL=0.
      DO 210 I2 = 1,3
        PARLSL = PARLSH + PARLPP * XGAUSS(I2)
        ASSSL = ASSSL + PGMAX * (1. - EXP(-PARLSL * EFF / PGMAX))
        $      * WGAUSS(I2)
210    CONTINUE

      PGROS = PGROS + ((1.-FSLLA)*ASSSH + FSLLA*ASSSL)*WGAUSS(L)
200 CONTINUE

*--- instantaneous crop gross assimilation (mg CO2 m-2 s-1)
      PGROS = PGROS * LAI

      RETURN
      END

```

After the listing of this subroutine, the listing is given of a datafile mimicking a greenhouse cover transmissivity of 100%.

VIII-2

```

*****
* Data file with transmissivities of greenhouse
* These data are to be read by SUBROUTINE TRANSM
*****
*
* Transmissivity data are from Venlo-type multispan glasshouse
*
* Greenhouse parameters were given as input to the model of
* Bot (1983)
* Output of the model were diffuse light transmissivity
* and table with transmissivities for direct light
* as dependent on solar position
*
* Greenhouse parameters :
*   ROOFSLOPE      = 26.000
*   REFR.INDEX     = 1.500
*   GLASS THICKNESS = 0.004
*   POWER ABS.COEFF. = 5
*   HEIGHT OF RIDGE
*     LOWER HALF   = 0.097
*     UPPER HALF   = 0.010
*   WIDTH OF RIDGE
*     AT LOWER SIDE = 0.057
*     AT UPPER SIDE = 0.025
*   HEIGHT OF GUTTER
*     LOWER HALF   = 0.035
*     UPPER HALF   = 0.050
*   WIDTH OF GUTTER
*     AT LOWER SIDE = 0.130
*     AT UPPER SIDE = 0.220
*   HEIGHT OF A BAR = 0.030
*   WIDTH OF A BAR  = 0.020
*   DISTANCE BARS   = 0.730
*   SPANWIDTH       = 3.200
*   HEIGHT OF A BEAD = 0.440
*   WIDTH OF A BEAD  = 0.040
*   DISTANCE BEADS   = 3.000
*
* Sky diffuse radiance:  $I_1 = 0.333 + 0.667 * \sin(\text{ELEVN})$ 
*-----
* DIFFUSE TRANSMISSIVITY
0.65
*-----
* DIRECT TRANSMISSIVITY - data for interpolation table
*-----
*
* NUMBER OF ELEVATION LAYERS (maximal 20)
18
* FORMAT FOR READING data of the azimuth, transmission of
* construction and transmission of glass
* belonging to a single elevation layer
* Maximal 20 azimuth values for each elevation layer
(9F8.3,/,9F8.3)
*
* DATA FOR EACH ELEVATION LAYER; format is:
*   elevation layer 1
*   number of entries
*     azimuth1, azimuth2, azimuth3, azimuth4, ....
*     .... azimuth n
*   tcon1, tcon2, tcon3, ....
*   .... tcon n
*   tglas1, tglas2, tglas3, ....
*   .... tglas n
*   elevation layer 2
*   number of entries
*     azimuth1, azimuth2, azimuth3, azimuth4, ....
*     .... azimuth m

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*   tcon1, tcon2, tcon3, ....
*   .... tcon m
*   tglas1, tglas2, tglas3, ....
*   .... tglas m
*
* Note: elevations should run from lowest to highest;
* dimensions are degrees
*
2.5
18
2.5, 7.5, 12.5, 17.5, 22.5, 27.5, 32.5, 37.5, 42.5,
47.5, 52.5, 57.5, 62.5, 67.5, 72.5, 77.5, 82.5, 87.5,
0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
0.147, 0.255, 0.322, 0.363, 0.401, 0.426, 0.447, 0.460, 0.471,
0.478, 0.482, 0.486, 0.488, 0.490, 0.490, 0.490, 0.490, 0.490,
7.5
17
2.6, 7.9, 13.2, 18.5, 23.8, 29.1, 34.4, 39.7, 45.0,
50.3, 55.6, 60.9, 66.2, 71.5, 76.8, 82.1, 87.4,
0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.007, 0.034, 0.062, 0.093,
0.132, 0.200, 0.281, 0.312, 0.342, 0.375, 0.402, 0.437,
0.320, 0.434, 0.526, 0.592, 0.637, 0.666, 0.684, 0.694, 0.700,
0.703, 0.706, 0.711, 0.714, 0.716, 0.717, 0.718, 0.718,
12.5
16
2.8, 8.4, 14.1, 19.7, 25.3, 30.9, 36.6, 42.2, 47.8,
53.4, 59.1, 64.7, 70.3, 75.9, 81.6, 87.2,
0.232, 0.234, 0.237, 0.244, 0.262, 0.302, 0.296, 0.314, 0.339,
0.367, 0.399, 0.433, 0.472, 0.514, 0.556, 0.594,
0.489, 0.530, 0.641, 0.700, 0.743, 0.773, 0.792, 0.804, 0.812,
0.816, 0.818, 0.819, 0.820, 0.820, 0.819, 0.819,
17.5
15
3.0, 9.0, 15.0, 21.0, 27.0, 33.0, 39.0, 45.0, 51.0,
57.0, 63.0, 69.0, 75.0, 81.0, 87.0,
0.400, 0.395, 0.402, 0.406, 0.415, 0.427, 0.464, 0.515, 0.521,
0.523, 0.541, 0.574, 0.609, 0.648, 0.684,
0.619, 0.635, 0.666, 0.767, 0.800, 0.824, 0.842, 0.853, 0.859,
0.863, 0.865, 0.866, 0.867, 0.867, 0.867,
22.5
14
3.2, 9.6, 16.1, 22.5, 28.9, 35.4, 41.8, 48.2, 54.6,
61.1, 67.5, 73.9, 80.4, 86.8,
0.501, 0.499, 0.506, 0.510, 0.517, 0.528, 0.543, 0.561, 0.606,
0.661, 0.706, 0.737, 0.764, 0.799,
0.711, 0.716, 0.737, 0.802, 0.838, 0.854, 0.866, 0.875, 0.881,
0.885, 0.887, 0.888, 0.889, 0.889,
27.5
13
3.5, 10.4, 17.3, 24.2, 31.2, 38.1, 45.0, 51.9, 58.8,
65.8, 72.7, 79.6, 86.5,
0.572, 0.570, 0.578, 0.582, 0.589, 0.600, 0.614, 0.632, 0.653,
0.678, 0.705, 0.745, 0.785,
0.775, 0.776, 0.783, 0.814, 0.858, 0.875, 0.882, 0.888, 0.891,
0.894, 0.895, 0.896, 0.897,
32.5
12
3.8, 11.3, 18.8, 26.3, 33.8, 41.3, 48.8, 56.3, 63.8,
71.3, 78.8, 86.3,
0.624, 0.623, 0.622, 0.636, 0.643, 0.654, 0.669, 0.687, 0.708,
0.733, 0.760, 0.789,
0.818, 0.817, 0.818, 0.825, 0.857, 0.887, 0.894, 0.897, 0.899,
0.900, 0.900, 0.900,
37.5
11

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VIII-3

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4.1, 12.3, 20.5, 28.6, 36.8, 45.0, 53.2, 61.4, 69.5,
77.7, 85.9,
0.664, 0.664, 0.664, 0.678, 0.686, 0.698, 0.714, 0.732, 0.754,
0.778, 0.806,
0.847, 0.846, 0.844, 0.847, 0.866, 0.891, 0.901, 0.904, 0.904,
0.905, 0.905,
42.5
10
4.5, 13.5, 22.5, 31.5, 40.5, 49.5, 58.5, 67.5, 76.5,
85.5,
0.697, 0.697, 0.698, 0.714, 0.722, 0.735, 0.751, 0.771, 0.794,
0.819,
0.866, 0.865, 0.863, 0.862, 0.863, 0.877, 0.902, 0.906, 0.908,
0.909,
47.5
9
5.0, 15.0, 25.0, 35.0, 45.0, 55.0, 65.0, 75.0, 85.0,
0.725, 0.725, 0.727, 0.732, 0.754, 0.768, 0.785, 0.806, 0.829,
0.879, 0.878, 0.875, 0.873, 0.873, 0.873, 0.887, 0.902, 0.906,
52.5
8
5.6, 16.9, 28.1, 39.4, 50.6, 61.9, 73.1, 84.4,
0.748, 0.750, 0.752, 0.759, 0.782, 0.797, 0.817, 0.839,
0.888, 0.886, 0.884, 0.882, 0.881, 0.880, 0.879, 0.885,
57.5
7
6.4, 19.3, 32.1, 45.0, 57.9, 70.7, 83.6,
0.769, 0.771, 0.775, 0.783, 0.809, 0.826, 0.847,
0.893, 0.892, 0.890, 0.888, 0.886, 0.886, 0.886,
62.5
6
7.5, 22.5, 37.5, 52.5, 67.5, 82.5,
0.788, 0.791, 0.796, 0.806, 0.821, 0.841,
0.897, 0.896, 0.894, 0.893, 0.891, 0.891,
67.5
5
9.0, 27.0, 45.0, 63.0, 81.0,
0.806, 0.810, 0.817, 0.829, 0.847,
0.899, 0.898, 0.897, 0.896, 0.895,
72.5
4
11.3, 33.8, 56.3, 78.8,
0.822, 0.828, 0.837, 0.853,
0.901, 0.900, 0.899, 0.898,
77.5
3
15.0, 45.0, 75.0,
0.838, 0.846, 0.860,
0.902, 0.901, 0.901,
82.5
2
22.5, 67.5,
0.853, 0.861,
0.902, 0.902,
87.5
1
45.0,
0.870,
0.903,

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*****
* Data file with transmissivities of greenhouse
* These data are to be read by SUBROUTINE TRANSM
*****
*
* DIFFUSE TRANSMISSIVITY
1.00
*-----
* DIRECT TRANSMISSIVITY - data for interpolation table
*-----
*
* NUMBER OF ELEVATION LAYERS (maximal 20)
2
* FORMAT FOR READING data of the azimuth, transmission of
* construction and transmission of glass
* belonging to a single elevation layer
* Maximal 20 azimuth values for each elevation layer
(9F8.3,/,/,9F8.3)
*
* DATA FOR EACH ELEVATION LAYER; format is:
*   elevation layer 1
*   number of entries
*       azimuth1, azimuth2, azimuth3, azimuth4, ....
*       .... azimuth n
*       tcon1, tcon2, tcon3, ....
*       . . . . . tcon n
*       tglas1, tglas2, tglas3, ....
*       . . . . . tglas n
*   elevation layer 2
*   number of entries
*       azimuth1, azimuth2, azimuth3, azimuth4, ....
*       .... azimuth m
*       tcon1, tcon2, tcon3, ....
*       . . . . . tcon m
*       tglas1, tglas2, tglas3, ....
*       . . . . . tglas m
*
* Note: elevations should run from lowest to highest; dimension is
degrees
*
2.5
2
2.5, 87.5,
1.0, 1.0,
1.0, 1.0,
87.5
1
45.0,
1.0,
1.0,

```


Appendix IX. Descriptions and dimensions of variables and parameters

Variable or parameter	Description	Dimension
ASRQLV	assimilate requirement leaves	$\text{g CH}_2\text{O g}^{-1} \text{ DM}$
ASRQRT	assimilate requirement roots	$\text{g CH}_2\text{O g}^{-1} \text{ DM}$
ASRQSO	assimilate requirement storage organs	$\text{g CH}_2\text{O g}^{-1} \text{ DM}$
ASRQST	assimilate requirement stems	$\text{g CH}_2\text{O g}^{-1} \text{ DM}$
ASSSH	assimilation rate of shaded leaf area	$\text{mg CO}_2 \text{ m}^{-2} \text{ leaf area s}^{-1}$
ASSSL	assimilation rate of sunlit leaf area	$\text{mg CO}_2 \text{ m}^{-2} \text{ leaf area s}^{-1}$
ATMTR	atmospheric transmission	-
AZIMGR	azimuth greenhouse	radians
AZIMS	azimuth of sun	radians
BDIF	parameter for angular distribution diffuse light	-
CLUSTF	clustering factor of leaves for radiation interception	-
CO2AIR	CO_2 concentration in greenhouse air	$\mu\text{l l}^{-1}$
CO2PFT	CO_2 production factor of crop dry weight increment	$\text{g CO}_2 \text{ g}^{-1} \text{ DM}$
COSLD	amplitude of sine of solar height	-
DAYL	astronomical daylength (base = 0 degrees)	h
DAYNR	day number (Jan 1st = 1)	-
DECL	declination of sun	radians
DELT	time step	d
DPARDF	daily diffuse PAR inside greenhouse	$\text{J m}^{-2} \text{ d}^{-1}$
DPARDR	daily direct PAR inside greenhouse	$\text{J m}^{-2} \text{ d}^{-1}$
DSINBE	daily total of effective solar height	s
DTASS	daily total of gross assimilates (sugars)	$\text{g CH}_2\text{O m}^{-2} \text{ d}^{-1}$
DTGA	daily total gross assimilation	$\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$
DTR	daily total of global radiation outside greenhouse	$\text{J m}^{-2} \text{ d}^{-1}$
DTRTB	table containing values of DTR	-
EFF	leaf initial light use efficiency	$\text{mg CO}_2 \text{ J}^{-1}$
EFF0	leaf initial light use efficiency without photorespiration	$\text{mg CO}_2 \text{ J}^{-1}$
ELEVN	elevation of sun	radians
FILTRN	name of file with transmissivity data	-
FINDAY	finishing day of simulation (SUKAM)	d
FLV	dry matter partitioning to leaves	-
FRACPAR	fraction PAR in global radiation	-
FRDIF	fraction diffuse radiation	-

FRT	dry matter partitioning to roots	-
FSO	dry matter partitioning to storage organs	-
FSLLA	fraction sunlit leaf area	-
FST	dry matter partitioning to stems	-
GAMMA	CO ₂ compensation point without dark respiration	$\mu\text{l l}^{-1}$
GC	inverse of carboxylation resistance	m s^{-1}
GCT	table of temperature dependency of GC	-
GLRADO	global radiation outside greenhouse	$\text{J m}^{-2} \text{s}^{-1}$
GLV	rate of DM increase of leaves	$\text{g m}^{-2} \text{d}^{-1}$
GRADCF	factor for converting radiation data to $\text{J m}^{-2} \text{d}^{-1}$	
GRRESP	crop growth respiration	$\text{g CO}_2 \text{m}^{-2} \text{h}^{-1}$
GRT	rate of DM increase of roots	$\text{g m}^{-2} \text{d}^{-1}$
GSO	rate of DM increase of storage organs	$\text{g m}^{-2} \text{d}^{-1}$
GST	rate of DM increase of stems	$\text{g m}^{-2} \text{d}^{-1}$
GTW	rate of DM increase of crop	$\text{g m}^{-2} \text{d}^{-1}$
HOUR	hour of day	h
IATTN	index for leaf angle distribution	-
ITASK	control variable for initialization, rate calculation, and other tasks	-
KDIF	extinction coefficient for diffuse light	-
KDIFBL	extinction coefficient for diffuse light, non-scattering leaves	-
LAI	Leaf Area Index	$\text{m}^2 \text{leaf m}^{-2} \text{ground}$
LAIC	partial Leaf Area Index (above reference point)	$\text{m}^2 \text{leaf m}^{-2} \text{ground}$
LAT	latitude of site	degrees/radians
LONG	longitude of site	degrees/radians
MAINT	crop maintenance respiration	$\text{g CH}_2\text{O m}^{-2} \text{d}^{-1}$
MAINTS	crop maintenance respiration at 25 °C	$\text{g CH}_2\text{O m}^{-2} \text{d}^{-1}$
MAINLV	maintenance costs of leaves	$\text{g CH}_2\text{O g}^{-1} \text{DM d}^{-1}$
MAINRT	maintenance costs of roots	$\text{g CH}_2\text{O g}^{-1} \text{DM d}^{-1}$
MAINSO	maintenance costs of storage organs	$\text{g CH}_2\text{O g}^{-1} \text{DM d}^{-1}$
MAINST	maintenance costs of stems	$\text{g CH}_2\text{O g}^{-1} \text{DM d}^{-1}$
MNRESP	crop maintenance respiration	$\text{g CO}_2 \text{m}^{-2} \text{h}^{-1}$
OAV	average projection of leaves into direction of sun	-
ONP	average projection of leaves into direction of sun, near-planophile l.a.d	-
OX	projection of leaves with given leaf angle into direction of sun	-
PAR	Photosynthetically Active Radiation inside greenhouse	$\text{J m}^{-2} \text{s}^{-1}$
PAROUT	Photosynthetically Active Radiation outside greenhouse	$\text{J m}^{-2} \text{s}^{-1}$

TBCON	table with transmissivity of construction as dependent on solar elevation	-
TBGLAS	table with transmissivity of cladding material of greenhouse cover, as dependent on solar elevation	-
TEFF	temperature effect on maintenance respiration	-
TEMPAI	temperature of greenhouse air	°C
TERMNL	control variable for ending simulation	-
TIMCOR	difference between solar and local time	h
TLEAF	leaf temperature	°C
TRCON	transmission of the construction for direct radiation	-
TRDIF	transmissivity of greenhouse for diffuse light	-
TRDIR	transmissivity of greenhouse for direct light	-
TRGLAS	transmission of the glass for direct radiation	-
TWT	dry weight of crop	g m ⁻²
WGAUS3	table for 3-point Gaussian weights	-
WGAUS5	table for 5-point Gaussian weights	-
WLV	dry weight of leaves	g m ⁻²
WLVI	initial leaf dry weight of crop	g m ⁻²
WRT	dry weight of roots	g m ⁻²
WRTI	initial root dry weight of crop	g m ⁻²
WSO	dry weight of storage organs	g m ⁻²
WSOI	initial dry weight of storage organs	g m ⁻²
WST	dry weight of stems	g m ⁻²
WSTI	initial stem dry weight of crop	g m ⁻²
XGAUS3	table for 3-point Gaussian distances	-
XGAUS5	table for 5-point Gaussian distances	-

MAINSO	0.01 g CH ₂ O g ⁻¹ DM d ⁻¹	typical value for annual crop, given by Spitters <i>et al.</i> (1989);
MAINST	0.015 g CH ₂ O g ⁻¹ DM d ⁻¹	typical value for annual crop, given by Spitters <i>et al.</i> (1989);
PMMT		table contains schematized response of leaf maximal endogeneous photosynthetic capacity; maximum based on Farquhar & von Caemmerer (1982);
Q10MN	2	from Spitters <i>et al.</i> (1989); equal to that of many metabolic processes;
Q10RD	2	temperature dependence dark respiration is assumed to be the same as that of many metabolic processes;
RB	100 s m ⁻¹	from Stanghellini (1985);
RD20	0.05 mg CO ₂ m ⁻² s ⁻¹	as assumed for a 'sun' leaf;
REFGR	0.	assumed as standard in simulation runs
REFTMP	25.	reference temperature maintenance respiration
RS	50 s m ⁻¹	based on Hicklenton & Jolliffe (1980), Paez <i>et al.</i> (1984), Bakker (1991) and Nederhoff <i>et al.</i> (1992)
SCP	0.15	average for cucumber, tomato and sweet pepper (unpublished results);
TBCON		table with transmissivity greenhouse construction for direct light; in the simulation runs a dark and a light greenhouse were assumed;
TBGLAS		table with transmissivity greenhouse cladding material for direct light; in the simulation runs a dark and a light greenhouse were assumed;
TRDIF	0.65	calculated with Bot's model for the dark greenhouse as used in the simulation runs